Hy4Heat
demonstrating hydrogen for heat

Department for Business, Energy & Industrial Strategy

WORK PACKAGE 7

Safety Assessment:
Experimental Testing – Ignition Potential

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 WP7 LOT 4.

Ignition Potential Testing with Hydrogen and Methane

Department for Business, Energy & Industrial Strategy

Report No.: 1, Rev. FINAL 1
Document No.: 636105
Date: 2020-01-20

Project name:	Hy4Heat WP7 Lot 4.
Report title:	Ignition Potential Testing with Hydrogen and Methane
Customer:	Department for Business, Energy & Industrial Strategy, 1 Victoria Street, SW1H 0ET, London, United Kingdom
Customer contact:	c/o Sophie Brown, Arup
Date of issue:	2020-01-20
Project No.:	10158500
Organisation unit:	Project Delivery
Report No.:	1, Rev. FINAL 1
Document No.:	636105

GL Industrial Services UK Ltd.
Region UK
Spadeadam Research and Testing
MoD R5, Gilsland,
Brampton, Cumbria CA8 7AU
United Kingdom
Tel: +44(0)16977 47404

Applicable contract(s) governing the provision of this Report:

1819/02/2019: Hy4Heat – WP7 – Safety assessments for the suitability of hydrogen in existing buildings: Lot4

Objective:

Convey results of Hy4Heat WP7 Lot4 Results

Prepared by:	Verified by:	Approved by:
Digitally signed by Rob Crewe Date: 2020.06.09 10:17:35 +01'00'	Digitally signed by Mike Johnson Date: 2020.06.09 11:00:59 +01'00'	Digitally signed by Dan Allason Date: 2020.06.09 09:08:30 +01'00'
Rob Crewe Project Engineer	Mike Johnson Senior Principal Consultant	Dan Allason Head of Section: Research and Innovation

DNV GL Distribution:

☐ OPEN. Unrestricted distribution, internal and external.

☐ INTERNAL use only. Internal DNV GL document.

☒ CONFIDENTIAL. Distribution within DNV GL according to applicable contract.

☐ SECRET. Authorized access only.

Keywords:
Ignition, hydrogen, methane

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
0	2020-1-21	DRAFT for Comment	R CREWE	D ALLASON	D ALLASON
1	2020-6-09	FINAL after comment	R CREWE	M JOHNSON	D ALLASON

Table of contents

EXECUTIVE SUMMARY

DNV GL were commissioned by BEIS to conduct three programmes of experimental studies (Lots 2-4) within WP7 of the Hy4Heat project. WP7 of the Hy4Heat programme is concerned with determining the relative safety of hydrogen within a domestic property (i.e. downstream of the gas distribution network's final valve) compared to natural gas.

This report provides the results from Lot 4, which assesses the potential for household electrical items to ignite hydrogen and methane mixtures with air.

Fifty-four tests have been performed. Electrical items were primarily chosen on the basis that they had at least one of three potential ignition mechanisms; hot surface, electrical contacts, or electrical motors. In addition, some electrical items were also selected because they had none of these mechanisms (as control samples). The items used in the test programme included white goods in new and used condition, plugs and switches, light fittings and extractor fans.

The items were placed into a 2.86 m^3 explosion chamber and operated for 10 minutes at increasing concentrations of hydrogen or methane in air. The majority of tests were carried out using one of five hydrogen air concentrations or one of two methane air concentrations. The larger number of hydrogen air concentrations reflects the much wider flammable range of hydrogen compared to methane. In the sequence of hydrogen or methane tests with a specific item, each concentration used was chosen to have a lower ignition energy and a faster laminar burning velocity than the previous. In other words, not only was each concentration expected to be easier to ignite, but any resulting combustion was expected to be more rapid.

It was found that:

- All ignitions that occurred in this test programme had at least one of three possible ignition mechanisms: hot surface, electrical motor, or electrical contacts.
- The extractor fans did not cause ignition. Although the electrical-motor-containing vacuum cleaner, tumble dryer, and hair dryer all caused hydrogen air to ignite, those other household items had other potential ignition sources.
- It took a long time for some household items to ignite hydrogen. In those cases, the key process controlling ignition may not be operational duration (or the concentration of hydrogen), but the ability of the hydrogen air mixture to diffuse into the device and reach the ignition source.
- The electrical switches readily ignited hydrogen.
- Although the electrical switches readily ignited hydrogen, they did not ignite methane, even at high electrical loading.
- Almost all the hydrogen ignitions occurred at the lowest concentration. However, the only ignition that occurred in methane at the lowest concentration level L1 was a smashed light bulb.
- The only electrical items that ignited methane had very hot surfaces. These were the cooker (operating with all four hobs concurrently), and the smashed electrical lightbulb
- When ignition occurred, the hydrogen ignitions were loud and fast when compared with methane ignitions at similar equivalence ratio which were more luminous, were quieter and were of a longer duration.

1 INTRODUCTION

The combustion of natural gas from the UK gas mains distribution network has been identified as a significant contributor to the UK's total release of carbon dioxide (CO_2), primarily due to domestic heating in the winter. The requirement to achieve a 'net-zero' target for the UK by the middle of this century cannot be achieved if heating by natural gas continues, making it essential that practicable alternatives are identified. One possible alternative is to replace natural gas in the gas distribution network with hydrogen.

The potential use of hydrogen as an energy carrier into domestic properties necessitates an understanding of the potential consequences of an accidental or deliberate release within a property. As part of developing this understanding, DNV GL have been commissioned by BEIS to conduct three programmes of experimental studies (Lots 2-4) within WP7 of the Hy4Heat project. WP7 of the Hy4Heat programme is concerned with determining the relative safety of hydrogen within a domestic property (i.e. downstream of the gas distribution network's final valve) compared to natural gas.

This report presents the results of Lot 4, which was commissioned to investigate the potential for igniting hydrogen air mixtures with household electrical items (lights, switches, white goods etc.), and to provide comparative information regarding the potential for igniting of methane air mixtures (methane is the main component of natural gas).

The items tested were ones that might be present in a domestic property and included switches, fan units, lights/fittings, and white goods. The items were chosen either because they had in some form any of three potential ignition mechanisms; hot surface, electrical contacts, or electrical motors; or because they possessed none of these (as control samples). Individual items were placed into a 2.86 m^3 explosion chamber which was then filled with a hydrogen or methane air mixture. Once a suitable concentration was achieved, the item was electrically switched for a set number of cycles.

The experimental work was carried out at the DNV GL Spadeadam Research & Testing centre in the latter months of 2019.

2 EXPERIMENTAL ARRANGEMENT

Each item was tested by placing it in a sealed explosion chamber and activating it once a flammable atmosphere had been established in the chamber. The explosion chamber used for these experiments is shown in Figure 1. It had a volume of 2.86 m^3 (internal dimensions of 1.4 x 1.2 x 1.7 m).

Figure 1 - Explosion chamber used for ignition potential experiments

The explosion chamber was filled using a recirculation system in which the mixture in the chamber was extracted into external pipework loop and then returned to the chamber at a different location and elevation. Hydrogen or methane was introduced by injecting the gas into the recirculation loop. The continual recirculation process provided a homogenous mixture. Well-mixed gas mixtures do not separate (see for example [1]). This meant that the recirculation system can be switched off before testing without worrying about losing the homogeneity of the mixture. A well-mixed hydrogen air mixture will have much lower density than normal ambient air, meaning that if the explosion chamber needed to be well sealed to prevent the mixture becoming lean through buoyancy driven ventilation.

Gas was supplied as either 100% hydrogen or 100% methane from bottle packs located remote from the explosion chamber. The concentration of either gas in the atmosphere was verified using a gas analyser procured from GDS Technologies, Leeds, in which the sensor was a SGX Sensortech VQ6 series thermal conductivity bridge type sensor. The analyser was calibrated before each test with certified calibration gases of approximately 10% hydrogen or methane with a balance of nitrogen.

Items were placed into the chamber through the roof which was opened and closed via pneumatically driven rams. The roof was an open frame that clamped down a plastic sheet onto the sides of the chamber. The plastic sheet is an intentional venting pathway: when an explosion occurs, the plastic sheet will fail, and the combustion products vent vertically upwards.

For a vent of this size, the plastic sheeting fails at an overpressure in excess of 70 mbar. In context, Mathurkar [2] as a part of the HySafe project, investigated the ignitability of hydrogen and methane in air at bench scale in a 0.004 m^3 steel tube (6" diameter x 232 mm length), and used 70 mbar pressure rise as indicative of successful ignition. In the tests described in this report, with one exception, failure of the plastic sheet was used as the marker of a successful ignition. The exception was a smashed light bulb in a very lean methane mixture. In that case the sheeting did not fail, but scorching was found on the light bulb casing (see Appendix A, A11).

3 TEST PROGRAMME

As stated, the focus of this test programme was the ignition potential of hydrogen from relevant ignition sources, with methane considered as a comparison.

A total of 43 hydrogen tests were conducted including 6 repeats. Those tests were conducted on 18 electrical items. These included: white goods in new and used condition, plugs & switches etc., light fittings, and extractor fans. The objects were selected because they possessed any of three potential ignition mechanisms; hot surface, electrical contacts, or electrical motors; or because they were electrical goods that possessed none of these (as control samples). The objects chosen for testing are summarised in Table 3. This also shows the potential ignition mechanisms identified. Each tested item is described in Appendix A.

Some objects were tested in more than one condition. For example, the switches were tested with varying electrical loads to try and identify a minimum electrical power that would cause ignition. The other testable electrical items were used as electrical loads. They were a hair dryer (high electrical load) down to a 7 W light bulb (low electrical load). Appendix A also describes the conditions in which each item was tested.

A further 11 tests were conducted using methane fuel which included 2 repeats. Only 9 of the items were tested with methane. Objects were only tested with methane if they had ignited hydrogen and had not been significantly damaged by doing so. Therefore, considering the total test programme (hydrogen + methane) a total of 54 tests (including 8 repeats) were conducted.

Each test was conducted in up to 5 different nominal hydrogen concentrations and 2 different nominal methane concentrations. Each concentration for a fuel was chosen to be more ignitable than the last. If an item caused ignition at one concentration, then testing moved onto the next item. In other words, it was assumed that ignition in a more-ignitable mixture was certain. When testing the electrical switches, the objects were tested in order of the largest-to-smallest electrical loads. If ignition did not occur at the largest electrical loading, testing at lower electrical loadings was generally not done. This aimed to find the boundary between non-ignition and ignition as quickly as possible (tests that cause ignition are generally finished faster than those that do not). These policies maximised the total number of tested configurations.

For hydrogen, the five nominal volumetric gas concentrations, as shown in Table 1, were: 5.9%, 8.9%, 17.8% 26.6%, and 29.6%. "Nominal" refers to the fact that in the real world, experiments need to be conducted in a concentration band. In this case each experiment was conducted at the listed nominal concentration +/- 0.3%.

The two tested nominal volume methane concentrations were 5.9% and 8.9%. These were partly chosen because they aligned with the lowest two nominal hydrogen concentrations (allowing a direct volumetric comparison), but also because those nominal concentrations were conveniently close to the lower flammability limit, and to an equivalence ratio of 1.

Table 1 shows that the nominal hydrogen equivalence ratios used in these tests were: 0.15, 0.23, 0.52, 0.86 and 1.00, and that the two nominal methane concentrations were 0.60 and 0.93. So, the higher of the two nominal methane concentrations was quite close to the most efficient mixture possible.

Table 2 shows the upper and lower flammability limits for hydrogen and methane. It shows that the third nominal hydrogen concentration (17.8%) was above the upper flammability limit for methane (15%). It also shows that the lowest nominal concentration (5.9%) was close to the lower flammability limit for both hydrogen and methane.

Level	Nominal Conc.	Conc. Range	Equivalence Ratio H2	Equivalence Ratio CH4
L1	5.90%	5.6 % - 6.2 %	0.15 (0.14 - 0.16)	0.60 (0.56 - 0.63)
L2	8.90%	8.6 % - 9.2 %	0.23 (0.22 - 0.24)	0.93 (0.90 - 0.96)
L3	17.80%	17.5 % - 18.1 %	0.52 (0.51 - 0.53)	N/A
L4	26.60%	26.3 % - 26.9 %	0.86 (0.85 - 0.88)	N/A
L5	29.60%	29.3 % - 29.9 %	1.00 (0.99 - 1.02)	N/A

Table 1 – Gas volume concentrations and derived equivalence ratios used in test series

Gas	Hydrogen	Methane[1]
Upper Flammability Limit (Vol%)	75.0 %	15.0 %
Lower Flammability Limit (Vol%)	4.0 %	5.3 %

Table 2 – Flammability limits of hydrogen and methane [2, 5]

Minimum ignition energy is a term that refers to the minimum amount of energy that can cause ignition. It is determined experimentally and subject to some error. Minimum ignition energy varies with concentration with the lowest values generally being not far from an equivalence ratio of 1.

Laminar burning velocity refers to the velocity a planar flame will propagate in a quiescent mixture if no turbulence is present (even very minor turbulence, such as wrinkling of the flame surface, will substantially increase the real-world flame speed). Laminar burning velocity also varies with concentration. Gas mixtures with higher laminar burning velocities produce more violent explosions.

Figure 2 shows representative minimum ignition energy and laminar burning velocity data for both hydrogen and methane as a function of gas concentration. The minimum ignition energy data has been reproduced from [2], and the hydrogen laminar burning velocity from [3].

Figure 2 also shows the concentration levels used in these tests. Each nominal concentration level is associated with an experimental range of +/- 0.3%. This figure (and Table 2) shows that hydrogen is ignitable over a much wider concentration range than methane. The figure also shows that hydrogen has a much lower ignition energy than methane and a much higher laminar burning velocity. Most importantly the figure shows that the progression of the five hydrogen nominal concentration levels for hydrogen, and the two nominal concentration levels for methane correspond to progressively lower ignition energies and progressively higher laminar burning velocities. In other words, they correspond to progressively more dangerous mixtures. The figure also shows that the higher methane concentration band aligns with the lowest part of the methane minimum ignition energy curve. Figure 3, expresses the data in Figure 2 in terms of equivalence ratio.

Each item was tested for a minimum period of 10 minutes at each concentration level. This meant that the explosion chamber would be filled to the concentration level of interest, then isolated, and then the item would be activated. . The 10-minute exposure period was chosen for reasons of practicality in that the concentration in the chamber could generally be maintained within the tolerances mentioned above for that duration. In cases of higher wind speeds; if the concentration of the atmosphere fell below the

[1] The LFL shown here is taken from [2] and is used for consistency with Figures 2 and 3. It is acknowledged that differing values for LFL exist in literature and this is somewhat dependent on the determination methods.

required concentration the item would be de-activated until the concentration in the explosion chamber had been brought back into the required range.

The "in service" behaviour of each item differed. For example, the toaster and the cooker hobs were fixed to be always on (and thus provide a hot surface ignition source) as long as power was supplied. On the other hand, the switches under test were continually activated on a 7.5 s cycle, and the fluorescent lights on a 15 s cycle. The duration of the cycle was chosen using experimental judgement to try and maximise the likelihood of ignition. No interpretation of the statistical significance of the number of cycles conducted in relation to the test result is made. The duration was chosen for reasons of efficiency and where repeats were performed, it was generally to confirm a test result (be it for an ignition or for a non-ignition).

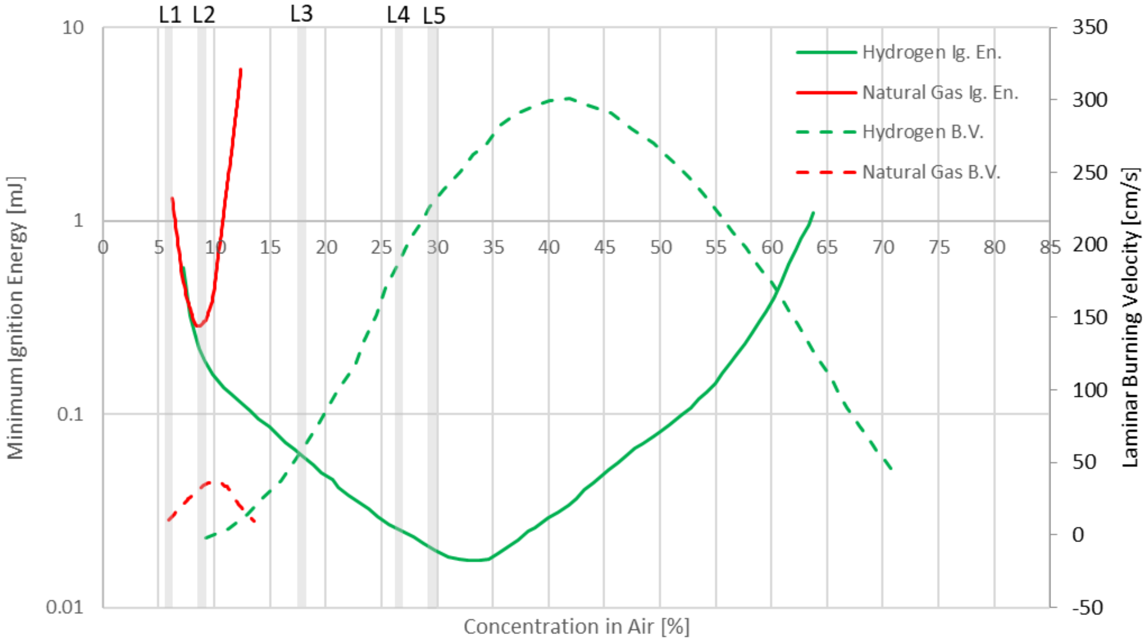

Figure 2 – Representative minimum ignition energies and laminar burning velocities of hydrogen and methane as a function of volumetric gas concentration. Ignition energy reproduced from [2], hydrogen burning velocity [3], methane burning velocity [4].

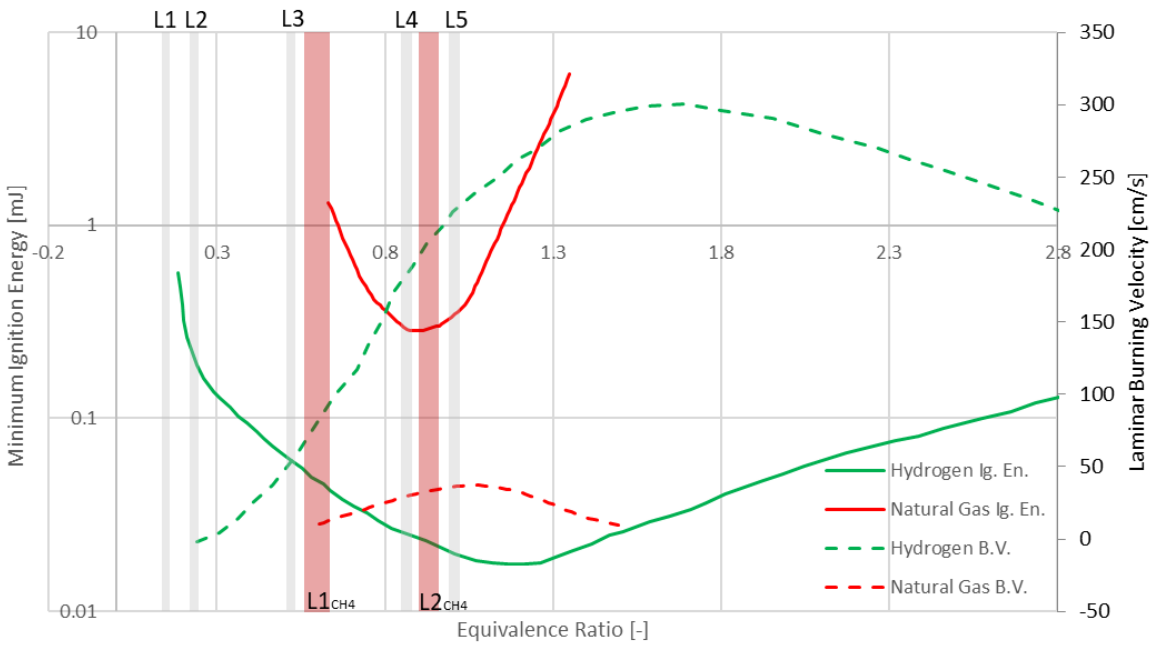

Figure 3 – Figure 2 expressed in equivalence ratio (representative minimum ignition energies and laminar burning velocities of hydrogen and methane as a function of Equivalence Ratio. Ignition energy reproduced from [2], hydrogen burning velocity [3], methane burning velocity [4]).

Fuel		Equipment	Notes	HotSurf	Motor	Contacts	Other
Hydrogen	Switches	Plug Socket (plugging/unplugging)	Load = Hair dryer			✓	
			Load = Microwave			✓	
			Load = Fluorescent bulb			✓	
			Load = 60W Bulb			✓	
			Load = 25W extractor fan			✓	
			Load = Fluorescent bulb (repeat)			✓	
			Load = 25W extractor fan (repeat)			✓	
			Load = 7W bulb			✓	
		Light Switch (push contact)	Load = Hair dryer			✓	
			Load = Microwave			✓	
			Load = Fluorescent bulb			✓	
			Load = 60W Bulb			✓	
		Pull Cord Light Switch (pull contact)	Load = Hair dryer			✓	
			Load = Microwave			✓	
			Load = Fluorescent bulb			✓	
			Load = 60W Bulb			✓	
			Load = 60W Bulb (repeat)			✓	
		Thermostat (push contact)	Load = Hair dryer			✓	
			Load = Hair dryer (repeat)			✓	
			Load = Microwave			✓	
			Load = Fluorescent bulb			✓	
			Load = 60W Bulb			✓	
	Fans	Small Extractor Fan #1 (new unit)	Manrose 11640		✓		
		Small Extractor Fan #2 (old unit)	Manrose XF100S		✓		
		Medium sized Extractor Fan #1 (old unit)	Vent Axia 17104020E		✓		
	Light Fittings	New LED Light Fitting	Sylvania 6412X LED Ceiling Light 24W				✓
		Old bayonet light fitting	LED FILLAMENT BULB				✓
			60W bulb				✓
			LED Filament bulb (smashed)				✓
			LED Filament bulb (smashed) (repeat)				✓
			60W bulb (smashed casing)			✓	
		Old fluorescent light fitting	Old but working				✓
			Old with faulty starter				✓
	White Goods	(old) hair dryer	Babyliss S190A, 2kW	✓	✓		
		(old) vacuum cleaner	Art Miele	✓	✓		
		(new) microwave oven	Tesco Microwave		✓		
			Tesco Microwave (repeat)		✓		
		(old) tumble dryer	Hotpoint Aquarius TVM570	✓	✓	✓	
		(old) fridge unit (door closed)	LEC R-RD40F		✓		
		(old) fridge unit (door open)			✓		
		(new) iron	TESCO's £10 Iron	✓		✓	
		(new) toaster	TESCO's £7 toaster	✓			
		(new) Electric Hob	Cooke & Lewis CLCER60A	✓			
Methane	Switches	Plug Socket (plugging/unplugging)	Load = hair dryer			✓	
		Light Switch (push contact)	Load = hair dryer			✓	
		Pull Cord Light Switch (pull contact)	Load = hair dryer			✓	
		Thermostat (push contact)	Load = hair dryer			✓	
	Light Fittin	Old bayonet light fitting	60W bulb (smashed casing)			✓	
			60W bulb (smashed casing) (repeat)			✓	
	White Goods	(old) hair dryer	Babyliss S190A, 2kW	✓	✓		
		(old) vacuum cleaner	Art Miele	✓	✓		
		(new) toaster	TESCO's £7 toaster	✓			
		(new) electric Hob	Cooke & Lewis CLCER60A	✓			
			Cooke & Lewis CLCER60A (repeat)	✓			

Table 3 – Items tested and their potential ignition mechanisms

4 RESULTS

Fuel	Equipment		Notes	Test#	Cycle#[1]/Time	IGNITION
Hydrogen	Switches	Plug Socket (plugging/unplugging)	Load = Hair dryer	21	1 (off*)	**L1**
			Load = Microwave	22	1 (off)	**L1**
			Load = Fluorescent bulb	23	20 (on)	**L1**
			Load = 60W Bulb	24	6(on)	**L1**
			Load = 25W extractor fan	25	11(off)	**L1**
			Load = Fluorescent bulb (repeat)	26	1(on)	**L1**
			Load = 25W extractor fan (repeat)	27	1(on)	**L1**
			Load = 7W bulb	28		NONE
		Light Switch (push contact)	Load = Hair dryer	29	2(off)	**L1**
			Load = Microwave	30	1(off)	**L1**
			Load = Fluorescent bulb	31		NONE
			Load = 60W Bulb	32		NONE
		Pull Cord Light Switch (pull contact)	Load = Hair dryer	33	1(off)	**L1**
			Load = Microwave	34	1(off)	**L1**
			Load = Fluorescent bulb	35	42(off)	**L3**
			Load = 60W Bulb	36		NONE
			Load = 60W Bulb (repeat)	37		NONE
		Thermostat (push contact)	Load = Hair dryer	38	8(off)	**L1**
			Load = Hair dryer (repeat)	39	1(off)	**L1**
			Load = Microwave	40	3(off)	**L1**
			Load = Fluorescent bulb	41	6(on)	**L2**
			Load = 60W Bulb	42		NONE
	Fans	Small Extractor Fan #1 (new unit)	Manrose 11640	7		NONE
		Small Extractor Fan #2 (old unit)	Manrose XF100S	9		NONE
		Medium sized Extractor Fan #1 (old unit)	Vent Axia 17104020E	14		NONE
	Light Fittings	New LED Light Fitting	Sylvania 6412X LED Ceiling Light 24W	6		NONE
		Old bayonet light fitting	LED FILLAMENT BULB	15		NONE
			60W bulb	10		NONE
			LED Filament bulb (smashed)	16		NONE
			LED Filament bulb (smashed) (repeat)	18		NONE
			60W bulb (smashed casing)	19	Immediate	**L1**
		Old fluorescent light fitting	Old but working	8		NONE
			Old with faulty starter	11		NONE
	White Goods	(old) hair dryer	Babyliss S190A, 2kW	1	Immediate	**L1**
		(old) vacuum cleaner	Art Miele	4	20sec	**L1**
		(new) microwave oven	Tesco Microwave	3		NONE
			Tesco Microwave (repeat)	20		NONE
		(old) tumble dryer	Hotpoint Aquarius TVM570	2	9min	**L1**
		(old) fridge unit (door closed)	LEC R-RD40F	12		NONE
		(old) fridge unit (door open)	(as above)	13		NONE
		(new) iron	TESCO's £10 Iron	5	8min	**L4**
		(new) toaster	TESCO's £7 toaster	17	Immediate	**L1**
		Electric Hob	Cooke & Lewis CLCER60A	43	5sec	**L1**
Methane	Switches	Plug Socket (plugging/unplugging)	Load = hair dryer	49		NONE
		Light Switch (push contact)	Load = hair dryer	48		NONE
		Pull Cord Light Switch (pull contact)	Load = hair dryer	47		NONE
		Thermostat (push contact)	Load = hair dryer	46		NONE
	Light Fittin	Old bayonet light fitting	60W bulb (smashed casing)	51	Immediate	**L1**
			60W bulb (smashed casing) (repeat)	52	Immediate	**L2**
	White Goods	(old) hair dryer	Babyliss S190A, 2kW	53		NONE
		(old) vacuum cleaner	Art Miele	54		NONE
		(new) toaster	TESCO's £7 toaster	50		NONE
		(new) electric Hob	Cooke & Lewis CLCER60A	44	14sec	**L2**
			Cooke & Lewis CLCER60A (repeat)	45	10sec	**L2**

Table 4 – Ignition of tested items. Also showing experimental order and number of cycles to ignition or time to ignition. * refers to if the switching loads caused ignition on the contacting or breaking part of the cycle. [1] Cycle# refers to the number of cycles required to achieve ignition. Alternatively, Time is the amount of time.

This test programme investigated the propensity of general electrical items such as switches and fans, and common consumer electronic devices such as toasters and microwaves, to ignite hydrogen air mixtures. The comparative ignition potential of methane was also considered. A total of 54 tests including 8 repeats were conducted in total. Of those tests, 43 were conducted on hydrogen air mixtures, and 11 on methane air mixtures.

The 5 hydrogen air mixtures and the 2 methane air mixtures used were chosen to be sequentially more ignitable. This was discussed in the previous section. The wide flammability limits of hydrogen compared to methane necessitated a larger range of ignitable mixtures. The lower ignition energy of hydrogen and faster laminar burning velocity at similar equivalence ratios implied that in very general terms hydrogen might be easier to ignite and result in more violent explosions.

The tested items were photographed. These are shown and the items are described in Appendix A. Some observations from the tests and a brief description of the items before/after the explosions are also present there. Table 4 collates whether those items caused ignition, the nominal concentration of the gas mixture (if ignition occurred), and the time of ignition. It also tabulates the chronological order of tests.

The following key points can be made:

- All ignitions that occurred in this test programme had at least one of three possible ignition mechanisms: hot surface, electrical motor, or electrical contacts. None of the control electrical items that exhibited none of those mechanisms (i.e. electrical lights) caused ignition.

- The extractor fans did not cause ignition. Although extractor fans are often suspected of causing domestic fires (after clogging with dust and overheating), they did not ignite hydrogen in either their new or used state. The electrical-motor-containing vacuum cleaner, tumble dryer, and hair dryer all caused hydrogen air to ignite but those other household items have other potential ignition sources: the tumble dryer and the vacuum cleaner might conceivably develop static charge during operation or they may have a thermostat associated with their heating elements.

- It took a long time for some household items to ignite hydrogen. The tumble dryer ignited after 9 minutes operational time on L1 hydrogen, and the iron on L4 hydrogen. In both cases, the key process controlling ignition may not be operational time (or the concentration of hydrogen), but the ability of the hydrogen air mixture to diffuse into the device and reach the ignition source. In the case of the tumble dryer, it was noted that the concentration in the explosion chamber dropped out of acceptable range immediately upon activation, necessitating many hydrogen "top ups" before ignition occurred – indicative of the various voids within the device filling with mixture much slower than the chamber around the device.

- The electrical switches readily ignited hydrogen. In real world use it is expected that they might be recessed in cavities (plug, pull & press light switch) or maintain their outer covers (thermostat). This would make it more difficult for the hydrogen air mixture to get diffuse into the electrical contacts (see above). However, the results are quite clear, these switches ignited hydrogen air mixtures at small electrical loads (down to a few tens of watts).

- There was no clear tendency for the electrical switches to ignite the hydrogen air mixtures on either the "on" strike or the "off" strike. In principle, in a dc circuit the arc generated as electrical contacts part will span a greater distance and can exist for a longer time than an arc generated as the contacts come together. However, this will also be affected by other properties of the circuit (e.g. inductance and capacitance) and the continual reversal of flow under AC power. The absence of a clear tendency for ignition to occur on the "off" strike could reflect the importance of these other factors. Equally, given the near instantaneous ignition of so many of these switching events, it could just mean that both the on and the off arcs were easily capable if igniting the mixture.

- Although the electrical switches readily ignited hydrogen, they did not ignite methane, even at high electrical loading (hair dryer).

- Almost all of the hydrogen ignitions occurred at the lowest concentration. As shown in Figure 2, at those low concentrations' ignition energies of hydrogen and methane are similar (approx. 0.3 mJ). However, the only ignition that occurred in methane at the lowest concentration level L1 was a smashed light bulb. As discussed in Appendix A11, that ignition did not break the plastic sheet and ignition was determined by discolouration of the smashed glass housing surrounding the filament.

- The only electrical items that ignited methane had very hot surfaces. These were the cooker (operating with all four hobs concurrently), and the smashed electrical lightbulb (when energised the filament rapidly heats and then breaks).

- When ignition occurred, the hydrogen ignitions were loud and fast when compared with methane ignitions at similar equivalence ratio which were more luminous, were quieter and were of a longer duration.

5 REFERENCES

[1]. Lowesmith BJ., Hankinson G., Spataru M., Stobbat M., Gas build-up in a domestic property following releases of methane/hydrogen mixtures., International Journal of Hydrogen Energy, 34(14), pp 5932 – 5939.

[2]. Mathurkar H., Minimum ignition energy and ignition probability for methane, hydrogen and their mixtures., Doctoral Thesis, Loughborough University., 2009

[3]. Dahoe AE., Laminar burning velocities of hydrogen air mixtures from closed vessel gas explosions., Journal of Loss Prevention in the Process Industries, 10, 152 – 166, 2005

[4]. Le Cong T., Dagaut P., Dayma G., Oxidation of natural gas, natural gas/syngas mixtures, and effect of burnt gas recirculation: experimental and detailed kinetic modelling., Journal of Engineering for Gas Turbines and Power, 130, 2008

[5]. Glassman I., Yetter RA., Glumac NG., Combustion 5th Ed., Elsevier Academic Press., 2015

[6]. Which? Article on domestic fire statistics: https://www.which.co.uk/news/2018/02/revealed-the-brands-linked-to-the-most-appliance-fires/

Appendix A – Description of Tested Items

A1. Plug & Socket

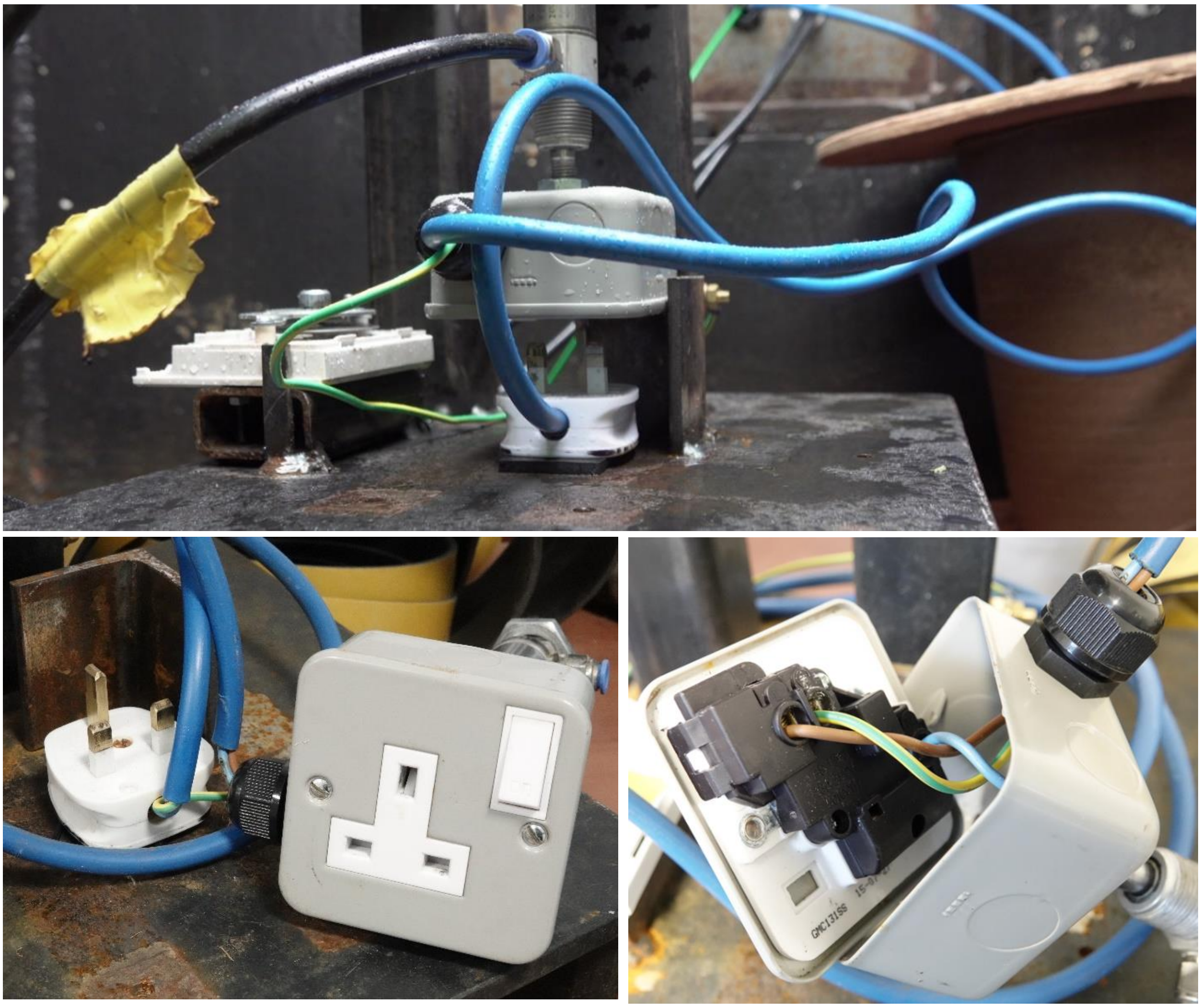

Figure A.1 – Plug and socket. Upper installed into pneumatic cycling mechanism (socket attached to table). Bottom left plug and socket. Bottom right insides of socket.

A plastic plug and metal socket were chosen to be representative of a domestic plug and the action of plugging in and unplugging electrical items. The items connected to the plug were located outside of the explosion chamber and were therefore away from the ignitable mixture. The plug was attached to a metal table and the socket to a pneumatic ram that pushed/pulled the socket onto/off the plug. The socket was permanently energised meaning that arcs could be produced as the electrical plug contacts were brought into contact and then separated again.

The ram was activated on a 7.5 second cycle (i.e. 'in' for 7.5 second then 'out' for 7.5 seconds).

With hydrogen the plugging/unplugging action was found to cause ignition when connected to the following electrical items: hair dryer, microwave, fluorescent bulb, 60W bulb, 25W extractor fan. The 7 W LED bulb did not cause ignition.

When ignition occurred, it always occurred at the lowest hydrogen concentration: L1, but not always on the first cycle.

The fluorescent bulb was tested twice. When it was first tested (test 23) ignition occurred on the 20th cycle (on the on strike). A repeat of that test (test 26) caused ignition immediately.

With methane the highest electrical load (hair dryer) failed to cause ignition at any concentration level.

Visual inspection carried out during and at the end of the test programme did not find any marks that could be attributed to the presence of combustion or the ignition of an explosion.

A2. Press Light Switch

Figure A.2 – Push light switch. Left: switch installed underneath a pneumatic ram. Upper right: connections on reverse side of switch. Lower right: closeup of ram over switch.

A plastic light switch was chosen to be representative of a domestic press light switch. The switch was spring return rather than the normal domestic "2-state" type.

The switch was activated in 7.5 s cycle (i.e. 'on' for 7.5 second then 'off' for 7.5 seconds). The items connected to the light switch were located outside of the explosion chamber and were therefore away from the ignitable mixture.

With hydrogen the pressing action was found to cause ignition when connected to the following electrical items: hair dryer, and microwave. Ignition occurred at the lowest hydrogen concentration: L1.

With methane, the highest electrical load (hair dryer) failed to cause ignition at any concentration level.

Visual inspection carried out during and at the end of the test programme did not find any marks that could be attributed to the presence of combustion or the ignition of an explosion.

A3. Pull Cord Light Switch

Figure A.3 – Pull cord light switch. Left: switch before tests. Right: underneath of switch with base removed.

A pull cord light switch was procured from a local hardware store and taken to be representative of a domestic pull cord switch (possibly for use in a damp environment such as a bathroom). The base unit was removed, and the pull cord was attached to the pneumatic ram (see plug socket and press light switch above), with the switching unit held down so that the ram pulled the cord. The switch was located near the floor of the explosion chamber.

The switch was activated in 7.5 s cycles cycle (i.e. 'in' for 7.5 second then 'out' for 7.5 seconds). The items connected to the switch were located outside of the explosion chamber and were therefore away from the ignitable mixture.

With hydrogen the activation action was found to cause ignition when connected to the following electrical items: hair dryer, microwave, and fluorescent bulb. Ignition with the fluorescent light took 42 cycles, but did not occur with the 60 W bulb at any concentration. When ignition occurred, it did so at the lowest hydrogen concentration: L1.

With methane, the highest electrical load (hair dryer) failed to cause ignition at any concentration level.

Visual inspection carried out during and at the end of the test programme did not find any marks that could be attributed to the presence of combustion or the ignition of an explosion.

A4. Thermostat

Figure A.4 – Thermostat. Upper: thermostat unboxed showing outer casing. Lower: internals of thermostat showing internal switch (small circle in centre of unit).

A Honeywell T6360 room thermostat was procured to represent a typical domestic thermostat. It was attached to a metal table directly underneath the pneumatic ram. The outer cover and control dial mechanism were removed exposing the internal switch (small white circle in centre of unit).

The thermostat was activated in 7.5 s cycles (i.e. 'in' for 7.5 second then 'out' for 7.5 seconds). The items connected to the thermostat were located outside of the explosion chamber and were therefore away from the ignitable mixture.

With hydrogen the switching action was found to cause ignition when connected to the following electrical items: hair dryer, microwave, and fluorescent bulb all caused ignition. Ignition occurred at the lowest hydrogen concentration: L1.

With methane, the highest electrical load (hair dryer) failed to cause ignition at any concentration level.

Visual inspection carried out during and at the end of the test programme did not find any marks that could be attributed to the presence of combustion or the ignition of an explosion.

A5. Small Extractor Fan #1

Figure A.5 – Manrose 11640 extractor fan unit.

A Manrose 11640 extractor fan unit was procured and assumed to be generically representative of small extractor fans in their as-new condition. The unit was switched on and off from outside the enclosure.

It was activated on a 15 s cycle (i.e. 'on' for 15 seconds then 'off' for 15 seconds).

The fan unit did not ignite hydrogen at any concentration. Because it did not ignite hydrogen, it was not tested with methane.

A6. Small Extractor Fan #2

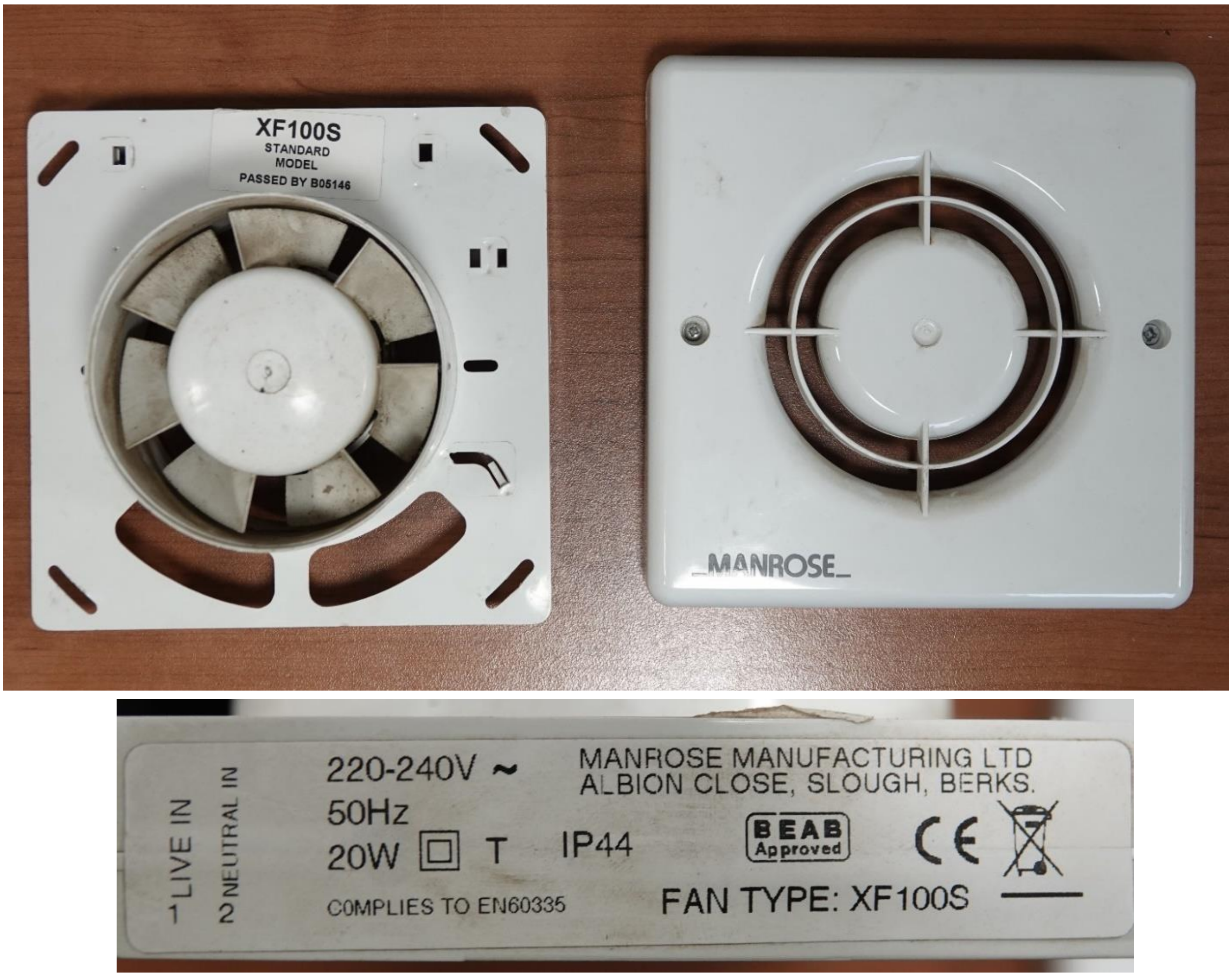

Figure A.6 – Manrose XF100S extractor fan unit. Upper: fan unit and cover plate. Lower: label

A Manrose XF100S was taken out of an old building. It was assumed to be generically representative of small extractor fans in a used condition with the assumption that an old brushed motor is more likely to produce sparks.

The unit was switched on and off from outside the enclosure. It was activated on a 15 s cycle (i.e. 'on' for 15 seconds then 'off' for 15 seconds).

The fan unit did not ignite hydrogen at any concentration. Because it did not ignite hydrogen, it was not tested with methane.

A7. Medium Sized Extractor Fan

Figure A.7 – Vent Axia 17104020E extractor fan unit. Upper: fan unit. Lower: label

A Vent Axia 17104020E was taken out of an old building. It was assumed to be generically representative of medium sized extractor fan in a used condition. It was hoped that in a used state, the electrical motor would be more likely to produce sparks.

The unit was switched on and off from outside the enclosure. It was activated on a 15 s cycle.

The fan unit did not ignite hydrogen at any concentration. Because it did not ignite hydrogen, it was not tested with methane.

A8. Incandescent Light Fitting #1

Figure A.8 – 24W Sylvania 6412X Ceiling Light.

An LED ceiling light was procured and assumed to be representative of modern lighting, 24W Sylvania 6412X ceiling light.

The unit was switched on and off from outside the enclosure. It was a low power LED device. It did not possess any of the main ignition criteria: hot surface, electric motor, electrical switching contacts. It was therefore a control sample and expected to not cause ignition.

It was activated on a 15 s cycle (i.e. ‘on’ for 15 seconds then ‘off’ for 15 seconds).

It did not ignite hydrogen at any concentration. Because it did not ignite hydrogen, it was not tested with methane.

A9. Incandescent Light Fitting #2

Figure A.9 – Old bayonet light fitting.

An old bayonet light fitting was taken from a building. It was assumed to be generically representative of bayonet light fittings everywhere.

It was tested with LED and 60W light bulbs. With the light bulbs connected as electrical load, and with the switching action occurring outside the chamber it did not possess any of the main ignition criteria: hot surface, electric motor, electrical switching contacts.   It was therefore a control sample and expected to not cause ignition.

The LED and 60 W bulbs were activated on 2 s cycles (i.e. 'on' for 2 seconds then 'off' for 2 seconds).

Ignition did not occur with hydrogen, so methane was not tested.

A10. LED Bulb

Figure A.10 – Modern LED Light bulb.

A modern LED lightbulb was used both as electrical load (into a bayonet light fitting (section A9) and as a potential ignition source with the casing smashed. Old fashioned (e.g. 100 W light bulbs) are known to be competent ignition sources when broken because the filament heats up and then melts causing a hot surface and possibly a spark. This LED bulb with the casing smashed, was tested as a comparison to a smashed 60 W light bulb.

It was activated on a 2 s cycle (i.e. ‘on’ for 2 seconds then ‘off’ for 2 seconds). It did not ignite hydrogen at any concentration. Because it did not ignite hydrogen, it was not tested with methane.

A11. 60W Bulb

Figure A.11 – Old fashioned filament light bulb (60W). Upper: after hydrogen ignition. Lower left: cabling after 2nd methane ignition. Lower right: discolouration of casing after first methane ignition.

60W versions of traditional light bulbs were tested as electrical ballast onto the old-fashioned bayonet light fitting (without successful ignition in any configuration), and as ignition sources in their own right. Old fashioned (e.g. 100 W light bulbs) are known to be competent ignition sources when broken because the filament heats up and then melts causing a hot surface and possibly a spark. With the casing smashed 60W light bulbs were found to be competent ignition sources of hydrogen at the lowest concentration level L1 (Test 19).

When tested with methane the plastic sheet on the explosion chamber did not break. This for all other experiments was taken as indicative of unsuccessful ignition. However, it was observed that the casing discoloured (see photo) and this has been assumed to be evidence of lean (possibly localised) combustion.

At the higher methane concentration level (L2). The plastic sheeting on the chamber was removed by the explosion and the wiring attached to the bulb was charred.

No charring of wiring was observed with any of the hydrogen explosion tests.

A12. Fluorescent Lights (#1 & #2)

Figure A.12 – Fluorescent light fitting. Centre: entire fitting. Lower left: ignitor

An aged fluorescent light fitting was removed from an old building. An old fitting was hoped to exhibit some sort of damage (possibly loose contacts) that might promote ignition. The light was activated from outside the explosion chamber meaning that the test did not satisfy the electrical contacts criteria of a competent ignition source. The fluorescent light was activated in a working condition and with a faulty ignitor. In both cases it was activated on a 7.5 s cycle (i.e. 'on' for 7.5 seconds then 'off' for 7.5 seconds).

Neither the working nor faulty condition caused ignition at any hydrogen concentration level and therefore it was not tested in a methane atmosphere.

A13. Hair Dryer

Figure A.13 – Babyliss S190A hair dryer

A second hand Babyliss S190A hair dryer was procured to represent a common household item. It was installed into the explosion chamber in a switched-on state and activated by connecting the power remotely. Therefore, it fulfilled both the hot surface and the electrical motor criteria but not necessarily the electrical contacts. When switched on, and from cold, it took approximately 40 seconds to reach maximum temperature.

It was operated on a 15 s cycle (15 s on and 15 s off).

It caused ignition in hydrogen mixtures at the lowest concentration immediately. In methane it did not cause ignition at any concentration.

The hair dryer was inspected during and after the test programme. At no point were any damages observed.

A14. Vacuum Cleaner

Figure A.14 – Old vacuum cleaner. Left: as tested state., Upper right: front of casing. Bottom right: filter slot showing melting and expansion damage.

An old Miele vacuum cleaner was procured to represent a used and common household item.

It was installed into the explosion chamber in a switched-on state and activated by connecting the power remotely. Therefore, it fulfilled the electrical motor ignition criteria.

It was operated on a 15 s cycle (15 s on and 15 s off).

It caused ignition in the lowest hydrogen mixture concentration after approximately 20 seconds. In methane it did not cause ignition at any concentration.

It was inspected during and after the test programme. Melting and expansion damage was observed at the filter slot, and the filter was partly pushed out of the plastic grill. It was not possible to remove the filter. It is suspected that this damage indicates that ignition occurred within the mechanism. Although some molten plastic was present, no sooting or charring was found.

A15. Microwave Oven

Figure A.15 – Cheap Tesco non-programmable microwave. Left: as tested state., Bottom right: label.

An brand new Tesco microwave was bought to represent a common household item and also a high current device. It had manual dials for operation.

It was installed into the explosion chamber with the dial switched to full power and at maximum time. When the chamber was at concentration, it was operated remotely on a 7.5 s cycle (7.5 s on and 7.5 s off).

It did not cause ignition in hydrogen at any concentration and was not subsequently tested in methane.

A16. Tumble Dryer

Figure A.16 – Hotpoint Aquarius TVM570. Upper left: as tested state. Upper right: after hydrogen explosion, Lower: separation of drum (upper) from chassis (lower).

Tumble dryers are a well-known source of fires [6] due to a tendency to collect fine dust and then deposit it on hot mechanisms. Their propensity to cause explosions is less well understood. A Hotpoint Aquarius TVM50 was procured as representative of a machine in a used condition. An initial inspection conducted by removing the casing found an accumulation of dust indicating that it was well used. Only one device of this type and in this condition was available.

It was placed into the chamber in a switched-on condition and an electrical supply was applied remotely. Tumble dryers contain electrical motors, heating elements, and thermostat's (electrical contacts).

It was operated on a 7.5 s cycle (i.e. 'on' for 7.5 seconds then 'off' for 7.5 seconds).

When tested with hydrogen ignition occurred after approximately 9 minutes use at the lowest concentration level. In this case, 9 minutes use meant stopping and topping up the explosion chamber several times. Initially, activating the tumble dryer caused the gas concentration to drop very quickly. After several top ups the rate at which the gas concentration stopped slowed. It is possible that the time to ignition is strongly influenced by the rate at which the flammable atmosphere was sucked into the internal mechanism.

The hydrogen explosion caused the casing to move outwards and dislodged the drum off the casing. No scorching was observed of either the device or the accumulated fluff.

It was not possible to fix the tumble dryer and so it was not tested with methane.

A17. Fridge Unit

Figure A.17 – LEC R-RD40F Fridge unit. Left: as bought condition showing unmodified control unit internally (main body top-right). Upper right: label. Central right: compressor unit. Lower right: switching mechanism.

A LEC R-RD40F fridge unit was procured in a used state. The internal thermostat control unit was bypassed, and the fridge was switched on and off remotely by connecting power. Connecting and disconnecting the power activated/deactivated the compressor unit.

The fridge was tested with the door closed, and then with the door open. It was cycled in 1 min intervals.

Hydrogen ignition did not occur either with the door closed or the door open. The fridge was not tested with methane.

A18. Iron

Figure A.18 – Tesco's Iron. Left: before testing. Right: after explosion in hydrogen, top part of housing has been blown away

A bottom-of-the-range Tesco iron was procured to represent a common household item.

It was installed into the explosion chamber on a large steel heat sink which had a temperature sensor in. The power was activated remotely and when the chamber was at the correct concentration it was kept switched on unless the heat sink was at a temperature of 70 °C or greater. If the temperature was above 70 °C then the experiment was paused until it had cooled to less than 50 °C.

Irons contain heating elements (hot surface ignition), and thermostats (electrical contacts).

The iron ignited hydrogen at the 4th concentration level. As was the case with the tumble dryer, it is quite likely that the time to ignition was controlled as much by the time required for the hydrogen to diffuse to the ignition source, as the competency of the ignition source itself.

The hydrogen explosion caused a plastic section at the top of the iron to become dislodged. This may indicate and explosion occurring within that volume. No scorching/blackening etc was observed.

The iron was not tested in a methane atmosphere. It was judged to provide a lower likelihood of ignition compared to the toaster, hair dryer and the vacuum cleaner (which ignited easily in hydrogen) had already failed to cause ignition.

A19. Toaster

Figure A.19 – Tesco's Toaster. Centre: packaging, Bottom right: closeup of heating elements

A bottom of the range Tesco toaster was used as a representative household item and an ignition of a hot surface ignition source.

The switching mechanism was tied down with electrical cabling, ensuring that it was always on when power was applied.

Each test was performed by raising the concentration of the explosion chamber to the required concentration and then connecting the power. Apart from when the concentration was being topped up, power was applied continuously.

When tested with hydrogen, the toaster ignited the lowest concentration within a few seconds. When tested with methane ignition did not occur.

A20. Electric Hob

Figure A.20 – Cooke & Lewis CLCER60A Electric Hob. Upper: as tested condition., Middle right: label., Lower right: exposed heating elements., Lower Left: inside of glass top after testing.

A Cooke and Lewis CLCER60A electric hob was procured as a representative modern electric cooking device. Removing the glass top exposed 4x heating elements surrounded by insulation. It was rewired internally to bypass the manual switches so that all 4 hobs activated simultaneously when the power was switched on remotely. The glass top was replaced for testing.

In common with the toaster, the potential ignition mechanism was hot surface ignition, and the hob was operated continuously and at full power when the gas concentration inside the explosion chamber was at the required level.

In a hydrogen atmosphere the hob caused an ignition almost immediately after being switched on. In a methane atmosphere, ignition was also almost immediate, but only occurred at the high L2 concentration.

About DNV GL

DNV GL is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software and independent expert advisory services to the maritime, oil & gas, power and renewables industries. We also provide certification, supply chain and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter and greener.