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1 A comparative study of odorants for gas 2 escape detection of natural gas and 3 hydrogen.

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11 Abstract

12 Decarbonising the residential heating and cooking sector is essential to meet national and international
13 carbon emission reduction targets. Hydrogen has been identified by the scientific community, industry,
14 and policy makers as part of the solution to this challenge. Hydrogen has been used for decades in many
15 industries, formerly making up approximately 50% of the Town Gas used for heating and cooking in UK
16 homes in the mid 20th century. It is now crucial to ensure safety regulations are met, and public
17 acceptance gained, before hydrogen can start being used for residential heating. Demonstration projects
18 require hydrogen distribution networks to be odorised. This study examines the use of sulphur-based
19 odorants, which are currently in use in the UK and Europe to odorise Natural Gas, to be used in a 100%
20 hydrogen gas demonstration network in the UK. We undertook a comparative testing programme to
21 evaluate the escape detection properties of odorised hydrogen against odorised methane and natural gas.
22 This comparative approach will help address the question asked by UK and EU regulators: is hydrogen
23 ‘as safe as’ natural gas? The results show that untrained participants can identify an escaping gas odorised
24 with Odorant New Blend and standby odorant 2, in hydrogen, natural gas or methane, at the regulatory
25 threshold of 1% gas in air. These results contribute to the safety-case of H100 led by SGN.

26 Introduction

27 Hydrogen is currently being considered to support the decarbonisation of the energy systems which are,
28 at present, overly reliant on GHG emitting natural gas. Ensuring that hydrogen is ‘as safe as’ natural gas is
29 a critical requirement for this transition to happen (Kopasz, 2007). Odorising hydrogen to allow escape
30 detection, without artificial sensors and training, is paramount in achieving the safety standards required
31 for domestic use. Here we present the need for hydrogen in the current energy system and what it means

32 for innovative projects like H100 led by SGN for which this work was carried out. We then follow by an
33 overview of the history of the odourisation of gases, and then highlight the remaining knowledge gaps that
34 need addressing to ensure that the rate of hydrogen uptake allows decarbonisation targets to be met.

35 Hydrogen in a changing Energy System

36 Hydrogen gas has been identified as a significant contributor to achieving a low-carbon future. Hydrogen
37 has been proposed as an alternative zero-carbon energy carrier, which can be converted to heat or
38 electricity, with the potential to be easily stored and transported (Pudukudy, Yaakob, Mohammad,
39 Narayanan, & Sopian, 2014). Hydrogen would also contribute to increasing the security of the energy
40 system by reducing the dependency on fossil fuels (Sheffield & Sheffield, 2007). Most importantly it
41 would act as a carrier allowing energy to be transmitted and used across the transport, heat, industry and
42 power generation sectors (Staffell et al., 2019). Hydrogen could indeed allow the decarbonisation of the
43 heat and transport sectors, which have proved challenging to decarbonise in comparison to electricity
44 generation (Staffell et al., 2019). In the UK, for example, which relies on natural gas to heat 84% of its
45 households, the gas emissions from the residential sector has reduced by only 16% from 1990 levels
46 (BEIS, 2019). This illustrates that the rate of decarbonisation of heating needs to be increased rapidly
47 (Staffell et al., 2019). Not only would hydrogen offer a way forward in speeding up the decarbonisation of
48 the residential sector, but it would also offer end users the opportunity to keep using heat in a familiar
49 and accepted way e.g. through combustion boilers and cookers, similar to the natural gas products in use
50 today (Dodds & Demoullin, 2013). Hydrogen would also offer, with some network reinforcement, a
51 decarbonised future to the vast national and international infrastructure used to deliver gas which has
52 been upgraded over the past 50 years (Dodds & Demoullin, 2013).

53 Hydrogen 100 Project – Residential heating and cooking through a 100% hydrogen 54 network

55 This work was commissioned by SGN and supports the safety case of the ‘Hydrogen 100’ innovation
56 project. SGN is a UK gas distribution network operator. The Hydrogen 100 project seeks to demonstrate
57 the feasibility of supplying 100% hydrogen to 300 selected homes which could include small businesses.
58 The project will ensure that new 100% hydrogen compatible appliances are installed and a new hydrogen
59 distribution network is built. We note that although a wider transition to hydrogen use would rely on both
60 new and existing infrastructure, this demonstration project relies on new assets to reduce risk and
61 uncertainty whilst gathering knowledge and experience. The work presented in this study investigates
62 whether odourised hydrogen releases within a conceptual domestic space would be as readily detectable as
63 a release from odourised natural gas. The Hydrogen 100 project includes a comprehensive investigation of
64 hydrogen delivery through a new polyethylene distribution network. Further investigations related to
65 odourants are being undertaken including physical testing of material exposed to odourised natural gas and
66 hydrogen.

67 [Brief history of gas odourisation](#)

68 Mining has historically been an industry where exposure to the hazards of odourless combustible gases
69 was frequent and deadly. When gas started to be used more readily in the 19th century in urban settings
70 the idea of odourising this gas, before use, was proposed by Julius Quaglio (in 1880) in Germany (Fink,
71 2015). Although gas from natural sources often contains impurities providing a natural odour, processing
72 techniques increased the odourless character of some pure gases like methane, carbon monoxide, carbon
73 dioxide and hydrogen, making them more dangerous. Natural gas has been odourised for more than a
74 century (Kilgallon, Gilfillan, Haszeldine, & McDermott, 2015). The odourisation of natural gas from
75 distribution networks became a legal obligation following the ‘New London School’ accident in Texas
76 (1937), which claimed the lives of 294 people (Kopasz, 2007). Odourisation is regulated because the
77 primary component of natural gas, methane, is colourless and odourless. Since the same is true for
78 hydrogen, artificial odourisation using an odorant compound would be required to meet regulations.

79 Still to this day, in order to deliver gas to customers via a distribution network, gas needs to be odourised.
80 Odourisation is a legal requirement in many countries because it is deemed an essential safety feature
81 (Dodds & Demoullin, 2013; Puri, 2006). Indeed, most healthy people untrained in olfactory detection will
82 be able to detect the distinctive smell associated with a gas escape due to the now widely enforced
83 odourisation practices.

84 [Research gap in hydrogen network odourisation assessment](#)

85 Significant research has been undertaken on the odourisation of natural gas in pipelines. Some key points
86 to consider with gas odourisation are the detectable limits of the gas odour, the type of odorant used (e.g.
87 sulphur based, acrylate), the odourisation technique, and the monitoring system used to ensure that
88 odorants meet the regulatory thresholds. These aspects are reviewed in Fant (1993).

89 The literature highlights both the importance of odourising hydrogen (Brewer, 1978) whilst acknowledging
90 that the odorants might not behave in the same way in hydrogen as they do in natural gas. This is
91 primarily due to the different chemical and physical properties of hydrogen (Dodds & Demoullin, 2013;
92 Kopasz, 2007). The chemical compatibility of sulphur based odorants with hydrogen during piped
93 transport has been demonstrated by the Health and Safety Executive of the UK (JP Hodges, Geary,
94 Graham, Hooker, & Goff, 2015).

95 However, there remains a lack of reported investigation into the physical and olfactory properties of high
96 purity hydrogen and odorant mixtures. This lack of investigation could hinder the progress of crucial
97 demonstration projects needed to prove the use and deployment of hydrogen at scale. To date most of
98 the focus on hydrogen odourisation has been placed on the end uses. In particular, fuel cells used to
99 produce electricity from hydrogen (de Wild, Nyqvist, de Bruijn, & Stobbe, 2006; Dodds & Demoullin,
100 2013; Imamura, Akai, & Watanabe, 2005; Kopasz, 2007). This is understandable since commonly used
101 sulphur based odorants are toxic to fuel cells, and fuel cells are likely to become a critical end use for

102 hydrogen (Staffell et al., 2019). Hence, a research focus to date has been placed on the desulfurization of
103 odourised gas (Kim et al. 2007, Bae et al. 2009, Oshima et al. 2020). However, our study addresses the lack
104 of investigation into the olfactory response to odourised hydrogen compared to natural gas, for an
105 equivalent end use aimed at combustion appliances. This work complements a previous study by Mouli-
106 Castillo et al. (2020) which investigates the likely olfactory characteristics of odourised hydrogen delivered
107 to consumers via a distribution network. The Mouli-Castillo et al. (2020) investigation focused on
108 applying standardised olfactory tests to odourised hydrogen. This method provided quantitative
109 information, using reproducible tests, but not a direct comparative assessment with odourised natural gas.
110 This comparative testing is important since the UK and EU regulators have sought demonstration (via
111 comparative testing) that hydrogen is ‘as safe as’ the natural gas currently in use (HyDeploy website and
112 (JRC, 2013)). In this study we report, for the first time, a set of comparative tests undertaken by Kiwa
113 Gastec on odourised hydrogen, methane and natural gas from the UK network. We discuss the findings in
114 the context of the wider Hydrogen 100 project, as well as the ‘as safe as’ approach sought by the
115 regulators.

116 Odourisation Practices in the UK

117 In this section we briefly introduce the regulations and standards governing gas odourisation practices in
118 the UK. In the UK, any gas supplied to end users from a network which has a pressure of 7 bar gauge or
119 below should be odourised (Gas Safety (Management) Regulations, 1996).

120 The gas should be odourised to impart an odour with an intensity of 2 on the Sales scale (Sales, 1958), that
121 is a ‘medium odour’. This will allow a gas escape to be detected by the population at 20% of the lower
122 flammability limit, which is equivalent to about 1% gas in air concentration for both natural gas and
123 hydrogen. In that sense odourisation is designed and regulated to provide warning prior to reaching
124 flammable gas mixtures. Hence this study focuses on gas detectability rather than explosion risk, which is
125 an important topic in its own right and is being actively investigated (e.g. Sinha et al., 2019; Lowesmith et
126 al., 2009, Makarov et al., 2018). ISO 13734:2013 presents the general characteristics of an effective
127 odorant:

- 128 a) The gas odorant should have a strong odour at very low concentration,
- 129 b) The odour character of the odorant needs to be unpleasant, distinctive and not confusable with
130 other frequently occurring odours so that it is unmistakably associated with a gas escape,
- 131 c) The odour character should be the same at different dilutions of natural gas with air,
- 132 d) The odorant should be sufficiently stable during storage and when mixed with natural gas,
- 133 e) The volatility of the odorant should be high enough so that the odorant does not appreciably
134 condense under the conditions (temperature and pressure) existing in the pipeline system,
- 135 f) Evaporation of the gas odorant should not appreciably leave residues,
- 136 g) The odorant should be useable at low temperatures, when required,
- 137 h) The combustion of the odorant should not leave significant solid deposits,
- 138 i) The addition of the odorant to natural gas should not make the resulting gas harmful,
139

140 Currently demonstration projects, which are designed to underpin and support the uptake of hydrogen as
141 a decarbonisation technology, are required to demonstrate that hydrogen can be used in a way which is ‘as
142 safe as’ natural gas is today (HyDeploy, 2019). We have formalised this approach into two research
143 hypotheses:

- 144 1. The odorants currently used with natural gas (generally sulphur based compounds) will be as
145 effective when used with hydrogen.
- 146 2. Very small escapes of hydrogen are detectable in the same way as an escape of natural gas in a
147 comparable room space.

148 These were tested through a series of comparative olfactory experiments that provided quantifiable,
149 verifiable, and comparable data on the olfactory response of human participants to both 1) odorised
150 hydrogen and 2) natural gas.

151 Methods

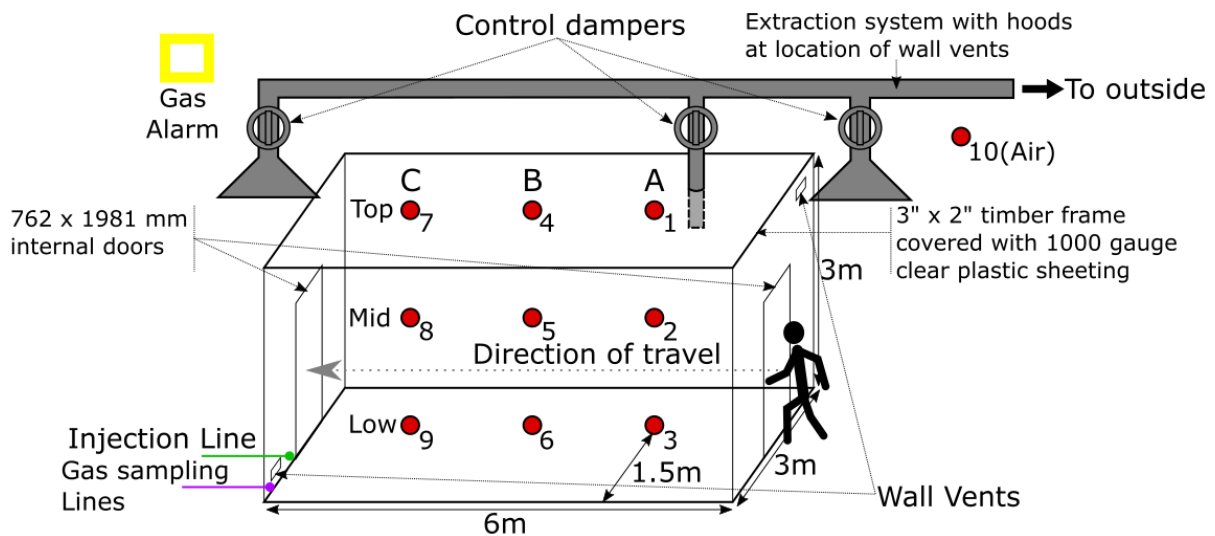
152 This section details the experimental setup, choice of participants, the rules the participants had to follow,
153 and finally the experimental matrix presenting the tests performed.

154 Experimental Setup

155 The experimental setup was designed to allow control of as many parameters as possible to ensure
156 reproducibility of the experimental conditions. The various elements of that setup are described below
157 and visualised in Figure 1.

- 158 1) An enclosure made of timber and heavy-duty polythene sheets. The dimensions of the enclosure
159 were 3 m wide by 6 m long and 3 m high, giving a total volume of 54 m³. These dimensions are
160 representative of a ≈ 25 m² living room (with a floor to ceiling height of 2.5 m), which was
161 typical for the 1970’s when domestic housing was converted to natural gas, and was consistent
162 with the standards of the time (LABCWarranty, 2019; Park, 2017). It is deemed appropriate to
163 use this comparative basis, as it is still representative of the type of UK housing likely to use gas
164 heating.
- 165 2) An extraction system was installed. It comprised two extraction hoods installed outside the
166 enclosure above the doors, and an extraction point inside the enclosure. All extraction points
167 were connected to an extraction duct leading outdoors. The system was design to clear gas from
168 the enclosure, the door area, and the waste gas from gas chromatographs. This ensured that the
169 space could be cleared from any gas prior to initiating each experiment i.e. resetting to baseline
170 conditions.
- 171 3) A system to mix pure gas with an odorant rich gas mixture, and then inject it into the enclosure
172 was designed. Injection in the range of 0.01 to 50 litres per minute could be used. The system

173 was designed to mix un-odorised gas with odorised gas to reach the 2 part per million volume
 174 (ppm) odorant concentration target (discussed below) in the injected gas stream.
 175 4) A sampling system was put in place which allowed a continuous and controlled extraction rate to
 176 be set for each of the sampling points. This ensured a fresh sample was always available and that
 177 there was no lag between any of the sample lines. Ten sample lines were used in total – nine to
 178 sample the enclosure, and one to sample the air outside to provide a reference sample to ensure
 179 the accuracy of the equipment.



180
 181 Figure 1: Experimental Setup. The height levels of the sampling points are as follow: Top at 2.7m, Mid at 1.5m and
 182 Low at 0.3m. The dimensions of the wall vents are 229 x 229 mm.

183 The experimental testing was conducted in a controlled, indoor environment in the Kiwa Gastec testing
 184 laboratories. This avoided the effects of wind on the dispersion of the gas and allowed rigorous control of
 185 the gas injection and dispersion, including for the final venting procedure at the end of each test. The
 186 tests were carried at ambient temperature, representative of dwellings in temperate climates, such as the
 187 UK. The results might not be representative of poorly insulated buildings in tropical, arid, and polar
 188 regions.

189 Sampling Procedure

190 Two gas chromatograph analysers (Inficon Micro GC Fusion) were used for measuring the levels of
 191 methane or hydrogen in the sampled gas in ppm. Each chromatograph used a molecular sieve-type
 192 column heated to 90 °C with an argon carrier gas injected at 69 Millibar (mbar). The chromatographs
 193 sampled each line in turn through the multipoint sampling valves and the gas in air concentrations (in
 194 ppm) was recorded. The analysis process consisted of a short purge with the sampled gas 15 s) followed
 195 by injection into the column within the chromatograph (100 ms) and then progression of the sample
 196 through the column (120 s). The multipoint sampling valves were moved to the next desired sampling
 197 line, and the process repeated. The concentration of the flammable gas in question was then calculated
 198 from the chromatograph, logged, and graphed in real time for visual verification. Using two

199 chromatographs in conjunction enabled for an offset logging sequence whereby the time delay between
200 each sampling point being measured was reduced. The sampling order is presented in Supplementary
201 Table 1.

202 Furthermore, the participants were not made aware of where in the enclosure the lines were sampling
203 from. In addition, the participants did not know that the lines and sample points were fixed during the
204 course of the experiment.

205

206 Tested Gases & Odorants

207 The gases used in this test programme prior to any mixing were:

- 208 1) Line gas from the local gas distribution network (odorised with odorant NB).
- 209 2) Un-odorised methane (reference fuel G20 with over 99% methane (EU Commission, 2017))
- 210 3) Un-odorised hydrogen (Grade 4.5, that is, with a purity of 99.995%)
- 211 4) Odorised methane and hydrogen (provided in bottles at 20 ppm odorant concentration)

212 Gases were supplied to the injection rig at a pressure of 0.5 bar. A target odorant concentration of 2 ppm
213 was achieved by diluting the odorised gas (at 20 ppm) with the equivalent un-odorised gas according to
214 the test specifications (Supplementary Table 3). 2 ppm is the concentration used in the UK gas network
215 (Mouli-Castillo et al., 2020). The specification for the odorant and gas mixtures used for the experimental
216 work were provided by the National Physical Laboratory, and supplemented their research programme on
217 the odourisation of hydrogen for gas distribution networks.

218 Odorant New Blend (NB) is in use in the UK. It is used, along with its diluted form (known as Standby
219 Odorant 2), by the UK distribution network operator SGN. Odorant THT is an odorant commonly used
220 on the European mainland. Odorants using mixes of the compounds tested here are also used in Japan
221 (Cagnon, 2011). Therefore, the findings from this study are directly applicable to support the
222 development of hydrogen networks in many countries.

223 The odorant components used are presented in Table 1.

224 Table 1: Odorant composition used in the tested mixtures.

| Odorant | Composition |
|-------------------|---|
| New Blend (NB) | 78% tert-Butylthiol, 22% Dimethyl Sulfide |
| Standby Odorant 2 | 34% Odorant NB, 64% Hexane |
| Odorant THT | 100% TetraHydroThiophene |

225

226 The injection rates used aimed for a nominal gas in air (GIA) concentration inside the enclosure of:

- 227 - 10,000 ppm (1%) which is the concentration of gas at the maximum level allowed by the
- 228 regulator (about 20% of the lower flammability limit).
- 229 - 1,000 (0.1%) an order of magnitude lower than the regulatory threshold.
- 230 - and 500 ppm (0.05%) 20 times lower than the regulatory threshold.

231 This range of concentrations allows for reasonable assessment of gas escape detectability before
232 dangerous levels of gas are reached, whilst avoiding ‘false alarms’ from very low concentrations.

233 Air Tightness

234 The air permeability of a ‘new build’ property was assumed a worst-case scenario (Crowther, Orr,
235 Thomas, Stephens, & Summerfield, 2015). An air tightness test was conducted to ensure the experimental
236 setup was representative of such worst case scenario. This test measured the enclosure’s permeability to
237 air. A new build property has an air tightness value of 10 m³/h/m² or less (Crowther et al., 2015).

238 An approved testing company undertook the testing at 0.5 mbar to EN 13829:2001. The 0.5 mbar
239 pressure used for the air tightness test is dictated by the standard and not related to the injection pressure
240 used in our tests. The air tightness test results (Supplementary Table 2) show that the test enclosure with
241 open vents performed comparably to a new build property. All the olfactory testing described in this
242 study was undertaken with the wall vents open to be representative of a new build property.

243

244 Test Programme

245 The test programme was divided into two phases. The first phase aimed to calibrate the equipment and
246 understand the pattern of gas dispersion within the enclosure. These tests were completed using un-
247 odorised methane and hydrogen, and enabled the determination of injection flow rates that would lead to
248 the targeted gas in air concentration in the second phase. In addition, these tests served to test various
249 sampling locations in the horizontal and vertical plane within the enclosure to ensure sampling locations
250 were representative and were not biased towards any potential gas accumulations (e.g. in the corners of
251 the enclosure). After each test, the enclosure and the space around it, were fully ventilated using the
252 extraction system.

253 Phase 2 of the experimental programme involved tests using natural gas (line gas), odorised hydrogen,
254 and odorised methane. At the start of each experiment, the enclosure was setup in the same manner. The
255 wall vents remained open, the centre vent on the extraction system was shut, and an integrity check was
256 performed on the gas injection and sample lines. The extraction vents from above either end of the
257 enclosure were left open for the duration of the test to allow for the extraction of any escaping gas
258 (including waste gas from the chromatographs).

259 Once the enclosure setup was completed, the test flow rates of both the odorised gas at 20 ppm, and the
260 un-odorised gas, were set using the mixing rig (Supplementary Table 3). Once the flow rates had stabilised

261 to provide approximately 2ppm of odorant within the un-odorised gas the mixed gas was injected into the
262 test enclosure via the open end of a 10 mm copper pipe. In order to simulate a domestic space in which
263 no active mixing of the volume would occur, it was decided not to homogenise the gas mixture inside the
264 enclosure. This implied that the actual gas concentrations inside the enclosure would vary (hence the nine
265 sampling points). The reference value of the 'gas in air concentration' (GIA), which was used to set up
266 the injected gas flow rate, was located at the centre of the enclosure (see curve labelled 'Mid B' in the
267 results section).

268 During the gas injection phase of the test, 'sniff tests' were carried out at specified time intervals using the
269 sampling ports (Supplementary Figure 1) which were connected to the ten sampling lines. Each sniff test
270 lasted a few seconds before the participant left the test area. Each participant was a voluntary Kiwa staff
271 member untrained in olfactory assessment. They were asked to smell each of the sample ports in turn and
272 to record whether they could detect a smell. If a smell was detected the participant was asked to rate the
273 intensity of the smell using the following scoring system of 1 to 5, otherwise a score of 0 was attributed.
274 The gas was considered detectable when 50% or more of the trial participants detected a smell on a given
275 sample line. The scoring system was based on a recognised odorant detection and perception scale; used
276 for air monitoring and odour science (IAQM, 2018; Nimmermark, Schmidt, Jacobson, & Gay, 2005).

- 277 1) Very faint, may be identified as a gas escape
- 278 2) Faint but identifiable as a gas escape
- 279 3) Easily detectable and easily identified as a gas escape
- 280 4) Strong and easily identified as a gas escape
- 281 5) Very strong/unpleasant easily identified as a gas escape

282 Five minutes after the start of injection the first sniff test was performed. This was followed by one every
283 15 minutes during the injection period. The last sniff test was performed following the cessation of
284 injection, once the concentrations had stabilised around the target level for that test. This final sniff test
285 usually occurred 10 minutes after the stop of injection. Following the sniff tests, the participants were
286 asked to complete a walkthrough of the test enclosure.

287 The walkthrough was designed as follows: each participant entered the enclosure through the door
288 located at the opposite end to the injection point. They then walked (as a group) through the enclosure
289 towards the injection point and exited the enclosure through the door located closest to the injection
290 point (Figure 1). The walkthroughs lasted approximately 15 seconds each. Following the walkthrough, the
291 participants were asked to comment on the strength of the odour inside the enclosure. The same scale as
292 the sniff test was used. In addition, participants were asked to indicate where the first odour was detected.
293 One of four locations could be indicated: 1) as soon as the door opened before entering the enclosure, 2)
294 as soon as they entered the enclosure, 3) midway through the enclosure, 4) at the injection point.

295 The doors of the enclosure were kept closed until the end of the test (except to let the participant exit and
296 enter the enclosure). As the focus of the study is placed on the detectability of gas escapes, the tests were
297 completed after the end of the walkthrough and no assessment of the dissipation of the gas in the
298 enclosure was conducted. Once the test had been completed the enclosure was vented to the outside
299 using the central vent of the extraction system (Figure 1).

300 Trial Rules

301 This section describes the rules that the participants had to follow during the tests. Safety procedures are
302 not described here in detail, only the rules pertaining to the scientific validity of the experiments. A
303 complete risk assessment was however carried out to ensure the safety of the participants and the trial
304 operators. Key safety measures which should be mentioned are that 1) the flammable gas/air mixtures
305 within the test facilities were continually monitored and never exceeded 1% gas in air (GIA), 2) potential
306 sources of ignition were not allowed in the enclosure, and 3) any potentially unaccounted for odorant risk
307 was mitigated by rotating participants, exposing them to odourised gas for only seconds at a time, and
308 asking them to vacate the test area immediately after each test.

309 The participants were not qualified in olfactometry and can be described as ‘naïve’ from that standpoint.
310 It should be noted that olfactory literature indicates that increasing age tends to reduce olfactory
311 sensitivity, whilst the effect of gender on olfactory sensitivity depends on several factors including the
312 study, odorant compound tested, and the test task performed (Bliss, Schulz, SENGHER, & Kaye, 1996;
313 James Evans, Cui, & Starr, 1995; Klimek, Gudziol, Owen, Pauli, & Hummel, 2000; Nguyen, Rumeau,
314 Gallet, & Jankowski, 2016). To ensure any that age and gender factors were captured in the study, both
315 female and male participants were selected over three age groups 1) under 30 years old, 2) 30 to 50 years
316 old and 3) over 50 years old. For each test a mix of males, females and ages was ensured.

317 To evaluate the public’s response to an escape of odourised gas, standards cannot be used as they require
318 olfactory experts rather than untrained members of the public (CEN, 2003). Using untrained participants
319 presented a methodological risk since the participants might not have constituted a representative sample
320 of the wider population. This could have introduced bias. To account for this bias, the research was
321 designed as a comparative study, assuming that any bias from the untrained participants would apply
322 equally to all gases and odorants tested. Further confidence can be had by comparing the findings with
323 standardised tests’ results, although these usually lack the comparative element added by this study (see
324 discussion section) (Mouli-Castillo et al., 2020). This allows a useful comparative analysis. Such
325 comparative assessments are needed to develop quantitative risk assessments (QRAs) for demonstration
326 projects.

327 To guarantee that no cross-contamination or ‘nose blindness’ occurred for the participants, the following
328 procedures were enforced:

- 329 1) The location of each sample point within the enclosure was not communicated to the participant.
330 This removed the opportunity for the participants to pre-assume a particular gas concentration,
331 and therefore bias their judgment (e.g. hydrogen concentrations are higher closer to the ceiling,
332 therefore odour should be greater too).
- 333 2) The participants did not know the gas injection rate and the target GIA (ppm) concentration.
334 This avoided any expectations as to whether or not an odour 'should' be detectable.
- 335 3) For the entire duration of the test the participant were prevented from accessing the zone where
336 the cylinders with the concentrated odorised gases (at 20 ppm) were stored. This avoided any
337 exposure to the odorant via a gas escape from the regulator, or from the valve of the cylinder.
- 338 4) The participants were instructed to leave the test area immediately after each experiment (sniff
339 test or walkthrough).
- 340 5) Participants were rotated regularly and limited to the number of tests which could be conducted
341 in a day.
- 342 6) Between 3 and 4 participants took part in each test.

343 [Experimental Matrix](#)

344 The experimental matrix used for the phase 2 of the testing can be found in the Supplementary Table 3.
345 A total of 18 tests were carried out. In test 1,2, and 3 it was observed that no odorant was detected at all.
346 This was attributed to the odorant being retained by the pipework in the initial tests. This is common
347 phenomenon and industrial pipes are commonly 'soaked' with odorants prior to being used for
348 commercial purposes. For this reason test 1,2 and 3, were repeated as test 6,7 and 13 respectively.

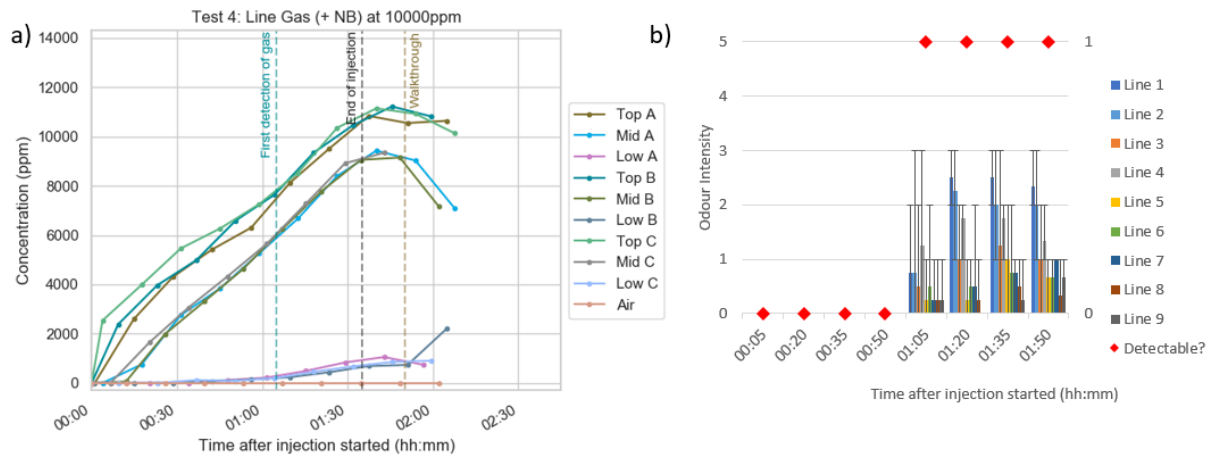
349

350 [Results](#)

351 The following sections present the results of the Phase 2 tests (presented in Supplementary Table 3) for
352 which odorant detection occurred. We also explicitly mention for which tests no detection occurred. For
353 each test the following items are presented: the GIA concentration obtained during the test, the time at
354 which the first detection via a sniff test occurred, and the time and gas concentration in the enclosure
355 when the walkthrough was conducted. The results are presented in subsection for each gas-odorant pair
356 tested. Each subsection presents the results for the different concentrations tested.

357 [Natural Gas](#)

358 The presence of natural gas (line gas) was detected during the 10,000 ppm GIA test 4 (Figure 2.a), but not
359 during the two 1,000 ppm GIA tests 3 and 13.



360

361 Figure 2: a) Test 4, natural gas (line gas) at a target concentration of 1% GIA. b) Test 4 - Average intensity recorded
 362 for the sniff tests.

363 Following initial detection after 1h05min of the natural gas odour on the sample lines 1 and 4, the odour
 364 remained detectable throughout the rest of the test period (Figure 2.b). The greatest odour intensity was
 365 usually recorded for sample lines 1 and 2 (the top and middle sample points furthest from the injection
 366 point), and line 4 at the high level in the middle of the enclosure (Figure 2.b).

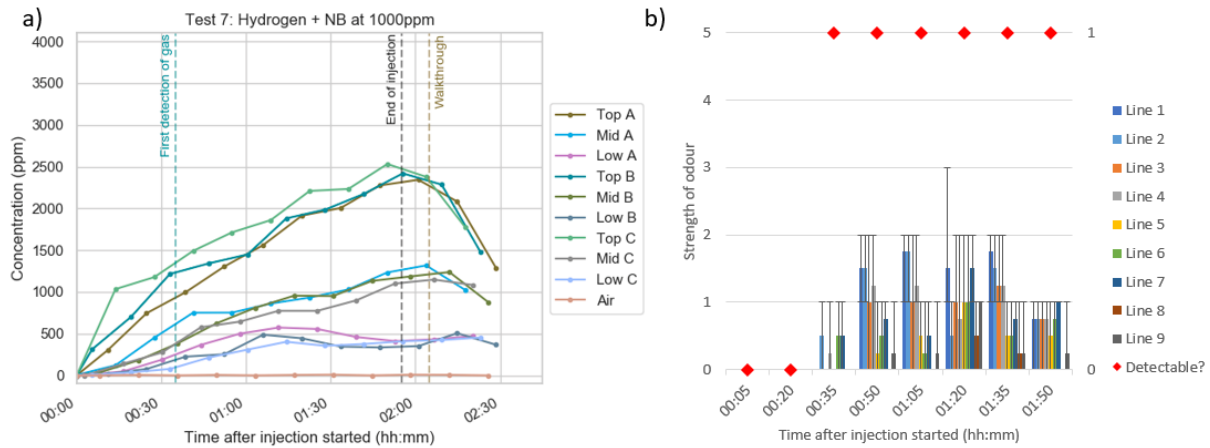
367 Hydrogen with Odorant NB

368 Hydrogen was tested with Odorant NB (the principal odorant used in the UK natural gas network).

369 During the 500 ppm, 1,000 ppm and 10,000 ppm GIA tests, gas odour was identified.

370 During the 500 ppm experiment, sniff detection scores were variable with a highest intensity of 1. This
 371 rose to a maximum of 2 during walkthrough (Table 2).

372 During the 1,000 ppm and 10,000 ppm experiments (Figure 3 and 5 respectively), once odours were
 373 detected in the sniff tests, the odour remained apparent for the remainder of the trial period. The
 374 maximum intensity during the 1,000 ppm sniff test was 3, with an average of 1 (Figure 3.b). This rose to 4
 375 during the walkthrough of the enclosure (Table 2). The gas smell was first identified in the enclosure at an
 376 average GIA concentration of about 600 ppm (maximum GIA of about 1,400 ppm Figure 3.a). A smell
 377 was detected on all sample lines, with lines 1 and 2 (top and mid-level furthest from the injection point)
 378 perceived to have the highest intensity of smell.

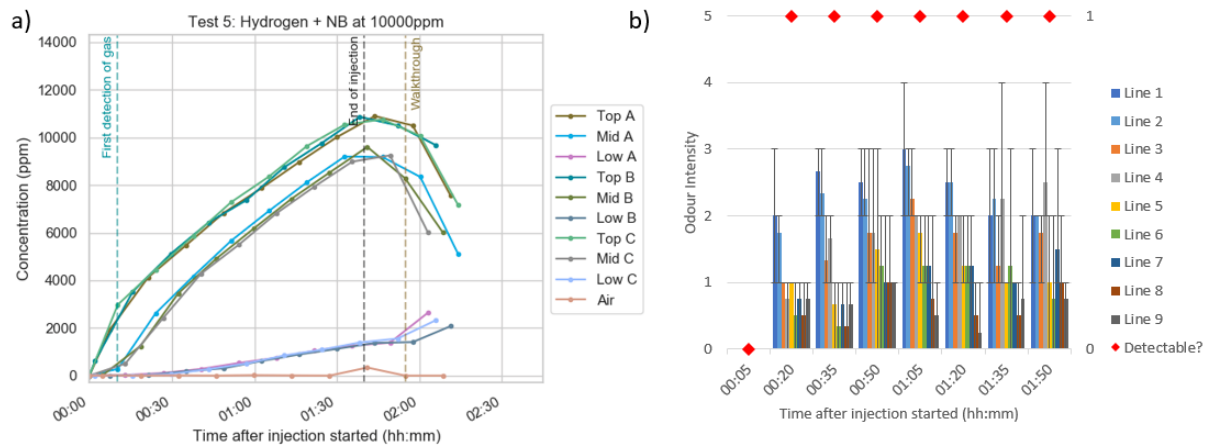


379

380 Figure 3: a) Test 7, hydrogen and odorant NB at a target concentration of 0.1% GIA. b) Test 7 Average intensity
 381 recorded for the sniff tests.

382 During the 10,000 ppm experiment, 20 minutes after the start of injection, an odour with an intensity of 2
 383 was detected (Figure 4.b). At which point the maximum GIA concentration within the enclosure was
 384 ~3,000 ppm, with an average of ~1,000 ppm (Figure 4.a). During the sniff tests the average odour level
 385 was 2 (Figure 4.b). This was lower than the recorded value during the walkthrough of the enclosure
 386 where an intensity of 4 was recorded by all participants (Table 2). Once again, the strongest intensity of
 387 smell was recorded on sample lines 1 and 2, followed closely by line 4 (top position in the centre of the
 388 enclosure).

389



390

391 Figure 4: a) Test 5, hydrogen and odorant NB at a target concentration of 1% GIA. b) Test 5 Average intensity
 392 recorded for the sniff tests.

393 Hydrogen with diluted Odorant NB (standby 2)

394 Hydrogen was tested with hexane-diluted Odorant NB i.e. standby odorant 2, which is used by SGN in
 395 the UK.

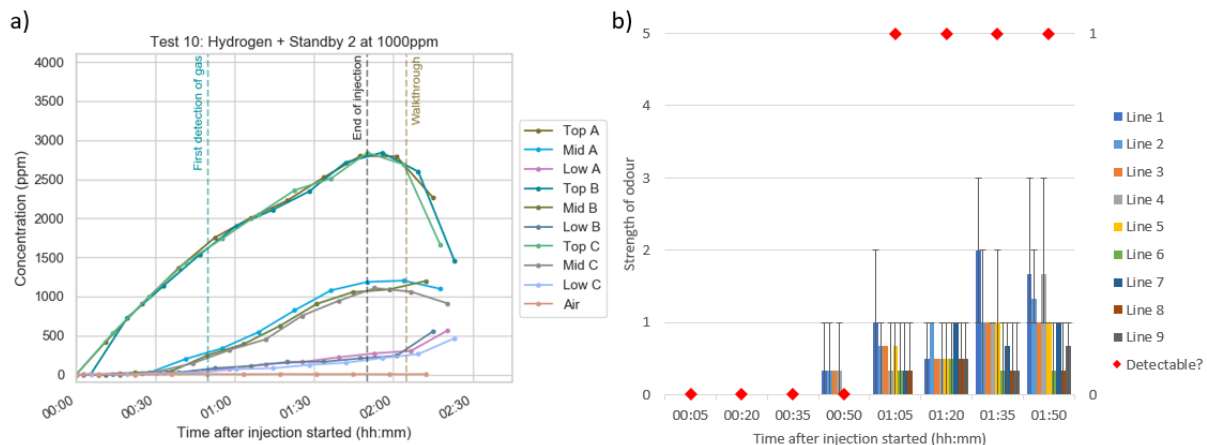
396 Once tests 5 to 8 had been performed it was determined that due to the intensity of the odorant, and the
 397 similarity between the standby odorant 2 and Odorant NB, if standby odorant 2 was detected at low GIA

398 concentrations, then testing at higher concentrations was not required, since Odorant NB had been
399 detectable at higher concentrations.

400 The presence of gas was not identifiable with standby odorant 2 at 500 ppm GIA concentrations.

401 During both the 1,000 ppm sniff tests and enclosure walkthrough, hydrogen odorized with standby
402 odorant 2 was reported at a maximum intensity of 3, although the average intensity oscillated between 0
403 and 1 (Figure 5.b). Some of the participants identified it as a gas escape in their comments. At the time of
404 first detection during the sniff tests, a maximum GIA concentration inside the enclosure of around 1,600
405 ppm was recorded, with an average GIA inside the room of about 650 ppm (Figure 5.a). Once identified
406 the gas odour stayed evident during the remainder of the sniff tests.

407 Once again, the strongest intensity of smell was consistently recorded on sample line 1. Following the
408 initial detection, the odour was identified on all the sample lines as presented in Figure 5.b.



409

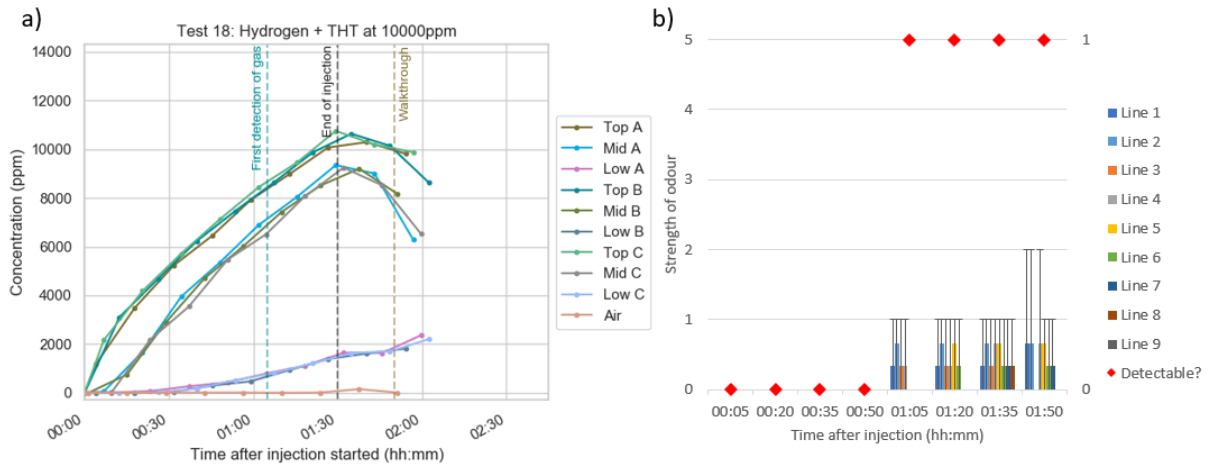
410 Figure 5: a) Test 10, hydrogen and standby odorant 2 at a target concentration of 0.1% GIA. b) Test 10 Average
411 intensity recorded for the sniff tests.

412 Hydrogen with THT

413 During the test of hydrogen odorised with odorant THT, gas was identified by the participants during the
414 10,000 ppm GIA concentration test (Figure 6 a). However, it was not detected for the tests with a GIA
415 concentration of 500 ppm or 1,000 ppm.

416 The sniff tests conducted during the 10,000 ppm GIA concentration experiment revealed that the
417 maximum odour intensity, which could be identified by the participants, was 2 (Figure 6.b). The
418 participants also recorded that the smell was unpleasant but not immediately identifiable as a gas escape.
419 The odour character was described as “chemically” or “similar to onion/garlic”. At the time of first
420 detection, 1h05, by sniff tests the maximum GIA concentration within the enclosure was about 8,500
421 ppm, with an average of around 5,400 ppm (Figure 6.a). As in most of the previous tests, the highest
422 odour intensity levels were recorded on sample lines 1, 2 and 4 (Figure 6.b).

423 The odour intensity registered by all but one of the participants during the walkthrough was of 4 (Table
 424 2). This is higher by two scale points than during the sniff tests. A participant commented that the
 425 enclosure had a musty odour, whilst only scoring that odour at an intensity score of 1. The participants
 426 characterised the odour as “chemically” or “very strong onion” or “garlic”.



427

428 Figure 6: a) Test 18, hydrogen and THT at a target concentration of 1% GIA. b) Test 18 Average intensity recorded
 429 for the sniff tests.

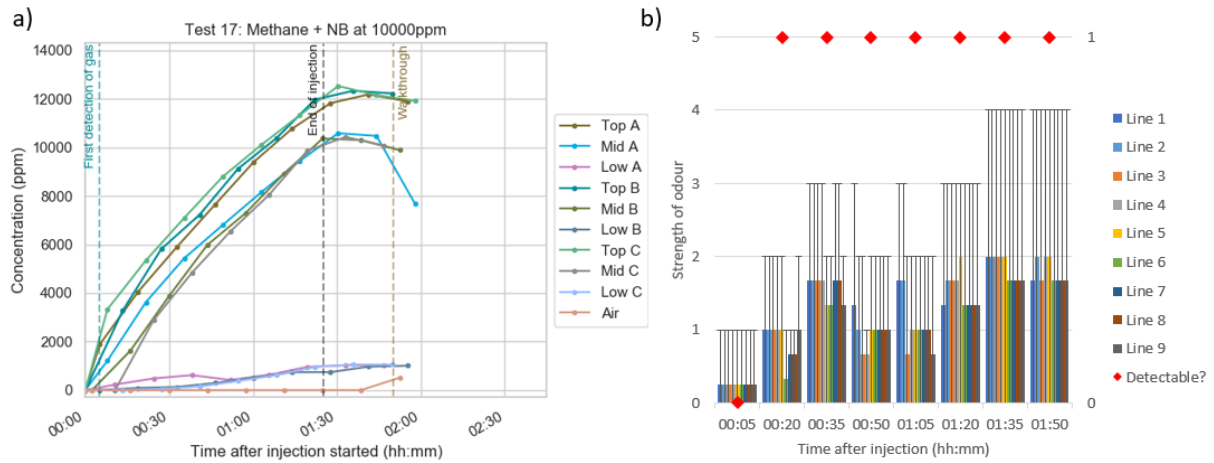
430 Methane with NB

431 Methane (G20) combined with Odorant NB at 2 ppm was tested. The presence of gas could be identified
 432 by smell by the participants during the 10,000 ppm GIA concentration test (Figure 7.a). No odour was
 433 detected for the tests conducted at GIA concentrations of 500 ppm and 1,000 ppm (tests 15 and 16).

434 The maximum odour intensity recorded in the sniff tests was a value of 4 (Figure 7.b). The detection
 435 occurred after 20 minutes of injection (Figure 7.b). The maximum odour intensity of 2 at the time of
 436 detection during the 10,000 ppm experiment (Figure 7.b). At the point of first detection, the highest GIA
 437 concentration within the enclosure was approximately 2,000 ppm, with an average of about 700 ppm
 438 (Figure 7.a). The average odour intensity as indicated on each sample line by the participants is shown in
 439 Figure 7.b.

440 During the walkthrough a maximum odour intensity of 4 was recorded inside the enclosure (Table 2).

441 This intensity is consistent with the maximum identified during the sniff tests.



442

443 Figure 7: a) Test 17, methane (G20) and odorant NB at a target concentration of 1% GIA. b) Test 17 Average
 444 intensity recorded for the sniff tests.

445

446 **Odorant Tracking**

447 Table 2 displays the walkthrough findings during which gas was identified and ranked on odour intensity.
 448 It indicates at which location the scent was identified—"Door Open" means the odour was perceived as
 449 the door opened before the participant entered the enclosure.

450 The entrance door was furthest from the point of injection. The point of injection was located at the end
 451 of the enclosure. Odour identification took place at the 'entry to enclosure' (Table 2). This is evidence
 452 that the odorant persisted within the gas as it passed through the room, or that the concentration of
 453 odorant within the gas was sufficiently intense to be detectable everywhere within the release area.

454 The detection of the various odorised gases during the 'sniff tests' at sample lines 1, 2 and 3 (located
 455 furthest and closest to the injection point) are consistent with the observation that odorants do indeed
 456 remain within the hydrogen. It is conceivable that after the odour was identified the participants became
 457 used to the odour, and thus the lines which were sampled last appeared less intense. In some cases, the
 458 participants of the experiment were asked to reverse the order in which they checked the sample lines
 459 (still without knowledge of which sample line corresponded to which sample point), however this led to
 460 only minor variation in the apparent strength of the odour.

461 Table 2: Odour intensity recorded by participants during the walkthrough of the enclosure at given target locations.
 462 The letter does not identify a specific participant.

| Test | Participant | Door Open | Entry to enclosure | Middle of enclosure | Point of gas injection |
|----------------------------|-------------|-----------|--------------------|---------------------|------------------------|
| 4 - 10,000 ppm Line Gas | A | 0 | 0 | 4 | 4 |
| | B | 0 | 0 | 3 | 3 |
| | C | 4 | 4 | 5 | 5 |
| | D | 4 | 4 | 5 | 5 |
| 5 - 10,000 ppm Hydrogen NB | A | 4 | 4 | 4 | 4 |

| | | | | | |
|-------------------------------|---|---|---|---|---|
| | B | 4 | 4 | 4 | 4 |
| | C | 4 | 4 | 4 | 4 |
| | D | 4 | 4 | 4 | 4 |
| 7 - 1,000 ppm Hydrogen NB | A | 0 | 3 | 3 | 3 |
| | B | 0 | 3 | 3 | 3 |
| | C | 0 | 3 | 3 | 3 |
| | D | 0 | 3 | 3 | 3 |
| 8 - 500 ppm Hydrogen NB | A | 0 | 2 | 2 | 2 |
| | B | 0 | 2 | 2 | 2 |
| | C | 0 | 1 | 1 | 1 |
| | D | 0 | 2 | 2 | 2 |
| 10 - 1,000 Hydrogen Standby 2 | A | 3 | 3 | 0 | 3 |
| | B | 2 | 2 | 0 | 0 |
| | C | 2 | 2 | 1 | 1 |
| 12 - 1,000 Hydrogen THT | A | 2 | 2 | 1 | 0 |
| | B | 0 | 0 | 0 | 0 |
| | C | 0 | 0 | 0 | 0 |
| | D | 2 | 2 | 1 | 1 |
| 17 - 10,000 Methane NB | A | 5 | 5 | 5 | 5 |
| | B | 4 | 4 | 4 | 4 |
| | C | 0 | 4 | 4 | 4 |
| 18 - 10,000 Hydrogen THT | A | 4 | 4 | 4 | 4 |
| | B | 4 | 4 | 4 | 4 |
| | C | 1 | 1 | 1 | 1 |

463 Discussion

464 This study tested the two hypothesis that 1) the odorants currently used with natural gas will have a
465 similar effectiveness when used with hydrogen, and 2) that the detection of very small escapes of
466 hydrogen are detectable in a similar way to a natural gas escape in an equivalent room volume. This
467 section discusses how the findings address these hypotheses and outlines the results limitations.

468 The study was designed around the UK's legal requirement that the presence of gas should be readily
469 detectable by smell at GIA concentration of 20% of the lower flammability limit. This equates to around
470 1% GIA for both methane and hydrogen (Gov, 1996). At this 1% GIA concentration, all the tested
471 odorants led to the gas releases being detected by the trial participants. When mixed with either hydrogen
472 or methane, both Odorant NB or Standby odorant 2 led to the smell being identified specifically as a gas
473 escape at concentrations of 1% GIA. As such, it can be concluded that, under the conditions of this trial,
474 the two hypothesis are verified.

475 During the hydrogen 'THT' tests the odorant was detected at 1% GIA concentration, but not identified
476 specifically as a gas escape by participants. The trial participants being UK residents could explain why
477 they did not identify a gas odorised with an odorant primarily used on the European mainland. This result

478 suggests how embedded the odour character of gas is in a given population and corroborates the
479 observation made by a report for the Health and Safety Executive of the UK (J. Hodges, Geary, Graham,
480 Hooker, & Goff, 2015). This illustrates that, should a different odorant to the ones being used today be
481 used in future hydrogen networks, the public should be correctly informed and educated to associate the
482 new odour character to a gas escape.

483 Another observation of note is that odorant NB, currently in use in the UK, was detected at much lower
484 concentrations (down to 0.05% GIA) when mixed with hydrogen in comparison with a detection
485 occurring at 1% GIA when mixed with methane, or as part of line gas. However, the testing method
486 does not allow for the cause of this to be determined with certainty. In addition, the results indicated that
487 stratification of the gases within an enclosure 3 m high does not negatively affect the detection potential
488 of a gas escape.

489 Additionally, we note that the THT target concentration in the gas was set to 2 ppm as per odorant NB
490 and standby odorant 2 in the UK. However, literature suggests that the THT concentration in use in the
491 European mainland are in the range of 3 to 11 ppm (Uni. Of. Miskolc & Hungarian Scientific Society of
492 energy Economics, 2008; Zhang, 2019). This could explain why THT appeared to be less easily detectable
493 than odorant NB.


494 Table 3 summarises that, for odorant NB and Standby odorant 2, the maximum and average GIA
495 concentrations within the enclosure are comparable between the hydrogen and methane tests. This also
496 confirms the hypotheses tested.

497 One important experimental design choice to consider is the use of volumetrically equivalent gas injection
498 rates, as opposed to energy injection rates. Indeed, due to the lower energy density of hydrogen at the
499 standard delivery pressure of domestic gas networks, the volumetric flow rate of hydrogen would be
500 about 3 times greater than that of natural gas to ensure an equivalent rate of energy delivery. However,
501 what our results have shown is that both hydrogen and methane escapes can be detected at equivalent
502 GIA concentrations and both at the required value of 1% GIA.

503

504 Table 3: Maximum and average gas in air concentrations within the enclosure at the point of first detection.

| Gas in air saturation (ppm) | Test 4 Line Gas 10000 ppm | Test 17 Methane + NB 10000 ppm | Test 5 Hydrogen + NB 10000 ppm | Test 7 Hydrogen + NB 1000 ppm | Test 10 Hydrogen + Standby2 1000ppm | Test 18 Hydrogen + THT 10000 ppm |
|-----------------------------|---------------------------|--------------------------------|--------------------------------|-------------------------------|-------------------------------------|----------------------------------|
| 9000 - 10000 | | | | | | |
| 8000 - 9000 | | | | | | |
| 7000 - 8000 | | | | | | |
| 6000 - 7000 | | | | | | |
| 5000 - 6000 | | | | | | |
| 4000 - 5000 | | | | | | |
| 3000 - 4000 | | | | | | |
| 2000 - 3000 | | | | | | |
| 1000 - 2000 | | | | | | |
| 0 - 1000 | | | | | | |



 Maximum ppm in the enclosure at the time of first detection
 Average ppm in the enclosure at the time of first detection

505

506 This study found that odorants appeared to remain with the hydrogen gas as it moves through an
 507 enclosed space. Sprague and Flynn (2013) discussed that the molecular weight and dispersion properties
 508 of hydrogen, relative to odorant compounds, were likely to lead to the odorant not remaining within the
 509 gas stream in a stagnant environment (US 8 394 553 B2, 2013). However, they also suggested that in a
 510 domestic dwelling, ventilation could be sufficient to drive dispersion and to keep the odorant mixed with
 511 the gas stream (US 8 394 553 B2, 2013). The finding of this study supports this for hydrogen, natural gas
 512 and methane.

513 One limitation of the study is the small number of participants in each test (3 to 4). The variation in
 514 participant responses is apparent in a few tests. Detection occurred at 2000 ppm for test 17, whilst gas
 515 concentration in tests 15 and 16 reached a maximum of 2500 ppm without the gas release being detected.
 516 A similar observation can be made for test 12 were the escape was detected (but not identified as a gas
 517 escape) at a lower concentration than the maximum measured in test 11, when no detection occurred in
 518 test 11. This can be explained by the definition of “detection” used in this study to be when at least one
 519 participant detected a smell. This increases the sensitivity of the results to the individual participant’s
 520 olfactory sensitivity. Despite these variations, if we compare our findings to previous olfactory testing
 521 from Mouli-Castillo et al. (2020), which was performed on odorised hydrogen using standardised tests in
 522 an accredited laboratory, we find that the odorant concentration in air from our work are within an order
 523 of magnitude from those presented in that study. More specifically, our detection thresholds for
 524 Hydrogen with New Blend, Standby Odorant 2 and THT, are 6.15, 4.5 and 2.2 times greater than the
 525 ones from that study respectively. This can be explained, in part, by the use of ‘naïve’ participants in our

526 study, compared to an expert panel in their study. Another contributing factor is likely to be the fact that
527 our study mimic a real new dwelling environment with natural ventilation resulting in uneven
528 concentrations in the test volume, whereas olfactory measurements undertaken in their study are carried
529 out on precisely measured samples. It should also be noted that a variation of less than an order of
530 magnitude between olfactory studies with different methodologies should be considered a good match
531 (Murnane, Lehocky, & Owens, 2013). Both studies' conclusions agree that odorant in hydrogen will
532 induce an equivalent olfactory response to odorant in natural gas.

533 Conclusion

534 This research is important because it addresses a key safety aspect of gas distribution: the odourisation of
535 gas to allow untrained people to detect gas escapes before they reach a flammable level. This research is
536 essential to the safety cases developed by hydrogen demonstration projects, in particular H100 in the UK
537 which aims to deliver 100% hydrogen to 300 homes via a purpose built distribution network.

538 By providing a direct comparison with methane, an approach which was not directly studied in the
539 standardised tests from Mouli-Castillo et al. (2020), it addresses the key requirement imposed by
540 regulators in the UK that hydrogen distribution should be demonstrated to be 'as safe as' the current
541 natural gas one.

542 Our work provides evidence that firstly, the odorants currently used within natural gas will have a similar
543 effectiveness in allowing escape detections when used with hydrogen. Secondly, that small escapes of
544 hydrogen are detectable in a comparable way to a natural gas escape in an equivalent room volume. These
545 conclusions can be considered robust as they were demonstrated by two different methodologies using
546 very different approaches.

547 These findings are also applicable to other innovation projects around the world which require the
548 demonstration that hydrogen can be effectively odourised and any releases detected. In particular, since the
549 odourant compounds tested are used in many countries.

550 References

- 551 Bae, Jong Wook, Suk-Hwan Kang, G. Murali Dhar, Ki-Won Jun, (2009). Effect of Al₂O₃ content on the
552 adsorptive properties of Cu/ZnO/Al₂O₃ for removal of odorant sulfur compounds. *International*
553 *Journal of Hydrogen Energy*, Volume 34, Issue 20, Pages 8733-8740, ISSN 0360-3199,
554 <https://doi.org/10.1016/j.ijhydene.2009.08.016>. BEIS. (2019). Provisional UK greenhouse gas
555 emissions national statistics 2018. Retrieved from
556 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789952/2018-provisional-emissions-data-tables.ods [Accessed 04/11/2020]
557
- 558 Bliss, P. J., Schulz, T. J., SENGGER, T., & Kaye, R. B. (1996). Odour measurement - Factors affecting
559 olfactometry panel performance. *Water Science and Technology - WATER SCI TECHNOL*, 34, 549–

560 556. [https://doi.org/10.1016/0273-1223\(96\)00595-1](https://doi.org/10.1016/0273-1223(96)00595-1)

561 Brewer, G. D. (1978). Some environmental and safety aspects of using hydrogen as a fuel. *International*
562 *Journal of Hydrogen Energy*, 3(4), 461–474. [https://doi.org/10.1016/0360-3199\(78\)90006-X](https://doi.org/10.1016/0360-3199(78)90006-X)

563 British Standards Institution. (2013). BSI Standards Publication Natural gas — Organic components used
564 as odorants — Requirements and test methods (ISO 13734 : 2013).

565 Cagnon, F. (2011). New methodologies to help natural gas odorisation. In *International Gas Union Research*
566 *Conference*. [http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-](http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/oral-presentations/k.-which-innovations-will-improve-distribution-system-operation/OP_K_2_Francois%20Cagnon_Paper.pdf)
567 [presentations/oral-presentations/k.-which-innovations-will-improve-distribution-system-](http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/oral-presentations/k.-which-innovations-will-improve-distribution-system-operation/OP_K_2_Francois%20Cagnon_Paper.pdf)
568 [operation/OP_K_2_Francois%20Cagnon_Paper.pdf](http://members.igu.org/old/IGU%20Events/igrc/igrc2011/igrc-2011-proceedings-and-presentations/oral-presentations/k.-which-innovations-will-improve-distribution-system-operation/OP_K_2_Francois%20Cagnon_Paper.pdf) [Accessed 04/11/2020]

569 CEN. (2003). BS EN 13725:2003: Air quality - Determination of odour concentration by dynamic
570 olfactometry. *British Standards*, (April 2006), 70.

571 Crowther, M., Orr, G., Thomas, J., Stephens, G., & Summerfield, I. (2015). *Energy Storage Component*
572 *Research & Feasibility Study Scheme: HyHouse Safety Issues Surrounding Hydrogen as an Energy Storage Vector*.
573 <https://www.kiwa.com/48cef5/globalassets/uk/reports/hy-house-report.pdf> [Accessed
574 04/11/2020]

575 de Wild, P. J., Nyqvist, R. G., de Bruijn, F. A., & Stobbe, E. R. (2006). Removal of sulphur-containing
576 odorants from fuel gases for fuel cell-based combined heat and power applications. *Journal of Power*
577 *Sources*, 159(2), 995–1004. <https://doi.org/10.1016/j.jpowsour.2005.11.100>

578 Dodds, P. E., & Demoullin, S. (2013). Conversion of the UK gas system to transport hydrogen.
579 *International Journal of Hydrogen Energy*, 38(18), 7189–7200.
580 <https://doi.org/10.1016/j.ijhydene.2013.03.070>

581 European Commission (2017). Commission Regulation (EU) 2017/1151 of 1 June 2017 supplementing
582 Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of
583 motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and
584 Euro 6) and on access to vehicle repair and maintenance information, amending Directive
585 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No
586 692/2008 and Commission Regulation (EU) No 1230/2012 and repealing Commission Regulation
587 (EC) No 692/2008. L 175/1

588 Fant, E. (1993). Odorization - a regulatory perspective. *IL: Institute of Gas Technology*, 3, 109–118.

589 Fink, J. (2015). Chapter 15 Odorization. In J. Fink (Ed.), *Petroleum Engineer's Guide to Oil Field Chemicals and*
590 *Fluids* (pp. 455–475). Gulf Professional Publishing. [https://doi.org/10.1016/B978-0-12-803734-](https://doi.org/10.1016/B978-0-12-803734-8.00015-1)
591 [8.00015-1](https://doi.org/10.1016/B978-0-12-803734-8.00015-1)

592 Flynn, J. P., & Sprague, M. (2013). *US 8 394 553 B2*. United States Patent. Retrieved from

593 <https://patentimages.storage.googleapis.com/b3/47/39/04d4db263e6cff/US8394553.pdf>
594 [Accessed 04/11/2020]

595 Gas Safety (Management) Regulations (1996). UK Statutory Instruments. UK Government. Retrieved
596 from <http://www.legislation.gov.uk/uksi/1996/551/contents/made> [Accessed 04/11/2020]

597 Hodges, JP, Geary, W., Graham, S., Hooker, P., & Goff, R. (2015). *Injecting hydrogen into the gas network – a*
598 *literature search. Health and Safety Laboratory*. Retrieved from
599 <http://www.hse.gov.uk/research/rrpdf/rr1047.pdf> [Accessed 04/11/2020]

600 HyDeploy. (2019). HyDeploy. Retrieved November 25, 2019, from <https://hydeploy.co.uk/>

601 IAQM. (2018). *Guidance on the assessment of odour for planning*. London.
602 <http://www.iaqm.co.uk/text/guidance/odour-guidance-2014.pdf> [Accessed 04/11/2020]

603 Imamura, D., Akai, M., & Watanabe, S. (2005). Exploration of hydrogen odorants for fuel cell vehicles.
604 *Journal of Power Sources*, 152(1–2), 226–232. <https://doi.org/10.1016/j.jpowsour.2005.01.007>

605 James Evans, W., Cui, L., & Starr, A. (1995). Olfactory event-related potentials in normal human subjects:
606 effects of age and gender. *Electroencephalography and Clinical Neurophysiology*, 95(4), 293–301.
607 [https://doi.org/10.1016/0013-4694\(95\)00055-4](https://doi.org/10.1016/0013-4694(95)00055-4)

608 JRC. (2013). *Science for Energy JRC thematic report- EUR 25939 EN*.
609 <https://ec.europa.eu/jrc/en/publication/thematic-reports/science-energy-jrc-thematic-report>
610 [Accessed 04/11/2020]

611 Kilgallon, R., Gilfillan, S. M. V, Haszeldine, R. S., & McDermott, C. I. (2015). Odourisation of CO₂
612 pipelines in the UK: Historical and current impacts of smell during gas transport. *International Journal*
613 *of Greenhouse Gas Control*, 37, 504–512. <https://doi.org/10.1016/j.ijggc.2015.04.010>

614 Kim, Hyung-Tae, Seung-Moon Kim, Ki-Won Jun, Young-Seek Yoon, Jin-Hong Kim, (2007)
615 Desulfurization of odorant-containing gas: Removal of t-butylmercaptan on Cu/ZnO/Al₂O₃.
616 *International Journal of Hydrogen Energy*, Volume 32, Issue 15, Pages 3603-3608, ISSN 0360-3199,
617 <https://doi.org/10.1016/j.ijhydene.2007.04.027>.

618 Klimek, G. K. L., Gudziol, M. W. H., Owen, A. T. C. M., Pauli, H. S. E., & Hummel, T. (2000).
619 Multicenter investigation of 1,036 subjects using a standardized method for the assessment of
620 olfactory function combining tests of odor identification, odor discrimination, and olfactory
621 thresholds, *European Archives of Oto-Rhino-Laryngology* volume 257, pages 205–211.
622 <https://doi.org/10.1007/s004050050223>

623 Kopasz, J. P. (2007). Fuel cells and odorants for hydrogen. *International Journal of Hydrogen Energy*, 32(13),
624 2527–2531. <https://doi.org/10.1016/j.ijhydene.2006.11.001>

625 LABCWarranty. (2019). Are Britain's Houses Getting Smaller. Retrieved January 29, 2020, from
626 <https://www.labcwarranty.co.uk/blog/are-britain-s-houses-getting-smaller-new-data/> [Accessed
627 04/11/2020]

628 Lowesmith B.J., Hankinson G., Spataru C., Stobbart M. (2009). Gas build-up in a domestic property
629 following releases of methane/hydrogen mixtures. *International Journal of Hydrogen Energy*.
630 <https://doi.org/10.1016/j.ijhydene.2009.01.060>

631 D. Makarov, P. Hooker, M. Kuznetsov, V. Molkov, (2018). Deflagrations of localised homogeneous and
632 inhomogeneous hydrogen-air mixtures in enclosures. *International Journal of Hydrogen Energy*. Volume
633 43, Issue 20, Pages 9848-9869, ISSN 0360-3199, <https://doi.org/10.1016/j.ijhydene.2018.03.159>.

634 Mannan, S. (Ed.). (2012). Chapter 17 Explosion. In *Lees' Loss Prevention in the Process Industries (Fourth*
635 *Edition)* (Fourth Edi, pp. 1367–1678). Oxford: Butterworth-Heinemann.
636 <https://doi.org/10.1016/B978-0-12-397189-0.00017-3>

637 Mouli-Castillo, J., Bartlett, S., Murugan, A., Badham, P., Wrynne, A., Haszeldine, R. S., ... McIntosh, A.
638 (2020). Olfactory appraisal of odorants for 100% hydrogen networks. *International Journal of Hydrogen*
639 *Energy*. <https://doi.org/10.1016/j.ijhydene.2020.02.095>

640 Murnane, S. S., Lehocky, A. H., & Owens, P. D. (2013). Table 6 . 1 – Odor Threshold Values. In S. S.
641 Murnane, A. H. Lehocky, & P. D. Owens (Eds.), *Odor Thresholds for Chemicals with Established Health*
642 *Standards* (Second Edi). Falls Church: American Industrial Hygiene Association. Retrieved from
643 <https://www.pdo.co.om/hseforcontractors/Health/Documents/HRAs/ODOR>
644 [THRESHOLDS.pdf?Mobile=1](https://www.pdo.co.om/hseforcontractors/Health/Documents/HRAs/ODOR) [Accessed 04/11/2020]

645 Nguyen, D. T., Rumeau, C., Gallet, P., & Jankowski, R. (2016). Olfactory exploration: State of the art.
646 *European Annals of Otorhinolaryngology, Head and Neck Diseases*, 133(2), 113–118.
647 <https://doi.org/10.1016/j.anorl.2015.08.038>

648 Nimmermark, S., Schmidt, D., Jacobson, L., & Gay, S. (2005). Predictions by the odor from feelots,
649 setback estimation tool (OFFSET) compared with observations by neighborhood monitors. *Journal*
650 *of the Air & Waste Management Association*, 55(9), 1306–1314.
651 <https://doi.org/10.1080/10473289.2005.10464730>

652 Oshima, Kazumasa, Rina Kadonaga, Munehiro Shiba, Minoru Sohmiya, Shigeo Satokawa, (2020)
653 Adsorption and catalytic decomposition of dimethyl sulfide on H-BEA zeolite. *International Journal of*
654 *Hydrogen Energy*, Volume 45, Issue 51, Pages 27644-27652, ISSN 0360-3199,
655 <https://doi.org/10.1016/j.ijhydene.2020.07.106>.

656 Park, J. (2017). *One Hundred Years of Housing Space Standards. What now?* housingspacestandards.co.uk.
657 Retrieved from http://housingspacestandards.co.uk/assets/space-standards_onscreen.pdf
658 [Accessed 04/11/2020]

- 659 Pudukudy, M., Yaakob, Z., Mohammad, M., Narayanan, B., & Sopian, K. (2014). Renewable hydrogen
660 economy in Asia - Opportunities and challenges: An overview. *Renewable and Sustainable Energy*
661 *Reviews*, 30, 743–757. <https://doi.org/10.1016/j.rser.2013.11.015>
- 662 Puri, P. S. (2006). Novel Methods of Hydrogen Escape Detection. In *16 World Hydrogen Energy Conference*
663 (p. 10).
664 <https://inis.iaea.org/search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=37101470>
665 [Accessed 04/11/2020]
- 666 Sales, M. (1958). Odeur et odorisation des gaz. In *IGU/36-58 7th Int. Gas Conf.* (pp. 36–58).
- 667 Sheffield, J. W., & Sheffield, Ç. (2007). *Assessment of Hydrogen Energy for Sustainable Development*. (J. W.
668 Sheffield & S. Ç., Eds.). Springer Netherlands. ISBN 978-1-4020-6442-5
- 669 Sinha, Anubhav, Vendra C. Madhav Rao, Jennifer X. Wen, (2019). Performance evaluation of empirical
670 models for vented lean hydrogen explosions. *International Journal of Hydrogen Energy*. Volume 44, Issue
671 17, Pages 8711-8726, ISSN 0360-3199, <https://doi.org/10.1016/j.ijhydene.2018.09.101>.
- 672 Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., ... Ward, K. R.
673 (2019). The role of hydrogen and fuel cells in the global energy system. *Energy and Environmental*
674 *Science*, 12(2), 463–491. <https://doi.org/10.1039/c8ee01157e>
- 675 Uni. Of. Miskolc & Hungarian Scientific Society of energy Economics (2008). A register of all gas
676 regulations and norms concerning the necessary gas quality for allowing the transport in the natural
677 gas grid. *Redubar WP06 D17. Europe* (EIE/06/221/SI2.442663).
678 [https://ec.europa.eu/energy/intelligent/projects/sites/iee-](https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/redubar_a_register_of_all_gas_regulations.pdf)
679 [projects/files/projects/documents/redubar_a_register_of_all_gas_regulations.pdf](https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/redubar_a_register_of_all_gas_regulations.pdf) [Accessed
680 04/11/2020]
- 681 Zhang, J. (2019). *Analysis of Tetrahydrothiophene (THT) in Natural Gas Using the Agilent 990 Micro GC*.
682 Retrieved from [https://www.agilent.com/cs/library/applications/application-tht-in-natural-gas-990-](https://www.agilent.com/cs/library/applications/application-tht-in-natural-gas-990-micro-gc-5994-1042en-agilent.pdf)
683 [micro-gc-5994-1042en-agilent.pdf](https://www.agilent.com/cs/library/applications/application-tht-in-natural-gas-990-micro-gc-5994-1042en-agilent.pdf) [Accessed 04/11/2020]

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687 MEC from Kiwa Gastec; experimental work and data analysis was carried out by GO, JT and NH. JMC
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694 We certify that any and all of our affiliations with, or financial involvement with, any organization or
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