Operation of UK Gas Appliances with Hydrogen Blended Natural Gas

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Abstract

The HyDeploy project has undertaken a programme of work to assess the effect of hydrogen addition on the safety and performance of gas appliances and installations. A representative set of eight appliances have been assessed in laboratory experiments with a range of test gases that explored high and low Wobbe Number and hydrogen concentrations up to 28.4 % mol/mol. Tests have demonstrated that the addition of hydrogen does not affect the key hazard areas of CO production, light back, flame out or the operation of flame failure devices. It was identified that for some designs of gas fire appliances the operation of the oxygen depletion sensors may be affected by the addition of hydrogen and further studies in this area are planned. A laboratory based study was supported by an onsite testing programme where 133 installations were assessed for gas tightness, appliance combustion safety and operation against normal line natural gas, G20 reference gas and two hydrogen blended gases. Where installations were gas tight for natural gas, analysis showed that no additional leakage occurred with hydrogen blended gases. There were also no issues identified with the combustion performance of appliances and onsite results were in line with those obtained in the laboratory testing programme.

INTRODUCTION

Background

Concerns relating to the production of carbon dioxide (CO_2) and its effects on global background temperatures have led to international efforts to reduce CO_2 emissions. One of the main contributors to CO_2 emissions is the burning of fossil fuels in domestic and commercial fuel supplies, especially that of burning natural gas comprised primarily of methane. HyDeploy [1] is a demonstration project funded by Ofgem, Cadent and Northern Gas Networks to establish the feasibility of supplementing natural gas supplies with hydrogen, which when combusted does not produce CO_2. As gas fired heating is used in the majority of UK households, the reduction of carbon dioxide emissions from a country-wide range of locations will allow the UK to contribute positively to a reduction in a gas linked to global warming.

The HyDeploy project consortium of Cadent, Northern Gas Networks, HSE Science and Research Centre, ITM Power, Progressive Energy and Keele University have undertaken a feasibility study of supplementing natural gas supplies with hydrogen up to a maximum injection level of 20 % mol/mol hydrogen. A combined study of laboratory-based have been undertaken to assess appliance performance with a range of test gases. This paper relates to the preparatory work

Gas Network and Supply

The gas network chosen for use in HyDeploy was at Keele University, UK. The network has a mixture of commercial and residential properties including rented and private homes. Keele University is the licensed gas supplier to the university campus, including the private homes, which allows for tighter control and assessment during trial than might have been available in more public gas supply region in the UK. Within the trial boundary, the network had 101 residential properties of which 47 were privately owned, 51 university owned and six student halls of residence. There were also 29 University owned facilities/commercial/recreational buildings; further details of the mixture of online assets are given in Table 1. Hereafter and for completeness, the test network at Keele University will be termed the “G3 network” as it was controlled by the G3 governor.

Table 1 Details for the Installation Types on the G3 Network

Building Type	Total
Domestic – flat	34
Domestic – semi-detached	35
Domestic – detached	29
Student halls	6
Non-residential	29
Total	133

Appliance Survey

To provide a catalogue of the appliances present within the G3 network, an appliance survey was completed prior to the start of testing; results are shown in Table 2.

Table 2 Appliance Population on the G3 Network

Appliance Category	Subcategory	Flat	Semi-detached	Detached	Student halls	Non-residential	Total
Gas fire / space heater	Decorative fuel effect fire		2	1			**3**
	Inset live fuel effect fire		2				**2**
	Radiant heaters					4	**4**
Central heating boilers	Combination	13	15	12		5	**45**
	Regular / system - condensing	16	14	6	12	26	**74**
	Regular / system - non-condensing	4	3	8	2	6	**23**
Domestic cooking	Built-in hob		4	5			**9**
	Built-in oven			1			**1**
	Cooker / range		9	13			**22**
Water heaters	Storage water heater				7		**7**
Commercial cooking	Hob					2	**2**
	Oven					3	**3**
	Salamander					1	**1**
	Fryer					2	**2**
	Brat pan					1	**1**
Total		**33**	**49**	**46**	**21**	**50**	**199**

Appliances in the domestic properties were dominated by system or combination boilers with every residence having some form of gas-based water heating system. The commercial boilers ranged in size from 28 kW to 539 kW.

In total, the variety of gas appliances and uses of the G3 network provided a sample of gas use scenarios with these scenarios representing a sub-set of appliance distribution on the wider UK network providing a stepping-stone towards wider demonstration.

EXPERIMENTAL

Overall Experimental Structure

The experimental study was split into three distinct phases:

1. Identification of a series of test gases to provide representative data on appliance performance (including application of suitable safety factors)

2. Selection of a range of representative appliances against which to assess test gas performance in a laboratory based environment, and

3. Provision of test gases to appliances on the G3 network to assess performance in a range of real-world scenarios

The three stage process was deemed to provide the greatest level of protection for the public within Phase 3 (ie phase 2 should identify any increase in potential hazard or risk). Within Phases 2 and 3, testing was based on appliance function (eg flame shape, energy output etc) plus industry standard safety checks (eg leak testing).

Selection of Test Gases

All gas appliances sold in the UK are tested in accordance with the Gas Appliances Directive (2009/142/EC) (GAD). GAD requires that a gas appliance is tested over a range of gas compositions and operating conditions; these conditions test the appliance over a wider range of limit conditions that will be encountered in normal operation, and so form extreme boundary conditions for the fuel gases. The purpose of the range of tests is to ensure that a safety margin exists in all appliances; this means that even where an appliance is poorly maintained or develops a defect during use, the margin of safety prevents a catastrophic situation. However this does not mean that poorly maintained appliances are intrinsically safe. However, the range of GAD test gases does not explore the full range of gas compositions envisaged within the test program (i.e. 0-20 % mol/mol H_2) so additional test gases were selected as shown in Figure 1.

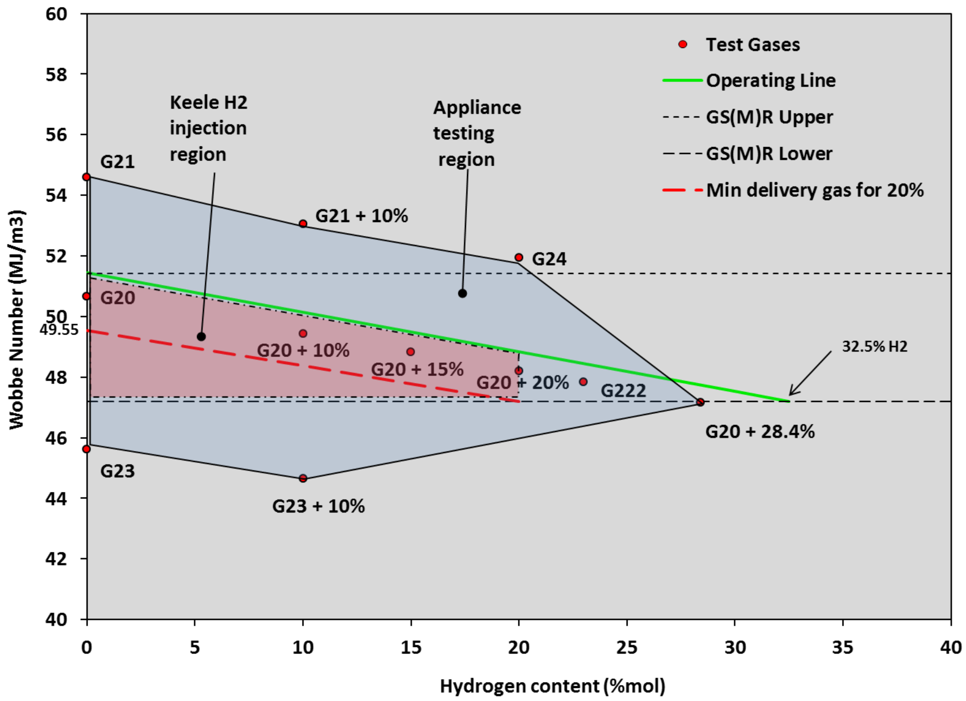

Figure 1 **Test Gases Used to Assess Appliance Operation**

The pink region in Figure 1 describes range of Wobbe Number and hydrogen concentrations that forms the injection region that will be used during the HyDeploy trial. The dotted lines in the figure show the upper and lower limits of Wobbe Number acceptable for compliance against the energy output limits of the Gas Safety Management Regulations (1996) (GSMR). Whilst HyDeploy will operate beyond the permitted hydrogen concentration, the gas quality will remain within the Wobbe Number limits specified by GSMR.

The green line shows the effect of hydrogen addition to gas at the high Wobbe Number specification of GSMR, showing the reduction in Wobbe Number with increasing hydrogen content (the reduction is due to the lower volumetric energy density of hydrogen gas compared to natural gas). The prediction shows that an upper boundary limit up to 32.5 % mol/mol hydrogen addition to a high specification GSMR compliant natural gas could be achieved whilst maintaining overall Wobbe number requirements of GSMR.

Similarly, the lower boundary condition for hydrogen addition is equal to the lower GSMR limit and the level of addition would depend on the Wobbe Number of the incoming gas feed. The red dashed line in Figure 1 shows that where the Wobbe Number of the incoming gas falls below 49.55 MJ/m^3, then injection of hydrogen would need to be constrained to a value of below 20 % mol/mol so that the lower GSMR Wobbe Number limit is not breached. The total range of test gases chosen for the study are detailed in Table 3, which included those gases that are normally used to test gas appliances plus additional gas mixtures that specifically examine the use of hydrogen in low and high Wobbe Number gas mixtures.

Table 3 **Appliance Test Gases**

Test Gas		Composition (% mol/mol)				Wobbe Number (MJ/m^3)
		CH_4	C_3H_8	H_2	N_2	
G21	Upper Wobbe Limit	87	13	0	0	54.6
G21 + 10%	Hydrogen enriched upper Wobbe Limit	78.3	11.7	10	0	53.0
G24	Over-heating limit gas	68	12	20	0	51.9
G20	Reference gas	100	0	0	0	50.7
G20 + 10%	Hydrogen enriched reference gas	90	0	10	0	49.4
G20 + 15%	Hydrogen enriched reference gas	85	0	15	0	48.8
G20 + 20%	Hydrogen enriched reference gas	80	0	20	0	48.2
G222	Light back limit gas	77	0	23	0	47.8
G20 + 28.4%	Hydrogen enriched reference gas at lower GSMR limit	71.6	0	28.4	0	47.2
G23	Lower Wobbe Limit	92.5	0	0	7.5	45.6
G23 + 10%	Hydrogen enriched lower Wobbe Limit	83.25	0	10	6.75	44.6

Selection of Laboratory Test Appliances and Test Regime

Laboratory based study was undertaken on a range of representative appliances to mimic those predicted to be encountered upon the G3 network. Table 4 shows the range of appliances used for the study.

Table 4 Gas Appliance Type and Manufacturer Used in the Laboratory Test Program.

	Make	Model	Rating (kW)	Flue Type	Appliance Category	Appliance Type	Combustion Premix	Test Standard
1	Zanussi	ZCG664GNCHob Burner	2.9	Flueless	Gas Cooker	Oven / Hob / Grill	Partial	BS EN 30-1-1
2	Trimford			Flueless	Gas Catering	Fryer	Partial	BS EN 203-1
3	Legend	Evora BF	4.5	Balanced Flue	Gas Fire	With delayed ignition relief panel	Partial	BS EN 613
4	Paragon	Focus HE S/C	5.5	Conventional	Gas Fire	Inset	Partial	BS 7977-1
5	Baxi	Bermuda 552	16 (Max)	Conventional	Gas Boiler	System (Back) Boiler	Partial	BS 7977-2
6	Myson	Marathon 500B	19.6 (Max)	Conventional	Gas Boiler	System Boiler	Partial	BS EN 15502-1
7	Worcester Bosch	Greenstar 30i ErP	30	Balanced Flue	Gas Boiler	Combi Boiler	Fully	BS EN 15502-1
8	Sime	Format 30 HE	30	Balanced Flue	Gas Boiler	Combi Boiler	Fully	BS EN 15502-1

In compiling the appropriate range of appliances to examine, consideration was given to:

(i) different types of combustion and fluing systems,

(ii) different safety approaches/devices,

(iii) different modes of operation, and

(iv) different appliance age

The representative set included four boilers, two of which were fully premixed and two partial premixed. One of the boilers was a combination boiler/central heating boiler. Two flued wall mounted fires were also examined, one of which included an oxygen depletion sensor. Prior to use, all appliances were installed to the manufacturers specifications by UK certified (Gas Safe) gas engineers and then subjected to the test assessments given in Table 5.

Table 5 Overview of Criteria for Laboratory Assessment

Test	Rationale
Installation integrity / Soundness	Determine whether hydrogen will leak from appliance fittings via pressure drop analysis
Ignition	Determine whether hydrogen will prevent or delay ignition or cause light back during ignition
Cross light	Ensure that cross lighting of all burner ports occurs
Combustion Characteristics	Identification of flame lift or light back
Flame shape	Visual assessment of flame picture for relevant appliances (not boilers)
Acoustic performance	Determine any changes in the acoustic output from device
Flue gas content: CO_2, CO, CO/CO_2 ratio, O_2, NO_x	Record flue gas composition across a range of test gases
Soot formation	Examine soot accumulation on combustion surfaces
Internal temperatures	Identify any changes in temperature local to any critical temperature sensitive components
Heat input / output	Determine the device efficiency
Flue gas temperature	Record flue gas temperature
Condensate quantity	Does the addition of hydrogen increase the accumulation of condensation
Safety devices	Determine under what condition flame detection devices do not operate correctly
Ionisation	Does the presence of hydrogen adversely affect the operation of any hazard identification or mitigation measure

RESULTS

Laboratory Testing

For the test programme in Table 5, the majority of sample results with test gases showed no deviation from a natural gas fuel. Table 6 shows a summary of results achieved from laboratory testing using the various test gases where some degree of deviation was observed or where a definitive statement of the test result is thought prudent.

Laboratory testing indicated that, with the exception of concern relating to ODS performance the use of hydrogen blends up to a limit of 28.4 % mol/mol hydrogen were not deleterious to the operation of the test appliances.

Table 6 Laboratory Test Results

Test Assessment	General Test Result	Variation Within Test Result	Comments
CO Production	No change or a reduction in CO production with increasing hydrogen concentration compared to that of natural gas: compliance demonstrated against BS 7967:2015	Appliances displayed similar behaviour albeit at different absolute levels due to predicted differences in combustion style [2]	Deviation from specification is not significant except in extreme conditions.
Combustion Behaviour including ignition efficiency, cross lighting and assessment of light back.	No evidence of deterioration in combustion performance, no ignition failings and no occurrence of light back [2]	None	No significant change in appliance performance.
Combustion behaviour (100% Hydrogen)	Light back at concentrations greater than 80 % mol/mol hydrogen. Below 80 % mol/mol, no ignition issues or occurrences of flame failure [2]	At > 80% mol/mol hydrogen ignition issues observed	Suggests an upper functional limit of 80% mol / mol hydrogen is present.
Function of Oxygen Depletion Sensor (ODS)	One of four live flame effect fires showed a compliance against ODS specification with G20 but failed the safety criteria when hydrogen was added.	The fire with oxy pilot ODS trialled against the various test gases failed to provide ODS function with sufficient safety factor to be acceptable. Further studies into ODS design and function is recommended.	Inset live flame effect fires contain an oxygen depletion sensor (ODS) to guard against flue blockage. BS EN 7977-1 requires that the ODS shuts off the gas supply before the CO concentration reaches 200 ppm in the test chamber
Flame Failure Devices (Ionisation Probe)	Up to 90 % mol/mol hydrogen the measured ionisation current in the Worcester Bosch boiler showed a reduction in ionisation current with increasing hydrogen concentration. No false flame out events occurred.	Ionisation current is used as a control mechanism by a number of boiler manufactures. None of these appliance types are present on the G3 network at Keele University and therefore this aspect has not been considered as part of the HyDeploy test programme.	It is a well-established consensus that there is limited ionisation current in hydrogen flames: the trials reaffirmed this consensus.
Energy Efficiency	Minimal effect of hydrogen on the efficiency of the appliances. [2]		The Wobbe Number of the delivered gas was kept within GSMR limit.

Onsite Testing

Appliance Condition and Repair

Gas Safe checks were undertaken as an upfront examination of all appliances prior to assessment with hydrogen blends. Additionally, combustion tests were undertaken to assess whether there were any issues with the appliance combustion. Generally, the appliance population was found to be in a good operating condition although seven instances where remedial work was required were identified, these instance are summarized in Table 7. Of these issues only one was identified as being immediately dangerous due to the release of combustion gas back in to the room.

Table 7 Appliance Remedial Works

Appliance Type	Identified Issue and Remedial work
Boiler	Seal had decayed and showed signs of soot. Some combustion products in room, with unsatisfactory repair. Declared immediately dangerous and disconnected. Replaced
Boiler	Heat exchanger leaking, not economically repairable. Replaced.
Gas fire	No name plate so - no testing could be carried out. Replaced.
Gas fire	Blocked chimney and no appliance information. Chimney cleared. Replaced.
Hob	Gas leak suspected from hob knobs. Replaced.
Oven	Bottom oven in two-oven installation not working. No remedial work could be carried out as no arrangement could be made with the tenant to readmit gas engineers for repairs.
Radiator system	Blocked radiators led to overheating of part of one property, without heat to another part. Radiator system was flushed.

Testing on the G3 Network

Following preliminary onsite safety checks for all appliances, provision of various mixed gases were achieved by the use of a mixing manifold connected to bottled gases of 100% methane (G20 reference ags) and two hydrogen blended gas mixtures. The gas blends chosen for detailed assessment were selected from the the range of laboratory test gases. The gases used are shown in Table 8.

Hydrogen Test Gas 1 was the standard G24 test gas which had a high Wobbe Number (51.9 MJ/m^3) and a hydrogen content of 20 % mol/mol, and is representative of the upper Wobbe Number of natural gas. In the absence of added hydrogen, this mixture represents a supply of 55.2 MJ/m^3 natural gas to Keele University that would be then subsequently admixed with hydrogen. This is to demonstrate that with high Wobbe Number gases, the appliance will not produce CO in excess of acceptable CO/CO_2 ratios.

Hydrogen Test Gas 2 was a mixture of G20 with 28.4 % mol/mol hydrogen which had Wobbe Number of 47.2 MJ/m^3, and is equal to the lower GSMR limit. This gas was used to assess the behaviour at the low Wobbe Number limit and to assess the response of appliances where the level of injected hydrogen went beyond the control limits of the hydrogen grid entry unit of 20 % mol/mol.

Table 8 Gas Mixtures for Onsite Testing at Keele University

Onsite Test Gas	Wobbe Number (MJ/m^3)	Hydrogen Concentration (% mol/mol)	Comments
Line Gas	47.20 – 50.85	0	The normal distributed gas on the Composition variable within GSMR limits
Reference Gas	50.7	0	G20 (100% methane)

			Standard gas mixture that is used by manufacturers to set appliance operating conditions.
Hydrogen Test Gas 1	51.9	20	G24 Examines the upper limit on the hydrogen injection High WI gas enriched with hydrogen
Hydrogen Test Gas 2	47.2	28.4	G20 + 28.4% H_2 Low WI Hydrogen Gas Hydrogen enriched reference gas at lower GSMR limit. Hydrogen content beyond 20% H_2 range

Assessment Results

Table 9 shows the areas of on-site investigation undertaken and the results of each study. The order of testing was sequential as shown in the table with purging between each assessment undertaken.

Table 9 Onsite Test Results

Test Assessment	General Test Result	Comments
Presence of correctly fitted CO Alarm with suitable placement	58 out of 91 properties (64% compliance)	Correct placement was within same room as gas appliance.
Presence of correctly fitted smoke alarm with suitable placement	52 out of 91 properties (57% compliance)	.
Presence of Detectors in non-domestic locations	Safety devices (eg fusible links) present in boiler locations.	
Ventilation sufficient for removal of flue gases and ensure efficient combustion	Adequate ventilation was provided at all properties	
Flueing	Adequate flueing present in all properties	Two premises had the flue outlet terminals closer to the ground than regulation (150 mm rather than 300 mm). One premises had the flue outlet installed upside down, allowing potential rain ingress. A chimney blocked by birds nest was also identified. In both of these scenarios the flueing was modified to ensure adequate flueing was present in all properties.
Combustion Behaviour: Gas Composition	Increases in CO production occurred when using hydrogen test gas 1 (higher Wobbe Number gas with added propane). Test gas 2, (low Wobbe Number gas), resulted in a reduction in CO. Both these observations were in line with laboratory results, the carbon content of the fuel and the stoichiometric oxygen requirement.	Flue gas analysis was undertaken on all appliances.
Combustion Behaviour : Heat Output	The addition of hydrogen to natural gas led to a reduction in CO due to a decrease in oxygen demand and move away from incomplete combustion at the burner surface; furthermore the lower carbon content	In accordance with the calorific content of the gases, higher energy input occurred with the higher Wobbe Number gases and the hydrogen test gas 2 had a lower rate of heat input.

	of the fuel gas led to a reduction in CO.	
Maloperation	See Discussion Below	
Gas Tightness	See Discussion Below	

Maloperation

Maloperation of an appliance was not an aspect specifically tested during the trial but data was taken from observations by the test engineer and/or combustion measurement from house-to-house enquiries. Two instances of maloperation were found at the test site.

1) A grill in the Chancellors refectory had a build-up of grease close to the burner ports. This was thought to potentially reduce the flow of air into the burner resulting in poor combustion and increased CO production. In this commercial kitchen environment however there was sufficient forced ventilation to mitigate this effect.

2) A boiler in a residential property had ad hoc repairs by a non-competent person. The boiler itself was poorly maintained and was emitting combustion products into the room. The boiler was deemed immediately dangerous, capped off and replaced with a new boiler.

Tightness Testing – Meters and Connections

As part of the gas safe checks routine assessment of the functionality of the installation of meters and fittings was undertaken. Deviation from standard requirements for four meters were found as detailed in Table 10. All other meters on the network where determined to be leak tight

Table 10 Installation remedial works for gas tight testing of meters with Natural Gas

Fitting type	Issue and remedial work
Meter	Old meter (1960s, imperial type) with lead pipes. Meter replaced.
Meter	Gas outlet rotated when an attempt to disconnect was made with the nut rotating rather than unscrewing. Meter replaced.
Meter	Leaking regulator found – regulator replaced.
Emergency control valve	False positive report of being unable to close fully. Further assessment found to be a very tight valve that could be closed.

Tightness Testing – Installations with Natural Gas

Of the 133 installations tested, three were found to fail the maximum permitted leak rate (MPLR) criteria defined in IGEM UP/1B [3]; this is detailed in Table 11.

Table 11 Installation Remedial Works Following Tightness Testing

Location	Issue and remedial work
Domestic Property	Gas leakage observed from the hob. This was replaced along with the gas fire and various other maintenance works
Science and Learning Centre	Failed due to a leak on the gas governor. Components replaced.
Sports Hall	The installation passed the initial two minute test but failed over the longer test duration conducted. A subsequent retest of the installation confirmed these findings. Onsite inspection identified the source to be a hot water heater in the plant room.

Tightness Testing – Hydrogen Test Gas 2

Tightness testing performed with hydrogen test gases were found to give spurious results. It was determined that this related to the gas supply being provided from pressurised bottles with the gas undergoing expansion leading to gas cooling in line with the Joule Thompson coefficient of the gas mixture. The consequence of this was that in the majority of cases, the gas volume in the installation pipework would slowly warm to equilibrate to the ambient temperature between the start and end of test, and in doing so indicated a pressure rise. It was eventually deemed not possible to assess whether the installation was leaking preferentially with hydrogen blended gas compared to natural gas to a suitable degree of data confidence.

As practical analysis could not be undertaken, a theoretical review of the leakage was undertaken. From this analysis it was possible to estimate what the results of a tightness test with a hydrogen blend could be based on the data obtained in the 'as found' tests with line gases. Setting the leak rate criteria to 90% of the line gas value provided a conservative assessment. Using this approach all the tightness tests were reassessed with 90% of the natural gas MLPR as the pass/fail criteria (as defined in the appropriate IGEM UP/1B standard that is used during a Gas Safe checks).

The leak rate data obtained during the onsite testing programme had generally shown very little pressure drop, even though data replication for a given installation was not possible due to the difficulties outlined above. When considering the outcome against 90% MLPR with hydrogen blended gas, all the installations were deemed to be gas tight for natural gas were still deemed gas tight for the hydrogen test gas.

CONCLUSION

A detailed laboratory-based programme of work has been undertaken to investigate the effect of hydrogen injection into a natural gas-based distribution network up to a hydrogen concentration of 20% mol/mol in preparation for live trials on a closed network at the Keele site. Some minor concerns have been identified specifically for the Keele network relating to the use of ODS and ionisation detectors. Difficulties were encountered relating to broken appliances, blocked flues, poor repairs, incorrect siting of detectors and failed leak tests. However, the majority of test data indicates no deterioration in public safety when using a hydrogen blended natural gas mixture.

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