# Opening up the Gas Market

Final report, October 2016

SGN
Your gas. Our network.

## How we keep the gas flowing

Over 5.9 million customers

24hr emergency response

**Keeping you safe**

74,000km of pipes

Safe and efficient streetworks

**Connecting the network**

Scotland and southern England

c. 22,000 new connections a year

**Always improving**

Volunteering and fundraising

Upgrading our pipes

**Engaging the community**

Investing in new technology

**Looking to the future**

Securing future gas supplies

Using new fuel sources such as biomethane

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**Acknowledgements**
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**Project delivery partners: Kiwa Gastec; Dave Lander Consulting; DNV GL.**

# The project in numbers and pictures

20+

successful customer and stakeholder engagement campaigns completed

1,787

appliances inspected

1 year

network trial using gases with Wobbe Index outside the GB regulations

1,104

Oban customers

>90%

access rate

18

appliance laboratory tests

7

special appliance tests

47

appliances replaced due to pre-existing conditions

# Key conclusions from the Opening up the Gas Market project

Using Oban as a statistical representation of GB, it is estimated that **2%** of the GB appliance population would be classified as **‘immediately dangerous’** against the Unsafe Situations Procedure currently.

An upper WI limit of 53.25 MJ/$m^3$ allows **sufficient headroom** for any deleterious unknowns in the field condition of the appliance.

Domestic and small commercial appliances correctly installed, serviced and operated can **safely burn gas** with WI of up to 54.76 MJ/$m^3$.

The interchangeability diagram can be **simplified and updated** to reflect current requirements.

Both the **Sooting Index** and the **Incomplete Combustion Factor** as stated in GS(M)R are no longer valid.

The cost of maintaining the current GS(M)R limits is **grossly disproportionate** to the risk involved in widening the WI limits to 53.25 MJ/$m^3$.

Currently only **10%** of the available LNG can be accepted into the GB gas network without processing. Increasing the WI range to 53.25 $MJ/m^3$ would allow **>90%** of the globally available LNG to be injected into the GB gas network without processing.

**No evidence of deterioration** in appliance performance was found after one full year operation on gas outside of GS(M)R limits.

CO campaigns that focus **solely on CO alarms** are not the most effective means of reducing CO risk.

Appliance maintenance, servicing and replacement when required produces a **7-fold reduction** in the absolute risk.

There is a **significant incentive** to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.

Increasing the WI to 53.25 $MJ/m^3$ has **negligible impact** on the efficiency, performance and life of domestic or small commercial appliances.

Using Oban as a statistical representation of GB, it is estimated that **4%** of the GB appliance population would be classified as **‘at risk’** against the Unsafe Situations Procedure currently.

The Oban Network **safely stored, injected, distributed and utilised** gas with WI ranging from 49 $MJ/m^3$ to 53.2 $MJ/m^3$ during the one-year trial period.

# Project background

# Executive summary

The two key concerns for energy customers are price and security of supply. These concerns along with the global need to reduce carbon emissions, forms the renowned energy trilemma.

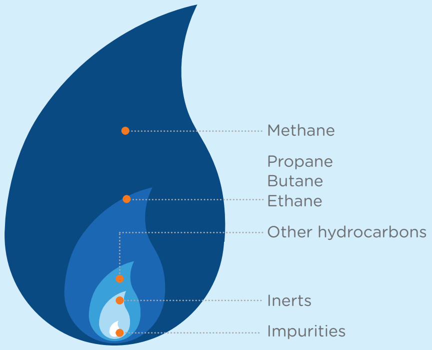
With over 80% of peak energy demand supplied by the gas network in Great Britain (GB), it has a very significant role to play in meeting energy needs and the journey to a lower carbon future. Key to this is a flexible distribution network that can adapt to the evolving needs of GB. The ‘Opening up the Gas Market’ (OGM) project was designed to tackle these issues, by challenging the legislative requirements for gas quality.

GB is now a net importer of gas, with prices and access to supply increasingly depending on international markets. Hence, GB gas prices exhibit volatility, given the short-term and/or spot market conditions.

## Gas composition

Although covered by a generic term, ‘natural gas’ varies in composition, and therefore quality, depending on its source as overall composition can vary in the type and proportion of gas present. While sources of new gas are numerous, GB’s specification for gas composition is very prescriptive, therefore restricting the sources of gases that can be used in their pure form and thus limiting the gas market.

**Fig. 1** Typical natural gas compositions



Not to scale

Combustion or burning is fundamental to all gas fuelled applications. It is a chemical reaction that occurs producing energy, usually in the form of heat and light. The composition or quality of the gas affects the overall combustion reaction.

Whilst there are many compositional factors that influence combustion, the Wobbe Index[1] (WI) is arguably the most important parameter in regards to natural gas. The WI is a measure of the amount of energy delivered to a burner and is an indicator of the compatibility between the gas supplied and the burner, often referred to as ‘interchangeability’.

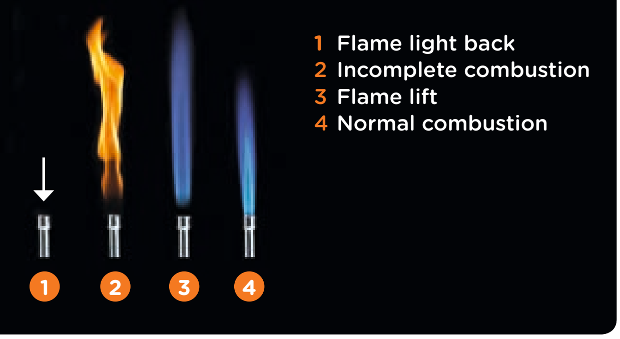
## Gas interchangeability

A gas that is interchangeable is considered safe to use on a natural gas appliance. It is the ability to substitute one gas for another in a combustion application without materially changing the operational performance of the application (its safety, efficiency or emissions). In GB, the regulations that govern combustion of natural gas are called Gas Safety (Management) Regulations (GS(M)R) 1996. This regulation stipulates the range of WI that should be used in order to ensure safe combustion of natural gas.

All gas-fired equipment is designed to operate within a particular range of WI. If gases outside this range are combusted, this can lead to a range of problems from poor quality combustion through to equipment damage and ultimately dangerous situations. Too high or too low a WI can cause greater emissions of carbon monoxide (CO) through incomplete combustion, as well as other undesirable flame effects.

The GS(M)R WI range was established following test work on appliances carried out in the 1970s and 1980s. Appliance technology has developed significantly since then. This coupled with rising import demand and declining indigenous supply led to the inception of this project with the aim of evaluating and redefining safe WI limits for GB that accommodates more gas sources.

**Fig. 2** Gas flame effects



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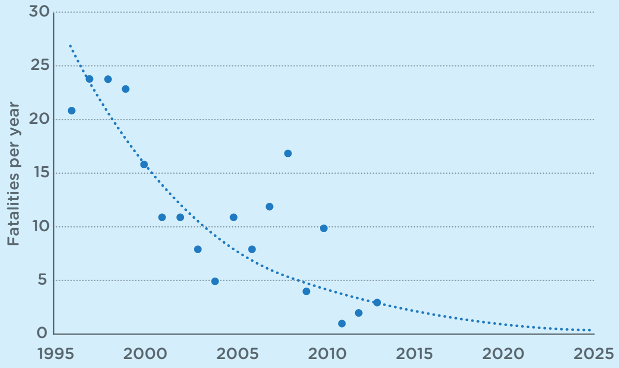
[1] At standard reference conditions 15°/15°C.

This project has carried out significant appliance testing to understand the impact of a wider range of WI in terms of appliance performance and safe use. CO is a poisonous gas at certain concentrations, so in considering a change to the WI, it was necessary to evidence whether a change to the limits of the WI will increase the risk of CO poisoning to occupants of the properties where the appliances are being used.

**Fig. 3** Fatality trend data to 2025



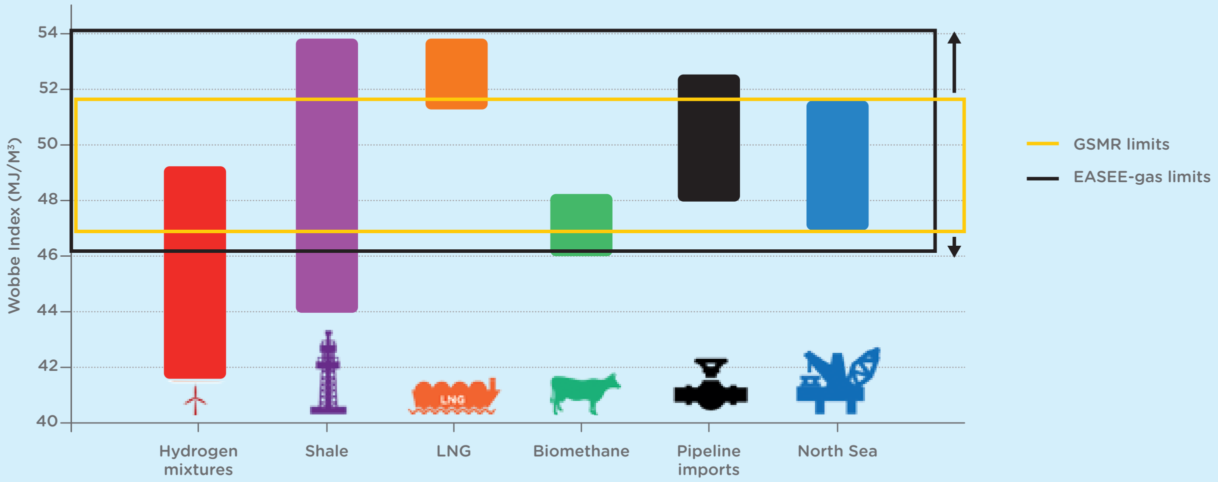
The assumption that numbers of CO incidents are directly proportional to the fraction of appliances with CO levels above an arbitrary level is not demonstrated and could be considered questionable given that CO incidents have continued to fall since records began, despite little change in WI of distributed gas (in fact WI has risen over the period since 1990). The linkage between CO incidents and CO above an arbitrary level is therefore more complex than originally assumed. This suggests that a high proportion of incidents were associated with factors other than gas quality. There is also a lack of a geographical correlation between CO incidents and gas WI. More incidents might be expected in the north of GB where consumers are supplied principally with higher WI St Fergus gas, but this is not the case.

Current arrangements dictate that in order for gases with compositions that sit outside of the GS(M)R WI range to be conveyed and used within GB, expensive gas processing is required to bring them within these specifications. Gas processing is a means of either increasing the WI of the gas by enrichment with propane or decreasing the WI of the gas by dilution with nitrogen (an inert gas). The types and sources of gas that can be used in GB without processing are limited, this ultimately leads to increased costs for the consumer estimated to reach £325m per annum by 2020[2].

If the GS(M)R WI range can be safely widened to accommodate more gas types and sources without processing, this will reduce the costs for the customer and open the market to new sources.

Gas specifications vary for different countries and were set to suit the local gas quality and

**Fig. 4** Typical Wobbe Index range of various gas sources



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[2] Current 2020 forecast estimate of £325m in GB from National Grid (IGEM presentation, 2014).

equipment at the time. GB has one of the narrowest acceptable WI ranges in Europe. This is often a barrier to trade. In Europe there is an ambition to extend and harmonise the WI across all member states called the European Association for the Streamlining of Energy Exchange-gas (EASEE-gas) specification.

### Opening up the Gas Market

The Opening up the Gas Market (OGM) project therefore sought to demonstrate whether gas, which meets the EASEE-gas specification but sits outside of the characteristics specified within GS(M)R can be distributed and utilised safely and efficiently in GB.

The limits EASEE-gas proposed are aspirational, but this work coupled with previous studies provided a useful starting point for this project, since the sources of gas seeking injection into the networks are more varied than ever before. This will only be exacerbated in future in pursuit of lower carbon sources, for example the injection of biogas and hydrogen.

For this demonstration project, the aim was to evaluate whether, through statistical sampling, gas appliance installations in GB are capable of burning gases with a wider quality variation, either higher (richer) or lower (leaner) WI than currently permitted in GB. The most important questions are whether this widening of the WI either increases the risk to any person or causes premature deterioration of burner components.

In order to do this, SGN was afforded a unique opportunity to utilise one of the discrete independent undertakings, the Oban gas network. Oban is a town in the Highlands of Scotland and was demonstrated to be statistically representative of GB on a socio-economical level (essentially a microcosm). A demographic study conducted by DNV GL[3] in May 2013 concluded that the 1,104 gas properties with a gas supply in Oban and the appliances within them could statistically represent that of GB in relation to the range of appliance types and models likely to be in use throughout GB. This enabled the findings to be evaluated as a potential solution to be scaled to GB.

The project was broken down into three distinct stages each with its own 'go/no go' stage gate. Each stage gate required a success criterion to be met before moving to the next stage.

**Fig. 5** Oban

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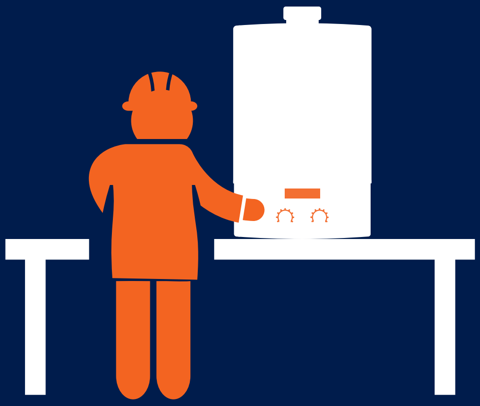
[3] DNV GL Demographic Analysis of Oban for Gas Testing, 2013.

## **Stage 1** Laboratory testing



In stage 1 a survey of gas appliances in 100 randomly selected properties in Oban was conducted. The survey results provided an understanding of appliance stock in Oban, recording their make, model, condition and manufacturer details. During this time, if any appliances encountered were considered to be unsafe or in need of repair, they were replaced or repaired free of charge.

### Laboratory tests

The appliance types present within the appliance survey data were considered typical and representative of the entire appliance population in Oban. This enabled the selection of 18 appliances of various types for laboratory testing using the recognised industry standard test gases over an extended WI range (45.66-54.76 MJ/m³)[4] that exceeded the current GS(M)R limits.

These 18 appliances were selected by each class (cooker, local space heater, boiler or commercial catering equipment) in combination with additional criteria such as manufacturer, product type, flueing, control type, age and condition. They were tested extensively in laboratory conditions by Kiwa Gastec, across the full EASEE-gas range and in various simulated scenarios, including but not limited to no ventilation, poor maintenance and mal-operation.

The laboratory tests concluded that for an appliance that was originally correctly designed, and has been installed and serviced according to manufacturer's recommendations there was no deterioration in appliance performance in terms of safety and efficiency due to the variation in WI up to 54.76 MJ/m³.

To allow for any deleterious unknowns in the field condition of the appliance, an element of safety termed 'headroom' was introduced. These could include low voltage (for appliances requiring electrical supplies), high or low gas pressure, uncharacteristically large differences in temperature of the combustion air and the natural gas or sub-optimal performance of the Oxygen Deficiency Sensors fitted to modern gas fires.

Following discussions with appliance manufacturers, a reduced upper limit of 53.25 MJ/m³ was proposed to account for the 'headroom'.

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[4] At reference conditions 15°/15°C.

## Additional tests

Additional laboratory work identified by and designed in collaboration with boiler manufacturers was carried out to investigate the effects of increased WI on appliance component life. Nearly all appliance manufacturers do not foresee an issue with more rapid burner aging resulting from higher WI, but the work did give manufacturers an opportunity to bring to attention the need for appliance servicing (especially after extended periods of operation). The test program established that internal component lifetime will not be materially affected by increasing gas WI of the supply and supports the assertion that no effect is expected upon boiler life.

Additional laboratory test work carried out demonstrated that it would be possible to adjust and operate the boilers tested on a gas supply network within a WI range between 48.00-53.00 MJ/m³ with only modest effects on CO production (i.e. ±2.50 MJ/m³ from a central point of 50.50 MJ/m³). Theoretically at least, outside this range, extreme adjustment (either low or high) fed with extreme opposite WI gas (either high or low) can lead to substantial increases of CO in the flue products. The likelihood of this is considered very low due to the Thermal Energy Regulations whereby biomethane plants add propane to the gas in order to meet the Flow Weighted Average Calorific Value (FWACV) of the network.

This compensates for the dilution effect the Biomethane would have on the FWACV which, in practice, means the WI of the Biomethane is likely to fall within the safe appliance adjustment zone.

If changes are proposed to the management of CV within networks going forward, this potential issue should be considered in detail.

## Implications for the interchangeability diagram

Additional laboratory tests found that the original method used for calculating the Incomplete Combustion Factor (ICF) over-predicts the true ICF for today's appliances. The tests in this project confirmed that for today's appliances, WI as a sole parameter is appropriate provided Relative Density (RD) is limited to no more than around 0.70.

Laboratory testing in this project also demonstrated that limiting relative density to 0.70 limits propensity for significant sooting. The current Sooting Index (SI) limit value of 0.60 is based on visual assessment of the discolouration of ceramic radiants of gas fires commonly on use at the time (1970/80s). Sooting at this level is not a safety consideration and only becomes of concern only when considering excessive deposition – in the flues of flame-effect fires, for instance.

Replotting the Interchangeability Diagram in terms of WI and RD has only a minor impact on the diagram because RD is a good proxy for equivalent ($N_2 + C_3H_8$). The results from the laboratory tests in this project have confirmed that for today's appliances, WI as a sole parameter is appropriate provided RD is limited to no more than 0.70. It is therefore recommended that the Interchangeability Diagram can be simplified and updated to reflect current requirements.

## **Stage 2** Field testing at customers’ properties

Stage 2 began in November 2014. The aim of stage 2 was to test all gas appliances in-situ at customers’ proprieties in Oban on different WI gases. A total of 903 properties with 1,787 appliances incorporating 2,524 burners were inspected, the majority tested using three different test gases, the same ones used in appliance certification testing[5]. Bespoke portable testing vehicles were designed and constructed to allow these gases to be transported and used efficiently and safely.

Bespoke test rig

### Field tests

Combustion performance was recorded and analysed for every appliance on each test gas. Appliances that were found to have pre-existing faults or were in poor condition upon arrival were serviced and/or fixed, or where appropriate, replaced for free under the project.

The results from the field testing confirmed that appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 $MJ/m^3$.

This corroborated the findings of the stage 1 laboratory tests (refer to Figures 6 and 7).

### Appliance health

Due to the statistical representativeness of Oban and the high level of access achieved, an insight into appliance health was obtained on a scale not seen since conversion from town gas to natural gas.

Of the appliances tested in Oban, 94% fell into the category as correctly installed, serviced and operated. The remaining 6% were considered ‘At Risk’ or ‘Immediately Dangerous’, as per the Gas Safety (Installation & Use) Regulations and the guidance given in the Gas Industry Unsafe Situations Procedure[6].

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[5] G20 (WI 50.72 $MJ/m^3$), G21 (WI 54.76 $MJ/m^3$), G23 (WI 45.66 $MJ/m^3$).

[6] https://www.gassaferegister.co.uk/media/1774/tb_001_-_gas_industry_unsafe_situation_procedure_-giusp-_edition-71.pdf

**Fig. 6** Average CO emissions vs Wobbe Index by appliance type (flued)

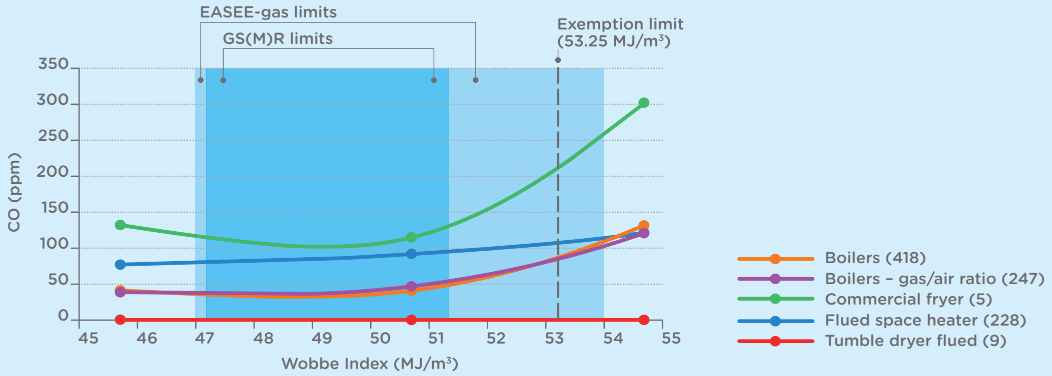
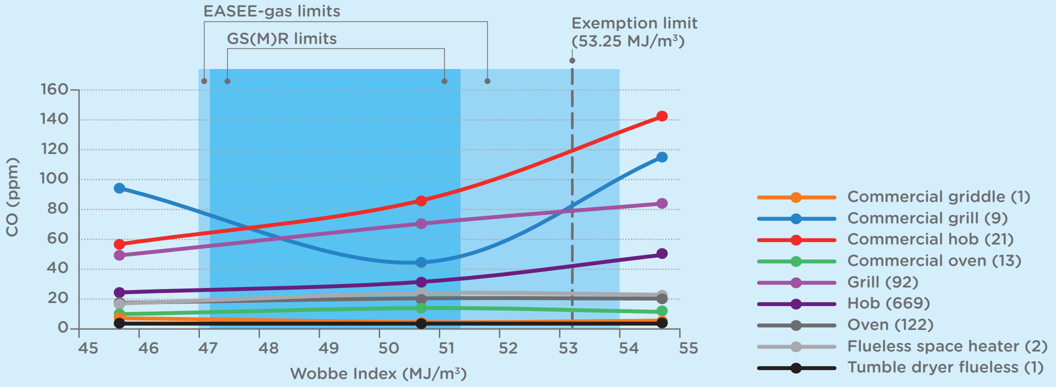


**Fig. 7** Average CO emissions vs Wobbe Index by appliance type (flueless)



This was due to the pre-existing condition of the appliance and not due to the performance results using the extreme test gas.

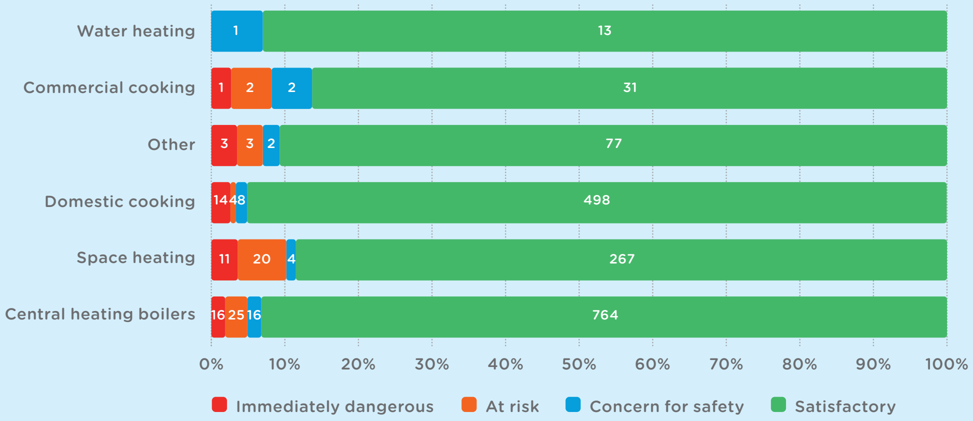
Those appliances that were found to be At Risk or Immediately Dangerous when tested on G20 test gas, were rectified or replaced free of charge under the project. The worst case appliances were removed from the customer's property and taken to the laboratory for further testing.

This involved testing faulty appliances and installations across a wide range of WI gases in a variety of fault scenarios such as blocked flue and inadequate ventilation. Examples of two grossly defective appliances removed from properties in Oban are shown opposite.

Examples of faulty appliances found in Oban

# Executive summary
*cont.*

**Fig. 8** Unsafe situations by appliance category – Oban



In one instance, due to a broken glass panel a local space heater was spilling combustion products into the living room. On another site the customer explained that the CO Alarm had been sounding for a few months but they had chosen to ignore it. This highlights the importance to distinguish between gas quality issues and unrelated appliance condition and/or customer behaviour issues.

## Customer participation

In order to provide a robust statistically representative dataset, high levels of customer participation were necessary. Customer and stakeholder engagement was therefore essential to the success of this project.

At a local level in Oban, the customers needed to be engaged and enthused to participate and allow access to their properties in order to test their appliances. This required much emphasis to be placed on communication methods and material. The project team worked alongside the local council, community groups and businesses to help encourage participation and access to customers' properties.

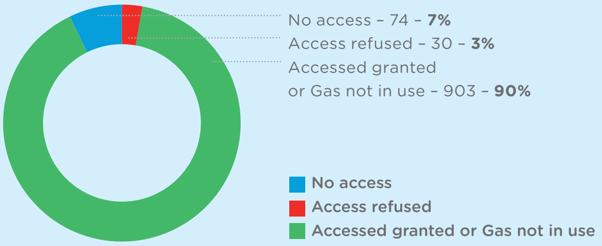
## Stakeholder engagement

An example of some of the local stakeholder initiatives undertaken by the project include hosting a 'Cooking with Gas' event whereby a professional chef provided cookery demonstrations on different blends of gas for the local community. Other examples are SGN sponsoring the Oban Winter Festival; drop in sessions in the town hall to provide an opportunity for customers to ask questions; and even showing the project film[7] as a trailer before films in the Oban cinema.

As a further benefit to customers, appliances encountered that were inoperable, dangerous or At Risk were either repaired or replaced and customers were issued with a free CO alarm. The engagement methods were extremely successful, resulting in over 90% of customers in Oban electing to participate in stage 2, providing a very strong, statistically representative dataset.

Cookery demonstrations at the Regent Hotel, Oban

**Fig. 9** Property access report



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[7] Project film can be found at www.sgn.co.uk/oban

Currently only **10%** of the available LNG can be accepted into the GB gas network without processing. Increasing the WI range to 53.25 MJ/m³ would allow **>90%** of the globally available LNG to be injected into the GB gas network without processing.

## **Stage 3** Field trial

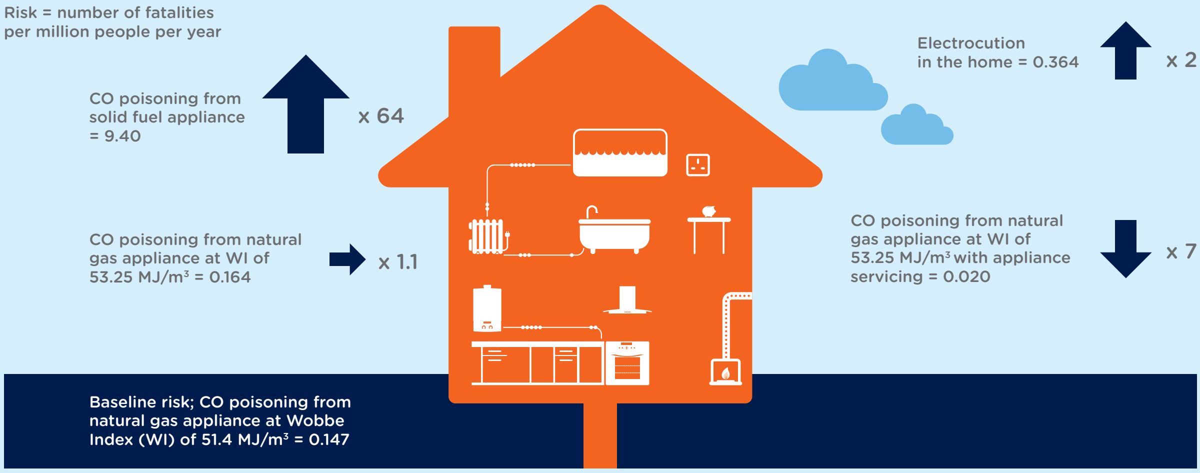
For the final stage, three different sources of gas with a higher WI than permitted in GS(M)R was selected and trialled in the Oban network for one year. In order to carry out the field trial an exemption from the requirements of GS(M)R was sought from the Health and Safety Executive (HSE).

### Quantitative risk assessment

As part of the evidence submitted for the exemption, a Quantitative Risk Assessment (QRA) was carried out by DNV GL. The assessment determined the change in risk associated with transporting gas with WI outside of limits currently allowed by GS(M)R. The results of the Laboratory and field tests fed into the QRA and showed that increasing the WI of the gas up to 53.25 MJ/m³ did not increase the magnitude of risk and appliance servicing/inspection reduces the absolute level of risk 7-fold.

The QRA also benchmarked risks against other common household risks and illustrated that CO risk from natural gas appliances, regardless of WI, is significantly less than that posed by solid fuel appliances.

**Fig. 10** Comparison of relative risks at home



## Global LNG availability

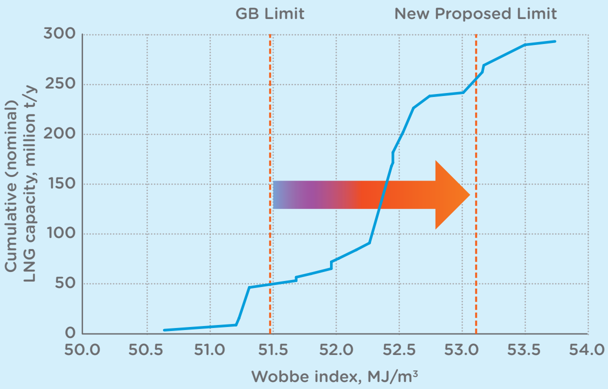
A review of globally available LNG carried out by Dave Lander Consulting showed that extending the upper WI limit of GS(M)R to 53.25 MJ/m³ would bring 90% of the globally available LNG into the allowable range without the need for processing. This would be a significant shift from the 10% currently available. The market benefits from this change are unquantifiable at this stage, but expected to surpass the significant savings from avoided processing of gas.

## Field trial

On Monday 6th July 2015 at 8.05am, SGN made gas industry history by injecting the first load of liquefied natural gas (LNG), all the way from Zeebrugge, into the Oban network.

Zeebrugge LNG being offloaded in Oban

**Fig. 11** Cumulative LNG production capacity



Three different LNG sources were injected into the Oban network across the 1 year:

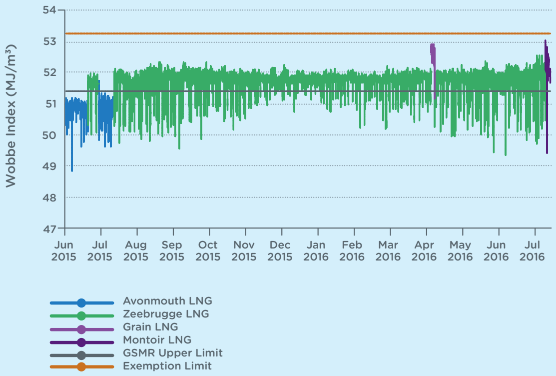
- Zeebrugge LNG, WI of 51.8 MJ/m³ (Average across year), trialled for 1 year – 2000t of LNG, 100 x road barrel tankers.
- Isle of Grain LNG, WI of 52.8 MJ/m³ – 20t of LNG, 1 x road barrel tanker.
- Montoir-de-Bretagne LNG, WI of 52.5 MJ/m³ – 15t of LNG, 1 x ISO tanker.

During the trial period, over 300 customers' properties were revisited at regular intervals to test how their appliances were performing on the new gas. All the appliance checks were satisfactory. There were no identifiable or material changes recorded in the burning characteristics and performance of appliances on the high WI gases when compared with the results witnessed on the G20 test gas during stage 2.

It was a significant challenge to make this possible involving setting up the first ever contract between a LNG terminal, GB Gas Shipper and Gas Distribution Network (GDN), establishing a complex gas nomination process and overcoming challenging haulage logistics.

Throughout the one year trial, the Oban network operated safely without incident, demonstrating that a higher WI gas can be injected, distributed and utilised safely.

**Fig. 12** Daily WI ranges – June 2015 to August 2016



## Outcomes against project objectives

| Objective | Outcome |
|---|---|
| 1. To demonstrate whether all gas appliances are capable of safely and efficiently burning gas which meets EASEE-gas specifications but sits outside GS(M)R; | Laboratory and field testing demonstrated that appliances (GAD and non-GAD) installed, serviced and operated correctly up to can safely and efficiently burn gas with a WI of up to 54.7 MJ/m³. Applying a headroom factor for appliance age/condition and discussions with manufacturers it was recommended that 53.25 MJ/m³ be the upper WI value. |
| 2. To establish the proportion of older gas appliances that constrict gas quality specification in GB through assessment of a representative appliance sample from Oban network; | Laboratory and field testing results found that all appliances installed, serviced and operated correctly, can safely and efficiently operate with a wider gas quality specification, regardless of age. |
| 3. To demonstrate through the sample population what is required to ensure GB's appliance population is capable of operating safely and efficiently over a wider range of gas quality; | The QRA showed that increasing the WI to 53.25 MJ/m³ has small increase in risk, albeit the risk remains of the same magnitude. The QRA also demonstrated that, if an appliance is maintained and serviced regularly then the increase in risk with WI is negligible. Therefore the small increase in risk for un-maintained appliances could be removed by refocusing CO campaigns on the importance of appliances servicing and maintenance. |
| 4. To identify and record all types/makes of gas appliances, identified through the representative appliance sample from Oban network that are not fit for operation using gas which meets EASEE-gas specifications but sits outside GS(M)R; | No appliances were found to be unfit for EASEE-gas specification. Unsafe appliances were already unsafe on GS(M)R specification gas. A minor reduction from the EASEE-gas specification to 53.25 MJ/m³ provides a headroom factor for appliances in poorer condition. |
| 5. To demonstrate whether gas that meets EASEE-gas specification but sits outside GS(M)R can be conveyed safely and efficiently in the GB gas network; | The field trial demonstrated that there are no network related issues with conveying gas with a WI outside of GS(M)R specification. Three alternative LNG source gases with Wobbe Index > 51.4 MJ/m³ were successfully introduced and used continuously over a 12 month period in the Oban network.<br>During the initial trial period 200 spot checks were carried out on random properties with no issues found. |
| 6. To capture and record all project learning to assist in a full GB roll out in the future; | All learning from the project has been captured and disseminated as appropriate and there is continuing engagement with OFGEM, DECC (now BEIS), HSE, HHIC and other key Stakeholders.<br>The project has led to the formation of the IGEM Gas Quality Working Group, with the objective of moving GS(M)R to an IGEM standard and widening the WI limits within. |
| 7. To compile a project completion report assessing the technical and commercial viability of accepting EASEE compliant gas in GB; | A £325m potential benefit due to less gas processing has been advocated by National Grid (NG). This project has proven that this is technically possible to achieve up to 53.25 MJ/m³ without the need to inspect or replace any appliances. |
| 8. To compile a list of appliances found to be incompatible which will be shared among all relevant stakeholders; | Laboratory and field testing results found that all appliances were compatible. All appliances installed, serviced and operated correctly, can cope with a wider gas quality specification. |

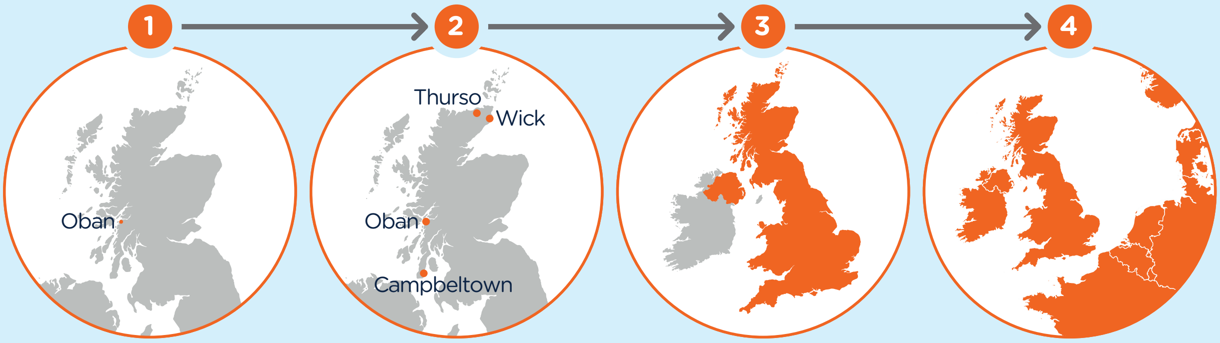
### Key conclusions

Based on the findings from the three stages of the project a number of conclusions were able to be drawn. The main conclusions are summarised below.

1. There is a significant incentive to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.
2. Currently only 10% of the available LNG can be accepted into the gas network without processing. Increasing the WI range to 53.25 $MJ/m^3$ would allow >90% of the globally available LNG to be accepted.
3. Domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 $MJ/m^3$.
4. An upper WI limit of 53.25 $MJ/m^3$ allows sufficient headroom for any deleterious unknowns in the field condition of the appliance.
5. The cost of maintaining the current GS(M)R limits is grossly disproportionate to the risk involved in widening the WI limits to 53.25 $MJ/m^3$.
6. Using Oban as a statistical representation of GB, it is estimated that 4% of the GB appliance population would be classified as ‘at risk’ against the Unsafe Situations Procedure currently.
7. Using Oban as a statistical representation of GB, it is estimated that 2% of the GB appliance population would be classified as ‘immediately dangerous’ against the Unsafe Situations Procedure currently.
8. Appliance maintenance, servicing and replacement when required produces a 7-fold reduction in the absolute risk.
9. Both the Sooting Index and the Incomplete Combustion Factor as stated in GS(M)R are no longer valid.
10. CO campaigns that focus solely on CO alarms are not the most effective means of reducing CO risk.
11. Increasing the WI to 53.25 $MJ/m^3$ has negligible impact on the efficiency, performance and life of a domestic or small commercial appliances.
12. The interchangeability diagram can be simplified and updated to reflect current requirements.
13. The Oban Network safely stored, injected, distributed and utilised gas with WI ranging from 49 $MJ/m^3$ to 53.2 $MJ/m^3$ during the one-year trial period.
14. No evidence of deterioration in appliance performance was found after one full year operation on gas outside of GS(M)R limits.

## Road map to GB roll-out

**Fig. 13** Road map for roll-out



### Recommendations

In review of the findings of this project, the following recommendations are made as part of the road map for GB roll-out:

1. The upper WI limit to be increased to 53.25 MJ/m³
2. No changes to the lower WI limit at current time
3. The interchangeability diagram to be updated
4. Transfer GS(M)R to IGEM Standard
5. Review CO guidance message
6. Permanent GS(M)R exemptions for the SIUs

### 1. The upper WI limit to be increased to 53.25 MJ/m³

Based on the results of the project it is recommended the upper WI limit in GB is increased from 51.40 MJ/m³ to 53.25 MJ/m³. Although the extensive appliance testing results demonstrated that all domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 MJ/m³, a reduced upper WI limit of 53.25 MJ/m³ is proposed to allow sufficient headroom for any deleterious unknowns in the field condition of appliances. This provides a safety margin (approximately 1.5 units) for factors such as:

- Appliance safety device performance.
- Ambient temperature effects.
- Start of exponential increase of CO around 53.50 MJ/m³ (for some appliances).
- Sub-optimal adjustment of air/gas ratio controlled fully premix boilers.
- Other deleterious unknowns and poor condition of appliances.

Furthermore, it was noted that this upper limit is only marginally above the current GS(M)R emergency limit (52.85 MJ/m³).

Using Oban as a statistical representation of GB, it is estimated that 4% of the GB appliance population would be classified as ‘at risk’ and 2% ‘immediately dangerous’ against the Unsafe Situations Procedure currently. The QRA determined that increasing 53.25 MJ/m³ does not materially affect CO risk. Appliance installation condition is the most significant contributor to risk.

There is a significant incentive in terms of LNG availability at this level. Currently only 10% of the available LNG can be accepted into the GB gas network without processing. Increasing the WI range to 53.25 MJ/m³ would allow >90% of the globally available LNG to be accepted.

### 2. No changes to the lower WI at current time

Although this project did not find any safety issue testing on gases as low as 45.66 MJ/m³ WI, it is suggested that more work is required in this area to investigate mal-adjustment of boilers with gas/air ratio controls. Extending the upper WI limit to 53.25 MJ/m³ and retaining 47.20 MJ/m³ at the lower end, would effectively widen the WI range beyond the 5-6 MJ/m³ safe operational range identified by the project. Thus an upper limit of 53.25 MJ/m³ leaves less scope to extend the lower limit below 47.20 MJ/m³ without potentially having to re-adjust boilers from their G20 factory set point, which the majority are set.

There have been concerns raised about re-commissioning 'repaired' gas appliances when the gas service operative does not know the quality of the gas being supplied to the property at that moment. This is a recognised problem in Germany[8] and other countries developing an alternative gas strategy. Therefore additional laboratory test work to determine materiality of this was carried out under the project. The laboratory test work demonstrated that it would be possible to adjust and operate the boilers tested on a gas supply network within a WI range between 48.00-53.00 MJ/m³ with only modest effects on CO production. (i.e. ±2.50 MJ/m³ from a central point of 50.50 MJ/m³).

A boiler could be factory set at either 48.00 or 53.00 MJ/m³ and still meet the safety action level on a gas network that has a WI that varies between these two extremes. For example, if the boiler was adjusted at 48.00 MJ/m³, the gas WI could increase by 5.00 MJ/m³ and the combustion would still be acceptable, and vice versa. In theory, if the boiler was adjusted at 48.00 MJ/m³ and the gas WI decreased by 5.00 MJ/m³, to 43.00 MJ/m³, the combustion would be still be satisfactory (48.00 MJ/m³ becomes the new upper point of adjustment). The same applies at 53.00 MJ/m³.

Theoretically, outside this range, extreme adjustment (either low or high) fed with extreme opposite WI gas (either high or low) could lead to substantial increases of CO in the flue products. In future this would essentially only be an issue in areas where Biomethane is injected into the distribution system unconstrained by thermal energy compliance. Currently, in order to comply with the Thermal Energy Regulations, biogas plants enrich the gas by adding propane in order to meet the Flow Weighted Average Calorific Value (FWACV) of the network. This compensates for the dilution effect the Biomethane would have on the FWACV. Therefore the WI of the Biomethane is likely to fall within the safe appliance adjustment zone.

The 'Oban limits' identified allow for WI headroom allocated to on-site appliance issues. Indeed notwithstanding this, many appliances (such as flued and room sealed) pose no potential for CO spillage to room. This is however an issue that should be considered in any unconstrained development, such as that being considered under the Real-time networks project[9]. Whilst the CO concentrations may not be harmful the appliance may be operating outside the manufacturer's recommended $CO/CO_2$ envelope, which could give future complications.

This is an example of where both the appliance industry and gas supply chain must continue to closely co-operate to understand future widening of sources in terms of thermal energy and gas quality management.

The driver for extending the lower WI limit may become more prevalent in the future as new renewable and unconventional gas sources with lower WIs become available. Therefore no changes to the lower WI limit of 47.20 MJ/m³ are recommended at this time.

### 3. The interchangeability diagram to be updated

The interchangeability diagram, published in the HSE's Guide to the GS(M)R[10], is a visual representation of the WI, ICF and SI limits embodied in Schedule 3 of the GS(M)R. These limits and the Interchangeability Diagram are a simplification of the limits introduced and operated by the British Gas Corporation prior to 1996 and the Dutton Diagram, published[11] following a series of work carried out by B.C.Dutton in the 1970-1980s. The interchangeability diagram has served GB well and was certainly fit for purpose based on the gases available and type of appliances in use at that time. In light of the work conducted under this project it is considered that it can be simplified and updated to reflect current requirements.

Figure 14 shows the existing interchangeability diagram and various limits as defined within GS(M)R.

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[8] Joint declaration by European transmission and distribution system operators to Pilot Study 2.0 Contribution to the pre-normative study of H-gas quality parameters (2016).

[9] https://www.sgn.co.uk/real-time-networks/

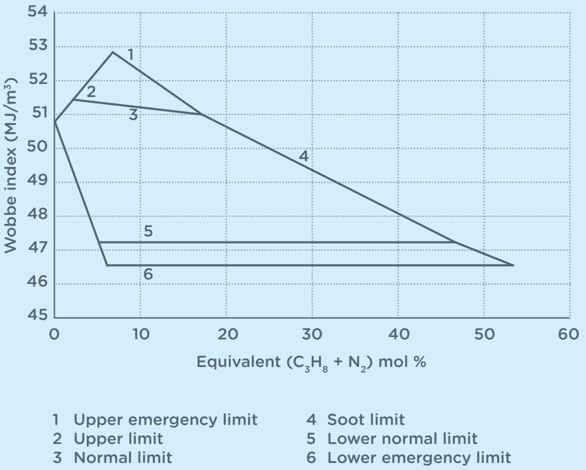
[10] Health and Safety Executive. 'A Guide to the Gas Safety (Management Regulations'. HSE Books ISBN 978 0 7176 1159 1.

[11] B.C.Dutton. 'A new dimension to gas interchangeability'. IGEM Communication 1246, 50th Autumn Meeting. 1984.

There is a **significant incentive** to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.

# Executive summary *cont.*

**Fig. 14** Existing interchangeability diagram



The abscissa in the current Interchangeability Diagram is based on the propane and nitrogen content of the equivalent mixture[12]. However, an alternative approach adopted within Europe is to plot WI against RD. This offers has a number of advantages:

- Simplification – reduction of composition to an equivalent mixture is not required.
- Harmonisation with European practice.

The EASEE-gas specification sets interchangeability limits solely in terms of WI and RD, so limits can be compared directly.

Replotting the Interchangeability Diagram in terms of WI and RD has only a minor impact on the diagram because RD is a good proxy for equivalent Nitrogen ($N_2$) and Propane ($C_3 H_8$) – this can be seen by a plot of the two terms for a series of hypothetical gas compositions selected by Monte-Carlo methods – see Figure 15. The hypothetical compositions were selected to reflect GB natural gases that were both compliant and non-compliant with the requirements of the GS(M)R.

**Fig. 15** Demonstration that RD is a good proxy for equivalent ($N_2$ + $C_3H_8$)

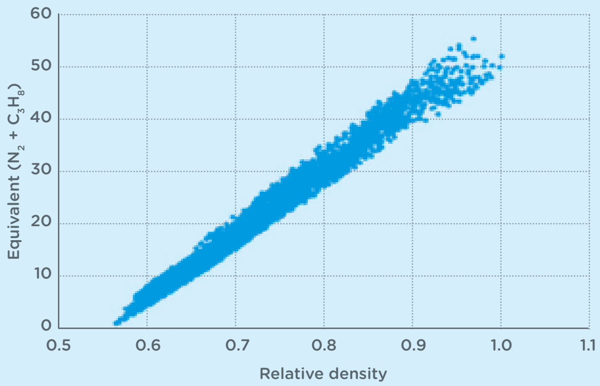


Figure 16 shows the modified Interchangeability diagram resulting from employing RD as the abscissa. Superimposed on the diagram are the EASEE-gas interchangeability limits in WI and RD. The diagram also shows the location of the stage 1 and 2 test gases and the stage 3 trial gases within the various boundaries. Note these gases are above GS(M)R normal upper limit and sit within the emergency envelope of GS(M)R.

**Fig. 16** Modified natural gas interchangeability diagram showing stage 3 gas positions

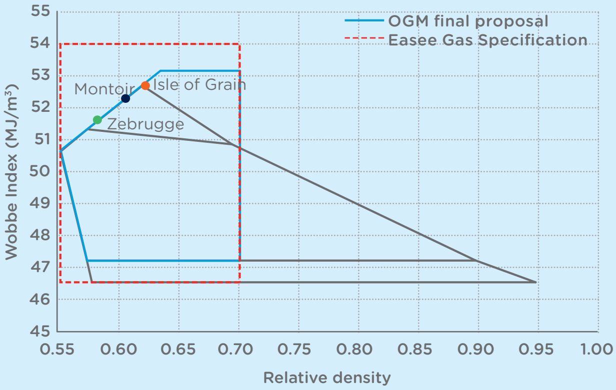


Figure 17 again depicts the GS(M)R, EASEE-gas and proposed Oban limits, but this contains the location of the globally available LNG within the various boundary limits. It illustrates the headroom below the EASEE-gas limits and how extending the upper WI limit to 53.25 MJ/m³ would accommodate most of globally available LNG without the requirement for processing, whilst satisfying appliance performance and safety considerations.

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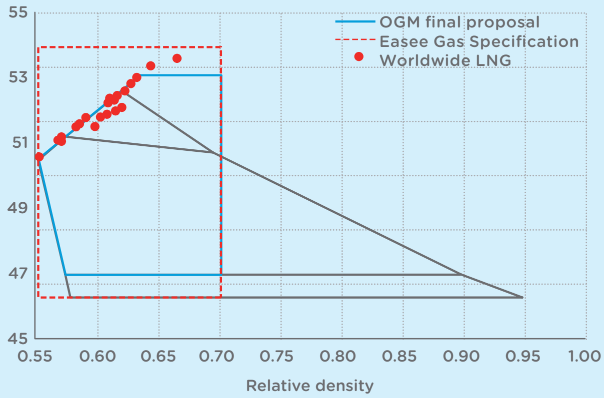
[12] The equivalent mixture is a hypothetical mixture of methane, propane, nitrogen and hydrogen that has the same Wobbe index as that of the gas under consideration.

**Fig. 17** Modified interchangeability diagram showing position of globally available LNG



The following proposals are therefore made to the interchangeability requirements of the GS(M)R:

**Incomplete combustion factor (ICF) is removed as a requirement**
The ICF parameter was introduced by Dutton because test results indicated a small dependence of flue gas $CO/CO_2$ ratio upon equivalent ($N_2 + C_3H_8$). In practice, this dependency is quite small over the range of interest (around 0 – 18%, corresponding to a relative density range of 0.55 – 0.70). Subsequent testing by the GASQUAL consortium and by KIWA in this project have confirmed that for today's appliances, WI as a sole parameter is appropriate provided RD is limited to no more than around 0.70.

ICF was derived by Dutton from the performance of instantaneous water heaters; these appliances (together with the radiant gas fire) were commonly found in most homes in the 1970s and generally generated flue gas $CO/CO_2$ ratios that doubled when WI was increased by approximately 1.5 MJ/m³. Such appliances are now rare and today's 'equivalent' appliance is the central heating/hot water boiler. Such appliances do not show such severe sensitivity to WI: KIWA testing of a combi boiler with partially premixed burner suggests doubling of flue gas $CO/CO_2$ ratios only occurs when WI is increased by 3.0 MJ/m³. As a result, Dutton's relationship for calculating ICF from composition over-predicts true ICF for today's appliances.

ICF is simply a measure of how flue gas $CO/CO_2$ ratio increases as WI increases and takes no account of flue gas CO content. Today's appliances tend to operate with much lower flue gas CO content and the GASQUAL consortium, for instance, characterised appliance performance by a combination of flue gas CO content and increase as WI increased.

**The upper WI limit is increased from 51.41 MJ/m³ to 53.25 MJ/m³**
This is the key finding from the project and is based on the findings of the laboratory, in-premises and field testing of a wide range of appliances.

The WI limit of 51.41 MJ/m³ arose from the selection of ICF limit of 0.48 by Dutton because this value corresponds approximately to the WI limit of 51.2 MJ/m³ that was in use by the British Gas Corporation following a survey of GB appliances carried out in 1978.

**Sooting Index is replaced by relative density**
Dutton's basis for limiting equivalent ($N_2 + C_3H_8$) was based on limiting sooting associated with higher density gases and the Sooting Index limit value of 0.60 is based on visual assessment of the discolouration of ceramic radiants of gas fires commonly in use at the time. Sooting at this level is not a safety consideration and becomes a concern only when considering excessive deposition – in the flues of flame-effect fires, for instance. Testing in this project and by the GASQUAL consortium shows that limiting relative density to 0.70 limits propensity for significant sooting.

It is worth pointing out that the relative density limit of 0.70 generally represents a stricter limitation compared with the SI limitation of the GS(M)R. Most natural gases have relative density lower than 0.70 and only some associated natural gases or heavily-enriched gases would be affected.

**No change to the lower WI limit**
The lower WI value of 47.20 MJ/m³ was originally proposed by Dutton on the basis heat service considerations, i.e. heat output from instantaneous water heaters (and to a lesser extent gas fires and cookers) led to consumer complaints if WI falls by more than 5% of the reference gas[13].

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[13] Note that reduction of WI to 95% of the reference gas corresponds to 48.18 and not 47.2 MJ/m³. Dutton's discussion of heat service limitation in the IGEM communication contains a number of discrepancies that are not readily interpreted.

The low emergency limit of the GS(M)R permits WI as low as 46.50 MJ/m³ to be conveyed in order to prevent a gas supply emergency and this limit value corresponds to the limit value for lift index of 1.16, which was established by visual assessment of flame detachment from the burners of cooker hobs.

No change in the lower WI limit is proposed at the current time, although there is scope for revision should assessment of future gas quality scenarios incorporating unconventional and renewable gases require this.

**No change to the hydrogen limit**
Prior to 1996 the British Gas Corporation employed a normal limit for hydrogen content of 10% (mol/mol), based on the consideration by Dutton of earlier work carried out in the 1970s. The limit was proposed by Dutton in anticipation of an imminent arrival of Substitute Natural Gases (SNGs) manufactured from petroleum feedstocks. In practice SNGs have not figured in GB energy mix to date and for the coming into force of the GS(M)R in 1996, hydrogen was set at an arbitrarily low value of 0.1 mol%. This removed the influence of hydrogen on calculation of WI, ICF and SI, effectively converting Dutton's three-dimensional 'interchangeability volume' into the current two-dimensional interchangeability diagram.

No change in the hydrogen limit is proposed at the current time, although there is scope for revision should assessment of future gas quality scenarios incorporating unconventional and renewable gases, together with hydrogen injection into natural gas grid, require this.

Figure 18 shows therefore the Modified Interchangeability Diagram resulting from the proposed changes discussed in the previous section. The majority of gases of Group H of the Second Gas Family sit within the boundary designated by the blue line. The arrows illustrate deviation from limits as follows:

A: High WI/low RD gases. Generally, these are not feasible, unless blending with low-density hydrogen is carried out (or significant helium is present, in which case its economic value would suggest extraction of helium prior to combustion).

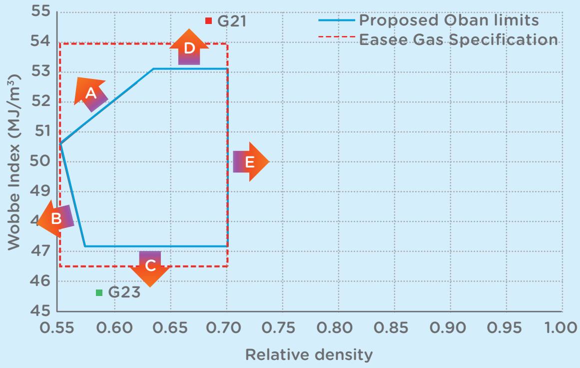
B: Low WI/low RD gases. Generally, these are not feasible, unless addition of low-density gases such as hydrogen is carried out (or significant helium is present).

C: Low WI gases. Generally, these are gases containing significant inerts (e.g. nitrogen, carbon dioxide) and little higher hydrocarbons. Some natural gases such as those from Morecambe bay and some biomethanes and coal bed methanes would fall into this category. Some shale gases may contain significant inerts and may also fit in this category.

D: High WI gases. Typically, these are likely to be a limited number LNG supplies, although some pipeline gases from Norwegian North Sea fields might fall into this category. Some ballasting with nitrogen would be required.

E: High density gases. Typically, this would be limited to: associated natural gases containing significant C2+ content; heavily enriched biogases (i.e. containing significant carbon dioxide – not biomethanes) and LPG-air mixtures (not employed in GB).

**Fig. 18** Modified natural gas interchangeability diagram



### 4. Transfer GS(M)R to IGEM Standard

An IGEM Gas Quality Standard working group should be established, based on representation from the whole GB Industry to consider evidence and determine the appropriateness of a new upper Wobbe Index Limit of 53.25 MJ/m³. If the Gas Quality Working Group supports a change to the gas quality requirements specified in GS(M)R Schedule 3, this should take the form of an IGEM Standard, simplifying the process for further changes to be accommodated within this area of the industry.

Following a number of meetings with IGEM, DECC, OFGEM and the HSE a structure has been agreed in principle, by the industry, that will oversee the transfer of schedule 3 of GS(M)R to an industry produced standard. This will support the rollout of the Oban findings and other work into GB. Simultaneously a wider review of the GS(M)R will be undertaken to ensure much needed changes are incorporated into the revised legislation at the same time.

#### Why an IGEM standard

An IGEM standard is regularly reviewed and amended and has the confidence of industry and government agencies. Incorporating Schedule 3 into an IGEM standard provides a robust approach with the flexibility of allowing the specification to be appropriately developed as and when new evidence emerges. The review of IGEM standards follows a peer review process which involves wide industry consultation. This flexibility will benefit the consumer and the industry as the nature of the composition of the gas being consumed by GB customers' changes. As innovation and diversity of supply continues this would present GB with a robust, flexible, appropriate and future proofed mechanism.

#### IGEM Gas Quality standard working group

This group and associated sub groups should compose subject matter experts from across the gas industry and other key stakeholders. The group should be an umbrella gas quality working group that initially considers the gas quality changes proposed in the Oban (Opening up the Gas Market) project, and then subsequently evaluates, identifies and facilitates projects toward gas quality changes. It will create a database of evidence in support of changes. It will potentially identify a number of offshoot projects, subject to a materiality and Cost benefit assessment.

The objectives of the working group are:

- Set up of a core group to drive the production of the standard and ensure appropriate representation from across the industry and supply chain.
- Identify and map relevant industry groups and bodies.
- Identify links and necessary representation for these both in GB and in the EU.
- Set up of sub groups (where required) which will examine the specific potential effects of a change in GS(M)R on the supply chain, industry, customers and asset owners.
- Develop database of current and previous studies into gas quality.
- Production of an IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.
- Evaluate, identify and facilitate projects toward future gas quality changes.
- Successful completion of the review process of the IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.
- Agreement and approval of the IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.

#### IGEM role

IGEM should take the lead in establishing and facilitating the core working group developing the standard for gas quality. This will involve engagement and consultation with industry, mapping of industry groups and identifying links and necessary representation both in GB and in the EU. The core group will comprise key stakeholders and subject matter experts on matters relating to schedule 3 of GS(M)R. IGEM will develop and maintain an evidence database of all relevant studies and projects, both previous and current.

### 5. Review CO guidance message

A key learning from the project is that around 6% of GB appliances are likely at risk or immediately dangerous currently. Gas Quality in the range proposed presents a very small component of CO risk from appliances.

The project has shown that the importance of CO safety lies predominantly with the effective maintenance of appliances, with the correct installation of a CO alarm being treated as a secondary safeguard, rather than as the sole preventative measure.

While CO alarms, when installed correctly, are effective at raising the alarm in the event of a CO leak, they are reactionary rather than preventative. Whereas effective maintenance means that an appliance limits CO exposure, by taking effective measures where required during an inspection, the CO alarm could only highlight that a leak has already occurred.

In order to address this finding, it is recommended a review of CO awareness campaigns to ensure focus is targeted in areas that offer the most cost effective and real risk reductions i.e. appliance maintenance, servicing and replacement.

Furthermore, the optimum frequency and nature of appliance servicing should be reviewed and discussed between the gas distribution, appliance industries and IGEM gas quality standard working group in order to inform CO campaigns. Opportunities to effectively reduce pre-existing CO risk and improve appliance performance should also be explored with the relevant governmental and regulatory bodies.

Although not exhaustive, a number of options range from a focused CO campaign, targeted appliance inspection and replacement via scrappage schemes, to mandated periodic appliance servicing. These measures would have to be proportionate to the reduction in risk they could achieve.

## 6. Permanent GS(M)R Exemptions for the SIUs

SGN own and operate four mainland SIUs (Scottish Independent Undertakings) in Oban, Wick, Thurso and Campbeltown. These are discrete networks that are not connected to the main gas grid, rather supplied by regasified LNG. Historically, LNG for the four mainland SIU's has been obtained from any one of four LNG liquefaction facilities across GB, namely Glenmavis, Partington, Denyvor Arms and Avonmouth. In recent years, Partington and Denyvor Arms have closed and in July 2010 National Grid LNG advised SGN of their doubt regarding the long-term viability of the LNG plant at Glenmavis due to the age and condition of critical equipment.

**Fig. 19** SGN's Mainland Scottish Independent Undertakings

In December 2010 SGN was notified that the liquefier had failed, causing LNG production to cease and that liquefaction facilities at Avonmouth would be the single source of compliant LNG supply for the SIU's. The originally selected Compressed Natural Gas (CNG) solution in 2011 was not viable and contingency LNG storage facilities were installed in Provan. In early 2013, National Grid announced that its Avonmouth LNG facility would be closing in 2018, therefore leaving SGN with no GS(M)R compliant supply option for the SIU's post 2018. Following an exhaustive review of multiple options, originally initiated when Glenmavis was due to close, it was determined that the most viable (in the time permitted) was to install nitrogen ballasting facilities at the four mainland SIU sites. Thus providing flexibility to procure LNG from any of the European truck loading LNG terminals and ballast the LNG to GS(M)R specification.

In parallel with this, in 2013 SGN received funding for this ambitious project (OGM) to assess the potential to widen the permissible Wobbe range under GS(M)R.

In December 2013 National Grid LNG announced they were going to expedite the closure of the Avonmouth facility to April 2016. The ballasting could not be ready on all sites until 2018. At this point in time, the OGM project was progressing well and the likelihood of its success significantly increased.

Following the comprehensive appliance testing and inspection programme in Oban, an exemption was granted by the HSE to allow SGN to supply rich WI gas in Oban in 2014. In parallel to the development of the ballasting solution, the learning from the OGM project, in terms of appliance inspection, was applied to the remaining mainland SIU's. Exemptions for all SIU's has now been granted until April 2018. It is recommended that from 2018 onwards the exemptions are made permanent based upon the learning of this project.

### Further works

The following recommendations for further work are made as part of the Road Map for GB roll out.

1. Study on the impact of gas quality changes on industry and large commercial gas fired equipment.
2. Study on the impact of gas quality changes on the National Transmission System.
3. Report on findings from wider SIU appliance inspections.

### 1. Impact on industrial and large commercial gas fired equipment

Large commercial and industrial appliances were out with the scope of this project as there are no such appliances located within the Oban network. Whilst it is broadly accepted that industrial and commercial gas fired equipment is more tolerant due to investment in more sophisticated process control, certain production processes could be affected by gas quality changes.

Appropriate evidentiary requirements should be identified and projects scoped by the IGEM Gas Quality Standard working group. This should include a commercial impact analysis both of the change and the cost of delay.

Industrial and commercial gas-fired equipment are designed to tolerate to a wider range of WI and calorific value. In general, installed equipment for industrial use has more sophisticated burner types and process controls. Burner types may include:

- Air blast burners.
- Diffusion flame or post aerated burners with no premixing of gas and air.
- Nozzle mix burners.
- Pulse combustors.
- Catalytic burners.

It is acknowledged, there are a number of industrial processes that could be sensitive to a change towards gas with a higher WI such as:

- Furnaces with controlled atmospheres.
- Ceramics and glazing processes.
- Gas engines.
- Direct fired textile processes.

From a safe operation perspective, there are few concerns amongst manufacturers and industrial users alike, however it is recognised that the consequences in lost production or heating services could be significant to individual customers who may be affected by gas quality changes.

The impacts of a change in WI on gas fired Combined Cycle Power Plants is variable and very much depends on the quality and hydrocarbon contents of the gas used. Use of higher WI gases that are outside the acceptable gas quality band for a particular turbine could lead to operational issues such as, but not limited to, combustion dynamics, increased emissions including NOx, decreased component life and the change in fuel characteristics could potentially lead to substantial load swings.

Experience has shown that the combustion system of gas turbines is impacted by variations in fuel quality. A number of research studies to identify robust combustion system configurations that are capable of reliable operation with variable gas quality have been undertaken over the years.

Gas turbines are usually designed to operate without significant impact on performance with WI gases that are typically +/- 10% of their optimum design criterion.

The current WI band for GB specification gas is 47.20 > 51.41 MJ/m$^3$, so turbines designed to work with natural gas in GB would have a WI design criterion of 49.30 MJ/m$^3$ (+/- 10%) which gives an allowable swing of 4.9 MJ/m$^3$. This is comfortably within the current GB gas specification but although they are capable of accepting quite wide variations in gas quality most generating companies would require either automation via control instrumentation or prior notice and manual intervention to allow optimisation of the machines.

If not already fitted there are various instrumentation packages available that allow gas turbines to operate on a wider range of gas quality whilst maintaining optimum performance and exhaust emission levels, these systems allow greater flexibility in fuel specification and hence would enable power generators to leverage cost reduction due to reduced processing costs at the Gas/LNG reception terminals.

Most manufacturers offer upgrades for their generator packages that have the ability to automatically accept a wide and rapid variation in WI whilst protecting the operational boundaries of the gas turbine and optimising its performance. These systems require no manual intervention and achieve fuel flexibility throughout the operating envelope of the machine. They would typically allow systems to accommodate a 20% swing in WI and a rate of change in excess of 18% per minute.

With dynamic control systems it is possible to effectively change Gas Turbine control settings to adequately compensate for measured changes in fuel composition, two examples are given below.

Where WI is the critical feature controlled fuel heating and variable Vane technology can be used to effectively modify the WI in response to a change in gas composition, for example there is a system available called Opflex Balance auto tune which utilises a high speed Wobbe meter and fuel heating in conjunction with variable vane technology to effectively and continuously optimise system behaviour.

On the same lines one manufacturer has a system called Integrated Fuel Characterisation which as above incorporates a high speed Wobbe meter, fuel heating and variable vane technology to modify the combustion characteristics of its Gas Turbines.

Both systems can be fitted from new with retrofit solutions available for most turbines currently in service. These systems help mitigate the risk associated with gas composition variations but as always operators need to be aware of these developments to ensure that potential variations in fuel gas composition are properly considered.

A number of manufacturers supply instruments and telemetry such with various instruments that could be used in power generation control systems.

In understanding potential issues with power generation and industrial uses, SGN carried out engagement with a number of organisations. For the purposes of this report, specific details of site operation efficiency and capacity are considered commercially sensitive therefore we have not referenced or included the detail discussed.

Thus anecdotally, a substantial widening of WI allowed under GS(M)R should not be an issue for power generators in the UK using gas turbines to generate electricity. Most sites would require some upgrade work, mostly software with some older sites requiring upgrades to telemetry and instrumentation, especially if within day changes to gas quality were likely to be experienced.

This should initially take the form of a detailed review of prior studies worldwide, some of which have been identified through Marcogaz Gas Quality Working group. Any gaps in understanding the effect should be identified with the relevant representations, such as ICOM and Energy UK, and subsequently a programme of in-situ testing should be carried out.
A number of older designs of industrial gas appliances incorporate partially premixed burners, where the natural gas is mixed with a sub-stoichiometric quantity of air at the injector and then additional combustion air diffused into the flame after its emergence from the burner ports. These burners tend to show a relatively flat response of CO emissions with WI variations i.e. CO emissions do not increase quickly as WI increases or decreases.

Fully pre-mixed burners using gas/air ratio controls effectively 'meter' precise quantities of natural gas and air into the appliance (at a fixed gas/air ratio) and no additional excess air permitted. Previous studies and the OGM project have shown that, depending on the Wobbe Index of initial adjustment, fully pre-mixed appliance performance can be sensitive to WI variations and CO emissions can rise as the WI of the gas supplied changes.

The OGM project has demonstrated that fully pre-mixed burners, which have been initially adjusted at a WI of 50.72 MJ/m$^3$ (G20), are shown to operate satisfactorily at the gas 'Oban limit' WI range i.e. 47.20-53.25 MJ/m$^3$.

However, it has not yet been confirmed that this also applies for large-scale Industrial and Commercial gas equipment.

It is recommended that further analysis is required to understand the impact of the change to Wobbe limits proposed. This should be co-ordinated through the proposed Gas Quality standard working group umbrella project.

**2. Impact on National Transmission System**
National Grid Gas Transmission (NGGT) is conducting a project[14] to understand the likely impact of different gas specifications on existing and future National Transmission System (NTS) assets and operations. The risks and impacts to the NTS asset capability due to a change in WI need to be identified, qualified and quantified. Of particular consideration is the % ethane content, as anecdotally it can behave differently above 12% in terms of hazardous areas and pipeline/storage failure characteristics.

The initial phase of the project will concentrate on the identification of assets, processes and operations that may be impacted by a change in the specification of GB gas quality in respect to all NTS assets.

An assessment will be carried out to qualify and quantify the risk and impact on specific performance of key NTS asset types that will be impacted by a change in specification. Where an adverse impact is identified, the risk will be quantified and where remedial action is possible, an estimation of outline cost will be provided. For emissions, the cost of remedial action will focus on those assets selected on highest risk and priority as advised by NGGT.

The results of the project should be reviewed by the IGEM Gas Quality Standard working group.

**3. Report on findings from wider SIU appliance inspections**
In December 2015 National Grid LNG announced that Avonmouth liquefaction facility was closing in April 2016. Avonmouth was the only facility left in GB that can supply GS(M)R compliant LNG to the SIUs.

SGN was planning to construct Nitrogen ballasting facilities in the SIUs, however these could not be commissioned in all four SIU sites until 2018 and hence SGN would not able to supply GS(M)R compliant gas to these sites until 2018.

A project was therefore undertaken by SGN to seek an exemption to GS(M)R by the HSE in order to supply high Wobbe Index LNG from Europe or Isle of Grain until such time that the ballasting facilities were installed.

The exemption application used the work already carried out in Oban under the 'Opening up the Gas Market' project as a blueprint for obtaining an exemption. Results from the OGM in Oban demonstrated that gas appliances correctly installed, serviced and operated can safely burn gas with WI up to 53.25 MJ/m$^3$.

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[14] http://www.smarternetworks.org/NIA_PEA_PDF/NIA_NGGT0094_4114.pdf

With this in mind and given the tight timescale until April 2016, it has was agreed with industry experts (Dave Lander Consulting and Kiwa) that the best approach to obtaining an exemption was to inspect all 5,981 appliance installations in the remaining SIUs to confirm that they are installed, serviced and operated correctly, and rectify where necessary. The work was also necessary to generate the required evidence base to support formal application to the HSE for GS(M)R exemption from gas quality limits in the SIUs until 2018.

An exemption level of 53.25 MJ/m$^3$ for each mainland SIU was subsequently approved by the HSE in April 2016. The exemptions are due to expire in 2018.

It is suggested that a full report detailing the findings of the appliance inspections is produced. This will add to the evidence produced from Oban to support the insight in to GB appliance health.

Data pertaining to CO alarms was captured that included a check for the existence of alarms in rooms with gas appliances and also whether or not the alarm  was fully functional and correctly installed.

This additional data should form part of this report to give an insight into the effectiveness of CO alarms installed in customers properties. This will support the data provided by 'The Carbon Monoxide – Be Alarmed!' campaign run by Energy UK on behalf of British Gas, EDF Energy, E.ON, npower, Scottish Power and SSE, in partnership with the Dominic Rodgers Trust[15].

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[15] http://www.co-bealarmed.co.uk/about/

# Background

## Introduction

Great Britain (GB[16]) is a net importer of gas, with prices and access to supply increasingly depending on international markets. Hence, GB gas prices exhibit volatility, given the short-term and/or spot market conditions. Whilst the sources of new natural gas are numerous, gases have different compositions and GB's specification for gas composition is very prescriptive, therefore limiting the gas market.

Current arrangements dictate that in order for gases with compositions that sit outside of GB's specification to be conveyed and used, expensive gas processing is required to bring them within these specifications. This limits the type and source of gases that can be distributed and used in GB and, in turn, ultimately leads to increased costs for the consumer.

The overriding objective of the Opening up the Gas Market (OGM) project was to demonstrate whether gas that sits outside of the characteristics of gas specified within GB Gas Safety (Management) Regulations GS(M)R 1996[17] can be distributed and utilised safely and efficiently in GB. For this demonstration, it was a unique opportunity to utilise one of our discrete, isolated networks that SGN operate in remote parts of Scotland, called the Scottish Independent Undertakings (SIUs).

This project was based on the principles of increasing competition for network entry, improving energy security, reducing the cost of gas for customers through opening up the market to new sources and reducing the requirement for expensive processing in the future.

The project was awarded funding through Ofgem's inaugural Network Innovation Competition (NIC). The project commenced on the 3rd of January 2014 and completed on the 8th August 2016.[18]

## GB gas supply

Increasingly, from around 2005 and beyond, dwindling gas reserves in GB have created security of supply concerns, leading to gas price increases. The current gas specification requirements, as set out in GS(M)R, differ from those employed elsewhere in the European community and internationally. This poses difficulties for the wider industry with regard to the increased importance of imported natural gas, LNG, and unconventional gas, such as shale gas and coal-bed methane, as all have different chemical compositions.

With a backdrop of this type change in supply dynamics coupled with market rigidity due to compositional requirements set out in legislation, it is necessary to continually review and if possible redefine GB gas specification in order to help tackle the problems associated with security of supply, carbon reduction and rising gas costs for the consumer.

Until now processing of gas sources has been deemed the most economical solution. This was primarily based on the premise that all appliances in GB would have to be inspected and tested. This project has sought to challenge this assumption.

## Legislation

The changing sources of gas for GB has created a need to consider changes to the legal framework that governs the gas industry. Two main sets of regulations in GB drive the minimum gas quality requirements for grid injection: the Gas Safety (Management) Regulations (GS(M)R) and the Gas (Calculation of Thermal Energy) Regulations (GCOTER). These regulations are enforced by HSE and Ofgem respectively.

Another set of regulations pertinent to this project is the Gas Appliance (Safety) Regulations 1995. This legislation supports the enforcement of the requirements of the Gas Appliances Directive (GAD). GAD sets out essential requirements for gas appliances so as to permit their supply throughout Europe.

It is prudent to point out that all European gas appliances, including those in GB, sold post 1993 are required to comply with the 1990 GAD 90/396/EEC[19] (as amended). These newer appliances are tested for commissioning a much wider range in gas quality than that specified in the GS(M)R. GAD sets out essential requirements for gas appliances so as to permit their supply throughout Europe. This project follows testing protocols as specified under GAD.

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[16] Funding for this project was obtained through Ofgem's Network Innovation Competition. Ofgem regulate the GB energy market (thus excluding Northern Ireland). For this reason the term 'GB' rather than 'UK' is used exclusively throughout this document, although it is acknowledge in many instances UK may be more appropriate.

[17] 'The National Archives', Gas Safety (Management) Regulations 1996 accessed August 2016 http://www.legislation.gov.uk/uksi/1996/551/contents/made

[18] https://www.sgn.co.uk/uploadedFiles/Marketing/Pages/Publications/Docs-Innovation-Oban/SGN-Gas-Network-Innovation-Competition-Full-Submission-Pro-forma.pdf

## Gas interchangeability

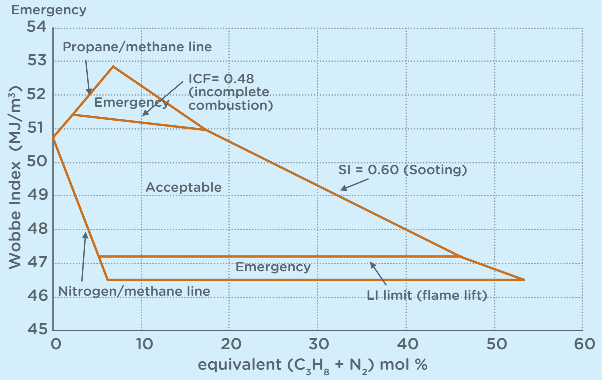
In GB, the concept of gas interchangeability, i.e. ensuring that gases were sufficiently similar in their combustion properties to be safely and efficiently combusted without appliance adjustment, grew out of studies conducted by B.C.Dutton[20] of the British Gas Corporation Research and Development Division in the 1970s. Dutton's approach – based on characterising natural gas on, its content of inerts and hydrocarbons other than methane, and its hydrogen content – was adopted by British Gas Corporation in its gas quality specifications for GB gas purchases. Following privatisation of the Gas Industry in the early 1990s, the Dutton approach, with some simplification and modification, was incorporated into the GS(M)R in 1996 as an 'interchangeability diagram' and has remained unchanged since then.

The interchangeability diagram is based on the performance of appliances in use at the time of Dutton's studies, some of which were originally designed for operation on town gas and converted for use with natural gas during the period 1967-77. Controlling gas quality in order to achieve full interchangeability necessarily required targeting specifications at the oldest and least adaptable appliances, rather than more modern appliances. However the resulting narrow specification in use in GB (compared with those in use elsewhere in Europe) means that, if security of supply is to be maintained, quality of newer supplies has to be altered – typically by costly addition of nitrogen ('ballasting').

The interchangeability diagram or 'Dutton Diagram' is a graphical representation of the interchangeability characteristics. Wobbe Index (WI) is plotted against the concentration of propane and nitrogen, corresponding to the higher hydrocarbon and inert equivalence (see Figure 20).

The characteristics of a gas which can be accepted into the network under normal conditions, and those which may be authorised by the Network Emergency Coordinator (NEC) as 'Emergency limits' to prevent a supply emergency, were derived from work carried out by Dutton et al[21] on gas interchangeability. Gases from diverse sources were burned on several types of gas appliance and their performance observed. From these parameters were established within which gases could be safely consumed. This led to the production of a 3-dimensional diagram together with equations for calculating the related indices for gases that contained significant quantities of hydrogen, and a simplified 2-dimensional version of the diagram for hydrogen-free gases as shown in Figure 20.

**Fig. 20** Dutton Diagram with GS(M)R limits



All gases supplied to GB are currently hydrogen-free.

Countries worldwide have specified different interchangeability measures, mainly arising from historical evolution of downstream equipment populations, and characteristics of locally sourced gas, for instance:

- In Continental Europe, limitations on WI and inert gases are considered to be sufficient for wholesale gas.
- GB looked further into parameters related to appliance non-optimum performance, such as the Lift Index (LI), Incomplete Combustion Factor (ICF) and Sooting Index (SI).

Historically in GB, gas appliance concerns have been the most significant barrier to widening the limits within GS(M)R, specifically in relation to the impact on the WI and ICF. At high WI limits, incomplete combustion can occur and certain appliances can emit higher levels of carbon monoxide (CO) and consequently present increased risk of harm from CO poisoning. At low WI, flame lift can occur and flames can become unstable and may detach or even extinguish, leading to emission of unburned gas.

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[19] Gas Appliances Directive 90/396/EEC implemented as the Gas Appliances (Safety) Regulations 1995, Statutory Instrument 1995 No 1629).

[20] Dutton B C and Wood S W, 'Gas interchangeability: prediction of soot deposition on domestic gas appliances with aerated burners', *Journal of the Institute of Energy*, September 1984, p381.

[21] Dutton B C and Souchard R J, 'Gas interchangeability: prediction of incomplete combustion', *Journal of the Institute of Energy*, December 1985, p210.

The GB approach recognised that different domestic appliances were more susceptible than others to particular changes in operation and the malfunction types mentioned above.

- The Incomplete Combustion Factor was most important for instantaneous water heaters, which may have short periods of operation under cold start-up conditions and therefore may be susceptible to peaks of high emissions.
- The Lift Index was identified for cooker hobs which require flame stability under controlled turndown.
- The Soot Index was most relevant for radiant fires with white ceramic radiants where sooting would be undesirable, not for safety but more from an aesthetics viewpoint.

WI is perhaps the most important and universal quality parameter in regards to the combustion of natural gas. The WI is used to compare the rate of combustion energy output of different composition fuel gases in combustion equipment. For two fuels with identical WI's, the energy output will be the same for given pressure and valve settings, and therefore considered interchangeable.

WI is defined as:

$$\text{Wobbe Index} = \frac{\text{Gross Calorific Value}}{\sqrt{\text{Relative Density}}}$$

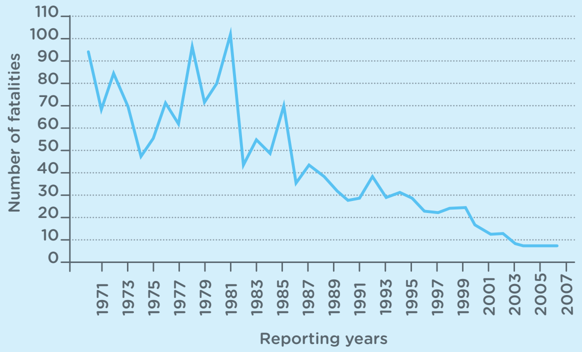
The current high WI limit embodied within the GS(M)R (51.41 MJ/m³) is based on the normal upper limit in ICF (0.48) set by the then British Gas Corporation based on the work of Dutton. This limit was re-examined following the 1991 National Combustion Performance Survey on the expectation that the upper limit could be restored to the upper limit traditionally operated in GB (WI of the reference gas +5%, or 53.30 MJ/m³) prior to the Dutton study. Despite some encouraging test results the decision was taken to leave the upper limit unchanged. However it must be acknowledged that North Sea gas was still in abundance at this time and its WI was relatively low such that it fitted in below the upper limits.

## Carbon monoxide

At certain concentrations CO can be dangerous. CO concentrations and CO/carbon dioxide ($CO_2$) ratios tend to increase with increasing WI. The degree to which these increase will depend on a number of factors, such as appliance and burner design. At the previous time of re-examining the upper WI limit there were concerns that CO incidents were proportional to the number of appliances where CO concentrations exceeded a given CO concentration. Assumptions based on the 1991 National Combustion Performance[22] Survey suggested that the then annual levels of CO incidents (around 40) would increase significantly.

However, the assumption that numbers of CO incidents are directly proportional to the fraction of appliances with CO concentrations above an arbitrary value is not demonstrated and could be considered questionable given that CO incidents have continued to fall since records began, despite little change in WI of distributed gas (in fact WI has risen over the period since 1990). The linkage between CO incidents and CO above an arbitrary level is therefore more complex than originally assumed.

**Fig. 21** CO fatality rate[23]



This suggests that a high proportion of incidents were associated with factors other than gas quality. There is also a lack of a geographical correlation between CO incidents and gas WI. More incidents might be expected in the north of GB where consumers are supplied principally with higher WI St Fergus gas, but this is not the case.

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[22] Advantica, 2002 'Combustion Performance Safety Action Levels for Domestic Gas Appliances', no. R5205, accessed August 2016 http://www.hse.gov.uk/gas/domestic/pdf/safetyactionlevels.pdf

[23] IGEM, 2016. Carbon monoxide – the past, the present and the future.

Key events and initiatives undertaken since 1990 that are believed to have contributed most significantly to the observed reduction are summarised in Table 1:

**Table 1** Contributing factors to decline in CO fatalities

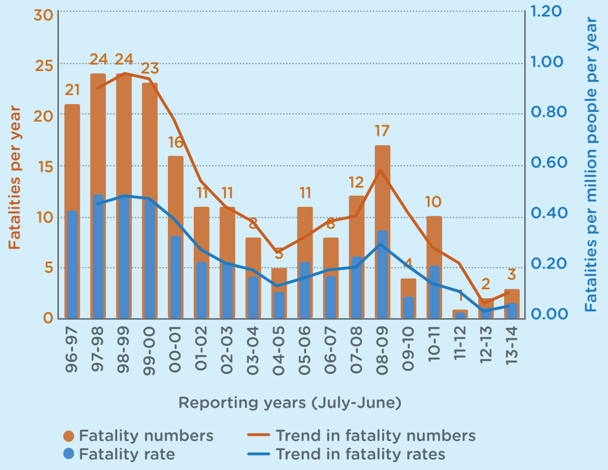
| Year | Description |
|---|---|
| 1986-1994 | The Water Heater Safety Exercise removed 186,000 open flued water heaters from bathrooms and Bedrooms[1]. |
| 1992 | Procedure for obtaining measurements to calculate a boiler's performance ratio using specified instrumentation (such as Flue Gas Analysers) adopted by British Gas Services[2]. |
| 1993-1996 | Compulsory GAD certification[3]. For high gas input appliances required either room sealing or Atmospheric Sensing Device (ASD) e.g. ODS or TTB. This has dramatically improved the safety of appliances. Essentially two faults are required to create a CO incident. |
| 1995 onwards | Introduction of CO alarms and continued rise in usage[4]. |
| 1998 | The Gas Safety (Installation and Use) Regulations 1998 require only CORGI qualified persons/ operatives carry out any work on any domestic installation pipework, fittings or gas appliances[5]. |
| 1998 | The Gas Safety (Installation and Use) Regulations 1998 require landlords to arrange an annual safety check for all appliances pipework and flues[6]. |
| 1998 | Compulsory Approved Code of Practice (ACOP) for gas operatives[6]. The ACOP including guidance notes and texts of the regulations was been issued. This gives practical advice on how to comply with the law. |
| 1998 | Compulsory Accredited Certification Scheme for Individual Gas Fitting Operatives (ACS), with 5 yearly re-tests[6]. This dramatically upskilled the gas operative industry. |
| 2005 | Since 2005, the Building Regulations state that all newly installed domestic boilers should be high efficiency condensing boilers[7]. These are always room sealed. |
| 2007 | Ofgem's Supply License Review[8] stated that licensees are obliged to send information to all customers annually on the dangers of carbon monoxide poisoning, the benefits of fitting a carbon monoxide alarm, the use of gas appliances and fittings, the benefits of gas safety checks and where to seek assistance if appliances are condemned as the result of a gas safety check. |
| 2009 | CORGI scheme replaced by Gas Safe Register[9]. New campaigns are launched to promote that gas engineers must be on the Gas Safe Register to do gas work lawfully. |
| 2010 | Boiler Scrappage Scheme (replaced old boilers with around 120,000 new 'A-rated condensing boilers)[2]. |

[1] IGEM, 2016. Carbon monoxide – the past, the present and the future
[2] Advantica, 2001. Further Evaluation of Proposed Procedures for the Measurement of Gas Appliance CO Emissions
[3] UK Government. Gas Appliance (safety) Regulations. Accessed August 2016 https://www.gov.uk/guidance/gas-appliance-safety-supplier-and-manufacturers-obligations
[4] HSE, 2011. Domestic Carbon Monoxide Alarms. Long-term reliability and use scoping study
[5] HSE, 2001. Joint Industry Programme on Carbon Monoxide Issues
[6] HSE. Gas Safety – Landlords and letting agents. Accessed August 2016 http://www.hse.gov.uk/gas/domestic/faqlandlord.htm
[7] Baxi. Condensing Boilers vs non-condensing boilers. Accessed September 2016 http://www.baxi.co.uk/gas-boilers/condensing-vs-non-condensing-boilers.htm
[8] Ofgem, 2007. Supply Licence Review, no. 128/07. Accessed August 2016 https://www.ofgem.gov.uk/ofgem-publications/38819/slr-final-proposals-decision-doc.pdf
[9] COGDEM. News and Events. accessed August 2016 http://www.cogdem.org.uk/

In addition to HSE published gas incident statistics the gas industry has its own long established mechanism of reporting and recording information on CO incident investigations via the use of the 'Downstream Incident Data Report' (DIDR) form. The DIDR form is usually completed by the gas supplier's GS(M)R investigator. These forms are used to produce an annual incident report that is published by the Gas Safety Trust. According to the latest CO trend data from the Gas Safety Trust, it is evident that the downward trend in CO fatalities has continued from 2007 onwards.

# Background
*cont.*

**Fig. 22** Fatality trend data[24]



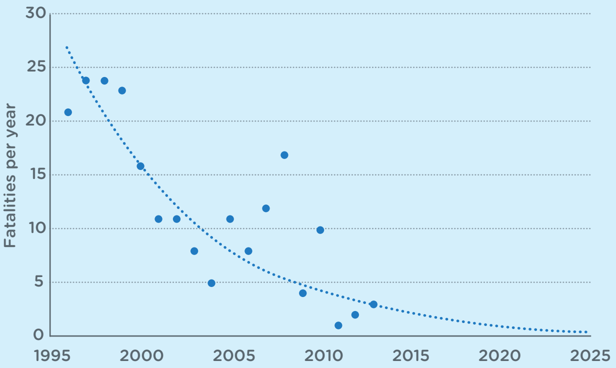
There are however notable spikes between 2008 and 2011. These spikes are largely attributable to one particular model of grill. This grill, manufactured prior to 2009, was subsequently identified as posing a serious safety risk in circumstances when operated with the grill door closed. In such circumstances there was a serious risk of carbon monoxide build-up. An extensive product recall has since been carried out. These incidents are peculiar to that model and not a grill in general.

Each type of domestic appliance poses a different CO risk due to its unique installation and use. In previous years, gas boilers were the most prevalent appliance type in CO incidents. However, these numbers have been decreasing in recent years, largely due many of the aforementioned initiatives. Other sources, including gas cookers, pose different risks which may not be as well recognised.

According to the All-Party Parliamentary Carbon Monoxide Group[25], the context of ‘home’ is important when considering safety measures to prevent CO incidents. Each appliance has a different interaction with the user and raising awareness in the right ways, relevant to each source and environment, is an important first step towards tackling CO poisoning. They suggest that all campaigning and advice given to reduce CO poisoning incidents should promote a ‘belt and braces’ approach of proper appliance use and servicing, along with the installation and use of BS EN 50291 Standard-compliant CO alarms as a vital back-up.

This sentiment is echoed by the HSE[26] in their study of CO Alarms whereby they state that CO alarms are a useful back-up precaution, but they are not a substitute for the proper installation and maintenance of combustion heating appliances and that it is important that all appliances are installed and maintained by competent engineers. The impact of ongoing CO initiatives is hoped to help maintain a low fatality rate into the future. Furthermore the recent influential think tank Policy Exchange Report[27] called for Department for Business, Energy and Industrial Strategy (BEIS) to rethink its heat strategy. It said that there is still significant potential to improve the efficiency of gas boilers. GB has already seen a significant improvement in boiler efficiency with the roll-out of condensing boilers, which have been mandatory for new installations since 2005. However there were still 11 million low-efficiency non-condensing boilers in homes in 2012, which ought to be upgraded as a matter of priority. This is predicted to have a positive effect on CO risk. Based on the DIDR data from July 1996 onwards an extrapolation is made to predict CO future trends in Figure 23.

**Fig. 23** Fatality trend data to 2025



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[24] Gas Safety Trust, 2014. DIDR Carbon Monoxide Incident Report for 2013/2014.

[25] All-Party Parliamentary Carbon Monoxide Group, 2015. From Awareness to Action.

[26] HSE, 2011. Domestic Carbon Monoxide Alarms. Long-term reliability and use scoping study.

[27] Policy Exchange, 2016. Too hot to handle?

The interchangeability diagram can be **simplified and updated** to reflect current requirements.

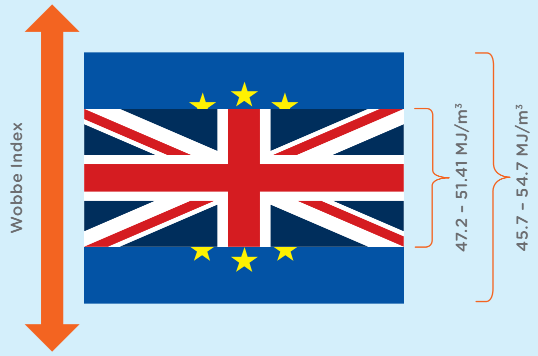
## European scene

As a major natural gas consumer in Europe, GB has one of the smallest permitted ranges of WI allowable. The GB market is therefore attractive in terms of volume but less attractive because of the requirement for gas processing (nitrogen ballasting) of LNG imports. A future harmonised European gas quality standards would improve GB's potential trading position.

The differences in the gas specifications around Europe mainly stem from difference in the appliance population, and the indigenous natural gas available. GB has the most developed and possibly the oldest domestic appliance populations in Europe.

European member states are working towards a harmonised and wider gas specification called the European Association for the Streamlining of Energy Exchange – gas (EASEE-gas); a legislative package derived from the EU's Third Energy Package, with a purpose to further open up the gas markets in the EU. Changing GS(M)R to align with EASEE-gas would widen the market and accommodate the introduction and use of abundantly available alternative sources of gas without the need for expensive processing.

**Fig. 24** GB WI vs EASEE-gas



There are currently no harmonised European or International standards that directly specify gas quality requirements for natural gas conveyed in GB transmission and distribution systems, although the European Committee for Standardisation (CEN) standard for Group 2H gases are currently under production. The European Commission have issued mandate M/400 to CEN[28] inviting them to draft European Standards for Natural Gas corresponding to Group 2H. The mandate is the end result of a number of European initiatives driven by the need to develop a common European gas market. A key aspect felt to be inhibiting development of such a market is interoperability, a term which embraces a number of aspects (such as communications protocols, commercial mechanisms, units of measurement, etc) but most important amongst these is a perceived barrier to free trade caused by differences between specifications for natural gas in many European countries.

The new standard is likely to contain a relatively wide range WI of 46.44–54.00 MJ/m³, with an accompanying statement that recognises that for some networks in various countries this range could be unacceptable.

The statement is intended to overcome the difficulties of countries currently specifying either a narrower range in the case of GB, or a wider range such as Spain.

## Previous studies

There have been a number of previous studies in this field, many of which contributed to the conception of this project.

In October 1965, a trial was undertaken to convert Canvey Island to from town gas to natural gas[29]. This involved 6,600 customers and 17,500 appliances. This was essentially the pilot trial for full UK conversion, which commenced in July 1966 at a rate of 175,000 customers per annum. This project in Oban has been informed by this pioneering work.

Advantica performed a study[30] for the HSE in 2002 that analysed combustion performance safety action levels for domestic appliances. The study stated that the equilibrium level of any pollutant emitting steadily into a mixed enclosed volume or room can be worked out using a simple continuity equation, providing the rate of emission and other input data are correctly assumed. The rate of emission of CO depends on the fraction of spillage and on the flue gas $CO/CO_2$ ratio, both of which could be higher

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28 Mandate to CEN for Standardisation in the Field of Gas Qualities M/400 EN January 2007 https://ec.europa.eu/energy/sites/ener/files/documents/2007_01_16_mandate_gas_quality_en.pdf

29 Always under Pressure: A History of North Thames Gas since 1949 page 89

30 Combustion performance safety action levels for domestic gas appliances. B. Cheney and J Cotton. Advantica Report R5205 (2002). Available from HSE website.

than their equilibrium values in the first few minutes after light-up. It follows that the longer the build-up time, the greater the accuracy of the calculated figure. A figure of 9 ppm CO was taken as the maximum increase that should be allowed, on the assumption that the outside ambient level will be approximately 1 ppm. If the ambient level was to be measured and was found to exceed 1 ppm, then the contribution permitted through spillage or leakage from an appliance should be correspondingly less.

For all flued appliances, basic equations were used to calculate the critical $CO/CO_2$ ratio appropriate to an equilibrium 9 parts per million (ppm) ambient CO level measured at 2 metres height in a room of volume appropriate for a given appliance. For unflued appliances, where equilibrium conditions do not apply, a value was assumed for the ratio and the peak CO calculated. It was concluded that a $CO/CO_2$ ratio of 0.008 for all flued appliances is achievable (based on the 1990 National Combustion Performance Survey) with the exception of some gas fires. For unflued appliances a $CO/CO_2$ ratio of 0.004 was suggested, based on calculations of the steady state ambient CO concentration in a room of volume appropriate for the appliance.

More recently, between 2003 and 2005 a study was carried out by Advantica[31] on behalf of the Department of Trade and Industry to look into the potential to change the GS(M)R WI specification. The study acknowledged that the GS(M)R specification was narrow in comparison with both European and international standards, however, would require an enormous programme of appliance testing, on the scale of conversion in the 1960s and 70s. The options were therefore identified as:

- No change (beyond 2020) to the GS(M)R at the cost of having to process the gas to bring it within GS(M)R limits; and
- At some time after 2020, adjust the gas quality specifications at the cost of having to check and potentially replace up to 45 million appliances in 22 million households so that they are capable of burning higher WI gas.

In 2007 the GB Governments' Department for Business, Enterprise and Regulatory Reform (BERR[32]) concluded that it would be too costly to change the specification in GB, as it would involve assessment of some 45 million consumer appliances. Resource availability, competence and cost were deemed prohibitive. A statement was therefore published proposing that a 'no change' approach be adopted based on cost, safety and practicality grounds. This conclusion was influenced by a technical uncertainty of current appliance capabilities coupled with the presumption that there was no suitable gas network section within which to pilot and demonstrate the effects of the increased WI limits.

Most recent studies on gas quality, such as the GASQUAL[33] studies suggested that in general, impacts of operation at higher WI are quite small below a WI of around 52.50–53.00 MJ/m³. Above this, levels of CO can increase quite markedly for some appliances. Secondary impacts, such as low voltages or elevated pressures may cause impacts to occur at lower WI.

At this point it is necessary to distinguish between two broad categories of gas appliance. Partially pre-mixed and fully pre-mixed. Traditionally nearly all gas appliances were partially pre-mixed. In this design the gas is injected into a venturi where it entrains air to create a fuel rich gas/air mixture which is passed to the burner where it is combusted with the necessary additional air defusing in from the surrounding atmosphere. Modern designs tend to be relatively insensitive to WI around their design point of pure methane (WI 50.72 MJ/m³ or G20). Regrettably such designs cannot give the very highest thermal efficiencies (approaching 100%) required by modern consumers so fully pre-mixed burners have been developed. These meter optimum quantities of air and natural gas direct to the burner. Unfortunately, outside a given band, these optimum quantities must be adjusted for WI (higher WI require larger volumes of air) hence their categorisation as adjustable appliances.

The GASQUAL study also highlighted the issue of adjustable appliances and potential to limit their range of operation at high WI, if adjusted on low WI gases, and vice versa. Adjustable appliances with their factory settings (i.e. adjusted on G20 reference gas) such appliances tolerate a wide range in WI.

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[31] Advantica R 7409 – Assessment of the Impact of Gas Quality on the Performance of Domestic Appliances (A Pilot Study) 2004.

[32] BERR, 2007, 'The PB Power Report on Future Network Architectures'. Future network Architectures, number 08/641, accessed August 2016, http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file46168.pdf

[33] GASQUAL, 2007. 'Investigations on new acceptable EU limits for gas quality'. Influence on the performance of new and installed gas appliances, accessed August 2016 http://www.gasqual.eu/

# Background
*cont.*

Notwithstanding these, the most influential study in GB that established gas quality requirements was the work undertaken by Dutton (discussed in relation to the interchangeability diagram earlier). The incomplete combustion limit currently in the GS(M)R of 0.48 was selected by Dutton on the basis of the upper limit traditionally being 105% of the reference gas. However, there are inconsistencies in Dutton's statements about this limit, in that this value is stated to be 52.10 MJ/m³, when it is in fact 53.20 MJ/m³. The final value of ICF of 0.48 was made on the basis that it approximated that of gases around 51.20 MJ/m³, which was the WI limit at the time imposed by the British Gas Corporation, following a survey of appliances in 1978. At the time of this survey, all gas appliances were essentially placed on the market prior to the GAD and most are likely to have been converted from town gas operation (conversion to natural gas in GB was carried out 1966-1978).

Regarding the lower WI limit, the GASQUAL and Advantica studies suggest that operation at low WI is less of a concern. The limit currently in the GS(M)R is set at 47.20 MJ/m³ from solely heat service considerations and the emergency limit of 46.50 MJ/m³ is set from Dutton's suggested limiting value of Lift Index (LI). Again there are some inconsistencies in Dutton's justification for this lower value.

The previous work carried out by Dutton, BERR, DTI, GASQUAL, Advantica and the Canvey Island pilot have all contributed to this project.

**Project participants**
The field of natural gas quality is highly specialised. The project partners were selected for their unique experience and competence in this area:

kiwa
Partner for progress

Kiwa Gastec (KIWA) are a Notified Body under the GAD and has extensive experience working on European-wide projects with interchangeability of gas. Kiwa Gastec are one of only two notified test laboratories in GB but is also closely involved in changing gas properties in the Netherlands. Kiwa provided support and expertise for the gas appliance testing during the project. Tasks undertaken by Kiwa included, but not limited to, site surveys, laboratory appliance tests, risk assessments, design and build of testing rigs, engineer training, report writing and supervision of field testing.

davelanderconsulting

Dave Lander is recognised in GB and internationally as an expert in the field of gas quality. He represents the GB gas distribution networks on gas quality for development of GB, European and International standards in gas quality. Dave Lander Consulting (DLC) participates in BSI/ISO standards committees (Natural Gas and Gas Analysis) and currently represents National Grid and GB at Marcogaz Expert Working Groups in Gas Quality, Energy Measurement and Biogas.

During the project DLC provided gas quality guidance and expertise. DLC also produced a number of project reports including; a review of relevant standards and legislation; a review of relevant previous and current work; and a study into the LNG market to identify the respective compositions of the sources of LNG that would be available.

DNV GL, who previously traded as GL Noble Denton, was the lead technical partner in GB Government three-phase gas quality exercise and undertook detailed studies of the emissions from domestic appliances as a function of supplied gas quality as well as performing cost benefit studies on the blending and ballasting of gases in GB gas network. DNV GL has recently been a partner in the GASQUAL consortium which carried out tests in support of the CEN Standardisation Mandate M/400 from the European Commission, and aimed at removing barriers to cross-border trading of gas.

DNV GL has significant expertise in the development of risk models and produced a Quantified Risk Assessment (QRA) for the injection of non-GS(M)R LNG into the Oban network.

### Project location

The SGN gas network chosen for the trial was Oban where gas is supplied to 1104 properties, is isolated from the National Transmission, Regional Transmission and Distribution systems and is supplied directly with vaporised LNG.

Oban town centre

The most important factor in the choice of network was that it had to be representative of the entire GB network. Therefore, to further support the case for Oban, a demographic study and analysis conducted by DNV GL in May 2013[34] was undertaken. The study considered data that was most relevant to gas usage and safety that included but not limited to age distribution, socio-economic groups, household composition, building type, climate, and gas incident records.

The justifications for not amending GS(M)R expressed in previous studies should not necessarily apply to Oban being a small discrete gas network, with only 1104 customers. Whilst on an integrated network on a GB scale it might not be cost effective to carry out appliance checks etc, it would be much more manageable on the scale of Oban. Oban SIU is a convenient site for a trial that afforded us an opportunity to evaluate the potential for this solution to be rolled out across GB.

Thus, Oban provided a unique setting for implementation of the OGM project and enabled the potential for proposed changes to gas quality generally for GB to be evaluated.

### History of supplies to Oban and the other SIUs

SGN own and operate four mainland SIUs in Oban, Wick, Thurso and Campbeltown. These are discrete networks that are not connected to the main gas grid, rather supplied by regasified LNG. Historically, LNG for the four mainland SIU's has been obtained from any one of four LNG liquefaction facilities across GB, namely Glenmavis, Partington, Denyvor Arms and Avonmouth. In recent years, Partington and Denyvor Arms have closed and in July 2010 National Grid LNG advised SGN of their doubt regarding the long-term viability of the LNG plant at Glenmavis due to the age and condition of critical equipment.

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[34] DNV GL Report Number: 14478 – Demographic Analysis of Oban for Gas Testing (October 2013).

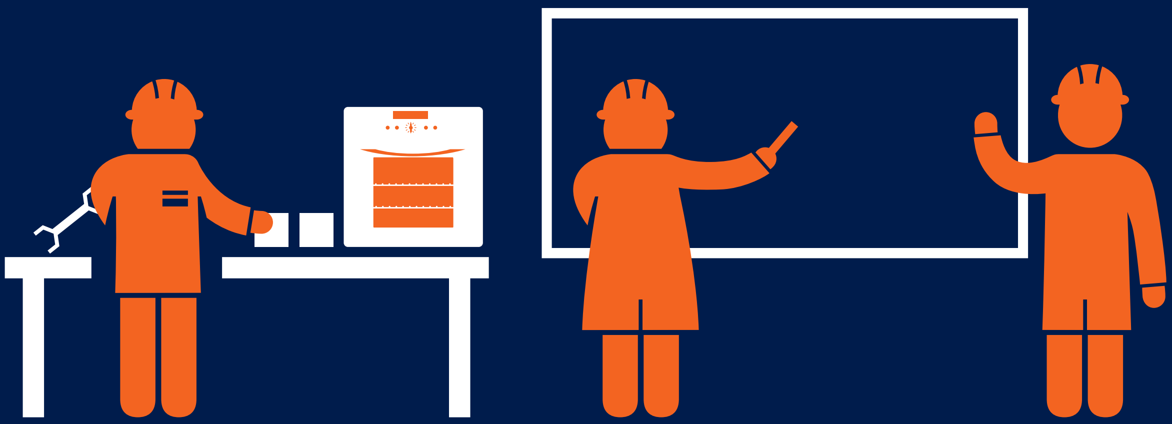
In December 2010 the liquefier failed, causing LNG production to cease and that liquefaction facilities at Avonmouth would be the single source of compliant LNG supply for the SIU's. The originally selected Compressed Natural Gas (CNG) solution in 2011 was not viable and contingency LNG storage facilities were installed in Provan. In early 2013, National Grid announced that its Avonmouth LNG facility would be closing in 2018, therefore leaving SGN with no GS(M)R compliant supply option for the SIU's post 2018. Following an exhaustive review of multiple options, originally initiated when Glenmavis was due to close, it was determined that the most viable (in the time permitted) was to install nitrogen ballasting (processing) facilities at the four mainland SIU sites.

In parallel with this, in 2013 SGN received funding for this ambitious project (OGM) to assess the potential to widen the permissible WI range under GS(M)R in GB, and thus remove or reduce the requirement for processing, particularly nitrogen ballasting. As this was an innovation project there was no guarantee of success.

In December 2013 National Grid LNG announced they were going to expedite the closure of the Avonmouth facility to April 2016. The ballasting could not be ready on all sites until 2018. At this point in time, the OGM project was progressing well and the likelihood of its success significantly increased.

Following comprehensive appliance testing and inspection, an exemption was granted by the Health and Safety Executive (HSE) to allow SGN to supply rich Wobbe Index (WI) gas in Oban in 2014 for one year. It was always intended that the Oban project, if successful, could be rolled out to the other SIUs as a first step towards GB adoption, therefore the learning from the OGM project, in terms of appliance inspection, was applied to the remaining mainland SIU's. An exemption for all SIU's has now been granted until April 2018.

# Laboratory testing



# Overview

The objectives of stage 1 laboratory testing were to:

- Demonstrate whether all gas appliances are capable of safely and efficiently burning gas that meets EASEE-gas specifications but sits outside GS(M)R.
- Establish how changes in Gas WI affects the safety and performance on a representatively selected sample of appliances identified from the survey.
- Examine all appliance performance results and to identify the need for, and conduct any, further investigative testing.
- Determine an appropriate WI limit for the field trial.

A mixture of 100 domestic and commercial properties in Oban were surveyed to identify the most common types of appliances and their condition. Based on the findings of the survey, a representative sample of 18 domestic gas appliances installed on the Oban network were selected according to appliance class and subjected to laboratory testing by KIWA Gastec. The laboratory testing investigated the effect of supplying gases covering the full EASEE-gas WI range to the selection of appliances. Most of the appliances tested in the laboratory were removed from Oban, however in some cases, such as commercial catering, they were procured separately. All appliances removed from Oban were replaced free of charge.

Where specific issues were identified with particular appliances, additional special laboratory testing was undertaken.

# Enabling activities

## Stakeholder engagement

Stage 1 required the participation of 100 customers in Oban in order to undertake the initial appliance survey. To achieve this, it was essential that local stakeholders supported the project. A stakeholder mapping exercise was carried out to identify all local stakeholders and categorise them by their influence/interest.

Engaging the local stakeholders would help ensure that should a customer consult one a local community group, or police service for example, the stakeholder consulted would be able to provide advice and information about the project, or have contact details to the project team directly. A 'Road to Social Proof' strategy was devised.

Local stakeholders included local MPs and MSPs, Argyll and Bute council, local housing associations, Citizens Advice Bureau, disability support groups (Argyll and Bute Learning Disability Service and, Oban Alzheimers Support Group) local charitable foundations (Oban Rotary Club, Oban and Lorn Lions Club) and the local police and fire services.

**Fig. 25** Road to social proof

It was important that the local authorities and associations were notified prior to customers being contacted. Therefore, they were ready to support customers when the stage 1 commenced. It also ensured that the appropriate permissions were acquired to attend homes that were registered under any associations.

A number of presentations were delivered to local stakeholder including the Scottish Energy Minister, MPs, MSPs, Oban Lorne and Isles Community Planning Group, Oban Councillors, NHS, Police Service, Fire Service, the housing associations, and Community Council).

Some project stakeholders were keen to get involved with the project, and offered their views and expertise to help plan and execute the project successfully. One housing association wrote bespoke letters to tenants to advise them of the project, and offered to accompany the testing engineers to any vulnerable tenants.

Specific 'Customer' Engagement activities are discussed in general under the stage 2 Enabling Activities.

## Appliance survey

The appliance survey took place over two weeks in April 2014. The purpose of the survey was to identify the most common types of appliances in Oban and gain an insight into their age and condition. A mixture of 100 random domestic and commercial properties in Oban were selected and surveyed.

Based on the findings of the survey, a representative sample of 18 domestic gas appliances installed on the Oban network were identified according to appliance class in combination with additional criteria such as: manufacturer, product type, flueing, control type, age and condition. This included 6 boilers, 6 local space heaters, and 6 domestic cooking and commercial catering equipment.

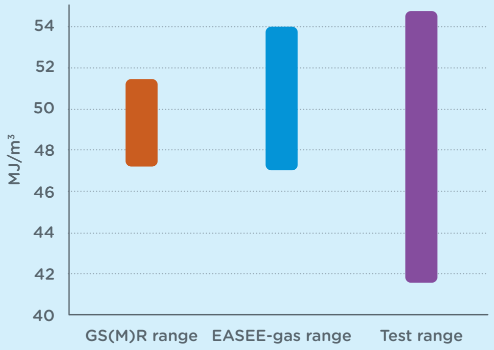
The selected sample of appliances were then tested in the laboratory on a range of WI gases covering the EASEE-gas specification. Most of the appliances tested were removed directly from Oban, however in some cases, such as commercial catering, they were procured separately. The appliances removed from Oban were replaced free of charge.

# Testing methodology

Laboratory appliance testing was initially carried out between June and September 2014 by KIWA.

The test program measured performance of the appliances with test gases specified in the European Standard BS EN 437:2003+A1, 2009, which specifies the various gas categories for gas appliances falling under the (GAD). The test gases selected cover a WI range of 41.52-54.76 MJ/$m^3$, which is wider WI range than that set in the current GS(M)R and current EASEE-gas specifications.

**Fig. 26** Range of laboratory test gases WI



It is likely that all gas appliances distributed and installed in GB since the advent of European Conformity (CE) marking (in 1996) have been tested and approved using gases of characteristics detailed in BS EN 437, and fall within the gas category of 2H (20). The characteristics of the reference, incomplete combustion and flame lift limit gases for this category are designated as G20, G21 and G23 respectively. In addition to these test gases, the characteristics of the reference gas for gas category 2L (G25) are listed in Table 2.

G25 test gas has a WI that lies below the minimum of normal and emergency GS(M)R limits. The G25 test gas was included in the testing to establish the performance of appliances at a significantly lower gas WI should there be future changes to the lower WI limit of the GS(M)R.

The laboratory test program was designed to establish how changes to gas supply conditions, such as WI, pressure and heat input affects safety and performance of domestic appliances under a series of normal and abnormal test conditions.

Appliances were tested under normal operating conditions, and dependent on appliance type, also under abnormal conditions i.e. blocked flue and/or burner subjected to linting (i.e. blockage of primary aeration ports by airborne dust and fibres) using each of the test gases and pressures shown in Table 3.

Tests conducted on all appliances were as follows:

- Gaseous and particulate emissions performance – CO, $CO_2$ and sooting.
- Appearance of flame – general appearance and stability during operation at all conditions of operation.

**Table 2** Characteristics of gases used for laboratory testing

| Description | Gas composition | Gross WI[1], MJ/$m^3$ |
|---|---|---:|
| G20[2] | 100% Methane | 50.72 |
| G21[2] | 87.0% Methane/<br>13.0% Propane | 54.76 |
| G23[2] | 92.5% Methane/<br>7.5% Nitrogen | 45.66 |
| G25[3] | 86.0% Methane/<br>14.0% Nitrogen | 41.52 |

1 Dry gas at 15°C and 1013.25 mbar.
2 EU Standard BS EN 437:2003+A1: 2009 gas appliances falling under the Directive on Appliances Burning Gaseous Fuels 2009/142/EC (ex-90/396/EEC) [GAD].
3 Category 2L ref gas – below the minimum normal emergency GS(M)R limits, included to establish the performance of appliances at a significantly lower WI.

**Table 3** Summary of gas supply conditions used for laboratory testing

| Test condition | Test gas | Supply pressure (mbar) |
|---|---|---:|
| 1 | G20, G21, G23 | 20 |
| 2 | G21, G23 | 25 |
| 3 | G25 | 17 |

Where specific issues were identified with particular appliances, special laboratory testing was undertaken to establish the potential risk factors, if any, of supply gases of higher WI and the operational WI range in which they will still safely work.

$CO/CO_2$ ratio is a common measurement used to determine the combustion performance of domestic gas appliances to confirm correct operation and/or the potential level of service an appliance may require. The maximum $CO/CO_2$ ratio safety action levels set depending on appliance types and referenced in BS 7967: 2015 – Guide for the use of electronic portable combustion gas analysers for the measurement of carbon monoxide in dwellings and the combustion performance of domestic gas-fired appliances (refer to Appendix 2).

Older British standards generally set acceptance standards for gas appliances of $CO/CO_2$ ratio to be less than 0.02 under 'overload' conditions. Overload conditions refer to increasing heat input and were traditionally achieved by increasing the inlet gas pressure. Overload is intended to simulate the four factors that increase $CO/CO_2$ ratio: tolerances in production; higher gas inlet pressure; operation with gas of higher WI; deterioration in performance between servicing.

Today's European standards generally set an acceptance standards of 1000 ppm (parts per million) CO dry air free (daf) under smaller overload conditions using reference test gas G20 (WI: 50.72 MJ/$m^3$), and an acceptance standard of 2000 ppm CO daf when overloaded with the incomplete combustion test gas G21 (WI: 54.76 MJ/$m^3$). 1000 ppm (daf) and 2000 ppm daf correspond to $CO/CO_2$ ratios of 0.0085 and 0.0170, respectively. It is stressed that these values are neat flue gas direct from the appliance. In the case of:

- Room sealed appliances these flue gases cannot enter the property (unless the installation is grossly defective).
- Open flued appliances these flue gases should not enter the property assuming the appliance is correctly installed.
- Flueless appliances the gas input to the appliance is so low and/or the combustion is such that the normal level of CO in the property is scarcely above background (often taken as <9 ppm).

CO (daf) basis enables correction of the data to reference conditions, to preclude the effect of dilution for operation of a particular appliance, and allows data comparison between different appliances to be made more easily. It should be noted however that daf CO values for appliances with high excess air levels (low $CO_2$ values) do overstate true CO concentrations. Whilst indicating poor combustion (and thus a poor state of appliance condition) in practice an appliance with a low absolute CO value but high CO daf value will offer little risk to householders.

The maximum CO daf limit being that as specified by each individual appliance standard.

Each appliance was installed in a room of large volume with adequate ventilation (KIWA test laboratory) in accordance with the manufacturer's instructions. Testing was then performed on each appliance using test gases under various test conditions in accordance with the relevant BS and EN testing standards (refer to Appendix 3).

Additional abnormal tests were undertaken by simulating the following conditions:

- Blocked flues.
- Burner linting, burners with primary air ports that could be subjected to linting were adjusted so that the $CO/CO_2$ ratio was 50% of the relevant appliance safety action level specified in BS 7967: 2015.
- Low Voltage – 85% of the nominal voltage stated on the appliance data plate where combustion performance could be affected by incorrect operation of electrical components at lower voltage e.g. combustion fans.

As a result of the laboratory testing, field testing stages (refer to stage 2) and discussions with other stakeholders, further appliance testing was identified for inclusion in the test programme and detailed in special testing.

Both the **Sooting Index** and the **Incomplete Combustion Factor** as stated in GS(M)R are no longer valid.

# Results and discussion

The stage 1 results have been split into 5 sections:

1. Local space heating
2. Gas boilers
3. Domestic cooking and commercial
4. Special tests
5. Other results

## Local space heating

Local space heater in laboratory

Results for the six local space heaters tested and shown in Figure 27. It was demonstrated that under normal combustion conditions, (daf) CO emissions and the $CO/CO_2$ ratio increased as the WI of the gas increased. It was concluded that, under normal test conditions, all well serviced or new appliances performed within the $CO/CO_2$ ratio safety action level and (daf) CO emission limits specified in the appropriate standards. None of the appliances showed any deterioration in flame picture or other fundamental cause for concern.

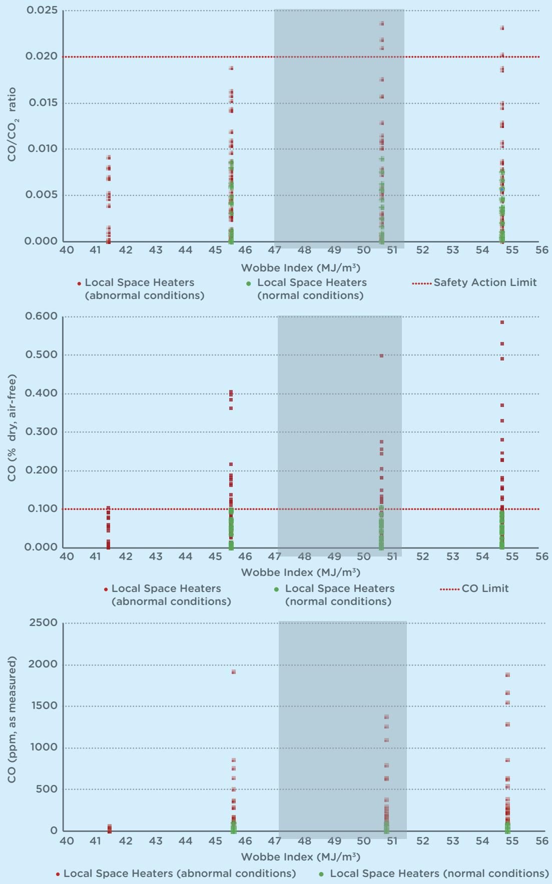
The only material performance issue identified was related to the Atmospheric Safety Device (ASD) performance and appliances not fitted with ASD's particularly when supplied with gases of higher Wobbe indices. In view of this further investigations were conducted on appliances fitted with ASD's (refer to special testing).

Open flued appliances have the potential to emit high levels of CO into a living space with blocked flue and none or inadequate purpose provided ventilation. This is the reason why since 1996, all such appliances have had to be fitted with an ASD. This is either a TTB (Thermische terugslag beveiliging), which detects spillage from a flue draught diverter, or more commonly an Oxygen Depletion Sensor (ODS), which detects a reduction of oxygen concentrations in the room and consequently shuts off the gas supply. These devices depend upon the CO concentration in the room not reaching dangerous levels prior to the oxygen concentration falling sufficiently to trigger closure of the gas valve. This is more reliably achieved with appliances with fundamentally low CO concentration in the flue gas.

As expected, when these appliances were tested in a sealed room with a blocked flue, the CO concentrations in the room increased to dangerous levels above the 0.10% (daf) limit.

However, when installed as per the manufacturer's instructions and operated under normal conditions, CO levels do not reach high levels.

**Fig. 27** Laboratory test results – local space heaters



Only when multiple abnormal conditions were present did significant CO concentration result (shown by the red dots). For example, linting and blocked flue alone were not enough to cause dangerous levels of CO, however, when these conditions are combined i.e. linted, in a sealed room and with a blocked flue, the CO concentrations in the room became high, in some cases over 1000 ppm.

By supplying a gas of increasing WI, the effect of sooting was not significantly increased, however when combined with a linted burner, some appliances did show significant sooting, particularly at high gas supply pressure. For all appliances, increasing WI produced flames with various degrees of yellow tipping, however, not in such as a way as to promote soot production.

In summary, appliance performance was satisfactory with gases up to and including a WI of 54.76 MJ/m³ (G21). Adoption of an upper WI at this level, however, makes no allowance for appliance malfunction due to (for example) age, lack of servicing or linting. Any selected upper WI limit should be restricted so that it is less than 54.76 MJ/m³ (G21), to allow a reasonable safe operating margin and correct operation of all ASD sensors types. This difference is conveniently termed 'headroom'.

For open flued appliances not fitted with primary safety devices, it is considered that the overall risk can be mitigated by correct installation with due consideration for the provision or maintenance of purpose provided ventilation followed by adoption of a regular appliance servicing/maintenance regime.

### Gas boilers

Six space heating boilers and combination boilers were tested and results shown in Figure 28. Under normal operating conditions (green dots), neither of the gas-air ratio control, fully premixed boilers or partial premix atmospheric boilers produced a $CO/CO_2$ ratio greater than the maximum safety action level or the CO (daf) limit specified in the standards (refer to green dots). The combustion performance of boilers with adjustable and non-adjustable gas-air ratio, fully premixed burner controls were found to be unaffected by variations in gas pressure or electrical supply voltage and are independent of gas WI.

Boiler in laboratory

However, as expected for fully pre-mixed boilers, their initial adjustment (usually factory set) markedly affected their sensitivity to changes in WI. For this reason, a further investigation was carried out on the two boiler types, (refer to section on special testing) to establish the operational WI range in which they would still operate safely.

Under progressively blocked flue conditions, the fully premixed boilers with gas-air ratio controls reacted according to type. For one of the boiler types, Boiler A, CO emissions are within the prescribed limits, whereas for the other type tested, Boiler B, CO emissions exceeded the maximum prescribed CO limit prior to shut down. However, being room sealed, these appliances offer only a modest concern for safety because of the low likelihood of combustion product re-entry into the living space under these conditions.

For all boiler types, the sooting propensity was unaffected by changes in gas WI, with the exception of the open flued back boiler unit (BBU) tested, when operating with G21 under linted conditions.

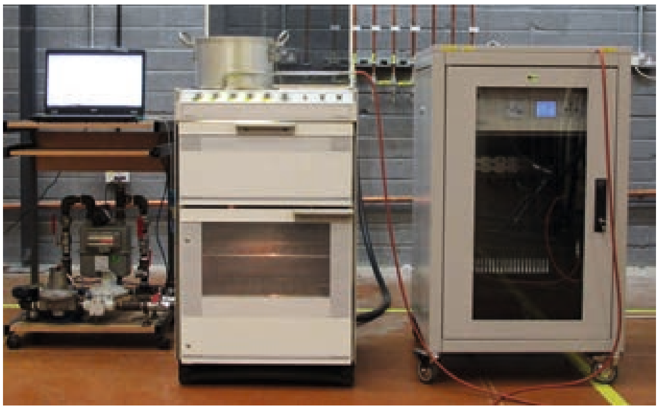
It was clear that open flued boilers have the potential to emit large volumes of CO at high concentrations into the living space under the blocked flue condition, whether unlinted or linted, if not fitted with a primary safety device and installed with adequate purpose provided ventilation.

Boilers with low level air intakes are more susceptible to linting. The CO emissions of the BBU under normal and blocked flue conditions were shown to considerably increase for all test gases. Gases of higher WI (such as G21) are shown to exacerbate this situation, increasing CO emissions (as ppm) to 4.5-5 times compared to G20 under the same conditions.

**Fig. 28** Laboratory test results – boilers

It is again worth repeating however that such risks are only relevant to pre-1996 boilers (due to the presence of ASD on later models), and that regular servicing effectively addresses these issues. This said many of these boilers are now becoming extremely old and have some of the lowest efficiencies; a further boiler scrappage scheme could be justifiable on energy efficiency grounds.

## Domestic cooking and commercial catering



Domestic cooker in laboratory

The results of all domestic cooking and commercial catering appliance burner types i.e. hobs, ovens and grills are shown in Figure 29 and 30 respectively. Analysis of these results show that all burners performed satisfactorily with G20 and G21, comfortably meeting the required safety action ratio and daf combustion limits irrespective of gas WI, pressure or heat input under the applied test conditions (in marked contrast to other appliances tested).

There were a few data points that exceed the safety action limit and CO limit under normal conditions (green dots) mainly because of poor sampling i.e. low $CO_2$ because of the difficulty in obtaining a representative combustion products sample from hob burners. However, despite the ratio being poor, the CO emissions were still well below the HSE short-term exposure limit[35] (15-minute reference period) of 200 ppm with G20 and G21.

There was, however, some concern regarding the performance of grills with G23 and G25 gases, which are at the lower end of the WI range examined (41.52-45.66 MJ/m³). These gases at reduced pressure conditions particularly affected CO emissions of some appliances.

Again, CO emissions at the burner discharge points were also found to be below the HSE short-term exposure limit with G20 and G21.

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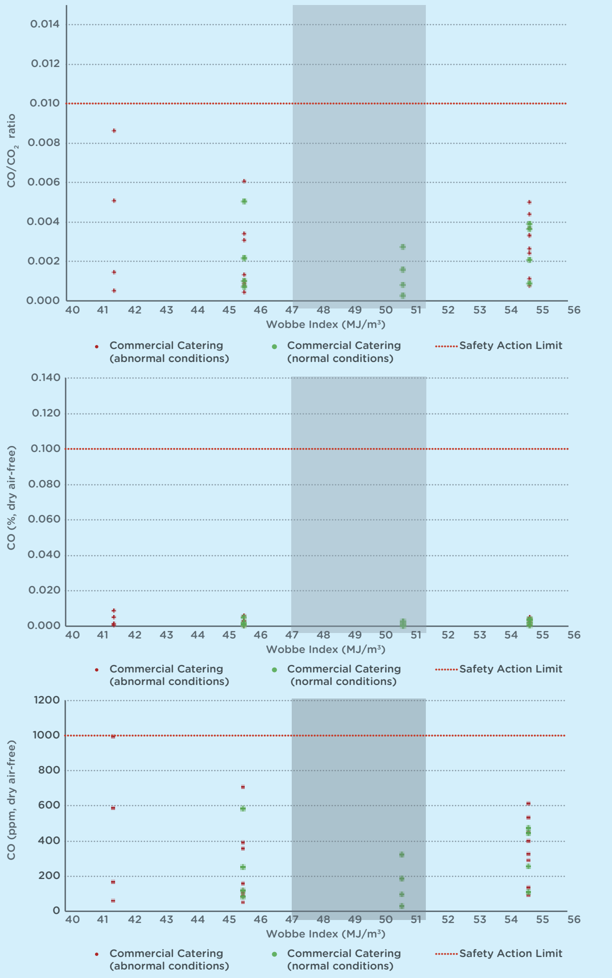
[35] Workplace exposure limits containing the list of workplace exposure limits for use with the Control of Substances Hazardous to Health Regulations (COSHH) 2002 (as amended).

# Results and discussion
*cont.*

**Fig. 29** Laboratory test results – domestic cookers

**Fig. 30** Laboratory test results – commercial catering



It was concluded that for the sample of domestic cooking and commercial catering appliances examined that:

- CO emissions from hob and oven burners varied depending on type and size (heat input), but performed within the daf limit and $CO/CO_2$ ratio safety action level, irrespective of gas WI, pressure or heat input under the applied test conditions.
- CO emissions from grills varied depending on type and condition, but, in general, were higher than those observed for hob or oven burners under the same test conditions.
- The CO emissions from grills are particularly affected by reduced gas pressure and decreasing WI.
- The flame picture of all appliances varied with gas WI, however, flame stability was maintained across the WI range tested at all inputs and pressures.
- Increasing WI produced flames with various degrees of yellow tipping, however, not in such as a way as to promote soot deposition.

Furthermore, it is considered supplying gas at a WI of 54.76 MJ/m³ to any domestic catering or commercial cooking appliance is unlikely to cause high incidences of CO emissions and only present a minimum risk to the householder/user provided that:

- Appliances are installed and operated according to the manufacturer’s instructions.
- They are only used for short term cooking.
- Are not misused for applications, such as space heating.

## Special testing

As a result of the laboratory studies and following detailed discussions with key stakeholders, a number of additional special investigations were also conducted by KIWA as listed. Subsequent sections that follow, provide a summary of the findings for each investigation:

1. Effect of WI on the combustion performance of combination boilers with adjustable gas-air ratio controls.
2. Assessment of the combustion performance of a domestic grill with gases of varying WI in a room with and without purpose provided ventilation.
3. Effect of WI on the atmospheric safety device on local space heating appliances.
4. Effect of gas WI on the performance of a poor condition local space heater and identification of the risks posed by the spillage of combustion products.
5. Assessment of the combustion performance of two domestic grills while cooking food with gases of varying WI.
6. Effect of increased gas WI on internal component temperatures in gas boilers.
7. Effect of non-methane components in natural gas on the performance of domestic gas appliances.

### Effect of WI on the combustion performance of combination boilers with adjustable gas-air ratio controls

A series of tests were undertaken to examine the effect of gas WI on the combustion performance of two fully pre-mixed combination boilers with adjustable gas/air ratio controls to determine the operational WI range in which the boilers can be adjusted and operated. The laboratory test work found that it would be possible to adjust and operate the boilers tested on a gas supply network within a WI range between 48.00-53.00 MJ/m³ with only modest effects on CO production (i.e. ±2.50 MJ/m³ from a central point of 50.50 MJ/m³). Theoretically at least, outside this range, extreme adjustment (either low or high) fed with extreme opposite WI gas (either high or low) can lead to substantial increases of CO in the flue products that was also confirmed in the GASQUAL study. Anecdotally, the likelihood of this is considered very low due to the Thermal Energy Regulations whereby biomethane gas in order to meet the Flow Weighted Average Calorific Value (FWACV) of the network.

**Fig. 31** Boiler Model A

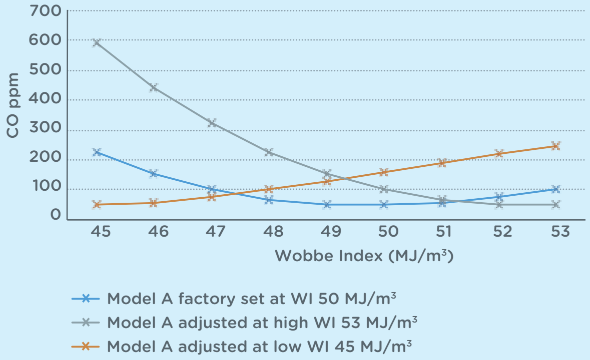


**Fig. 32** Boiler Model B

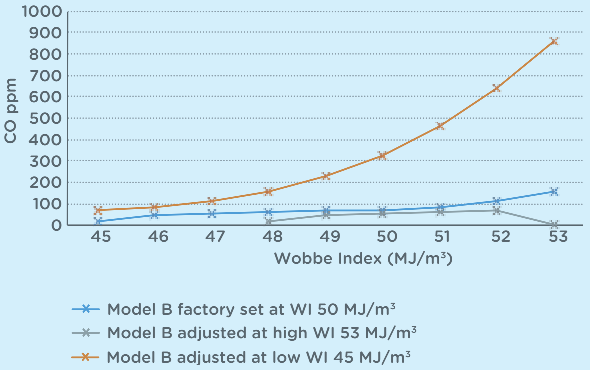
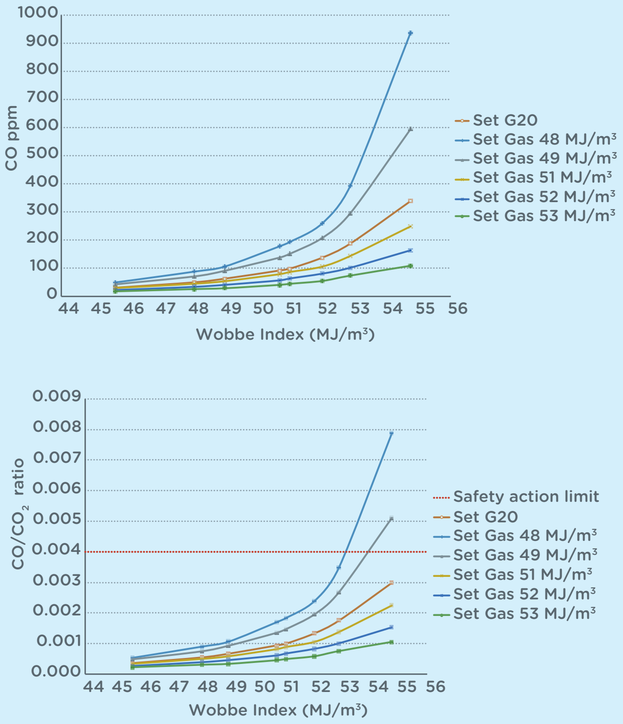


Figure 31 shows Model A (by way of example) designed to be adjusted to a nominal $CO_2$ of 8.74% at a WI of 50 MJ/m³. The CO will be 49 ppm. The boiler will operate satisfactorily in a WI range of 45 to 53 MJ/m³. The issue arises if the gas operative (especially after repairing the boiler) sets the $CO_2$ at 8.74% at an actual WI of 45 MJ/m³. Conversely if the gas is at an actual WI of 53 MJ/m³ and adjusted to a nominal $CO_2$ of 8.74%, and the WI falls to a WI of 45 MJ/m³, the CO is predicted to rise sharply to 593 ppm.

Model B has similar, but slightly different issues as shown in Figure 32. Both Model A and Model B are amalgamations of data, but the principle of the issue is well known. If the spread of WI is limited to 5 or 6 MJ/m³, the problem is far more tractable. This desirability for operatives to know instantaneous WI and adjust the $CO_2$ to an appropriate value is significant. This, combined with the potential inaccuracy of many operatives' flue gas analysers, can lead to incorrect adjustment. A smaller difference between upper and lower WI limits is less likely to result in mal-operation and result in excessive CO emissions.

As can be seen in Figure 33, a fully premixed burner with automatic gas air ratio control, the graph of CO emissions vs. gas WI shows the high WI side of the so called 'bath-tub' curve. The range of CO values arise from pre-setting the boiler to the manufacturers required flue gas setting with a gas of selected WI and testing with a range of gases of differing WI. CO emission values remain relatively low, except when pre-set with a gas of WI 48.00 $MJ/m^3$. Figure 33 also indicates that when this boiler is initially adjusted with gases of WI between 48.00-53.00 $MJ/m^3$, the combustion performance remains within the $CO/CO_2$ ratio safety action level of 0.004 and a maximum CO emission of ≤0.10% dry air-free specified in EU standards for boilers when tested across this range and when supplied with gases of Wobbe indices between 45.66-54.76 $MJ/m^3$.

**Fig. 33** Effect of WI on pre-mixed burners when set up on different WI settings



This shows that due consideration must be taken regarding the ability of a fully pre-mixed burner (such as high efficiency combi boilers) to operate safely with both the highest and lowest WI supplied to a network. If the appliance has been adjusted to the manufacturers' recommended $CO_2$ levels at the other extreme. In the case of the above boiler this is equivalent to $CO_2$ levels between about 7 and 11% $CO_2$. Allowing for variations such as gas rate, burner pressure, this is equivalent to about 5 to 6 $MJ/m^3$[36]. Figure 33 indicates a CO concentration of about 400 ppm at WI 53.00 $MJ/m^3$ when set up with WI 48.00 $MJ/m^3$ whilst the observed $CO/CO_2$ ratio is within the safety action level for air/gas ratio type boilers of 0.004.

The laboratory testing demonstrated that:

- The combustion performance under normal conditions met the required $CO/CO_2$ safety action level and maximum CO emission specified by the standards for boilers.
- If the WI of the primary adjustment varies significantly from gas subsequently supplied, the rate at which CO emissions rise increases (as does the absolute value).
- It would be possible to adjust and operate the boilers tested on a gas supply network within a WI range of between 48.00-53.00 $MJ/m^3$. i.e. ±2.50 $MJ/m^3$ about a central point of 50.50 $MJ/m^3$.

### Assessment of the combustion performance of a domestic grill with gases of varying WI in a room with and without purpose provided ventilation

A commercial grill from a property in Oban was found to have poor combustion when initially tested in-situ, generating high CO emissions and a $CO/CO_2$ ratio in excess of the safety action level of 0.020 for non-CE marked, so was removed for further laboratory testing. The aim of laboratory testing was to identify the risks associated with operating the grill in a room both with and without purpose provided ventilation in combination with gases over an extended WI range of 45.66-54.76 $MJ/m^3$ using test gases G20, G21 and G23.

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[36] Willcox. S. (2014) '*Special Investigation: The Effect of Wobbe Index on the Combustion Performance of Combination Boilers with Adjustable Gas-Air Ratio Controls*'. Report 30254/1. Kiwa Gastec.

Appliance maintenance, servicing and replacement when required produces a **7-fold reduction** in the absolute risk.

The laboratory testing demonstrated that:

- The combustion performance of the grill under normal conditions when re-tested in the laboratory was found to be below the safety action level of 0.020 specified in BS 7967: 2015 for non CE marked grills with all test gases used, possibly due to dirt or other body being dislodged during transportation.
- For a flueless appliance the rate at which the CO concentration rises is directly related to gas WI, rising quicker as this increases.
- Purpose provided ventilation only affects the rate at which the room CO concentration rises, but not the peak concentration.

This test reinforced the fact that providing the appliance is installed and operated correctly i.e. in a sufficiently ventilated room and only used for short time cooking there would be no increased risk from the appliance. Installing a larger commercial cooking appliance in a small domestic kitchen could present a risk to the user. However, if correct installation procedures are followed then these situations should never occur.

### Effect of WI on the atmospheric safety device on local space heating appliances

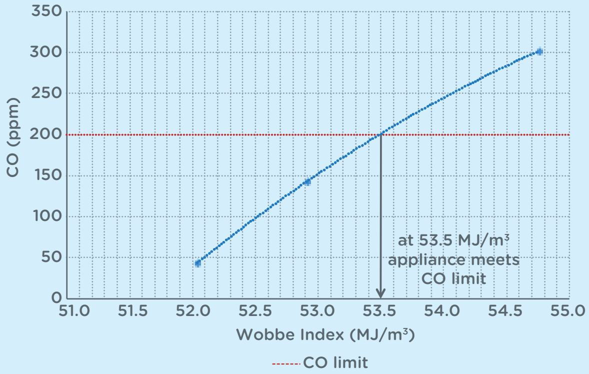
Laboratory testing on a space heating appliance (gas fire) fitted with ASD's found that, the device failed to shut off the appliance before the required maximum CO pass criterion of ≤200 ppm specified in BS 7977-1 when supplied with a high WI gas (G21).

Additional follow up investigations were undertaken to determine the level at which this device would operate satisfactory.

The laboratory testing demonstrated that:

- The level of CO at which the ASD operates increases as the gas WI increases above 50.72 MJ/m³ (G20).
- In order to meet the CO pass criteria of ≤200 ppm then the maximum WI value is approximately 53.50 MJ/m³ (refer to Figure 34).
- A headroom of 10% (20 ppm) between the maximum CO recorded at the point of shut off, and the pass criterion of ≤200 ppm would be achieved if the appliance was supplied with a gas of maximum WI of 53.26 MJ/m³.

**Fig. 34** Effect of WI on the ASD activation point



### Effect of gas WI on the performance of a local space heater and identification of the risks posed by the spillage of combustion products

A live fuel effect local space heater (gas fire) was discovered during the survey to have a broken glass side panel and considered to be potentially dangerous due to spillage of combustion products into the living space. The appliance was removed and replaced and a laboratory test program was conducted on this appliance in order to identify the severity of the potential spillage and to determine the effect of operating this fire on gases over an extended WI range of 45.66-54.76 MJ/m³ using G20, G21 and G23.

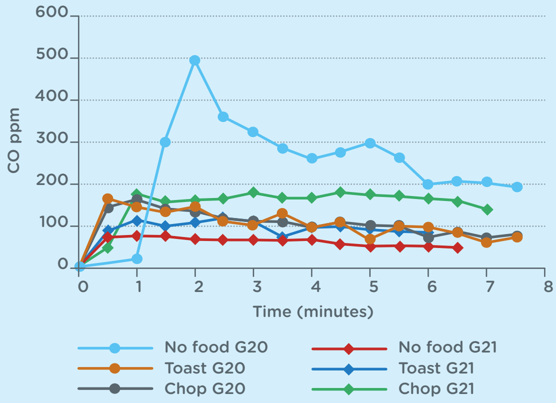
Fuel effect local space heater

The laboratory testing demonstrated that:

- The appliance as presented (with broken glass) has the potential to spill harmful quantities of CO into the room irrespective of flue height and would cause a serious risk to health in a small, poorly ventilated room if used with any gas for extended periods of time unless a CO alarm is fitted.
- The appliance combustion performance remains within the $CO/CO_2$ safety action level and the limit specified in EU standards for appliances of this type when tested with gases of WI between 45.66-54.76 MJ/m³.
- The rate at which the CO concentration rises in a room without purpose provided ventilation is directly related to gas WI, rising faster as gas WI increases.
- Gases of higher WI pose the greatest short term risk to human health in the event of an appliance with a blocked flue in combination with a room fitted with no/inadequate purpose provided ventilation. Gases of a higher WI have a higher air requirement and consume the air within the room more quickly than gases of a lower WI.
- The potential overall risk to human health caused by CO re-entry into a room is similar for all gases in the event of an appliance with a blocked flue in combination with a room fitted with adequate purpose provided ventilation.
- Purpose provided ventilation is effective and has the effect of reducing the rate at which room CO concentration rises.

Domestic grills tested with varying WI

**Fig. 35** Effect of grilling food when using G20 and G21 test gases



### Assessment of the combustion performance of two domestic grills whilst cooking food with gases of varying WI

Two domestic cookers with grill burners were selected for laboratory tests to study the effect on combustion emissions when food is grilled under a grill and the combined effect that both grilling and increasing gas WI had on combustion emissions. This was done to examine the effect on CO emissions of cooking different food types at normal and higher WI. The effect of the grilling sliced bread and meat chops was investigated with the appliances fuelled with both G20 and G21 test gases (refer to Figure 35).

The laboratory testing demonstrated that:

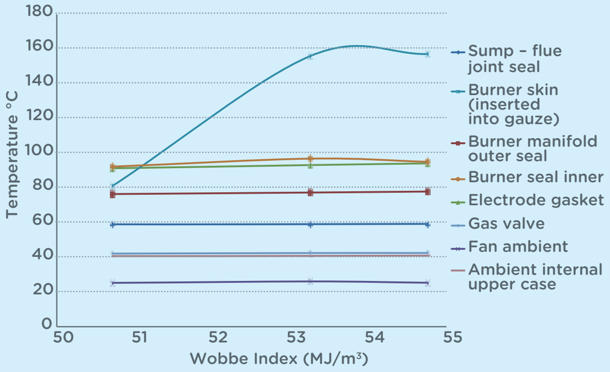
- The foods being cooked can impact on CO emissions.
- Operating a grill with no food produces less variable and lower CO emissions and $CO/CO_2$ ratios, whereas grilling food leads to more variable and increased emissions. Grilling of sliced bread produced more variable emissions than a meat chop.
- Except for a short initial period, the grilling of food using the grills tested did not generate $CO/CO_2$ ratios which would cause the grills to exceed the safety action level of 0.010 specified BS 7967: 2015 irrespective of gas type used.
- Cooker grill burners perform differently depending on factors such as design, age, condition and heat input. Cooker grills that do not have existing defects are more likely to perform within current safety action levels when food is being grilled, as opposed to grills that already have an existing defect that is causing poor combustion performance.

Based on the tests performed it was confirmed that a gas with a WI of 54.76 MJ/m³ would not markedly affect combustion performance (and thus increase risk), in terms of increased CO emissions or CO/$CO_2$ ratio, of cooker grills which do not have an existing defect, whether food was being cooked or not.

### Effect of increased gas WI on internal component temperatures in gas boilers

A prominent GB gas boiler manufacturer proposed an additional laboratory test to investigate the effect of increased WI on gas appliance internal components. It was hypothesized that future increases of the WI of the gas supplied in the GB gas network will increase the energy input into boilers and consequently may increase the internal temperatures of internal components and potentially shorten the useful lifetime of internal components and of the boiler itself. Temperature rises in metallic components, such as ducts which convey the gas/air mixture into the burner chamber were considered not to be an issue. Polymeric materials which might be used for gaskets and used to seal between the burner and heat exchanger, were of particular interest. A laboratory test programme was therefore undertaken on five fully premixed boilers to understand and establish the effect of high gas WI up to 54.76 MJ/m³ on internal component temperatures to prove that gases of higher WI do not have, a significant effect on internal component temperatures or result in accelerated long term component degradation. The results of one particular boiler are shown in Figure 36.

**Fig. 36** Effect of WI on boiler component temperatures



The laboratory testing demonstrated that:

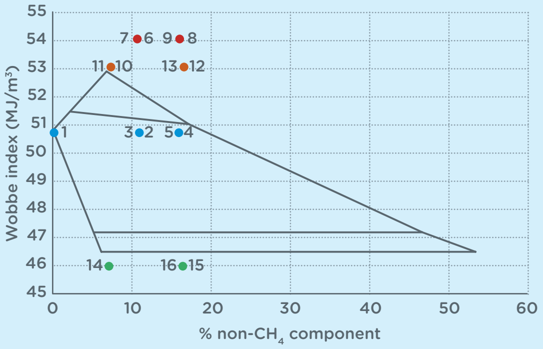
- Only areas close to the burner are affected and arise because of reduced excess air levels which increase both $CO_2$ and flame temperature.
- Due to the intermittent operation of highest output boilers (especially combination boilers in domestic hot water mode) combined with relatively small increases in component temperatures measured (even at the highest gas input rates) and the infrequency of flexible seal failure reported by one manufacturer, indicates that raising WI is unlikely to materially affect internal boiler life.

The internal temperature profile of components inside the manufacturers own products were supplied for review and comment. Two out of three manufacturer's, who supplied products for testing, perceived that if the WI of the gas distributed increased to 54.76 MJ/m³, there would be no long term performance, service or warranty issues. The other manufacturer highlighted areas for further analysis before they could draw any firm conclusions in relation to whether increased gas WI results in accelerated long term component degradation and premature failure.

### Effect of non-methane components in natural gas on the performance of domestic gas appliances

A laboratory test program was undertaken to understand the effect of gases with the same WI but different chemical compositions on appliance performance. Tests were performed on a range of appliance types using 16 gases of different composition, in the WI range 46.00-54.00 MJ/m³ (refer to Figure 37).

**Fig. 37** Position of the test gas mixtures plotted on the interchangeability diagram



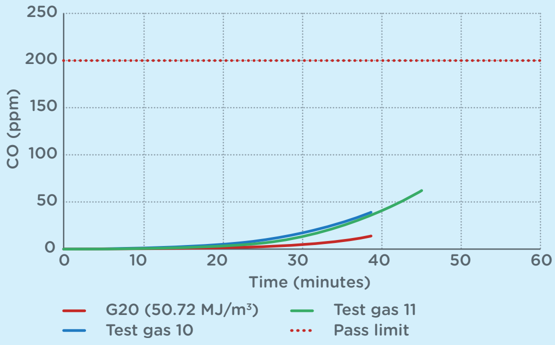
The hypothesis expressed by the current interchangeability diagram is that methane/ethane mixtures behave equivalently to methane/propane mixtures when combusted at an appliance burner. As part of the project it was felt prudent to investigate if this hypothesis is still valid for these new gases.

The laboratory testing demonstrated that:

- The measured $CO/CO_2$ ratio and CO emissions of all the appliances tested remained within the safety action levels set out in BS 7967:2015 and daf CO combustion limits specified in the applicable standards under all test conditions for all gases and compositions.
- For one of the gas fires (freestanding gas stove) tested, gases of higher WI, containing increased levels of methane and ethane, give higher SI compared to gases of the same WI of different composition.
- The ASD performance of gas fires differs depending on gas WI and composition. Methane/ethane mixtures shutdown the appliances at higher, but still compliant with test standard, maximum CO concentrations compared to methane/propane mixtures at the same WI of 53.00 MJ/m³ (refer to Figure 38).
- For all gas compositions, at individual WI, $CO/CO_2$ ratio, CO and Oxides of Nitrogen ($NO_x$) emissions are similar, with little variation between individual measurement points across the WI range 46.00-54.00 MJ/m³ for all appliances tested in this study.

The testing concluded that the hypothesis expressed by the existing interchangeability diagram can be still applied for prediction of combustion performance of equivalent gas mixtures on appliances. In some instances, small differences in results were witnessed on different gas mixtures with the same WI which may warrant future further investigation.

**Fig. 38** Effect of different gas mixtures on a space heater Oxypilot (ASD) performance test



## Other results and discussions

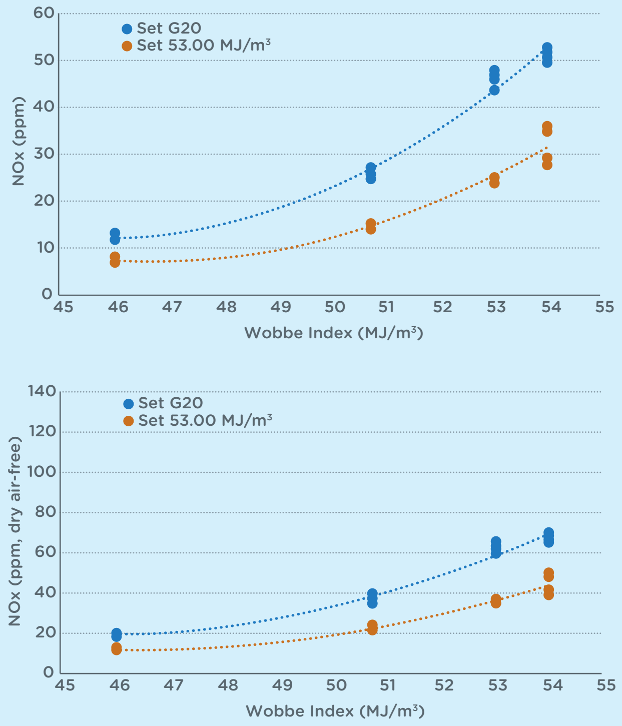
This section will summarise and discuss a number of supplementary results that were derived from the laboratory testing.

### Oxides of nitrogen

$NO_x$ emissions vary, and increase at different rates with increasing gas WI, depending on appliance/burner type and heat input. Typically, appliances followed the GASQUAL data, thus those with moderate $NO_x$ emissions (>100 ppm) rise slowly e.g. gas fires, partial premix boilers and domestic cooker burners (hob, oven and grill), whereas fully premix burners (with very low $NO_x$ levels initially <50 ppm) show a greater sensitivity to gas WI Increases, with $NO_x$ emissions almost doubling as WI increases from 50.72 to 54.00 MJ/m³. All $NO_x$ emissions are considered to be typical for their appliance types.

$NO_x$ levels remained within modern standards for the appliances tested although, this is to be expected as since the introduction of the GAD all appliances have been tested with these limit gases, and prior to this many British Gas approved appliances broadly complied with good engineering practice at these levels.

**Fig. 39** Total $NO_x$ emissions at maximum heat input for a typical fully premixed combination boiler – set for G20 and 53.00 MJ/m³



### Effect of WI on appliance efficiency

From a theoretical perspective appliance efficiency is not expected to be significantly affected by WI. In the extreme, gas appliances are generally considered to have similar efficiencies when fired with Liquid Petroleum Gas (LPG) and Natural Gas. The findings of the Advantica Report (2004)[37], concluded that “appliance efficiencies and flue gas temperatures show only a slight dependence on the WI of the fuel gas”. “For each type of the domestic appliance tested (cookers, boilers and gas fires) there is a modest increase in net thermal efficiency with increasing WI”. This project did not include specific investigation of efficiencies, but none of the results seen would indicate that the results would be any different. Gross thermal efficiencies (used in GB and the most recent EU legislation) are expected to show very similar patterns to Net Thermal efficiencies, conventionally declared for gas appliances.

### Concept of headroom recommendations

In considering any safe limits, as in this case the WI, it is normal practice to include a safety margin. It is expected that a significant number of appliances in the GB population are likely to be in sub-optimal condition, caused by age, general wear and tear and/or lack of servicing. Appliances in poor condition are more sensitive to WI changes (as demonstrated by the GASQUAL study) and prone to poorer combustion performance (increased $CO/CO_2$ ratio and CO emissions) as gas WI deviates from the gas type on which it was originally designed to operate. Distribution of gases nearer to the appliance design specification (i.e. G20) will always tend to give the best combustion performance, unless the appliance has a pre-existing fault or requires servicing. A safety margin provides headroom to accommodate for the deleterious unknowns in the field condition and operation environment of appliances, such as:

- Appliance age and condition.
- Lack of inspection and servicing.
- Wear and tear throughout the appliance life cycle.
- Manufacturing tolerances.
- Extreme voltage variations (for appliances containing fans).
- Operation of inbuilt safety devices, such as ASDs.
- Climatic conditions (variation of the gas and combustion air temperature, humidity, atmospheric pressure and wind).
- Moisture in the mains gas supply.
- Usage pattern of the appliance over an extended period.
- Tolerances for gas/air ratio adjustable appliances.

### Ambient temperature effects on WI values

Provided the gas and air are at the same temperature WI is unaffected, however in reality there are deviations in supply conditions (mainly air temperature) that modifies the WI of the gas supplied to the burner. Under high temperature conditions the relative density (RD) of the gas decreases with increasing temperature, thus the mass flow of air decreases, and WI increases. Raising the combustion air temperature by itself effectively creates a more fuel rich environment. If the maximum air temperature at any location is taken as 15°C above the gas (likely to be piped underground and indoors), this is equivalent to

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[37] Advantica R 7409 – Assessment of the Impact of Gas Quality on the Performance of Domestic Appliances (A Pilot Study) 2004.

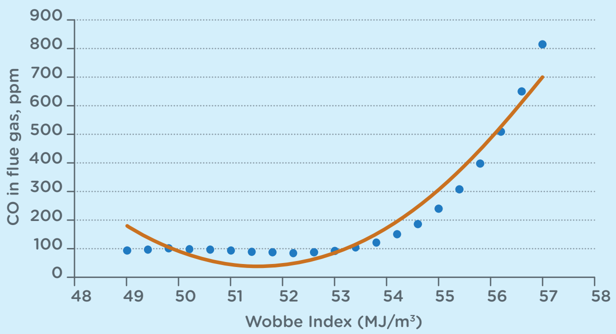
raising the WI by a factor of 1.025 relative to 15/15°C. For example, a gas with WI of 53.42 MJ/m³ (at 15/15°C) will effectively increase to a WI of 54.76 MJ/m³ (G21) if the combustion air alone is increased to 30°C. This phenomenon has been reported in Spain where boilers with gas-air ratio premix boilers operating at high WI (reportedly up to 54.76 MJ/m³ at 15/15°C) start to operate noisy during operation caused by the insufficient supply of excess air. Thus it was considered necessary to take account of ambient temperature effects within the headroom of any proposed changes to the WI limits.

**Selection of the upper WI limit**

Increasing gas WI effectively makes the pre-mixed combustion gas being fed to the burner more fuel rich, which means more secondary air is required for complete combustion that has to defuse into the flame as it emerges from the burner holes. Initially this tends to increase the concentration of $CO_2$ in the flue gases, with negligible effect on CO emissions. As WI increases still further there will be a point where insufficient secondary air is available (which varies from burner to burner) and the level of CO in the flue gas increases exponentially.

In making decisions regarding the new proposed upper WI limit, it is useful to examine the results to understand the reason for the 'bathtub' shape of the curve and the points at which the CO begins to rise. WI against average CO emissions is plotted in Figure 40 using a cross correlation of all the laboratory test data.

**Fig. 40** Effect of WI on CO ppm



This shows that taking the average of a range of standard and extreme test conditions there is no significant change between CO emissions at WI between 50.72 MJ/m³ (G20) and 53.00 MJ/m³ (as indicated by a relatively flat line profile), this is comparable with other previous studies. It is not until approaching WI of 53.50 MJ/m³ that the CO begins to increase in an exponential fashion.

Based on the results of stage 1 laboratory testing it was demonstrated that domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas up to WI 54.76 MJ/m³. It was recommended by KIWA that any increase to the upper WI should be limited to 53.25 MJ/m³ to allow sufficient headroom (approx. 1.5 units) for factors previously discussed such as;

- Appliance safety device performance.
- Ambient temperature effects.
- Start of exponential increase of CO around 53.50 MJ/m³ (for some appliances).
- Sub-optimal adjustment of air/gas ratio controlled fully premix boilers.
- Other deleterious unknowns and poor condition of appliances.

Furthermore, it was noted that this upper limit is only marginally above the current GS(M)R emergency limit (52.85 MJ/m³) whilst other EU countries can typically have limits as high as 53.60 MJ/m³ who install appliances subject to a similar EU test regime.

**Selection of lower WI limit**

Decreasing gas WI effectively makes the pre-mixed combustion gas being fed to the burner more fuel weak. This means that $CO_2$ tends to decrease and CO emission again remains unaffected until the flame actually becomes unstable either trying to light back due to higher concentrations of hydrogen in the fuel gas due to increased flame speed, or the flame will try to lift due to higher levels of inert gases present. Both conditions create unstable combustion which will eventually causes increased CO concentrations. Interestingly, however, the current lower WI is set by virtue of underperforming water heaters and some fires that exhibit increased risk from flame instability and increased CO.

The results of the laboratory test identified no safety issues on appliances when tested on G23 (45.66 MJ/m$^3$). However, Kiwa recommended no change to the lower WI limit and to retain the existing limit of 47.20 MJ/m$^3$. This is because of the potential difficulties with adjusting fully pre-mix appliances (primarily condensing boilers) in the field. The performance of such appliances is model dependent but generally optimum performance is maintained in a range +/- 2.5 MJ/m$^3$ of their set point.

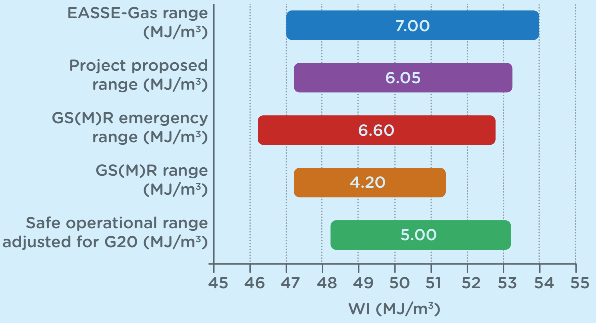
This means a boiler set up in the factory at WI 50.70 can operate optimally up to WI 53.20 and down to WI 48.3. without the need to be readjusted (refer to Figure 41). In practice fully premix boilers can be safely operated outside these limits and are compliant with the CO/CO$_2$ ratio limit at WI 53.00 even when adjusted at WI 48.00.

In GB, all modern gas boilers are factory pre-set at the correct gas-air ratio and gas operatives are deprecated from adjusting this. This issue of potential for incorrect adjustment will only arise after replacement of a defective component. It could be addressed by providing real time information to gas operatives in the field. This is currently being investigated in the SGN Real Time Networks project.

Extending the upper WI limit to 53.25 MJ/m$^3$ and retaining 47.20 MJ/m$^3$ at the lower end, would effectively widen the WI range beyond the 5 MJ/m$^3$ safe operational range identified for fully pre-mixed boilers. Thus an upper limit of 53.25 MJ/m$^3$ leaves less scope to extend the lower limit below 47.20 MJ/m$^3$ without having to re-adjust boilers. It is acknowledged that, together, the existing lower limit of 47.20 MJ/m$^3$ and the proposed upper limit of 53.25 MJ/m$^3$ exceed the 5 MJ/m$^3$ range identified, however this is not considered a material issue as in practice the WI of the gas in the network is always likely to be in excess of 48.00 MJ/m$^3$, for reasons as discussed previously.

In Germany (where they have wider range of WI) routine minor adjustment of appliances with WI has been found dis-advantageous and it was considered that all appliances that have the potential for adjustment should remain as found. The potential risk from encouraging installers to break seals on satisfactorily performing appliances for the sake of small adjustments may well be counter-productive in terms of risk reduction i.e. the risk of incorrect adjustment has the potential to outweigh the modest benefits of correct adjustment. However, this issue is due consideration for future work if a change to the lower WI limit is to be considered for GB.

**Fig. 41** Comparison of safe operation WI range of adjustable boilers at G20 against existing/proposed WI ranges



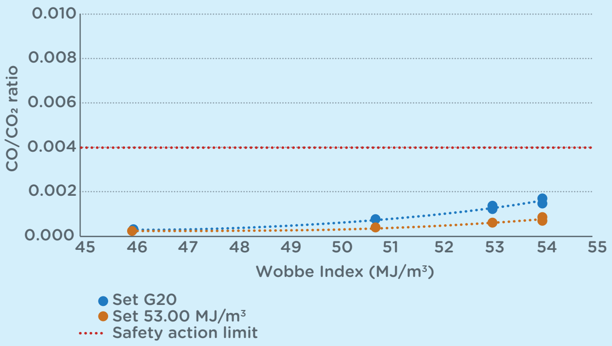
## Implications for ICF and SI

Dutton's assertion was that any natural gas can be represented by an equivalent gas comprising three components; methane, propane and nitrogen, and developed a gas interchangeability diagram along with Incomplete Combustion Factor (ICF) and Soot Index (SI) to demonstrate interchangeability. Gases which lie within the envelope of the Interchangeability prediction diagram are compliant with the GS(M)R and therefore interchangeable with the gas currently in use.

ICF is simply a measure of how flue gas CO/CO$_2$ ratio increases as WI increases and takes no account of flue gas CO content. The ICF parameter was introduced by Dutton because test results indicated a small dependence of flue gas CO/CO$_2$ ratio upon equivalent ($N_2$ + $C_3H_8$). ICF was derived by Dutton from the performance of instantaneous water heaters; these appliances (together with the radiant gas fire) were commonly found in most homes in the 1970s and generally generated flue gas CO/CO$_2$ ratios that doubled when WI was increased by approximately 1.5 MJ/m$^3$. Such appliances are now rare and today's 'equivalent' appliance is the central heating/hot water boiler. Such appliances do not show such severe sensitivity to WI.

The Laboratory testing of a combi boiler with partially premixed burner suggests doubling of flue gas $CO/CO_2$ ratios only occurs when WI is increased by 3.0 MJ/m³. See Figure 42. As a result Dutton's relationship for calculating ICF from composition over-predicts true ICF for today's appliances.

**Fig. 42** $CO/CO_2$ ratio vs WI – partially premixed combi boiler



Dutton's basis for limiting equivalent ($N_2$ + $C_3H_8$) was based on limiting sooting associated with higher density gases and the Sooting Index limit value of 0.6 is based on visual assessment of the discolouration of ceramic radiants of gas fires commonly on use at the time. Sooting at this level is not a safety consideration and only becomes of concern only when considering excessive deposition – in the flues of flame-effect fires, for instance. Laboratory testing in this project shows that limiting relative density to 0.70 limits propensity for significant sooting.

It is worth pointing out that the relative density limit of 0.70 generally represents a stricter limitation compared with the SI limitation of the GS(M)R. Most natural gases have relative density lower than 0.70 and only some associated natural gases or heavily-enriched gases would be affected.

# Conclusions

The main conclusions from stage 1 are:

1. Domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 MJ/m³.
2. An upper WI limit of 53.25 MJ/m³ allows sufficient headroom for any deleterious unknowns in the field condition of the appliance.
3. Increasing the WI to 53.25 MJ/m³ has negligible impact on the efficiency, performance and life of a domestic or small commercial appliances.
4. Both the Sooting Index and the Incomplete Combustion Factor as stated in GS(M)R are no longer valid.

# Field testing

# Overview

The objectives of stage 2 field testing were to:

- Establish the proportion of older gas appliances that constrict gas quality specification in GB through assessment of a representative appliance sample from Oban Network.
- Demonstrate through the sample population what is required to ensure GB's appliance population is capable of operating safely and efficiently over a wider range of gas quality.
- Identify and record all types/makes of gas appliances, identified through the representative appliance sample from Oban network that are not fit for operation using gas which meets EASEE-gas specifications but sits outside GS(M)R.

The field testing of appliances was undertaken in Oban between November 2014 and July 2015 using test gases G20, G21, G23. Testing was conducted by a team of qualified GasSafe registered Engineers. The aim was to test all gas appliances in every gas user's property to demonstrate combustion performance. This sample of appliances would be statistically representative of the appliance population in GB. It would also give an insight into appliance health.

With access to properties being a fundamental requirement to the success of the project, a number of initiatives were developed that were designed to ensure customers and stakeholders were engaged.

In particular it was important to ensure customers were adequately informed about the purpose of the testing and to ensure that there would be minimal disruption throughout the project.

Gas installations at each property were initially inspected for safety in accordance with the current Unsafe Situations Procedures and appliance health as found reported. Any installations that were found to be unsafe or in need of repair were then repaired and/or appliances replaced free of charge.

A purpose build mobile unit and testing rig was used to transport and connect the 3 test gases to the properties allowing test gases to be introduced to each appliance upon which combustion performance tests were then undertaken.

# Enabling activities

## Customer engagement

Customer and local stakeholder engagement was essential to ensure success of the project. Customers needed to be fully engaged in order to achieve a high level of participation. The project worked alongside the local council, community groups and businesses to help engagement.

To ensure customers' participation, it was essential that they had all the information they needed. Building on the ‘road to social proof’ established under stage one, an updated customer engagement plan was published and a project website was launched[38].

A short project film was produced for customers. It provided customers with an overview of the project and a visual understanding of what appliance testing entailed. The project film was uploaded to SGN’s YouTube[39] channel in October 2014 and was also shown at Oban’s Phoenix Cinema during trailers for 20 weeks. The video has received over 5,000 online hits, was seen in the cinema by over 2,000 individuals and has been shown to hundreds of delegates during project presentations at conferences.

Customers were contacted directly via personal letters containing their proposed appointment time for the appliance testing in their home. An information leaflet that provided further details into who SGN are, what the project involved, when and why it was being carried out; and the reasons behind Oban being selected accompanied this. It also offered an opportunity for customers to contact SGN to ask questions, obtain further information, reschedule appointments or opt out of the testing.

The project was promoted using local media channels in Oban. The local newspaper paper provided updates on progress and advertised project events. A local radio station was used to air project details, in an attempt to reach more customers.

A number of other communication activities, materials and customer incentives were implemented both prior and during the field testing that included:

Customer engagement examples

Cookery demonstrations at the Regent Hotel, Oban

- Hosting a ‘cooking with gas’ event whereby a professional chef provided cookery demonstrations for the local community. Following the demonstrations, the Project team held lively Q & A sessions.
- Sponsorship of the Oban Winter Festival.
- Creation of a short Project awareness film played as a trailer to featured movies at the Oban cinema.
- Sessions in the town hall that provided opportunity for customers to ask questions.
- Free CO alarm to all properties tested.
- Free repairs or replacement appliance where the appliance was found to be faulty.

This project was the largest European gas appliance study ever conducted and thanks to the creative approach to customer engagement it was successful in accessing over 90% of the Oban gas population.

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[38] SGN: ‘Innovating in Oban’, 2014. https://www.sgn.co.uk/oban/
[39] SGN: ‘Opening up the Gas Market’, 2014. www.youtube.com/watch?v=ZdBz-ibwPpA

# Testing methodology

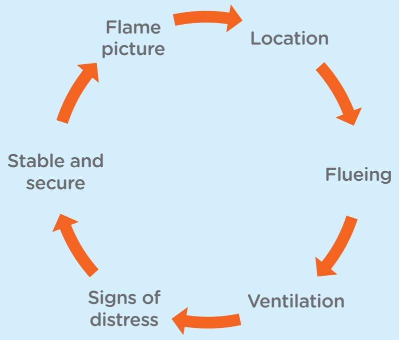
To facilitate the testing various compositions of gas it was necessary to be able to transport and then connect these gases to each of the properties in Oban. The purpose built mobile units included other ancillary equipment such as a test rig to safely control pressure and hose equipment to connect the gas supply to each of the meter outlets.

Mobile test rig

Test rig and hose

At each property information relating to appliance type, location and condition was captured. A visual risk assessment Figure 43 was carried also out in accordance with the Unsafe Situations Procedure[40] for each appliance.

**Fig. 43** Unsafe situations visual risk assessment diagram



The whole testing procedure took around an hour but could vary depending on the number of appliances in the property. The testing consisted of:

Removal of the existing meter and reconnection of the testing rig complete with pressure regulating devices to allow test gases from the mobile unit that were connected via flexible hose, to be introduced in turn to each property.

Each property was tested for soundness and the complete system fully purged prior to commencing the testing.

Two engineers were used to carry out these procedures, one situated inside the property that carried out the appliance testing whom was in contact by two-way radio with the second Engineer stationed outside and on board the mobile unit whom managed valve changeover operations to introduce each test gases as and when required by the appliance tester.

Prior to carrying out the combustion performance tests the appliances were set to their maximum output setting and given sufficient heating up time (5 mins) to ensure a good sample was recorded.

Gross heat input of the appliance (or individual burners) at the time of testing was also captured.

Combustion performance analysis using electronic portable combustion gas analysers (conforming to BS EN 50379-3) and sampling probes (as detailed in BS7967: 2015, Annex C) a combustion performance analysis was undertaken to record CO (ppm), $CO/CO_2$ ratio and $O_2$.

The above combustion performance tests were repeated for all 3 test gases and a visual assessment of the flame with respect to flame stability, shape, length and colour was recorded.

In cases where it was not possible to introduce test gases at the property the burners were tested on mains gas only.

Any appliances that did not pass the test performance criteria, e.g. those exhibiting high CO emissions, poor condition or incorrectly installed were either rectified or replaced during the project free of charge.

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[40] https://www.gassaferegister.co.uk/media/1774/tb_001_-_gas_industry_unsafe_situation_procedure_-giusp-_edition-71.pdf

Using Oban as a statistical representation of GB, it is estimated that **4%** of the GB appliance population would be classified as **‘at risk’** against the Unsafe Situations Procedure currently.

# Results and discussion

The stage 2 results have been split into 4 sections:

1. Access rates
2. Appliance health
3. Combustion performance
4. Other results and discussions

### Access rates

The project needed to confirm that all appliances connected to the gas supply in Oban would operate safely with the gas supplied to them.

The project concept was that all premises where gas could be used must be identified and all appliances installed checked in some way to confirm safe operation with the proposed supply gas.

Xoserve maintains the primary database of information about gas connections.[41] The data set originally supplied contained 1104 addresses associated with gas meter points. In principle this data set distinguishes between current gas users, gas meters not in use and capped supplies.

However, there were issues with regards to the precision of address information (e.g. particularly in multi-dwelling buildings where addresses of individual flats are inconsistent) and the completeness of the data set. Accurate and unambiguous identification of active meter points was more complex and challenging than anticipated. This had implications for the work where it was planned to inspect all connected gas appliances.

It was found that the gas supply status needed to be categorised as shown in Table 4.

**Table 4** Gas supply categories

| Gas supply status | No. |
|---|---|
| Duplicate address | 9 |
| No gas ECV capped | 34 |
| No gas meter removed | 4 |
| Customer advised no gas in use | 39 |
| Meter live gas not in use | 11 |
| No access | 74 |
| Refused access (some possibly burning gas) | 30 |
| Meter live – gas in use | 903 |
| **TOTAL** | **1104** |

The picture is not complete and the main reasons for this are:

- Imprecise address (e.g. for individual flats in blocks or converted houses).
- Incorrect address (locations in areas not supplied with gas).

It was very important that all customers were identified as part of the process. Considerable effort was applied to obtaining the most accurate meter point data set possible. Cross checks between postcode and meter point data locations were made and by the end of the project all properties burning gas were visited.

Given the perceived weaknesses in the address data validation of meter point addresses and identification of gas supply points not included in the data set was carried out.

The findings from this work were:

- Based on the investigations it was concluded that there were properties connected to the gas grid that were not recorded in the XoServe data set used for Oban.
- The proportion of properties consuming gas but where it has not been possible to confirm this directly as access was not possible to the properties in question is higher (30 in records or about 3%). Some of these appear to be supplied with gas based on the comments.
- Although there may be 4% of properties where the status of gas use is uncertain, this does not necessarily imply that there is a specific hazard within these properties.
- Even where such a hazard may exist this may be associated with the condition of the equipment rather than to any change in the gas supply.
- These findings suggest that the overall probability of incident occurring with an appliance in these properties is low and is probably no higher than that associated with inadequate care and maintenance of appliances generally.

It should be noted that generally gas operatives on the ground were well received, and access was not a problem however there were a small minority that either refused access or simply claimed they did not burn gas.

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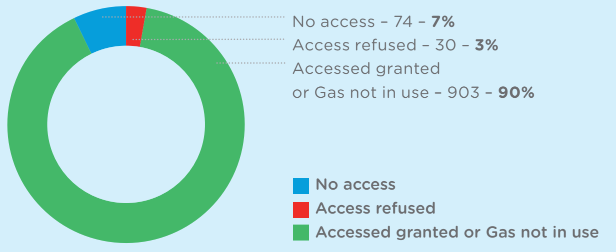
[41] Xoserve data management of 22 million Gas meter points http://www.xoserve.com

This analysis showed confidence that gas was being used at the remaining 1,010 properties out of the original 1,104.

The aim was to visit every gas user in Oban to ensure every appliance connected to the network was tested. Figure 44 shows the project success rate in gaining access to the 1,010 properties on the Oban network.

**Fig. 44** Property access report



'Access Refused' properties relate to customers who 'opted out' of participating in the testing. 'No Access' properties are properties that were not accessed and there was no customer opt out or in. Empty properties such as holiday homes make up a large proportion of the no access properties. In some cases, however Landlords and letting agents assisted the project by allowing us to access their empty properties.

It was considered that the number of properties that were accessed as part of the project was an overwhelming success and was due largely to the stakeholder and customer engagement that took place.

At the end of stage 2 the project team reviewed the 104 remaining no access and refused properties.

Although by definition, appliances in no access and refused premises were not tested, a number of considerations were made in order to assess and if required, mitigate, the risk presented to individual consumers and decide the appropriate action. Examples of actions considered by the team in order of preference included:

- qualitative and quantitative assessment of individual risk at no-access premises based on local information regarding appliances, current gas use (for properties with outside meter boxes), likely flueing, ventilation, service history and other relevant national and local data;
- Isolation of gas supply to 'no-access' premises or forced entry to 'no-access' premises under the Gas Safety (Rights of Entry) Regulations 1996; and
- Postponement or suspension of the Field Trial.

The exact choice of action would depend on a number of circumstances, result of external visual risk assessment, information available about the premises and the reasons for no-access (e.g. premises not occupied, access persistently refused by occupier).

The visual inspections and investigations that were undertaken on each of the 104 properties included a check to establish if the property was vacant or using gas:

1. Inside building completely empty, no furniture or maintenance to garden etc.
2. Building undergoing complete renovation.
3. Property furnished but large amount of mail behind front door (possible holiday home).
4. External meter box, check if ECV has been isolated and/or gas supply cut off.

Following this a further investigation was also carried out to establish the tenure type of the property i.e. owner occupied, housing association or rented privately. This was achieved by contacting local authorities, letting agencies and where possible questioning of nearby neighbouring properties, noting that properties that are managed by housing associations and letting agencies should have regular appliance inspection/maintenance implying there is unlikely to be issues within these types of properties.

Further external checks were carried out to determine the type of flue and ventilation as follows:

Flue types:

Fan flue or balanced flue type boilers – Flues of this type indicate room sealed appliances which are considered very low risk as discussed in more detail later.

Conventional Flue type boilers – These boilers can use external flue pipe however in most cases now internal flue pipework and/or in conjunction with a chimney stack with a flue that either terminates as a ridge tile, through a tiled roof or on a chimney stack.

Where possible, the integrity of flue terminal and the area around the terminal was visual assessed to look for evidence of broken/loose tiles, cement missing or showing signs of deterioration on chimney stacks, wrong or incorrectly installed terminal etc. More importantly, a check was also made to look for signs of soot formation, indicating a high risk that would require further action.

Ventilation:

A visual check was made to determine if ventilation grills were present, in particular where it was suspected that a conventional type boiler exists. Although this visual check is limited to the external wall, it is useful in identifying risks in particular where it is common to see external walls rendered without due regard for existing or required ventilation to the property.

All the above information gathered was then reviewed on a case by case basis by the project supervisor.

In all instances of refused and no access properties both the investigations and external visual risk assessment determined that no further action was required.

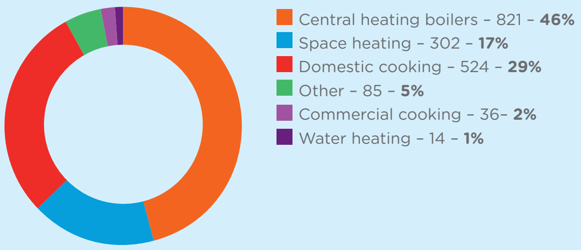
## Appliance health

Using Oban as a representative sample of GB, this project gives the largest scale insight into appliance health in GB in recent times. Appliance health is an umbrella term for things such as condition and age of installation.

For these results data was organised into appliance category namely, Central Heating Boiler, Domestic Cooking, Space Heating, Commercial Cooking and also by sub categories i.e. Appliance Type which included Combination Boiler, Regular System – Condensing/Non condensing, Inset Live Fuel Fire, Radiant Fire etc. All sub-category charts by appliance type can be found in Appendix 4.

The appliance category population profile for Oban is shown in Figure 45.

**Fig. 45** Appliance category population



Using Oban as a statistical representation of GB, the appliance profile presents the most update insight into the proportional split of appliances in GB.

General appliance health was visually assessed for each installation and reported under the following classifications, New, Good, Fair and Poor. Figure 46 shows the general condition based on appliance category for Oban.

The effect of promotional campaigns on energy efficient type appliances was evident, whereas a higher percentage of appliances reported as poor tend to be those types being phased out e.g. eye level grill cookers/fan warm air systems.

Results of the unsafe situation assessments were recorded against each appliance as either Satisfactory, Immediately Dangerous, At Risk or a Concern for Safety. Figure 47 show total numbers reported as a percentage of the overall population of appliance categories in Oban with the total number of Immediately Dangerous appliances reported as 2% and At Risk was 4%. All of these installations were rectified or, where necessary, the appliance was removed and replaced. Generally, these appliance installations were over 20 years old.

Further analyses of the data were carried out by considering the fault classification types reported for each of the unsafe situation i.e. Flueing, Ventilation, Combustion or Other.

**Fig. 46** Condition by appliance category

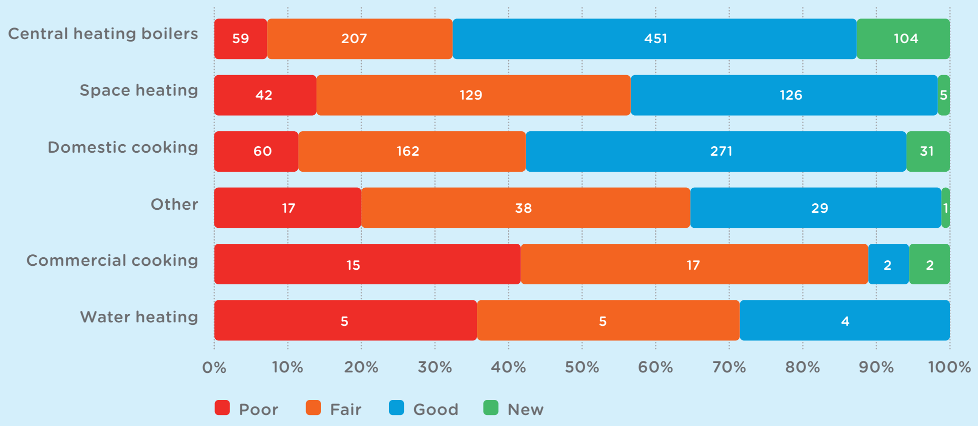


**Fig. 47** Unsafe situations by appliance category

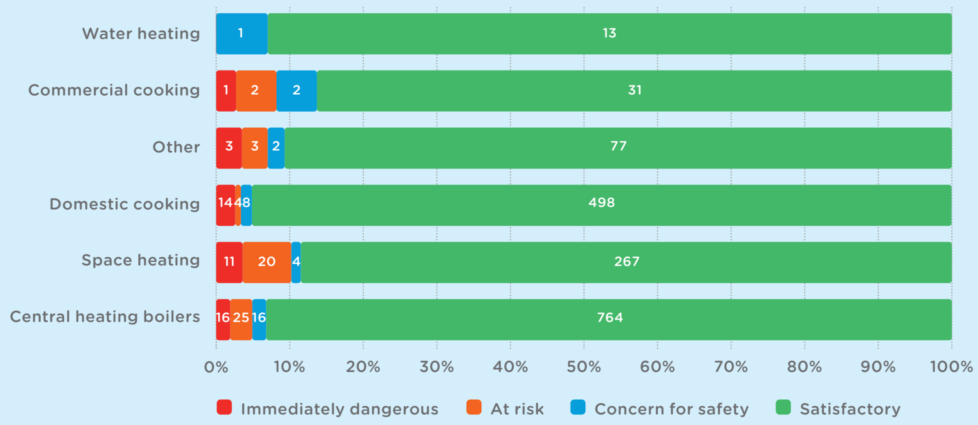


**Fig. 48** Unsafe situations (fault classification) by appliance category

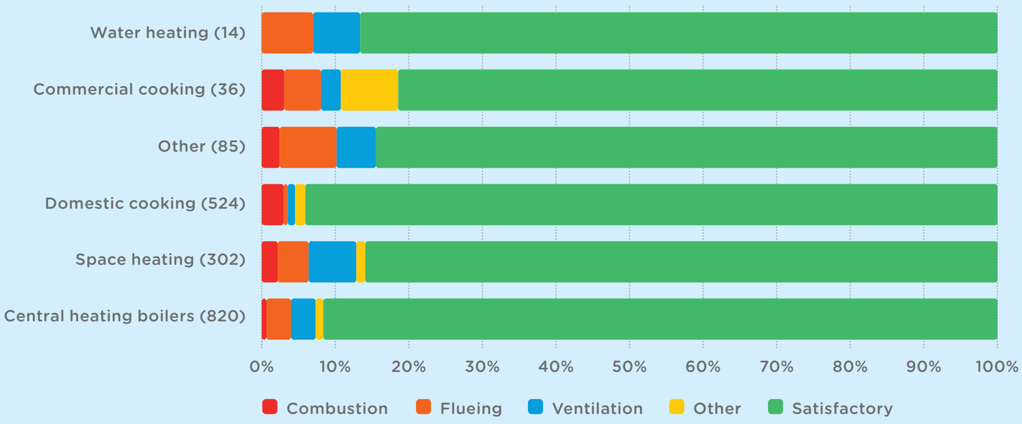
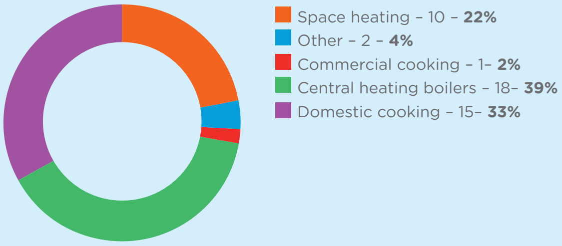


Figure 48 shows the numbers of fault classifications that were reported by appliance Category.

The charts indicate that the highest proportion of combustion problems were associated with the domestic cooking (high level grills) and local space heating (decorative/inset live fuel effect fires).

Figure 49 shows the breakdown of the 47 appliances that were replaced during the project. The reasons for replacement are summarised in Appendix 5.

**Fig. 49** Appliances replaced by appliance category



Tenure Type and property type were recorded during the visits undertaken, however, following analysis it has proved difficult to ascertain any statistically valid conclusions from these classifications.

A large scale statistically representative gas appliance survey has not been carried out in GB for over 25 years.

In general, the majority of appliances and their installation in Oban (94%) were found to be satisfactory, and the number of sub-optimal installations low (2% Immediately Dangerous and 4% At Risk, note this does not relate to the change of WI testing). Thus similar proportions are predicted for GB.

Looking at the 6% in more detail and using an element of qualitative analysis the actual risk is considered low as these are unlikely to turn into a CO incident, as many of these appliances are of low gas input (cooker burners) used for short periods in rooms that may be well ventilated. This is further supported by the special laboratory testing undertaken during stage 1 on unsafe appliances removed from Oban which demonstrated that whilst CO emissions increased as a result of WI increases, this was not considered to materially increase the risk to the occupant.

## Combustion performance

The most significant results from stage 2 are the combustion performance of the appliances on the different test gases.

Table 5 identifies the total number of appliances and burners that were identified at the 903 properties accessed. As the results show, in certain circumstances it was not always possible to carry out the full 3 gas tests, in these cases the appliance was either tested on main gas only or visual inspections were undertaken.

Reasons for testing on mains gas only, visual only or aborted tests include meter and flue access issues, test gas issues, unsafe situation encountered and customer inconvenience.

A small number of appliance/burner test were also reported to contain erroneous data following a data quality exercise which were subsequently removed from the final data set of results.

**Table 5** Appliance/burner test completion report

| Test result description | Appliances | Burners |
|---|---|---|
| Tested on All 3 test gases | 1280 | 1875 |
| Tested on mains gas only | 225 | 344 |
| Visual inspection only | 176 | 199 |
| Test incomplete/aborted | 63 | 63 |
| Erroneous data | 43 | 43 |
| **TOTAL** | **1787** | **2524** |

As engineering teams were operating within homes there were a number of reasons why tests were aborted, sometimes on grounds of safety, or at the request of the householder who, for example, might have had visitor arrive.

It is important to categorise properties in this way because it clarifies that individual properties did not contain substantial numbers of defective appliances that were never acknowledged, all 1787 appliances at the very minimum received a visual safety inspection that was sufficient to identify and record any underlying safety issues which were subsequently rectified.

Combustion performance can be measured in several different ways which immediately raises the issue of whether to present absolute CO emissions or $CO/CO_2$ ratios as the key performance indicator (KPI) of poor combustion.

Over the past 15 years (since the advent of portable flue gas analysers) the gas industry has moved to $CO/CO_2$ ratios as the true indicator of the quality of combustion. Thus a low $CO/CO_2$ (below KPI as defined by BS7967: 2015) indicates nearly all of the natural gas is being correctly combusted and vice versa. In this report, classification of appliance combustion is based upon $CO/CO_2$ ratios. However, it is absolute CO concentrations that cause ill-health, so this document will often refer to both values. Thus, (in the case of a small hob burner) the $CO/CO_2$ ratio may be poor (indicating either poor combustion or difficulties with flue gas sampling) but the absolute level of CO emissions (in ppm) may be extremely low, and in practice such a hob is unlikely to create a significant risk.

Figures 50 to 53 show both GS(M)R and EASEE-gas Limits as shaded areas, results from the various combustion performance tests were then grouped into a number of appliance category types and flue type to examine the effect each of the 3 test gases had on the properties measured i.e. $CO/CO_2$ Ratio and CO ppm and show the overall averages for both flued and flueless appliances.

In order to plot performance against the $CO/CO_2$ action levels, appliances were grouped into the respective burner type categories i.e. boilers with/without Air/Gas ratio control, cooking appliances by burner type e.g. Hobs, Oven, Grills etc. as action levels are specific to burner type as opposed to appliance type.

**Fig. 50** Average CO emissions vs Wobbe Index by appliance type (flued)

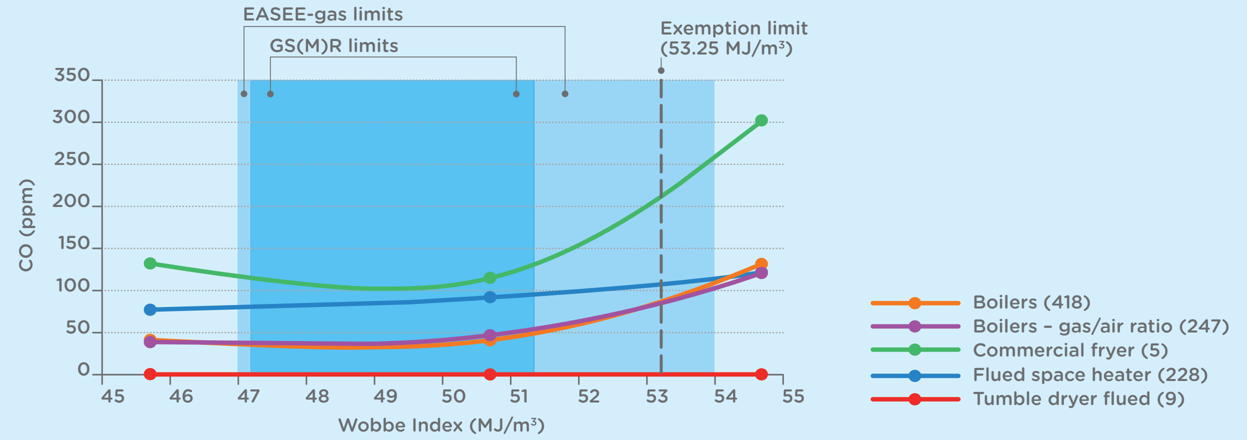


**Fig. 51** Average CO/CO₂ ratio results vs Wobbe Index by appliance type (flued)

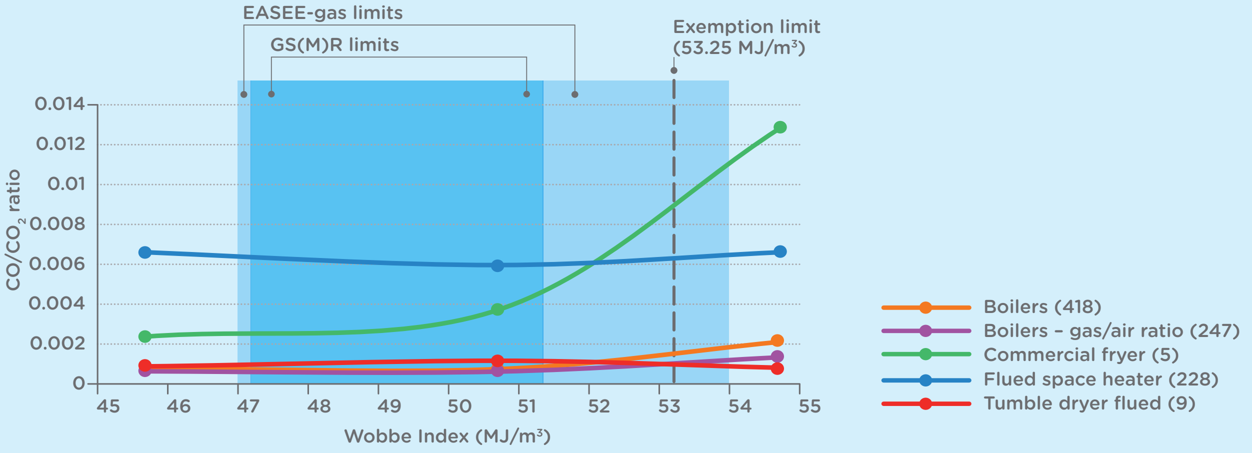


**Fig. 52** Average CO emissions vs Wobbe Index by appliance type (flueless)

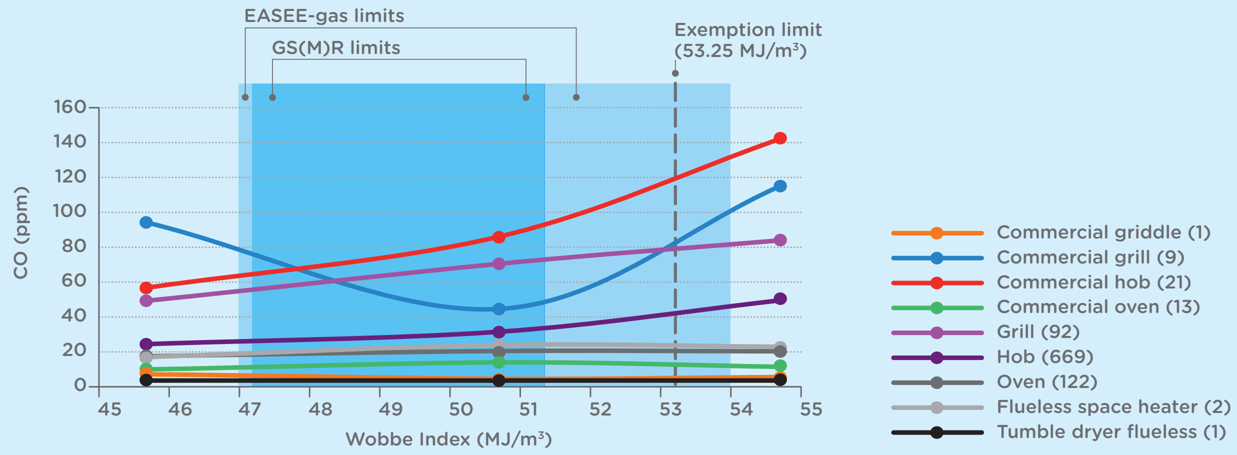
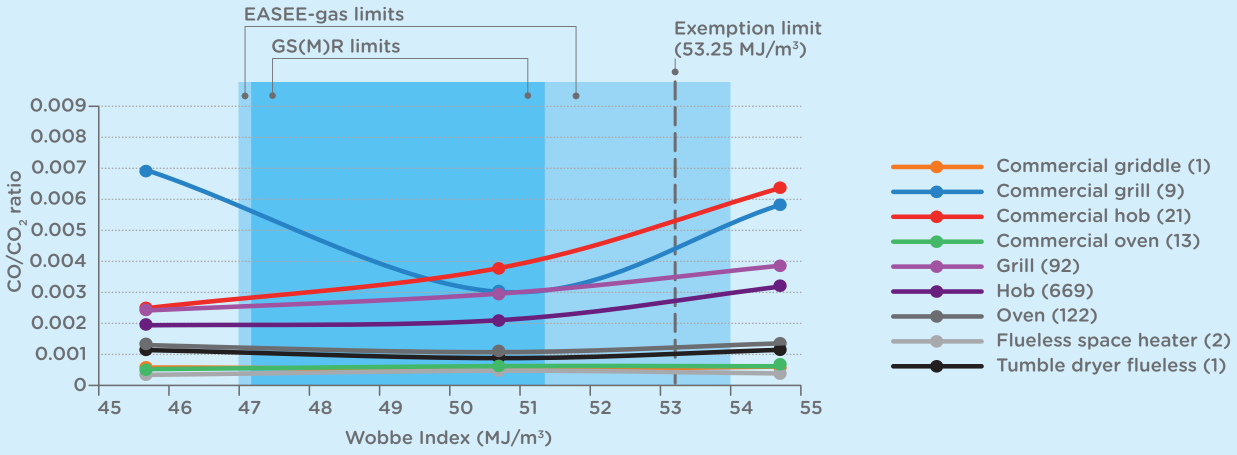


**Fig. 53** Average CO/$CO_2$ ratio results vs Wobbe Index by appliance type (flueless)



An upper WI limit of 53.25 MJ/m$^3$ allows **sufficient headroom** for any deleterious unknowns in the field condition of the appliance.

## Results and discussion *cont.*

These set of charts are subdivided further into the respective burner type categories and included in Appendix 6. Please note that those appliances which exceeded the safety action level on G20 are excluded from the charts within Appendix 6.

The results show only a small number of appliances exceeded the $CO/CO_2$ action limits on the test gases. Focusing on the upper limits only, this number reduced further when using 53.25 MJ/m³ interpolated by using a best fit curve between the test gas results for G23, G20 and G21. This is considered conservative as it was determined from the Stage 1 Laboratory testing and previous studies that the exponential increase of CO often occurs around 53.50 MJ/m³. It was important to balance the number of test gases with the required duration of the testing in customers' properties. More data points (i.e. test gases) may have been beneficial to help plot a truer 'bathtub curve', however based on the laboratory testing it was deemed unnecessary. This can be confidently reflected in the conservative interpolation.

Table 6 shows a summary of the test type undertaken by appliance burner type. It summarises the total appliances inspected, those that were tested on 3 gases/mains gas only or where only an appliance visual inspection was achievable for reasons already discussed.

The results identifying the total number of appliance burner types that exceeded the Safety Action Level on the test gas (G20), limit gases (G21 and G23) and the interpolated value for a gas at WI 53.25 MJ/m³ are shown in Appendix 7.

The most common appliance category groups are discussed individually in the following sections.

**Table 6** Summary of the test type undertaken by appliance burner type

| Appliance burner type | Tested on 3 gases | Test mains gas only | Visual inspection only | Test incomplete/ aborted | Erroneous data | Total |
|---|---|---|---|---|---|---|
| Boilers | 418 | 67 | 67 | 15 | 5 | 572 |
| Boilers (gas/air ratio) | 249 | 27 | 14 | 6 | 8 | 304 |
| Hob | 699 | 104 | 18 | 20 | 7 | 848 |
| Flued space heater | 228 | 21 | 47 | 6 | 9 | 311 |
| Oven | 122 | 18 | 4 | 5 | 2 | 151 |
| Grill | 92 | 20 | 6 | 10 | 6 | 134 |
| Commercial hob | 21 | 34 | 3 | | | 58 |
| Commercial oven | 13 | 11 | 3 | | | 27 |
| Commercial fryer | 5 | 6 | 4 | 1 | 1 | 17 |
| Commercial griddle | 1 | | 1 | | | 2 |
| Commercial grill | 9 | 20 | 1 | | | 30 |
| Commercial other | | | 4 | | | 4 |
| Commercial solid top | | 2 | 0 | | | 2 |
| Commercial stockpot stove | | 1 | 0 | | | 1 |
| Flueless space heater | 2 | | 12 | | | 14 |
| Tumble dryer flued | 10 | 5 | 5 | | 4 | 24 |
| Tumble dryer flueless | 1 | | 1 | | | 2 |
| Warm air heater | | 2 | 3 | | | 5 |
| Water heater flued/flueless | 5 | 6 | 6 | | 1 | 18 |
| **TOTAL** | **1875** | **344** | **199** | **63** | **43** | **2524** |

### Gas boilers

Boiler test

876 boilers and water heaters were inspected, of which 80% were room sealed (i.e. ventilation and flueing is sealed to the external of the property). Historically, it has been shown that for these type of appliances to cause harm the level of CO within the flue gases has to rise to several thousand ppm; this is because the risk only arises from flue gases re-entering the property through windows or air vents as inevitably this causes very substantial dilution. This is different to an open flued device where an ineffective flue (caused by either a physical blockage or local atmospheric conditions) can cause discharge of all of the flue products directly into the property.

Having been correctly adjusted with a 'standard gas' (G20) all of these room sealed boilers will operate safely on WI up to 53.25 MJ/m$^3$ and down to about 48.00 MJ/m$^3$ (refer to Appendix 6). This does however leave the 20% of open flued boilers the overwhelming majority being old or almost certainly of poor efficiency. Prior to about 2005, these were a major contributor to CO incidents, primarily through blocked flues. Fortunately, the absolute level of CO in the flue gas from most of these boilers is little affected by increasing WI.

Of the 876, 37 (including 11 open flued) were reported as having a potential flue fault, although these would be unlikely to materially increase CO concentrations in the property. These were:

- A room sealed combi (Property No (PN) 7349), with a burner control fault being room sealed, is unlikely the combi offered a risk to the householder.
- Two open flued (PN 7206 and 7069) that needed replacing. These two elderly open flued boilers offered a real risk to the householders. In one property the CO alarm had been alarming, yet was ignored by the occupants. It is recommended that these types of appliances are best replaced.

Thus the boilers that offer the highest uncontrolled CO emission and risk to occupants, about 0.40% of the boiler population could be reduced by servicing or (especially in the case of elderly open flued boilers) eliminated by replacement.

### Local space heaters

Local space heater test

The flue type of these appliances is almost the reverse of boilers with about 90% being open flued. There were 325 local space heaters (gas fires or similar), of which 18 were room sealed, plus another 5 fan flued. 16 (of the total) were listed as having a flue fault and two were also recorded as having high CO with G20, although the actual CO concentration at about 600 ppm (as measured) was still less than that permitted by the appropriate appliance EN standard (refer to Appendix 6). 12 had a problem associated with the flue and 22 due to ventilation, although particularly in the case of the latter, many of these may not in practice be significant. One fire (Property No 7479) had a broken glass side panel, as did another fire which although not included in this list, it had been visited during the initial assessment of 100 properties and was removed. Analysis of the test results identified 8 gas fires (PN 7737, 7479, 7245, 6991, 7773, 7510,7375, and 7654) that appeared to have issues however, only 4 (PN 7737, 7510, 7215 and 7375) was related to combustion. These 4 appliances represent 1.2% of the total gas fire population.

Similarly, to open flued boilers by nature of the combustion they are less sensitive to changes in WI than (for example) condensing boilers, but inevitably there is a greater risk of flue gases entering the living space than with a room sealed product in the event of a blocked or poorly performing flue however since 1996 all open flued products are fitted with ASD's, which will protect consumers in the majority of circumstances.

These appliances should also be serviced at appropriate intervals.

### Warm air heaters

Only 5 appliances were inspected, 3 of which had pre-existing faults however none of which were related to combustion.

### Grills

Of the 134 domestic grills inspected, 10 exceeded the safety action level on G20, this increased to 13 on G21 and fell to 7 on G23. 18 grills showed suspect flame pictures with G20 and 16 with G21. This discrepancy can be explained due to the gas operatives testing with G20 first and it is known that CO concentrations fall as the grill becomes hotter. Two of these grills (PN 7065 and 6885) had CO concentrations around 2500 ppm and one (PN 7630) about 6500 ppm all of which were eye level grills.

The above 3 grills tested initially on G20 only as further tests were then aborted.

### Hobs

Hob test

848 hobs were inspected of which 38 were regarded as giving unsatisfactory combustion on G20. 57 exceeded the action levels on G21, falling to 26 on G23. However it is known to be difficult to take quality samples from some hobs, hence the adoption of flame picture to judge combustion as mentioned in BS 7967:2015. CO Incidents from hobs are known to be rare and almost always related to vitiation due to excessively large pans. It is suspected many of the apparently high values for $CO/CO_2$ ratio from the field data are as a result of sampling difficulties, but there are also a number of burnt out or damaged hob top plates that needed replacement. Identified PN's included 7079 (by two), 7063, 7016, 6885, 7289, 7630 (by two), 7407 (by four), 7107, 6931, 7439 and 7472.

### Ovens

151 ovens were inspected, 3 exceeded the action limit on G20 and 5 on G21 with respect to $CO/CO_2$ although in reality probably only 2 (PN 7570 and 6805) of the five gave any cause for concern the others being sampling issues (refer to Appendix 6). Thermostatically controlled gas ovens are again very rarely a cause of CO poisoning. Incidents are nearly always as a result of food blockage of the combustion ports.

### Commercial catering

141 commercial catering burners were inspected, of which one Fryer (PR 7404) was Immediately Dangerous due to the flue ways being soiled heavily with soot. One Salamander with two burners (PR 7359) had high levels of CO, although the reasons were not clear (refer to Appendix 6). Another 3 burners were categorised as At Risk but not for combustion related issues. Many of the appliances had technical infringements of the ventilation standards. None of these appliances would be materially affected by a modest increase in WI.

## Other results and discussions

### Burner safety sensitivity analysis

It is convenient to discuss relative safety of an appliance in terms of its positioning on Figures 54 and 55. The charts are spilt into 3 zones, green, amber and red. An appliance that is positioned in the green shaded area is considered to be acceptable, could be considered at risk if positioned in the amber area and immediately dangerous if in the red area. The red, amber, green sections have been derived based on the CO concentration factor and the time element detailed in Appendix 8 taken from BS 7967 Part 5 (2010)[42].

These charts plot the change in CO emissions from G20 when increased to 53.25 MJ/m³ (note the value at 53.25 MJ/m³ being derived by interpolation using a best fit curve between the test gas results for G23, G20 and G21). The x-axis displays the concentration of CO recorded on G20. The y-axis displays the factor of change in CO concentration as a ratio between the values at 53.25 MJ/m³ to that recorded using G20.

- Appliances results located at the bottom left corner pose the least risk. These have low levels of CO (most frequently less than 200 ppm) and changing to 53.25 MJ/m³ only increases this value by a small multiplier i.e. their performance is relatively independent of WI.
- Those in the top left have required further analysis. Absolute CO concentrations even after changing to 53.25 MJ/m³ are low as the initial value is low, but this increase may show that the

**Fig. 54** Flueless appliances 53.25/G20

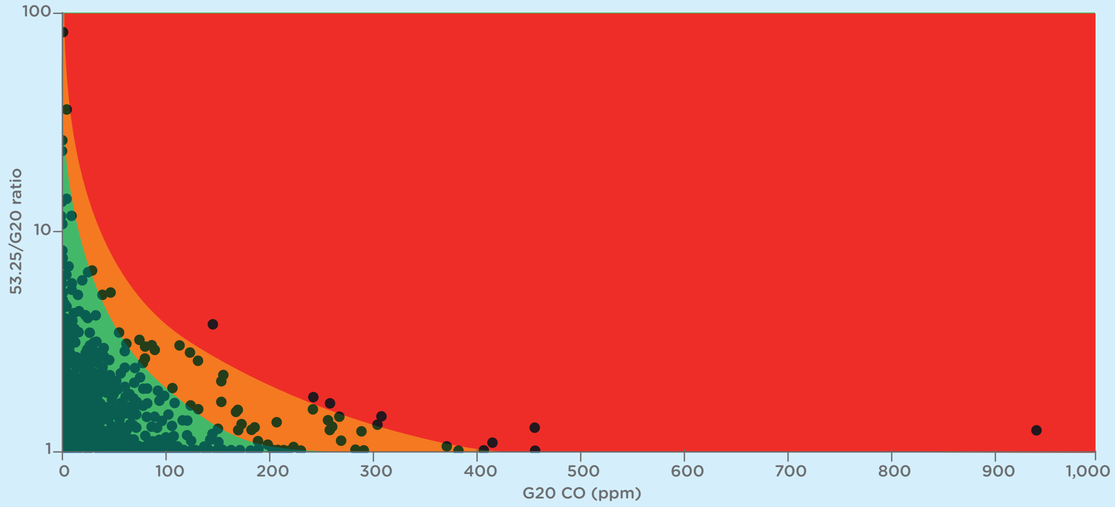
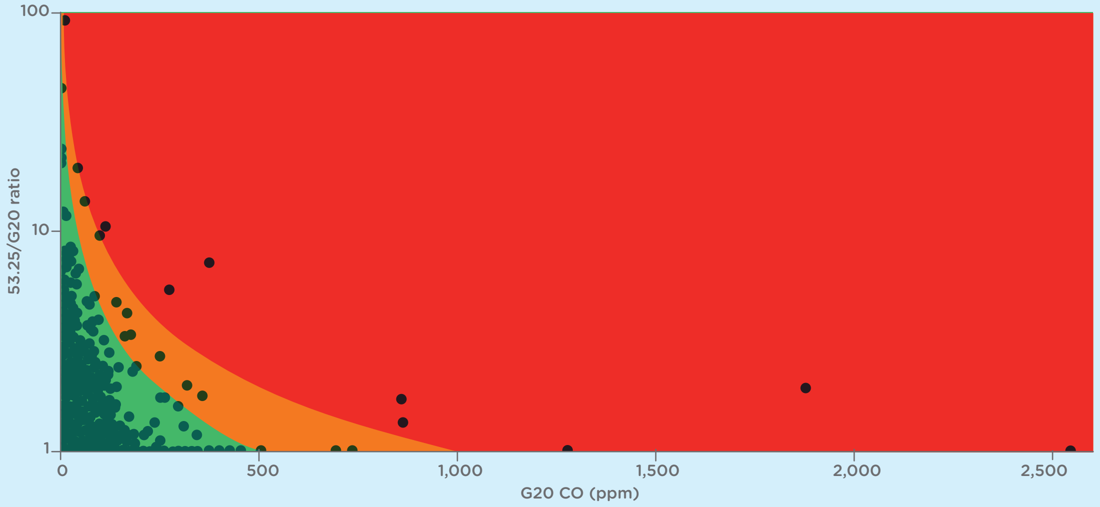


**Fig. 55** Flued appliances 53.25/G20



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[42] BS 7967-5:2010 'Carbon monoxide in dwellings and other premises and the combustion performance of gas-fired appliances. Guide for using electronic portable combustion gas analysers in non-domestic premises for the measurement of carbon monoxide and carbon dioxide levels and the determination of combustion performance', September 2010.

CO campaigns that focus **solely on CO alarms** are not the most effective means of reducing CO risk.

appliance is becoming sensitive to gas WI or might be due to factors such as age or indicate lack of servicing or combination of both.
- Those in the top right would offer most concern for safety. However as illustrated in all these charts, there are currently no appliances in the Oban population that have fallen into this area.
- Those in the bottom right would offer some concern, but the change in gas WI has had little impact on the CO emissions. Indicate they already have CO concentrations higher than typical although this may still be less than those permitted by $CO/CO_2$ safety action levels. Again poor combustion performance may be due to factors such as age or indicate lack of servicing or combination of both.
- Domestic flueless appliances always have low gas input rates so the volume of flue gas and hence total CO is low. This will result in low CO concentrations in the room.

The flued data was then separated into flue type categories i.e. Room sealed and Open Flued as shown in Figures 56 and 57. It can be seen although open flued appliances tend to result

**Fig. 56** Room sealed appliances 53.25/G20

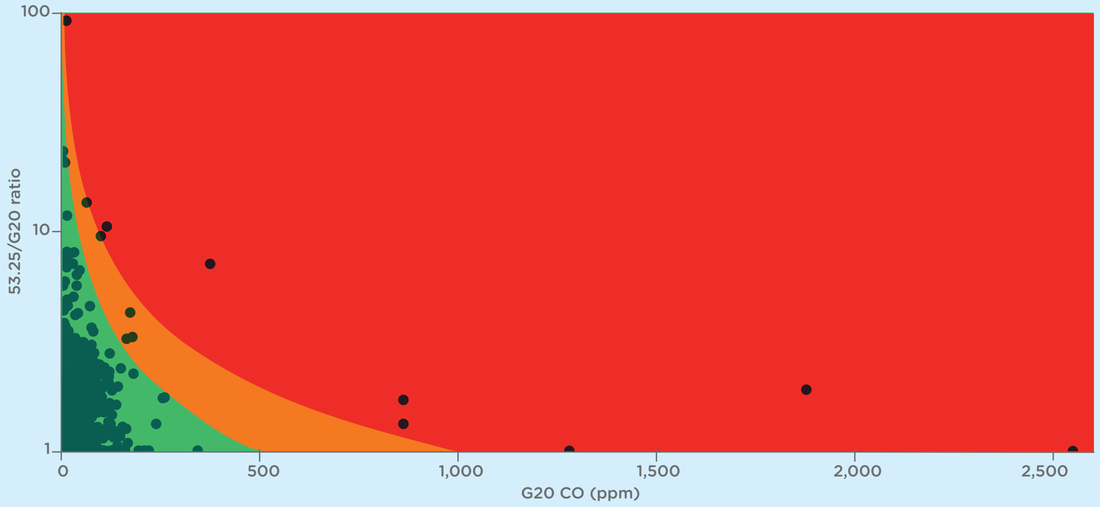
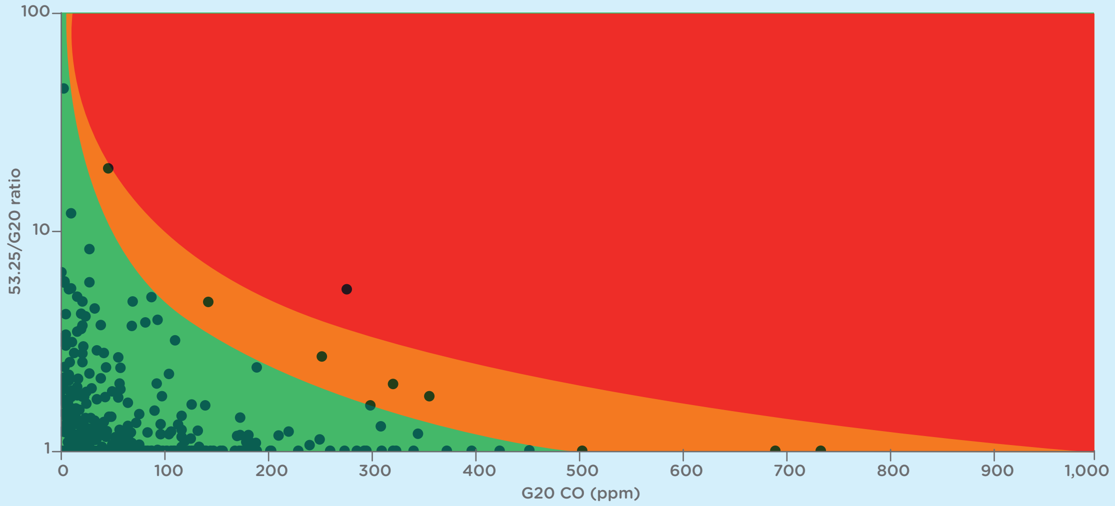


**Fig. 57** Open flued appliances 53.25/G20



a greater number of higher CO readings on G20 (shown by the points further right on the x axis) than for room sealed appliances, the effect of increasing the WI to 53.25 MJ/m³ shows that generally CO increases much less for open flued appliances when compared to room sealed appliances. In other words, room sealed appliances are more sensitive to higher WI however, room sealed are considered less of a risk to an occupant due to the fact they are by definition 'room sealed'. Further analysis by flue type is shown in Appendix 10 to illustrate that the vast majority of appliances are not materially impacted by a change in WI.

### Analysis of burners outside the safe zone

Table 7 summarises the flued and flueless Appliance burners falling in the red zone. In the case of the flued appliances the majority of these were combination boilers or Regular System boilers and were corrected by servicing, replacement parts or boiler.

Flued appliances where the flues are in good working order, any products of combustion are safely transported to outside the building however by nature in the case of flueless appliances these products are dispersed directly into the room the appliance is installed.

To take further steps into the understanding of whether the above flueless appliances would still lead to dangerous situation it is necessary to take into consideration a number of other key factors:

- Gas flow rate of appliance
- Concentration of CO in the flue gases
- Volume of the room
- Room ventilation rates
- Occupancy/exposure time in the room

**Table 7** Details of appliance burners in the red zone

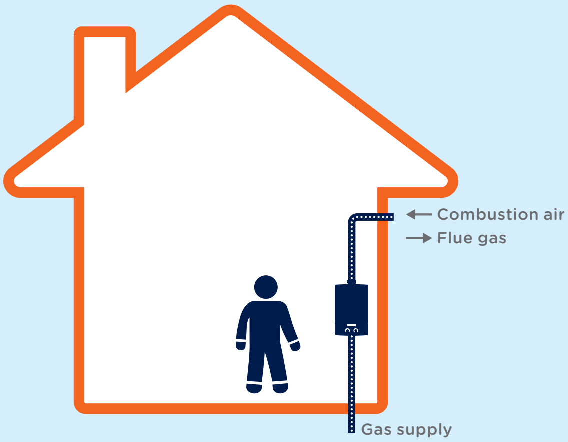
| Burner ID | Appliance category | Appliance type | Burner category | Flue type | Appliance condition |
|---|---|---|---|---|---|
| 14426 | Central heating boilers | Regular/system – non-condensing | Boilers | Open flued | Good |
| 15774 | Central heating boilers | Combination boiler | Boilers (gas/air ratio) | Room sealed | Good |
| 15582 | Central heating boilers | Regular/system – non-condensing | Boilers (gas/air ratio) | Room sealed | New |
| 15060 | Central heating boilers | Combination boiler | Boilers | Room sealed | Fair |
| 15447 | Central heating boilers | Combination boiler | Boilers | Room sealed | Good |
| 14690 | Central heating boilers | Combination boiler | Boilers | Room sealed | Fair |
| 14719 | Central heating boilers | Regular/system – non-condensing | Boilers | Room sealed | Good |
| 15452 | Central heating boilers | Regular/system – non-condensing | Boilers | Room sealed | Fair |
| 15300 | Space heating | Radiant | Flued space heater | Room sealed | Fair |
| 15819 | Commercial cooking | Salamander | Commercial grill | Flueless | Poor |
| 15120 | Domestic cooking | Built in hob | Hob | Flueless | Fair |
| 15719 | Domestic cooking | Built in hob | Hob | Flueless | Fair |
| 14810 | Domestic cooking | Built in oven | Grill | Flueless | Good |
| 14414 | Domestic cooking | Built in oven | Grill | Flueless | Fair |
| 14315 | Domestic cooking | Cooker – eye level grill | Hob | Flueless | Fair |
| 14760 | Domestic cooking | Cooker – slot In | Hob | Flueless | Good |
| 14513 | Domestic cooking | Cooker – slot In | Grill | Flueless | Good |
| 13738 | Domestic cooking | Cooker – slot In | Oven | Flueless | Poor |
| 15321 | Domestic cooking | Range | Hob | Flueless | Poor |

**Fig. 58** Typical flueless appliance

Flueless appliances have small gas input rates. They have simple very clean combustion. A hob may only produce 0.1$m^3$ of $CO_2$ per hour. This is only 0.001$m^3$ of CO. Hobs are typically used for less than half an hour. In even a small kitchen of 30$m^3$ values are much less than the HSE limit of 30 ppm for 8 hours or 200 ppm for 15 minutes.

Only the smallest intermittently used appliances do not require permanent ventilation, most require a vent or an openable window. This ensures that the air in room changes regularly and that even the very small quantities of CO formed can never build up.

**Fig. 59** Typical room sealed appliance

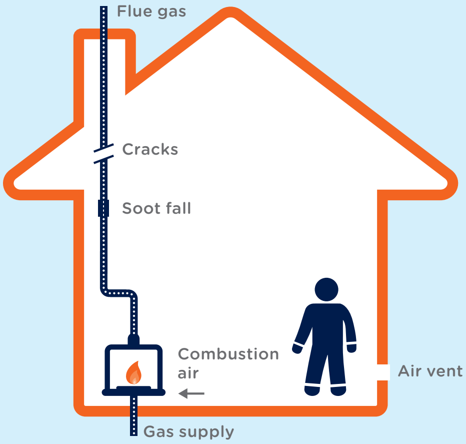


Room sealed appliances such as combination boilers discharge all products of combustion to outside.

Concentration of CO in flue gas has no relationship with CO in the room.

As flue is typically concentric within the combustion air supply it is very difficult for fumes to escape the room unless there is a fault with the flue.

**Fig. 60** Typical open flued appliance



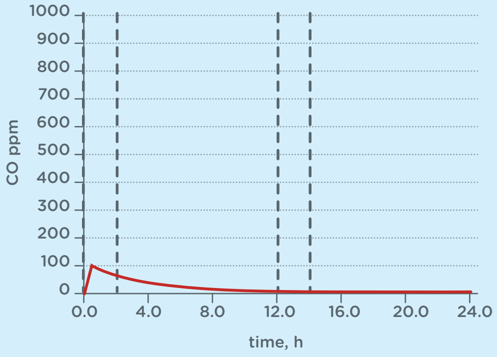
Open flued appliances such as local space heaters take their combustion air from inside the room and discharge the products of combustion to outside via a flue.

There is an extremely small risk of cracks in the flue or a soot fall blocking the flue. Since 1996 all new open flued gas appliances must have an ASD (Atmosphere Sensing Device) that is checking for this and will turn off the appliance if it occurs. In GB this is typically an ODS (Oxygen Deficiency Sensor).

This was accomplished by development of a CO exposure model in order to aid assessment of the risk posed by an appliance emitting flue gases containing a given level of CO. The principles behind and details of the CO exposure model are described in Appendix 9.

**Model testing on poor performing grills**
One of the poorest condition appliances encountered during stage 2 was a grill that had a CO emission of 2500 ppm on G20. Grills are rarely used for more than 30 minutes at full output and are even less likely to be used at more than 2kW levels for this period. Figure 61 is an extract from the CO exposure model for this grill.

**Fig. 61** Example exposure model concentrations



The model predicts that for a grill with a net heat input of 2kW producing CO of 2500 ppm, operating for 24 minutes in a room of $17m^3$ with a room air change rate of 0.25 air changes per hour, will only give a peak CO reading of 100 ppm (i.e. less than half of the HSE 15 minute exposure limit) and an average CO of 74 ppm (if door left closed). In practice a kitchen door or window is likely to be opened and additional air changes will occur.

It should be noted that the grill fatalities that have occurred in the recent past (due to poor appliance design) have arisen from grills producing an estimated 25,000 ppm of CO. Although appliances can produce CO levels in excess of the safety limit when applying these to the model using the most conservative figures for the other variables such as ventilation and periods of exposures it can be seen that the maximum level in the room is far lower than that recorded by the appliance and well below a level that could create a risk.

**Confirmation of upper WI limit**
The stage 2 field tests confirmed the findings observed during the stage 1 laboratory tests that all domestic and small commercial appliances, correctly installed, serviced and operated can safely burn gas with a WI of up to 54.76 $MJ/m^3$.

Stage 2 however identified a number of appliance installations with pre-existing faults and issues. This supports the application of headroom to account for deleterious unknowns in the field condition of appliances and thus supports the proposed upper WI limit of 53.25 $MJ/m^3$.

# Conclusions

The main conclusions from stage 2 are:

1. Using Oban as a statistical representation of GB, it is estimated that 4% of the GB appliance population would be classified as ‘at risk’ against the Unsafe Situations Procedure currently.
2. Using Oban as a statistical representation of GB, it is estimated that 2% of the GB appliance population would be classified as ‘immediately dangerous’ against the Unsafe Situations Procedure currently.

Stage 2 also further confirmed the two main conclusions drawn from stage 1:

1. Domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 MJ/m$^3$.
2. An upper WI limit of 53.25 MJ/m$^3$ allows sufficient headroom for any deleterious unknowns in the field condition of the appliance.

# Field trial

# Overview

The objective of stage 3 field trial was to:

- Demonstrate whether gas that meets EASEE-gas specification but sits outside GS(M)R can be conveyed safely and efficiently in the GB gas network;

This would be achieved by injecting alternative LNG sources with a WI higher than currently permitted under GS(M)R into the Oban network for a trial period of one year. One predominant source would be used throughout the trial period with two additional sources of higher WI trial at later stages in the trial. Prior to commencement it was necessary to complete a number of enabling activities that related to the establishment of legal permission to permit non-compliant gas into the network, contractual arrangements with a gas shipper and a review of the logistics associated with the transportation of LNG.

Permission to convey non-compliant gas was sought through the HSE by means of a GS(M)R Exemption application including a Quantitative Risk Assessment each of which building on the evidence acquired from stages 1 and 2 of the project.

On Monday 6th July 2015 at 8.05am, SGN made GB gas industry history by injecting the first load of non-GS(M)R compliant gas from Zeebrugge, into the Oban network.

# Enabling activities

**National stakeholder engagement**
Key to the success of the project has been stakeholder engagement, knowledge sharing and dissemination. Stakeholders at a national level were engaged throughout the project to ensure results were disseminated nationally on an ongoing basis.

The primary national stakeholders included Ofgem, the GB energy regulator, the Health and Safety Executive (HSE), who enforce GS(M)R, (from which approval for an exemption from legislation would be necessary to allow the injection of the new gas into the network), and the Department for Energy and climate change (DECC), subsequently BEIS. Regular interface meeting were held with each stakeholder.

A technical stakeholder group with industry-wide representation was also set up to support the project and the case for future GB roll out. Participants of the technical stakeholder group included:

- Department for Business Innovation and Skills (BIS)
- Department for Energy and Climate Change (DECC)
- Energy Networks Association (ENA)
- Heating and Hot Water Industries Council (HHIC)
- IGEM
- KIWA
- National Grid
- Northern Gas Networks
- Ofgem
- Wales and West Utilities

A ‘dissemination by design’ approach ensured all sectors of the gas industry and supply chain locally, nationally and internationally were engaged.

The dissemination activities have led to numerous successful outcomes, such as further laboratory testing, advising the EU and DECC on CEN234 standard, securing future supplies for the SIUs and establishing an IGEM Gas Quality Working Group to consider the appropriateness of the proposed WI within GS(M)R.

The project team completed over 20 presentations to stakeholders to disseminate findings. These have included local stakeholders in Oban itself, industry experts at national conferences, as well as a number of international events. An end of project dissemination event is planned for October 2016 and it is intended that all areas of the gas industry are represented at this event.

The majority of key dissemination activities took place from the end of Stage 2 onwards, after a substantial volume of results had been obtained. Table 8 gives details of key dissemination activities.

**Installation of a gas chromatograph**
Oban SIU regasification plant has a gas chromatograph that monitors the gas quality at Oban. This gas quality check was, prior to the field trial, used to reference the gas quality in the other three mainland SIUs (Campbeltown, Thurso & Wick). This was possible as all four received their gas from a single source, i.e. Avonmouth liquefaction plant. Due to the fact that the field trial would mean a new gas source for Oban whereas the other three would continue to be supplied from Avonmouth, a new gas chromatograph required to be installed at another SIU site prior to the commencement of the trial. This chromatograph would act as the new reference device for the other 3 SIUs. Thurso was chosen as the location to install this new gas chromatograph.

The construction programme went through the full design and appraisal process and the device was commissioned in June 2015.

Chromatograph installed in Thurso

**Table 8** Overview of stakeholder engagement and dissemination activities

| Date | Stakeholder | Description of engagement | Outcome |
|---|---|---|---|
| June 2015 | IGU & WGC Delegates | The project was the winner of the IGU Global Gas Award, winning from over 500 worldwide entries. As part of the prize, the Project Director presented a keynote speech on the project to over 5000 delegates from over 100 countries. | Details of project were disseminated to international audience. |
| June 2015 | HHIC, Worcester Bosch, BAXI and other key appliance manufacturers | A technical presentation was given to the HHIC and gas boiler manufacturers, including Worcester Bosch and BAXI, on the project progress. The results up until that point were discussed and the plan for GB roll out was outlined. | Appliance manufacturers helped shape subsequent 'special' laboratory appliance investigations. |
| August 2015 | Fluxys | A meeting was held to discuss how Oban SIU operates & meet new key stakeholders. | Knowledge was shared with Fluxy's on how to operate small scale regasification plants. |
| September 2015 | IGEM | A presentation was given on the Stage 2 results and the procedures put in place in preparation of Stage 3. | Knowledge was disseminated to an audience with a cross representation of the gas industry. |
| October 2015 | IGEM | An article was published in the IGEM Gas International News on the success of the project following completion of Stage 2. The article outlined the procedures carried out in each stage and the findings so far. | Knowledge was disseminated to an audience with a cross representation of the gas industry. |
| November 2015 | PRASEG | The Project Director presented at the PRASEG 'Future of Gas' event on OGM. Key stakeholders who were present included DECC, National Grid, ENA and UCL. | Project objectives was disseminated to key parliamentarian stakeholders. With support advocated by MPs in audience.<br>The learning dissemination here generated a lot of interest on social media. A key discussion following the presentation was regarding 'customer choice', which often gets missed in the energy trilemma debate and the key to the Oban project is about providing flexibility. |
| November 2015 | EON | Project Manager and Project Officer met with EON to discuss findings from OGM and a similar project being undertaking in Germany on Hydrogen. | SGN advised EON on successful customer engagement activities. The issue of adjustable boilers was discussed. |
| November 2015 | ENA & LCNI Conference delegates | The project team attended the LCNI 2015 conference in Liverpool. The Project Director gave a keynote speech on the OGM Customer Engagement and the Project Manager discussed the OGM Project results at the Gas Futures seminar. | Knowledge sharing with a relevant group of industry stakeholders. |
| November 2015 | Marcogaz and DVGW (German Technical & Scientific Association for Gas and Water)<br>(Brussels) | The EU gas quality working group met for a brainstorming session in Brussels to discuss the launch of EU Gas Quality Harmonisation Pilot. Attendees included, DECC, National Grid and Dave Lander Consulting. | Oban results were used to help shape future EU gas quality pilot. |

**Table 8** Overview of stakeholder engagement and dissemination activities (continued)

| Date | Stakeholder | Description of engagement | Outcome |
|---|---|---|---|
| December 2015 | DECC | A Gas Quality Meeting to discuss requirements for a GB roll out with HSE, IGEM, Ofgem and DECC. The group agreed GB's changing gas mix, in particular future predictions regarding increased imports of LNG, the use of shale as well as European standardisation plans provide compelling reasons to examine the gas quality question. | It was agreed that domestic evidence would help shape GB's position in Europe. |
| January 2016 | Worcester Bosch | Project Manager and Project director met with the manufacturer to discuss gas quality and the impact of OGM to appliance manufacturers. Focused on Wobbe, how it could vary, and what effects that may have on long term performance of gas boiler. | A subsequent boiler laboratory test programme was agreed and undertaken by Kiwa to investigate if an increase in WI does not affect the longevity of an appliance. |
| March 2016 | IGEM, DECC, Ofgem, HSE | Project Manager and Project director attended a meeting to discuss the further roll-out of the OGM project into the other SIUs, and how to consider amending GS(M)R to allow a GB roll-out. | It was agreed to form a working group to look to move GS(M)R into an IGEM standard. |
| March 2016 | DECC Heat Team | Project Manager gave a presentation on the benefits of the OGM project and how its success has impacted on other large-scale projects, such as SGN's new Real-Time Networks NIC project. | DECC heat team aware of project and have a deeper understanding. |
| March 2016 | Joint Office Shrinkage Forum | Project team contributed to a presentation on the impact of OGM and a wider discussion on energy delivery capacity and network pressures. | Provided gas shippers with understanding of project. |
| March 2016 | HHIC | Project manager attended a meeting to provide a detailed update on the project, including results seen so far. The meeting also discussed how the OGM project has allowed for a rollout into the SIUs. | Appliance manufacturers donated appliances to undergo component life testing at Kiwa laboratory. |
| March 2016 | Utility Week Future Energy Conference | SGN's CEO presented on OGM and making the gas network more flexible. | Project knowledge disseminated to a wide range of influential stakeholders. |
| April 2016 | IGEM and National Grid Transmission | Project Manager and Project Director attended a meeting to discuss the process of the OGM project and the impacts on the National Transmission System. | National Grid Gas Transmission offered to participate in IGEM working group tasked with changing GS(M)R. |
| May 2016 | IGEM and Northern Gas Networks | Project officer gave presentation on the project, an overview with details of the project process, results and next steps. | Greater understanding of project in IGEM's Northern Section. |
| May 2016 | Utility Week Live | Project Director gave presentation on the project, an overview with details of the project process, results and next steps. | Project knowledge disseminated to a wide range of influential stakeholders. |
| May 2016 | Energy Select Committee | SGN's MD Scotland and Director of Stakeholder Relations discussed OGM with MPs Angus MacNeil (Chair of Energy Select Committee and MPs for Stornoway) and Brendan O'Hara (MP for Oban). | Project knowledge disseminated to influential stakeholders. |

## Quantitative Risk Assessment

A key task to support the HSE Exemption was the Quantitative Risk Assessment (QRA). This assessment was conducted by DNV GL using results from stages 1 and 2 and determined the change in risk associated with transporting gas with WI outside those currently allowed by GS(M)R.

Risk was estimated using a fault tree approach[43], and examined the risk associated with CO and changing the acceptable gas quality compared against current baseline risks where risk was defined as the number of fatalities per million people per year.

The fault tree method provides a structured approach to the QRA process. It provides a mechanism to highlight the potential impact and includes factors that may lead to that impact.

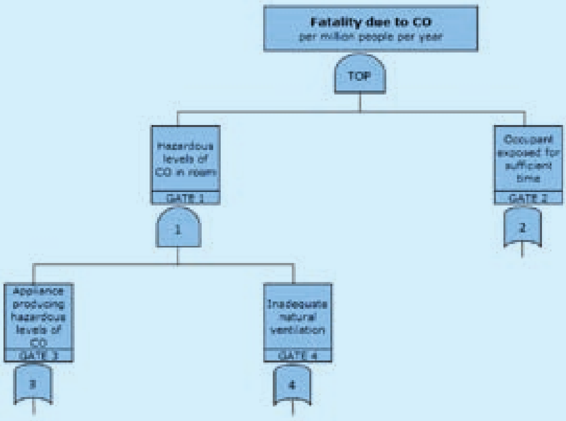
The approach uses a Boolean system where factors can be combined to provide pathways for coupled effects that can give rise to a specific event or fault. These 'Gates' are 'AND' or 'OR' gates and represent factors that require single or multiple actions to have an overall effect. 'NOT' gates determine the probability of an event not occurring. In general, single event pathways lead to higher levels of risk whereas factors that require combined or multiple events tend to have lower risk ratings.

**Fig. 62** Fault tree gates

The fault tree developed attempts to provide an overview of the factors or topics that could influence a CO poisoning event. For demonstration purposes the fault tree has been broken down into several components in the following sections.

## Part 1 – CO incident

**Fig. 63** Fault tree section 1



The top level of the fault tree is 'Fatality due to Carbon Monoxide Poisoning'; the events underneath this top level consist of the individual incidents which may or may not lead to a fatality.

In the first section of the fault tree, the top level impact 'Fatality due to CO Poisoning' has two factors:

- High CO concentration within the room.
- An occupant that is exposed to that high concentration for sufficient time to cause injury.

These factors are not fully independent as CO poisoning has a concentration/exposure time relationship due to the accumulation of carboxyhaemoglobin (COHb) within the blood stream when the occupant is in an environment containing CO.

The concentration of CO in the room is dependent on two factors:

- A source of CO – assumed to be from domestic appliances present in the room.
- Ineffective removal of CO through natural ventilation.

These relationships provide a basis on which the potential risk of a CO incident may arise.

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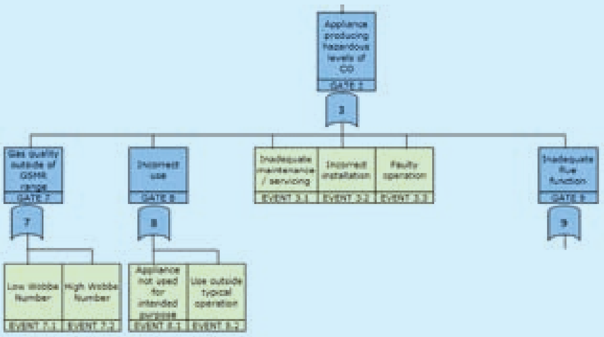
[43] 'FaultTree+' software package (V11.2.3), Isograph Ltd.

### Part 2 – Appliance producing high CO concentration

**Fig. 64** Fault tree section 2



In Figure 64, the fault tree branch related to the domestic appliances producing hazardous CO concentrations is considered. There are several factors and mechanisms that could give rise to high emission rates of CO and these include:

- Gas quality outside of the normal range – both high and low WI gas may give rise to increased CO concentration in the flue gas products. The response of the appliance to change in gas quality is dependent on several factors, including appliance design, burner-type and overall operation.
- Incorrect use – Here it is recognised that sometimes appliances are not used for the purpose they were designed for. The most common 'Incorrect Use' is for the cooker/hob to be used for space heating – often correlated with specific demographics. The other instance is when the appliance is used in a way that is not typical and outside of its normal mode of operation. A recent survey in Oban found that a cooker burner was producing high CO concentration as a result of an oversized pan on the hob giving rise to excessive flame quenching and restriction of secondary air.
- Incorrect installation – If an appliance has not been installed correctly then it may give rise to increased CO emissions. This factor is thought to be significant for boilers, water heaters and space heaters, but not cookers/hobs.
- Faulty operation – If the appliance develops a fault that does not render it inoperable then this may give rise to increased emissions
- Age of the appliance – It is known that general 'wear and tear' through ageing of the appliance may impact on the overall combustion performance, and may give rise to elevated CO concentration in the flue gas products.
- Inadequate maintenance/servicing.
- Inadequate flue function

### Part 3 – Inadequate ventilation

**Fig. 65** Inadequate ventilation

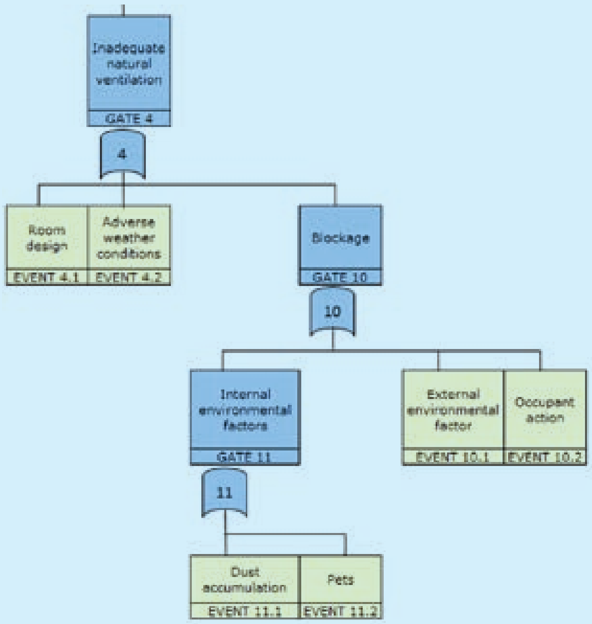


Figure 65, develops the Fault Tree approach focussing on inadequate ventilation and the factors that may give rise to increased CO production potential. These include:

- Room design – This category endeavours to cover specific aspects related to the building and the room containing the appliance. An example of the effect could be if a property has been extended and the ventilation for the appliance has not been taken into consideration during the building work. This could give rise to restricted ventilation.
- Blockage – The combustion air required for correct appliance operation could be restricted due to blockage of either the main room vents (air bricks) or the air intake for the appliances. These effects are appliance-type dependent and the impacts are greatest when the appliance draws its combustion air from

Increasing the WI to 53.25 MJ/m³ has **negligible impact** on the efficiency, performance and life of domestic or small commercial appliances.

the room containing the appliance. 'Linting' of some appliances, especially Back Boiler units is a known issue and lint screens can become clogged by pet hairs or general household detritus. External factors can also lead to vent blockage. Grilles can become blocked through accumulation of leaves or waste, and ivy growing up walls can also lead to vent blockage. An additional cause of air vent blockage is the deliberate action of the occupant. Vents are often deemed to be sources of cold-air draughts and in some cases are blocked by the occupant – either temporarily or permanently. Also, natural room ventilation through suspended floors (ventilated under the floor) can be restricted through floor covering type. Vinyl flooring is known to inhibit fortuitous underfloor ventilation.

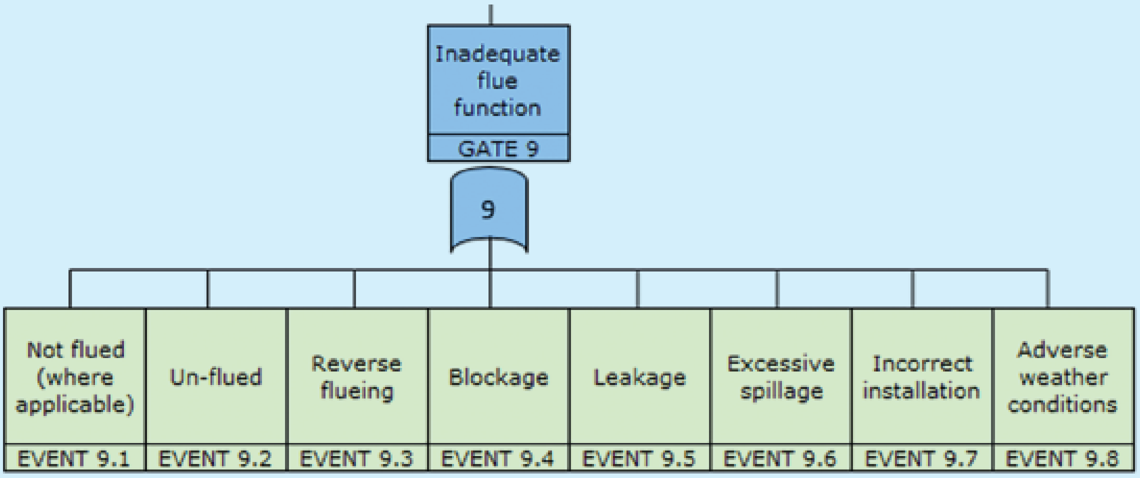
- Adverse weather conditions – Strong winds impacting directly on flues may prevent CO being removed from the room.

For commercial equipment, factors that can impact on operation and give rise to potential risk include:

- Evidence that the ventilation system is not used or is unreliable.
- Small room volume.
- Obvious poor design/maintenance of the ventilation system (long, convoluted ducts, broken fans, leaking ductwork, visible escape of cooking fumes/steam etc).
- Lack of user awareness of the effect of using gas appliances without adequate ventilation.
- Poor general ventilation.
- Extensive use of gas-fired appliances for long periods.
- Ageing system/installation.
- Lack of routine or planned maintenance.

**Part 4 – Inadequate flue function**
In Figure 66, a similar approach to ventilation is applied to the flue function. Some appliances are unflued and are expected to discharge combustion products into the room volume. This links with the ventilation aspect as sufficient ventilation is required to not only provide the combustion air but also dilute the combustion products. The frequency of these events found during the project was taken into consideration in the overall risk calculations.

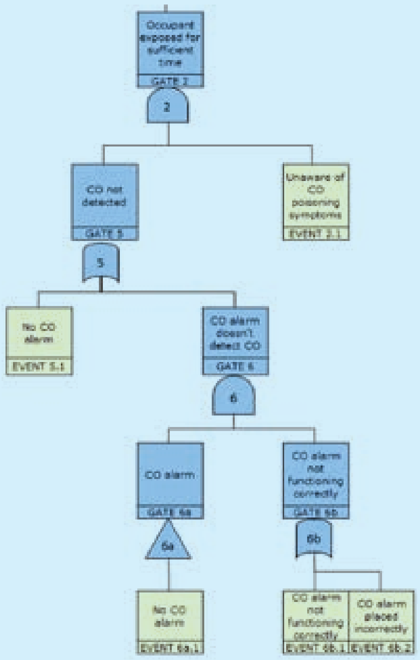
**Fig. 66** Inadequate flue function



- Incorrect installation – If the flue has not been installed correctly then it may discharge into the dwelling, possibly not in the room where the appliance is located. Long flues in roof voids (often between floors in flats, apartments or tenements) may not be installed correctly and the flue sections may separate as the flue expands – leading to potential discharge of combustion products in the dwelling.
- Reverse flueing – This is generally a result of two appliances requiring combustion air from the same room volume, and this may have been caused by internal knocking-though. An example could be a boiler and gas fire, each with its own flue, but the boiler flue may be dominant. Here, if sufficient natural ventilation is not available then the boiler may draw 'air' (and combustion products) down the flue from the gas fire and into the room. This 'reverse flue' effect can result in high CO concentrations within the room volume.
- Flue blockage – If the flue is blocked or partially blocked then this may result in combustion products being discharged into the room volume. The blockage may be from birds' nests or vegetation (ivy, leaves or other material), from general household waste, or from damage to the flue terminal.
- Flue leakage – If there is general 'wear and tear' then the flue may leak in the dwelling. An example of this may be unlined flues in traditional chimneys. Here the older brick type flues may crack or the mortar fails giving a potential flue path into the dwelling.
- Spillage – Spillage may occur when an appliance is first lit from cold. Without the draw from the chimney, it is possible for the combustion products to enter the room. This event usually stops as the chimney/flue warms up, but there is the possibility that excessive spillage may occur in some circumstances. This can often be detected as staining or scorching around the vents of appliances
- Adverse weather conditions – Strong winds impacting directly on flues may give rise to incorrect operation. This will be appliance type and flue specific.
- Not flued (where applicable) – This refers to appliances that are required to have a flue but do not have one installed.
- Un-flued – This refers to appliances that do not require a flue.

## Part 5 – Occupant exposed for sufficient time

**Fig. 67** Occupant exposure for sufficient time



In Figure 67, it is recognised that the occupant may be a factor in the build-up of CO in the dwelling by either failing to detect or mitigate the presence of combustion products. Here, the occupant may be unaware of CO poisoning symptoms, or there may not be a CO alarm in the property. The additional factors relate to incorrect location of CO alarms or faulty alarms.

The results from the QRA are discussed in the results section.

### GS(M)R exemption

An application was submitted to the HSE in March 2015 that was structured around the safety case headings required by Schedule 1 of the GS(M)R whereby the exemption requested for the conveyance of regasified LNG not compliant with the interchangeability requirements of Part I of Schedule 3 of the GS(M)R.

The application sought an exemption to permit conveyance for a period of one year of gases having a maximum WI of 53.25 MJ/m³, ICF of 1.77 and SI of 0.62 into the Oban Network as part of the field trial.

This application was supported with the results of the QRA and evidence in the form of interim reports using the results acquired during stages 1 and 2 of the project.

Following a detailed review process, approval was granted in June 2015 for the 12-month trial period.

The HSE established a multidisciplinary team with pipeline, gas, appliance and statistical experts from the Health and Safety Laboratories (HSL) to assist with the following:

- Ensuring sample methods and test methods were appropriate.
- Ensuring SGN considered all relevant failure modes e.g. Network (impact on pipes/seals and other perishable fittings).
- Assessing heat impact on appliance servicing requirements.
- Assessing Impact on $CO/CO_2$ generation.

### Gas shipper contracts

Taking into account the requirements of the Gas Directive, the Gas Act and the transporter licence, several options to facilitate the injection of the trial gas sources into the Oban network were identified and reviewed. The outcome of the options review was a recommendation to enter in to an agreement with a gas shipper.

The steps taken to successfully execute this first of its kind contract were:

- Initial Consultations with shippers.
- Expression of Interest to possible shippers.
- Responses received to this Expression of Interest.
- Heads of Terms submitted to interested shippers.
- Agree price with potential shippers.
- Choose preferred shipper.
- Negotiate contract terms.
- Agree and finalise contract terms.

This was an unprecedented contract arrangement between a Gas Distribution Network and a Gas Shipper that consequently required a significant level of engagement and negotiations between the parties. A detailed procurement process was undertaken to agree this contract.

SGN held initial consultations in February 2014. These consultations were to ensure the procurement was possible, using existing informal contacts SGN had with shippers. The positive responses received here ensured SGN could be confident of securing an agreement following an Expression of Interest.

In March 2014, an Expression of Interest was submitted to procurement managers at 238 Ofgem registered gas shipping companies for approximately 2,000 tonnes of LNG (with the option for more if necessary) to be collected by road tankers from an LNG terminal. This would be the predominant gas source for this trial.

SGN submitted Heads of Terms to the interested shippers in early May 2014. These detailed the arrangements of a mooted contract and requested a price for the LNG based on the terms.

Two shippers submitted tenders after agreeing to the Heads of Terms. SGN carried out a review of gas prices on the basis of their submissions. Both had differing structures to their costing.

Shipper A based their costs on indices tracking the difference between Zeebrugge hub (ZEE), the National Balancing Point hub (NBP) and the System Marginal Sell Price (SMSP). They also included a consignment management fee.

Shipper B's cost was linked to the Brent Crude Oil index, and also included a form of management fee. Shipper B was subsequently deemed to be of a higher risk due to the volatility of Brent Crude Oil prices.

The true cost of the contract was viewed to be dependent on three main variables:

- Oban Gas Demand;
- Zeebrugge Hub Gas Price; and
- NBP System Marginal Sell Price.

SGN estimated each variable based on market trends and analysis. Nevertheless, despite best endeavours to estimate an accurate cost this could not be taken as guaranteed due to gas market price uncertainty. Therefore, an option for a fixed cost contract was discussed with the potential shippers but soon after dismissed on the grounds increased costs with little value.

However, further analysis was carried out by SGN to identify other alternative options to limit the potential fallout from future price spikes. Hedging was considered as a potential option. There are a number of different financial instruments that can be used for hedging gas price, each with its own pros and cons.

The various hedging strategies were considered and analysed by an energy trading expert. The recommendation was made not to hedge the LNG shipping contract based on the following:

- The relatively low volume of gas which will be procured.
- ZEE and NBP hub closely track each other.
- The purchase order for the LNG can be split into quarterly orders.

It was concluded that the risk of ZEE price rising significantly above NBP SMSP for an extended period of time is low. This risk could be further mitigated by splitting purchase orders for the LNG into quarterly orders therefore reducing risk of prolonged exposure to high costs.

Following the detailed procurement process, SGN awarded the contract to Eni Trading and Shipping UK Ltd for 2000t of LNG from the Zeebrugge LNG Terminal.

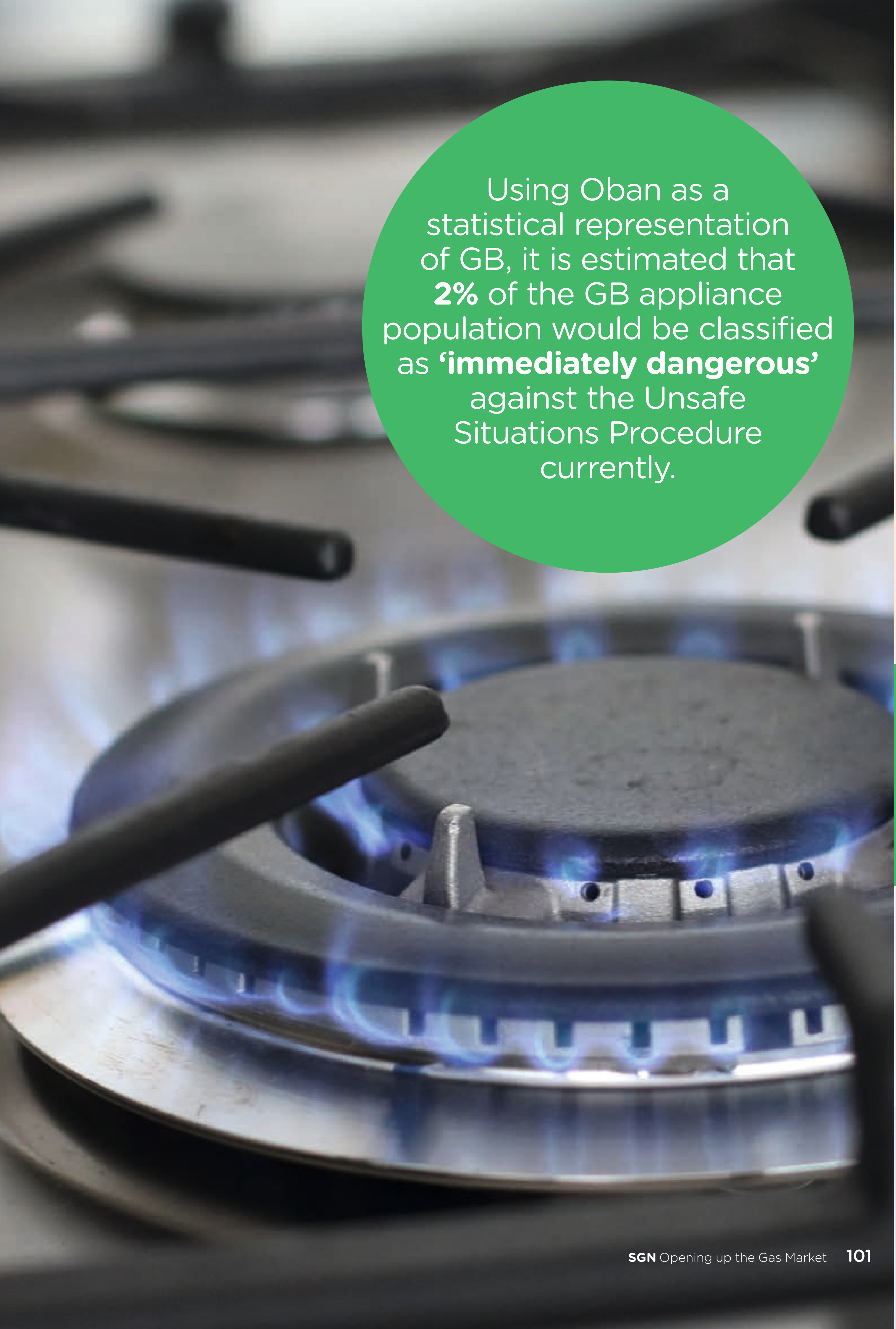
For the supply of the supplementary additional gas sources wither higher WIs a secondary contract was subsequently agreed with Flogas Ltd to supply LNG from Isle of Grain in England and Montoir de Bretagne, in France. One load from each terminal was trialled during stage 3 following a separate procurement process

**LNG terminal contracts**
Prior to the execution of the gas shipper contracts, a detailed analysis was carried out to investigate the potential LNG terminals that could be used to source the gas for the trial. This review was supported by Dave Lander Consulting (DLC) Ltd. The criterion for terminal eligibility was based on WI, tanker loading facilities and location.

It was essential that the terminals selected had road tanker facilities to allow the loading of SGN road tankers before transport to Oban. Many LNG terminals were consequently ruled out of the full one-year trial as they did not provide this service. Of those that did provide this, DLC researched their typical export WI ranges, to confirm that the LNG at the terminal was suitable for the trial i.e. WI exceeded GS(M)R.

As Zeebrugge terminal met all the necessary requirements, and was the closest terminal to Oban geographically (Isle of Grain road tanker facility was not commissioned until October 2015, thus after the trial commenced) it was considered the most appropriate terminal to act as the predominant source the LNG for the one-year trial. Montoir in France and Bilbao in Spain were initially identified as the most likely location for the two other additional sources. However, Bilbao was subsequently ruled out and changed to Isle of Grain in England following discussions with the Shipper when it was confirmed that SGN's road tankers were not compatible with the loading facility in Bilbao.

SGN successfully contracted with the terminal operators at Zeebrugge, Isle of Grain and Montoir to ensure the required number of road tanker filling slots were made available. The terminal operators were Fluxys, Grain LNG and Elengy respectively.



Using Oban as a statistical representation of GB, it is estimated that **2%** of the GB appliance population would be classified as **‘immediately dangerous’** against the Unsafe Situations Procedure currently.

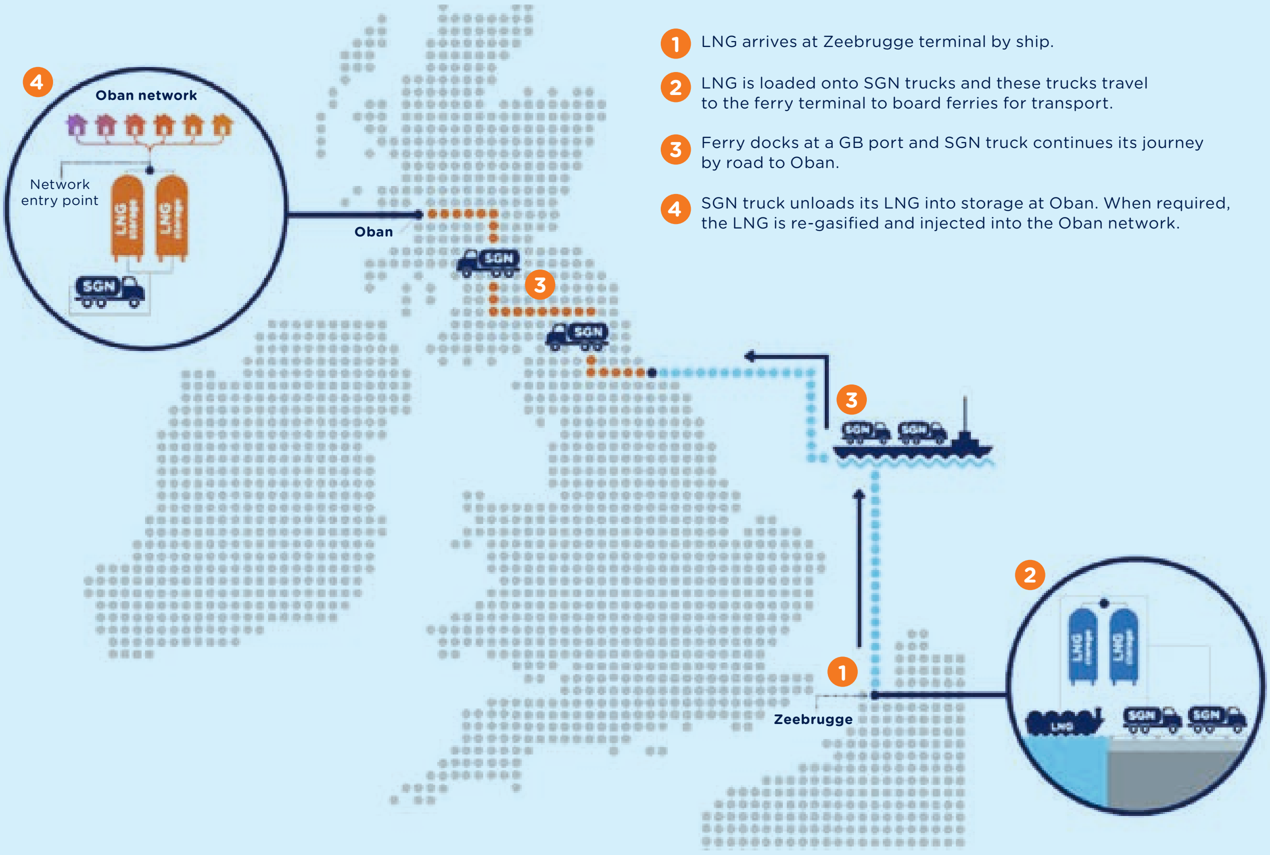
### LNG transportation

Detailed analysis of the logistics of transporting gas from the selected LNG terminals to Oban was conducted. Various haulage routes and costs were considered to identify the most suitable and cost effective route.

The frequency of sailings and reduced capacity for handling tankers during winter's high demand period meant some ferry operators would be insufficient to cover SGN's requirements initially. For the Zeebrugge LNG, the chosen ferry operator offered an interconnecting road joining their dock compound with the Fluxys terminal, with written procedures agreed between the two companies and the local council which avoided the need for the vehicle to use the public roads/highways and thus reducing the risk of delays due to traffic or spillages due to vehicle accidents. It was concluded that Zeebrugge – Killingholme represented the most practical route at that time in terms of both meeting all the necessary criteria, and being the best value for money.

'One-off' logistics processes were established for the additional Isle of Grain and Montoir sources.

**Fig. 68** The gas journey from Zeebrugge to Oban: the physical transport



① LNG arrives at Zeebrugge terminal by ship.

② LNG is loaded onto SGN trucks and these trucks travel to the ferry terminal to board ferries for transport.

③ Ferry docks at a GB port and SGN truck continues its journey by road to Oban.

④ SGN truck unloads its LNG into storage at Oban. When required, the LNG is re-gasified and injected into the Oban network.

# Results and discussion

The stage 3 results have been spilt into 5 sections:

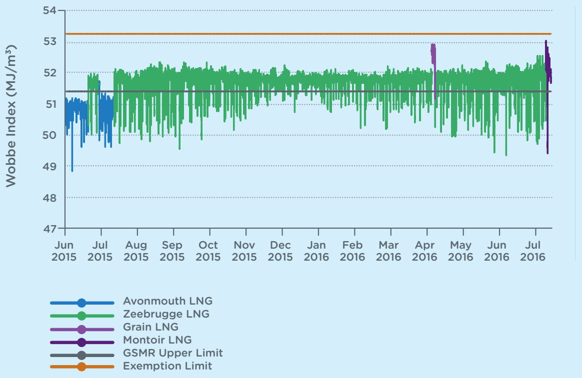
1. WI monitoring
2. Appliance spot checks
3. Network analysis
4. Results from QRA
5. Other results and discussions

### WI monitoring

WI readings were recorded using the existing gas chromatograph at the Oban regasification plant. The device records readings at 8 minute intervals and was used to monitor and analyse the WI value throughout the trial period.

Figure 69 shows the points at which the trial gases were injected into the system i.e. Zeebrugge June 2015, Grain LNG April 2016 and Montoir in July 2016.

**Fig. 69** Daily WI ranges – June 2015 to August 2016



As illustrated Avonmouth is compliant with GS(M)R upper limit. An initial trial for two weeks on Zeebrugge was conducted at the end of June. The first section spike of WI illustrates this. The site was then reverted to Avonmouth LNG whilst the results from the initial trial. Following successful analysis of the chromatograph plus a number of appliances checks it was confirmed that the trial could start in earnest. The step change in WI from Zeebrugge to the additional sources is evident in April and July 2016.

Although a range of WI occurs across the day, the WI predominantly sits at the upper end of the range. The reason for the change in WI is due to the inherent characteristic of the regasification plant whereby the gas composition and thereby WI can change depending on factors such as flow, weather, demand and site operation.

The three different LNG sources injected into the Oban network (1987.28t in total, delivered using 102 tankers):

- Zeebrugge LNG, WI of 51.8 MJ/m³ (Average across year), trialled for 1 year – 2000t of LNG, 100 x road barrel tankers.
- Isle of Grain LNG, WI of 52.8 MJ/m³ – 20t of LNG, 1 x road barrel tanker.
- Montoir-de-Bretagne LNG, WI of 52.5 MJ/m³ – 15t of LNG, 1 x ISO tanker.

### Appliance spot checks

The exemption case included a commitment that during the field trial, appliance performance would be continually monitored. Properties were chosen for the spot checks in a manner that would ensure the sample properties were representative of the entire Oban population by including a proportional spread of the area and property type i.e. commercial and domestic. To achieve this the spot checks were split into three categories:

- Random – checks on the appliances in randomly selected properties, performed one-off per property at regular intervals across the 1 year trial. Random testing weeks took place in October 2015, January, April and June 2016 whereby, approximately 50-60 properties were tested during each week.
- Continuous – checks on the appliances at one property, performed daily for the duration of the 1 year trial.
- Contract – checks on the appliances in SGN service contract properties[44], performed as and when the customer's annual service was due.

The following parameters were recorded and compared against the original results recorded during stage 2:

- CO (ppm)
- CO/$CO_2$ Ratio
- Flame Picture

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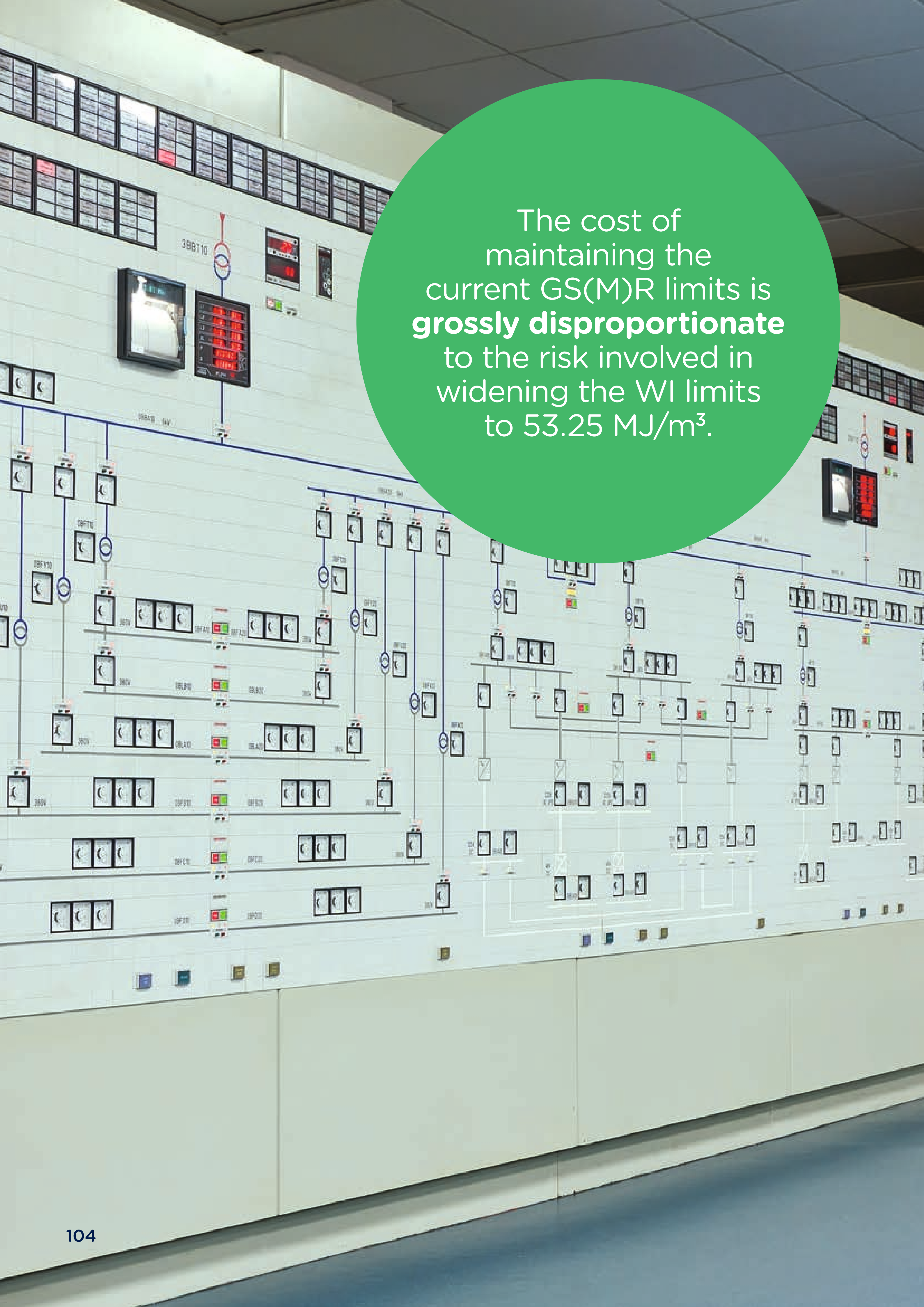
[44] In the SIUs, SGN operate a gas appliance maintenance and service contract business. This commercial service is limited exclusively to customers in the SIUs.



The cost of maintaining the current GS(M)R limits is **grossly disproportionate** to the risk involved in widening the WI limits to 53.25 MJ/m³.

Results from the spot checks undertaken were positive with no adverse results recorded in any of the 318 appliance spot checks conducted. There were no identifiable material changes recorded in the burning characteristics and performance of appliances on rich WI trial gas when compared to the burning characteristics witnessed on the G20 test gas during stage 2. Table 9 summarises the number of spot checks undertaken by properties and appliances.

**Table 9** Summary of spot checks undertaken

| | No. of appliance checks | No. of properties |
|---|---|---|
| Random | 400 | 188 |
| Continuous | 683 | 1 |
| Contract | 215 | 129 |
| **TOTAL** | **1298** | **318** |

No evidence of deterioration in appliance performance was found after one full year operation on gas outside of GS(M)R limits.

### Network analysis

The Oban network safely stored, injected, distributed and utilised gas with WI ranging from 49.00 MJ/m³ to 53.20 MJ/m³ during the one-year trial period. In order to determine the impact of the LNG supplied from Zeebrugge on network performance, a compare and contrast was carried out using Synergi, steady state modelling software.

Following the switch to Zeebrugge gas, five Osprey pressure validators were installed on the Oban low pressure (LP) network and pressures recorded at 6-minute intervals throughout the one year trial. Referenced against the validated network model (built in 2012), pressures collected at each of the logger locations were assigned to the network models for two specific days demonstrating typical cold winter and warm summer conditions respectively. With the network demands aligned to forecast and throughput, in both models, all recorded pressures showed an increase of between 1 and 5mbar above modelled expectations, indicating a relative increase in network capacity freed up by the richer specification of gas.

To further explain the effects of higher WI on network pressures it is necessary to explain the principles behind network analysis modelling which are as follows:

- The actual network model in itself, consisting of an intricate system of interconnecting pipework of varying lengths and diameters with a number of key nodal locations that will be required for the network modelling.
- Output (Demand load) – data on the number and type and location of gas user within the network, expressed in an energy equivalent demand i.e. MJ/m³ which is then input to determine the load at each and all the key nodal points.
- Input (source points i.e. regulators) Nodal points are created for each source and these loads are input into the model similar to the demand loads, as delivered energy equivalent in MJ/m³. The amount of energy that is input being dependent on the design flow capacity of the regulating unit together with the outlet pressure setting.

After all the input and output loads have been entered, the model is then used to determine the following:

- The extremity location of low pressure points within the network, these points are required in order to ensure that the network can operate safely by maintaining minimum pressures throughout the entire network under all anticipated conditions.
- The model is then used to determine the regulator outlet pressure set point to maintain sufficient pressure in the network i.e. the maximum regulator settings required to ensure that at the models lowest pressure point pressure can be maintained under all flow conditions i.e. 1 in 20 winter.
- A key factor (in particular in older network) is to ensure pressures are kept to an absolute minimum as excessive pressures in these older network lead to increases shrinkage i.e. leakage.

In essence, good network models are essential in order to fine tune networks to reduce leakage and to determine when a reinforcement of the network is required for example:

- To predict when a regulator is reaching capacity.
- The low point pressure can no longer be maintained as upstream pressures settings are outside the regulator design specification or in the case of older networks could create significant safety issues with regard to leakage.

As discussed one of the key factors when using the network modelling is energy input and output that are expressed in MJ/m³.

In our particular case as the RD remains reasonably constant the increase in WI is effectively proportional to the increase in the CV of the gas which is a key requirement to calculate energy input/output in a network.

The CV of the Zeebrugge trial gas was calculated to be around 39.70 MJ/m³, whereas the actual CV prior to commencing the stage 3 trial was around 37.90 MJ/m³, this equates to a 4.5% increase in CV.

The simplified scenario below explains the effect this increase in energy /m³ has on both the input and output sources and the effect that this then has on the flow rate within the network and hence network pressures.

The effects on appliances when using a higher CV gas:

- Boilers – these appliances would use less volume of gas to heat a specified quantity of hot water i.e. the burner would commence modulation and/or remain at a low output rate for longer periods.
- Ovens – in this case the burner would reach the thermostatic temperature setting much earlier.
- Gas Fires – the room temperature would reach the desired level sooner and the customer is then most likely turn down the settings much sooner.

In all cases where appliances use a gas containing more energy (higher CV) it follows they will consume less volume of gas to produce the same amount of work over the same time period.

Introducing the time factor then implies that the actual flow rate in all sections of the network is reduced and as many of the factors in the pipe flow calculation remain constant i.e. Area of pipe, friction factors etc then it follows that the effect of lower flow rates reduces the pressures throughout the entire network.

Using the Oban network model, Figure 70 show the network analysis results using lower WI gas i.e. CV of 37.90 MJ/m³ in which case the regulator was set at 50 mbar that ensured the modelled extremity low point at Crannag A Mhinistier gave a minimum pressure of 21.04 mbar.

Figure 71 shows the same model with the higher WI Zeebrugge gas i.e. CV 39.70 and shows that if the regulator remains at 50 mbar the extremity low point pressures increases to 23.47.

The final analysis, Figure 72 shows that the network pressures can be reduce at the regulator to 47.5 mbar and still achieve the minimum pressure of 20.9 mbar at the lowest extremity point with additional reductions shown at all other extremity points.

The significance of supplying a higher CV gas is as follows:

- It increases the available capacity of a network by 4.5% i.e. regulators can operate at much lower pressures/flow rate i.e. this available capacity is in the form of being able to add additional loads to the network with subsequent increase in regulator setting i.e. back to 50 mbar.
- Older networks susceptible to leakage that are already operating at capacity i.e. elevated pressures or the need for expensive higher capacity regulators and/or network reinforcement would also benefit from these reduce pressures.

**Fig. 70** Oban network pressures on previous gas

Corran Esplanade: 37.47
Dunollie Road: 22.83
Oban DG: 50.00
Crannag A'Mhinisteir: 21.04
Glen Cruitten Drive: 38.37
Soroba Road: 28.00

**Fig. 71** Oban network pressures on trial gas

Corran Esplanade: 38.44
Dunollie Road: 25.13
Oban DG: 50.00
Crannag A'Mhinisteir: 23.47
Glen Cruitten Drive: 39.31
Soroba Road: 29.82

**Fig. 72** Oban network pressure reduction on trial gas

Corran Esplanade: 35.92
Dunollie Road: 22.57
Oban DG: 47.50
Crannag A'Mhinisteir: 20.91
Glen Cruitten Drive: 36.77
Soroba Road: 27.27

It is worth noting that the average CV at Local Distribution Zone (LDZ) level is generally much higher than in the SIUs. In 2015/16 the average CVs for all SGN's LDZs were as follows:

- South 39.30 MJ/m³
- South East 39.23 MJ/m³
- Scotland 39.67 MJ/m³

These are much closer to the CV of the gas currently being used at Oban i.e. 39.7 MJ/m³. Based on this increase in CV then potentially the increase in capacity would be:

- South 1%
- South East 1.12%
- Scotland 0.07%

This approach is simplistic and is, in reality, more complex, however nonetheless it provides a crude demonstration of the potential to increase energy capacity through increasing the WI of the gas.

To further highlight this point, it is useful to consider the energy deliver capacity in terms of tonnes of LNG delivered to Oban. By means of a demonstration refer to Table 10.

Table 10 illustrates that for a period with a similar gas demand, the trial period required less tonnes of LNG to meet that demand. Thus illustrating the increased energy within each tonne of LNG delivered (due to the higher hydrocarbon content and hence higher WI).

Theoretically this means that a gas appliance requires less gas input to produce the same energy output. This however does not affect the efficiency of the boiler as the gas input will consequently be of higher energy.

The consumer's bill is not affected by this either positively or negatively as, although in theory less gas will pass through the meter, the energy of the gas that does will be of a higher CV (directly proportional to the increase in WI) and thus the FWACV of the network will be higher. In simple terms the customer consumes less volume for the same output but, the actual energy used is the same, and it is the energy consumed that is used for charging purposes and hence no change in billing in this respect is expected, other than the avoided cost in processing and the intangible benefit of 'opening up the gas market'.

### Results from QRA

The risk factors for the QRA have been estimated by looking at both the ratio between CO ppm values for G20 and G21 gases (i.e. the increase in CO from one WI to another), as well as an upper threshold for the absolute CO ppm values. During the original analysis the following rules were applied, with each increasing the base risk by a conservative factor of 2, whilst a factor of 1 is applied if the statement is not true:

- G20 CO ≥ 200 ppm
- G21 CO ≥ 200 ppm
- Ratio between CO ppm(G21) and CO ppm (G20) ≥ 4

The upper threshold value of 200 ppm was taken from the short-term exposure limit in the HSE standard for workplace exposure limits.

The ratio factor highlights the sensitivity of the appliance to change in gas quality, irrespective of the starting baseline emission on G20. It forms a 'belt and braces' approach to understanding the impact of gas quality and is introduced to account for the impact of appliance ageing. It is known that, in general, emissions increase with

**Table 10** LNG demand comparison against LNG delivered

| Period | CV (MJ/m³) | Scotland volumetric demand/year (Mscm/year) | Scotland energy demand/year (MJ) | LNG deliveries to Oban network (tonnes/year) |
|---|---|---|---|---|
| Aug 2013-Jul 2014 | 37.4 | 4484 | 167,701,600,000 | 2001 |
| Aug 2015-Jul 2016 | 39.7 | 4557 | 180,912,900,000 | 1987 |
| % change in energy demand and tonnes of LNG delivered | | 1.6% | 7.9% | -0.7% |

appliance use and age, and as such it is appropriate to introduce a factor that accounts for this. Previous appliance testing suggested that a reasonable estimate for a G20 CO emission on an appliance that had been correctly installed and operated was around 50 ppm. [Note this estimate has been corroborated by the appliance test work undertaken on the population of Oban appliances where an average of 56 ppm was observed.] The maximum ratio that can result from this 50 ppm to the G21 CO emission threshold of 200 ppm is thus equal to 4. This factor was deemed an appropriate ratio factor to use to provide a conservative estimate of risk.

Individual factors have been multiplied to create a 'Total factor'. The total factor was calculated for all individual appliance data. The set of individual appliance data was then averaged with no weighting factors, and the resulting value contains information from appliances where there is no material change i.e. a factor of 1, to appliances with a more sensitive response to WI and these may have a higher factor. The base risk was then multiplied by this average total factor, the difference between these two values resulted in the percentage change in risk from G20 to G21. The estimated change in risk for a Wobbe Index of 53.25 MJ/m$^3$ was then interpolated between these two values, using a linear fit. The linear fit was recognised as a conservative approach.

An updated QRA was produced at project end to reflect the learning of the project. The updates considered the following:

Different CO ppm threshold values by flue type:

- Flueless (FL) and open flue (OF) appliances.
- Fan flue (FF), room-sealed balanced flue (BF) and room sealed fanned balanced flue (FBF) appliances.
- Room sealed appliances will not vent into the room and will only be a hazard if they are not sealed properly.

Increase in CO ppm threshold:

- Investigation of 250 ppm CO emission threshold for OF and FL appliances and 500 ppm for FF, FBF and BF appliances. 250 ppm is not unreasonable for the OF and FL appliances, and these two concentrations were used in some of the GasQual work.

Increased ratio:

- The ratio value can be increased from 4 to 5 – which parallels the change from 200 to 250 ppm for the CO threshold.

The scenarios in Table 11 were investigated.

Since the original risk evaluation work was undertaken, additional data has become available. This data, published by the Gas Safety Trust (as discussed earlier in the report), provides more recent information regarding the number of incidents and fatalities associated with natural gas in Great Britain. These new data have extended the existing data set and the overall result is presented in Figure 73.

In line with the general trends since the late 1990s, the overall fatality rate is declining.

Using a ten-year average approach, the baseline risk changes from 0.179 fatalities per million people per year (as used in the original evaluation using data from 2002 to 2012) to 0.147 fatalities per million people per year (for the ten years starting in 2005). This reinforces the general trend that the risk of CO poisoning from gas use is declining.

**Table 11** QRA scenarios

| Rule | Original | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|---|
| G20 and G21 CO threshold for FL/OF (ppm) | 200 | 200 | 200 | 250 |
| G20 and G21 CO threshold for FF/BF/FBF (ppm) | 200 | 500 | 500 | 500 |
| Ratio value | 4 | 4 | 5 | 5 |

**Fig. 73** CO fatality statistics

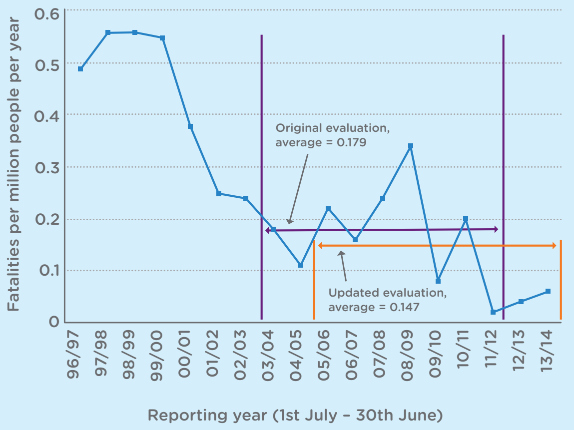
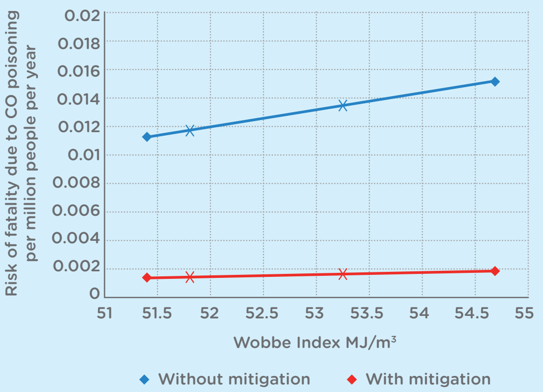


**Fig. 74** Risk vs Wobbe Index



The updated evaluation associated with change in gas quality from gas with a Wobbe Index of 50.72 MJ/m³ to the proposed new GS(M)R limit of 53.25 MJ/m³, shows that the risk increases by around 11%, and this factor is independent of the baseline starting value.

However, as the baseline has decreased by 18% over the last two years, it is clear that even with a slight increase in risk due to gas quality, the overall changes in risk are small.

The new data also highlights the key factors with regard to risk and these include:

- Appliance faults
- Flue/terminal faults
- Ventilation fault

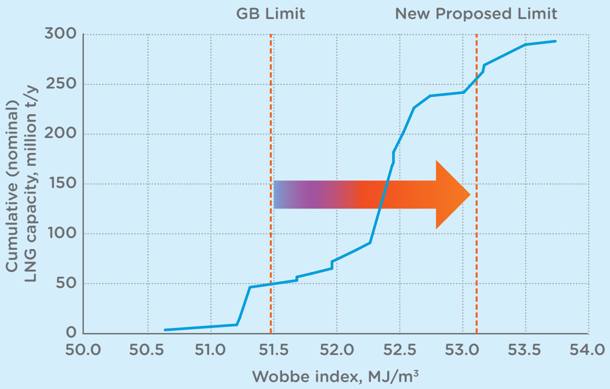
Figure 74 shows risk against WI with and without mitigation between G20 and G21 using the updated base risk of 0.147 fatalities per million people per year. Mitigation refers to appliances, maintenance, service and replacement when required as conducted in Oban. The risk for a WI of 53.25 MJ/m³ has been linearly interpolated between these values. There is little increase in risk from G20 to G21 with mitigation and therefore can be considered independent of change in gas quality.

## Other results and discussions

### Availability of global LNG Sources

As a precursor to selecting the appropriate LNG source for the trial, Dave Lander Consulting carried out a review of the WI of all the globally available LNG was carried out by Dave Lander Consulting. The review showed only 10% of the currently available LNG fell within current GS(M)R limits. Extending the upper WI limit of GS(M)R to 53.25 MJ/m³ would bring 90% of the globally available LNG into the allowable range without the need for processing.

**Fig. 75** Cumulative LNG production capacity



Engagement with Grain LNG and IGEM[45] led to the estimation that current processing costs in GB exceed £180m and this will rise to in the region of £325m by 2020 as LNG importation and terminal utilisation increases.

Therefore, there is a significant incentive to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.

**Determination of as low as reasonably practical**
In GB, there are various legal frameworks that affect the management of risks, which in general require some test of proportionality – that the costs of risk reduction are justified by the benefits.

'Reasonably practicable' lies at the heart of the British health and safety system. It is a key part of the general duties of the Health and Safety at Work. Act 1974 and many sets of health and safety regulations that are enforced. The legal interpretation of this is that a risk reduction measure should be implemented unless there is a 'gross disproportion' between the cost of a control measure and the benefits of the risk reduction that will be achieved.

The HSE's concept of 'as low as reasonably practicable' (ALARP) is a method of weighing up how much time and money to invest in controlling the severity and likelihood of a risk.

The decision is weighted in favour of health and safety because the presumption is that the duty-holder should implement the risk reduction measure. To avoid having to implement the risk reduction measure, the duty-holder must be able to show that it would be grossly disproportionate to the benefits of risk reduction that would be achieved. The HSE gives the following as extreme examples[46]:

- To spend £1m to prevent five employees suffering bruised knees is grossly disproportionate; but
- To spend £1m to prevent a major explosion capable of 150 fatalities people is proportionate.

The HSE advise duty holders to use a cost-benefit analysis (CBA) to help make judgements on whether risk reduction measures are reasonably practicable. The CBA, quantifies in monetary terms as many of the costs and benefits of a proposal as feasible, including items for which the market does not provide a satisfactory measure of economic value.

In a standard CBA, the usual rule applied is that the measure should be adopted only if benefits outweigh costs. However, in ALARP judgments, the rule is that the measure must be adopted unless the sacrifice is grossly disproportionate to the risk. This means, the costs can outweigh benefits and the measure could still be reasonably practicable to introduce. Something is reasonably practicable unless its costs are grossly disproportionate to the benefits.

How much costs can outweigh benefits before being judged grossly disproportionate depends on factors such as the severity and likelihood of the risk (the larger the risk, the greater can be the disproportion between the cost and risk).

A simple method for coarse screening of risk reduction measures is presented in the following equation[47]. This puts the costs and benefits into a common format of '£s per year'. To calculate this, if:

$$\frac{\textbf{Costs}}{\textbf{Benefits}} > \textbf{Disproportionate factor}$$

then the measure can be considered unreasonable for the risk reduction achieved.

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[45] Current 2020 forecast estimate of £325m in GB from National Grid (IGEM presentation, 2014).
[46] http://www.hse.gov.uk/risk/theory/alarpglance.htm
[47] http://www.hse.gov.uk/risk/theory/alarpcheck.htm

To calculate the benefits, a monetary valuation of preventing specific health and safety effects are used.

ALARP calculations were carried out by DNV GL as part of their QRA to determine the justifiable spend for mitigating the CO risks associated with the change in gas quality. The parameters used in the calculation are shown in Table 12.

**Table 12** Inputs for ALARP CBA

| Input | Value | Comment |
|---|---|---|
| Value of preventing a fatality (VPF) | £1,889,000[48] | From Rail Safety Standards Board |
| Gross disproportion factor | 10 | Conservative estimate from HSE guidance |
| Number of gas consumers | 50,000,000 | Average occupancy of 2.3 people in approximately 22 million properties supplied by gas |

Two conditions were tested:

- Applying the mitigation measures that were undertaken during the OGM Project (that is, checking all appliances in GB and maintaining/replacing appliances as required).
- The continuation of nitrogen ballasting of LNG at a cost of £325M per annum.

The value of the baseline risk used was derided from the QRA:

- 0.147 fatalities per million people per year for the ten-year average starting from 2005.

The increase in risk associated with changing the Wobbe Index from 50.72 $MJ/m^3$ to the proposed new GS(M)R limit of 53.25 $MJ/m^3$ was 11%, and this factor is independent of the baseline starting value.

The risk of fatalities following the mitigation measures undertaken during the OGM Project is also independent of the baseline value and remains at 0.027 fatalities per million people per year.

**Table 13** ALARP calculations showing justifiable spend on risk reduction measured

CBA for applying appliance mitigation measures to all of GB

| Baseline risk 10 year averaging period | Wobbe Index/ ($MJ/m^3$) | Risk in fatalities per million people per year from QRA | Comment | Justifiable spend per million people per year | Justifiable spend per household (average of 2.3 people) |
|---|---|---|---|---|---|
| 2005-2015 | 51.4 | 0.147 | Baseline | £2,569,040 | £1.12 |
| | 53.25 | 0.163 | No mitigation | | |
| | 53.25 | 0.027 | With mitigation[49] | | |

CBA for nitrogen ballasting in GB

| Baseline risk 10 year averaging period | Wobbe Index/ ($MJ/m^3$) | Risk in fatalities per million people per year from QRA | Comment | Justifiable spend per million people per year | Current cost of ballasting per million people per year |
|---|---|---|---|---|---|
| 2005-2015 | 51.4 | 0.147 | Baseline | £302,240 | £6,500,000 |
| | 53.25 | 0.163 | No mitigation | | |

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[48] Rail Safety and Standards Board Guidance on the use of cost-benefit analysis when determining whether a measure is necessary to ensure safety so far as is reasonably practicable July 2014 http://www.rssb.co.uk/risk-analysis-and-safety-reporting/risk-analysis/taking-safe-decisions/taking-safe-decisions-safety-related-cba

[49] Mitigation includes surveying appliance installations regarding their condition and performance, and rectifying where necessary.

The ALARP calculations demonstrate that applying the risk mitigation of appliance servicing/maintenance to the whole of GB is grossly disproportionate to the level of risk that it would reduce. The calculations also show that the current cost of maintaining the current GS(M)R WI limits (in terms of nitrogen ballasting) are disproportionate to the risk involved in widening the WI limits to 53.25 MJ/$m^3$:

As can be seen, ballasting is grossly disproportionate by a factor far in excess of 10 to the level of risk reduction it achieves.

It is acknowledged that in reality the outcome of a CBA is only one of several considerations that go towards the judgment that a risk has been reduced ALARP and thus the calculation is for demonstration purposes only.

$$\frac{\textbf{Cost of ballasting per million people}}{\textbf{VPF x risk reduction achieved by ballasting per million people}} > \textbf{Disproportionate factor}$$

$$\frac{£6.5\text{m}}{£1.889\text{m} \times (0.163 - 0.147)} > 10$$

$$\frac{£6.5\text{m}}{£0.30384\text{m}} > 10$$

$$£302{,}240 > 10$$

# Conclusions

The main conclusions from stage 3 are:

1. There is a significant incentive to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.
2. Currently only 10% of the available LNG can be accepted into the gas network without processing. Increasing the WI range to 53.25 MJ/m$^3$ would allow >90% of the globally available LNG to be accepted.
3. Appliance maintenance, servicing and replacement when required produces a 7-fold reduction in the absolute risk.
4. CO campaigns that focus solely on CO alarms are not the most effective means of reducing CO risk.
5. The cost of maintaining the current GS(M)R limits is grossly disproportionate to the risk involved in widening the WI limits to 53.25 MJ/m$^3$.
6. The Oban Network safely stored, injected, distributed and utilised gas with WI ranging from 49 MJ/m$^3$ to 53.2 MJ/m$^3$ during the one-year trial period.
7. No evidence of deterioration in appliance performance was found after one full year operation on gas outside of GS(M)R limits.
8. The interchangeability diagram can be simplified and updated to reflect current requirements.

# Conclusion

The Oban Network **safely stored, injected, distributed and utilised** gas with WI ranging from 49 MJ/m³ to 53.2 MJ/m³ during the one-year trial period.

# Outcomes against project objectives

| Objective | Outcome |
|---|---|
| 1. To demonstrate whether all gas appliances are capable of safely and efficiently burning gas which meets EASEE-gas specifications but sits outside GS(M)R; | Laboratory and field testing demonstrated that appliances (GAD and non-GAD) installed, serviced and operated correctly up to can safely and efficiently burn gas with a WI of up to 54.7 MJ/m³. Applying a headroom factor for appliance age/condition and discussions with manufacturers it was recommended that 53.25 MJ/m³ be the upper WI value. |
| 2. To establish the proportion of older gas appliances that constrict gas quality specification in GB through assessment of a representative appliance sample from Oban network; | Laboratory and field testing results found that all appliances installed, serviced and operated correctly, can safely and efficiently operate with a wider gas quality specification, regardless of age. |
| 3. To demonstrate through the sample population what is required to ensure GB's appliance population is capable of operating safely and efficiently over a wider range of gas quality; | The QRA showed that increasing the WI to 53.25 MJ/m³ has small increase in risk, albeit the risk remains of the same magnitude. The QRA also demonstrated that, if an appliance is maintained and serviced regularly then the increase in risk with WI is negligible. Therefore the small increase in risk for un-maintained appliances could be removed by refocusing CO campaigns on the importance of appliances servicing and maintenance. |
| 4. To identify and record all types/makes of gas appliances, identified through the representative appliance sample from Oban network that are not fit for operation using gas which meets EASEE-gas specifications but sits outside GS(M)R; | No appliances were found to be unfit for EASEE-gas specification. Unsafe appliances were already unsafe on GS(M)R specification gas. A minor reduction from the EASEE-gas specification to 53.25 MJ/m³ provides a headroom factor for appliances in poorer condition. |
| 5. To demonstrate whether gas that meets EASEE-gas specification but sits outside GS(M)R can be conveyed safely and efficiently in the GB gas network; | The field trial demonstrated that there are no network related issues with conveying gas with a WI outside of GS(M)R specification. Three alternative LNG source gases with Wobbe Index > 51.4 MJ/m³ were successfully introduced and used continuously over a 12 month period in the Oban network.<br>During the initial trial period 200 spot checks were carried out on random properties with no issues found. |
| 6. To capture and record all project learning to assist in a full GB roll out in the future; | All learning from the project has been captured and disseminated as appropriate and there is continuing engagement with OFGEM, DECC (now BEIS), HSE, HHIC and other key Stakeholders.<br>The project has led to the formation of the IGEM Gas Quality Working Group, with the objective of moving GS(M)R to an IGEM standard and widening the WI limits within. |
| 7. To compile a project completion report assessing the technical and commercial viability of accepting EASEE compliant gas in GB; | A £325m potential benefit due to less gas processing has been advocated by National Grid (NG). This project has proven that this is technically possible to achieve up to 53.25 MJ/m³ without the need to inspect or replace any appliances. |
| 8. To compile a list of appliances found to be incompatible which will be shared among all relevant stakeholders; | Laboratory and field testing results found that all appliances were compatible. All appliances installed, serviced and operated correctly, can cope with a wider gas quality specification. |

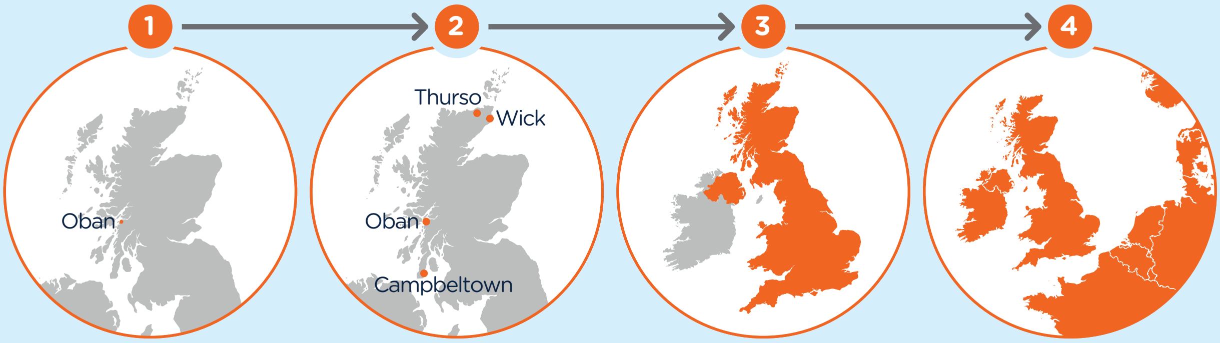
# Conclusions

Based on the findings from the three stages of the project a number of conclusions were able to be drawn. The main conclusions are summarised below.

1. There is a significant incentive to change the allowable gas quality in GB, specifically the WI, circa £325m per annum for avoided Nitrogen ballasting.
2. Currently only 10% of the available LNG can be accepted into the gas network without processing. Increasing the WI range to 53.25 MJ/m$^3$ would allow >90% of the globally available LNG to be accepted.
3. Domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 MJ/m$^3$.
4. An upper WI limit of 53.25 MJ/m$^3$ allows sufficient headroom for any deleterious unknowns in the field condition of the appliance.
5. The cost of maintaining the current GS(M)R limits is grossly disproportionate to the risk involved in widening the WI limits to 53.25 MJ/m$^3$.
6. Using Oban as a statistical representation of GB, it is estimated that 4% of the GB appliance population would be classified as ‘at risk’ against the Unsafe Situations Procedure currently.
7. Using Oban as a statistical representation of GB, it is estimated that 2% of the GB appliance population would be classified as ‘immediately dangerous’ against the Unsafe Situations Procedure currently.
8. Appliance maintenance, servicing and replacement when required produces a 7-fold reduction in the absolute risk.
9. Both the Sooting Index and the Incomplete Combustion Factor as stated in GS(M)R are no longer valid.
10. CO campaigns that focus solely on CO alarms are not the most effective means of reducing CO risk.
11. Increasing the WI to 53.25 MJ/m$^3$ has negligible impact on the efficiency, performance and life of a domestic or small commercial appliances.
12. The interchangeability diagram can be simplified and updated to reflect current requirements.
13. The Oban Network safely stored, injected, distributed and utilised gas with WI ranging from 49 MJ/m$^3$ to 53.2 MJ/m$^3$ during the one-year trial period.
14. No evidence of deterioration in appliance performance was found after one full year operation on gas outside of GS(M)R limits.

# Road map for GB roll-out

**Fig. 76** Road map for roll-out



**Recommendations**
In review of the findings of this project, the following recommendations are made as part of the road map for GB roll-out:

1. The upper WI limit to be increased to 53.25 $MJ/m^3$
2. No changes to the lower WI limit at current time
3. The interchangeability diagram to be updated
4. Transfer GS(M)R to IGEM Standard
5. Review CO guidance message
6. Permanent GS(M)R exemptions for the SIUs

### 1. The upper WI limit to be increased to 53.25 $MJ/m^3$

Based on the results of the project it is recommended the upper WI limit in GB is increased from 51.40 $MJ/m^3$ to 53.25 $MJ/m^3$. Although the extensive appliance testing results demonstrated that all domestic and small commercial appliances correctly installed, serviced and operated can safely burn gas with WI of up to 54.76 $MJ/m^3$, a reduced upper WI limit of 53.25 $MJ/m^3$ is proposed to allow sufficient headroom for any deleterious unknowns in the field condition of appliances. This provides a safety margin (approximately 1.5 units) for factors such as:

- Appliance safety device performance.
- Ambient temperature effects.
- Start of exponential increase of CO around 53.50 $MJ/m^3$ (for some appliances).
- Sub-optimal adjustment of air/gas ratio controlled fully premix boilers.
- Other deleterious unknowns and poor condition of appliances.

Furthermore, it was noted that this upper limit is only marginally above the current GS(M)R emergency limit (52.85 $MJ/m^3$).

Using Oban as a statistical representation of GB, it is estimated that 4% of the GB appliance population would be classified as ‘at risk’ and 2% ‘immediately dangerous’ against the Unsafe Situations Procedure currently. The QRA determined that increasing 53.25 $MJ/m^3$ does not materially affect CO risk. Appliance installation condition is the most significant contributor to risk.

There is a significant incentive in terms of LNG availability at this level. Currently only 10% of the available LNG can be accepted into the GB gas network without processing. Increasing the WI range to 53.25 $MJ/m^3$ would allow >90% of the globally available LNG to be accepted.

### 2. No changes to the lower WI at current time

Although this project did not find any safety issue testing on gases as low as 45.66 $MJ/m^3$ WI, it is suggested that more work is required in this area to investigate mal-adjustment of boilers with gas/air ratio controls. Extending the upper WI limit to 53.25 $MJ/m^3$ and retaining 47.20 $MJ/m^3$ at the lower end, would effectively widen the WI range beyond the 5-6 $MJ/m^3$ safe operational range identified by the project. Thus an upper limit of 53.25 MJ/m³ leaves less scope to extend the lower limit below 47.20 MJ/m³ without potentially having to re-adjust boilers from their G20 factory set point, which the majority are set.

There have been concerns raised about re-commissioning 'repaired' gas appliances when the gas service operative does not know the quality of the gas being supplied to the property at that moment. This is a recognised problem in Germany[50] and other countries developing an alternative gas strategy. Therefore additional laboratory test work to determine materiality of this was carried out under the project. The laboratory test work demonstrated that it would be possible to adjust and operate the boilers tested on a gas supply network within a WI range between 48.00-53.00 MJ/m³ with only modest effects on CO production. (i.e. ±2.50 MJ/m³ from a central point of 50.50 MJ/m³).

A boiler could be factory set at either 48.00 or 53.00 MJ/m³ and still meet the safety action level on a gas network that has a WI that varies between these two extremes. For example, if the boiler was adjusted at 48.00 MJ/m³, the gas WI could increase by 5.00 MJ/m³ and the combustion would still be acceptable, and vice versa. In theory, if the boiler was adjusted at 48.00 MJ/m³ and the gas WI decreased by 5.00 MJ/m³, to 43.00 MJ/m³, the combustion would be still be satisfactory (48.00 MJ/m³ becomes the new upper point of adjustment). The same applies at 53.00 MJ/m³.

Theoretically, outside this range, extreme adjustment (either low or high) fed with extreme opposite WI gas (either high or low) could lead to substantial increases of CO in the flue products. In future this would essentially only be an issue in areas where Biomethane is injected into the distribution system unconstrained by thermal energy compliance. Currently, in order to comply with the Thermal Energy Regulations, biogas plants enrich the gas by adding propane in order to meet the Flow Weighted Average Calorific Value (FWACV) of the network. This compensates for the dilution effect the Biomethane would have on the FWACV. Therefore the WI of the Biomethane is likely to fall within the safe appliance adjustment zone.

The 'Oban limits' identified allow for WI headroom allocated to on-site appliance issues. Indeed notwithstanding this, many appliances (such as flued and room sealed) pose no potential for CO spillage to room. This is however an issue that should be considered in any unconstrained development, such as that being considered under the Real-time networks project[51]. Whilst the CO concentrations may not be harmful the appliance may be operating outside the manufacturer's recommended $CO/CO_2$ envelope, which could give future complications.

This is an example of where both the appliance industry and gas supply chain must continue to closely co-operate to understand future widening of sources in terms of thermal energy and gas quality management.

The driver for extending the lower WI limit may become more prevalent in the future as new renewable and unconventional gas sources with lower WIs become available. Therefore no changes to the lower WI limit of 47.20 MJ/m³ are recommended at this time.

### 3. The interchangeability diagram to be updated

The interchangeability diagram, published in the HSE's Guide to the GS(M)R[52], is a visual representation of the WI, ICF and SI limits embodied in Schedule 3 of the GS(M)R. These limits and the Interchangeability Diagram are a simplification of the limits introduced and operated by the British Gas Corporation prior to 1996 and the Dutton Diagram, published[53] following a series of work carried out by B.C.Dutton in the 1970-1980s. The interchangeability diagram has served GB well and was certainly fit for purpose based on the gases available and type of appliances in use at that time. In light of the work conducted under this project it is considered that it can be simplified and updated to reflect current requirements.

Figure 77 shows the existing interchangeability diagram and various limits as defined within GS(M)R.

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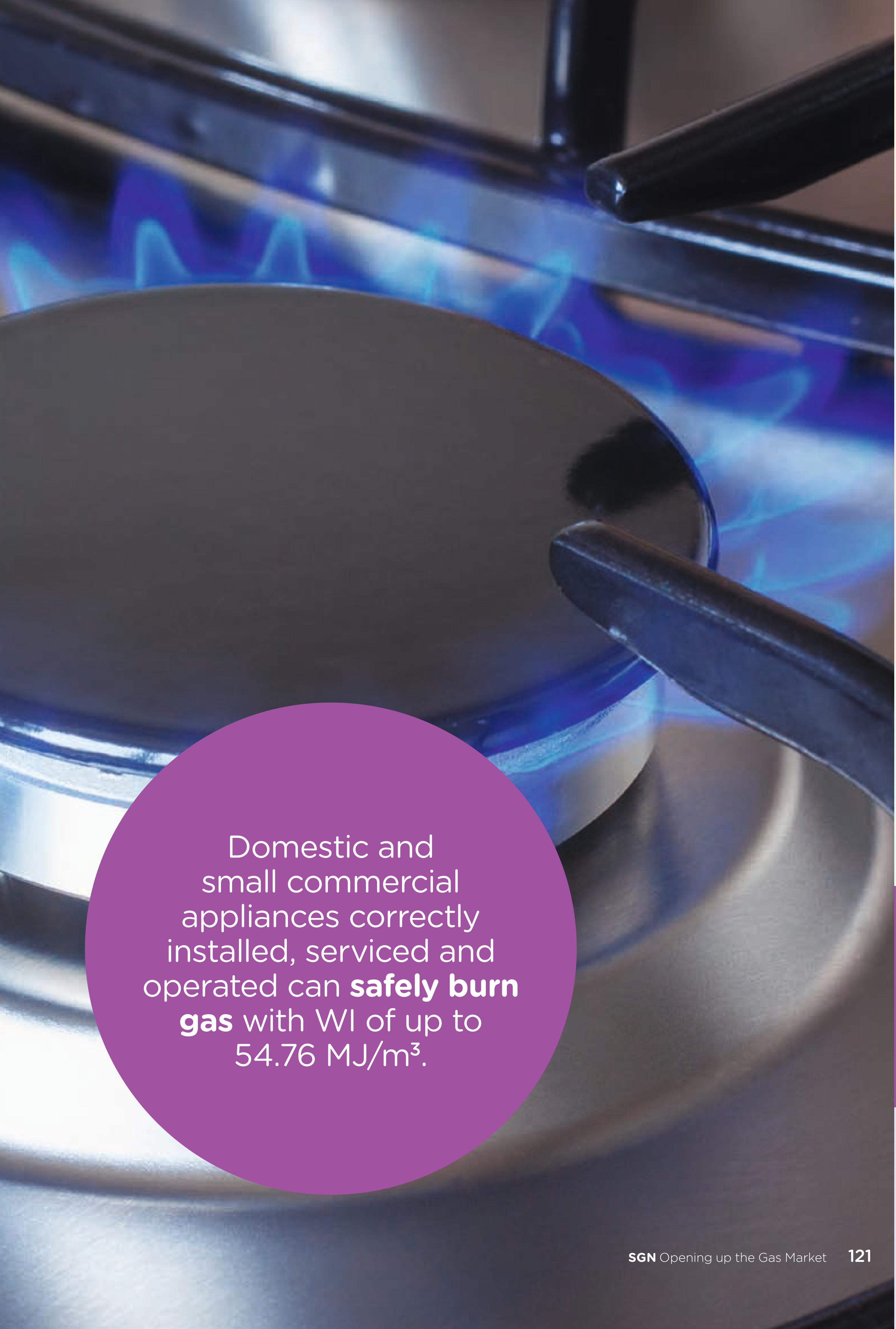
[50] Joint declaration by European transmission and distribution system operators to Pilot Study 2.0 Contribution to the pre-normative study of H-gas quality parameters (2016).

[51] https://www.sgn.co.uk/real-time-networks/

[52] Health and Safety Executive. 'A Guide to the Gas Safety (Management Regulations'. HSE Books ISBN 978 0 7176 1159 1.

[53] B.C.Dutton. 'A new dimension to gas interchangeability'. IGEM Communication 1246, 50th Autumn Meeting. 1984.



Domestic and small commercial appliances correctly installed, serviced and operated can **safely burn gas** with WI of up to 54.76 MJ/m³.

**Fig. 77** Existing interchangeability diagram

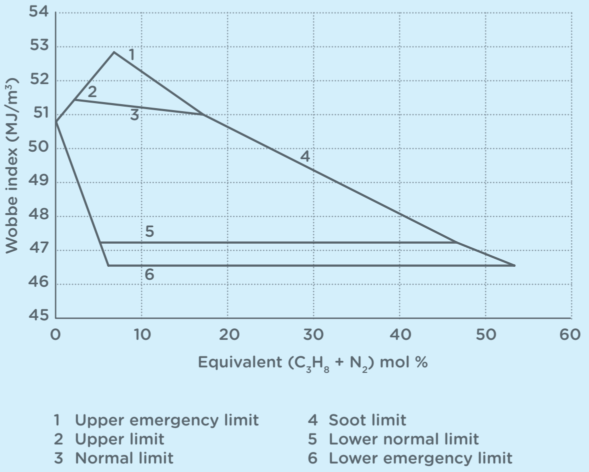
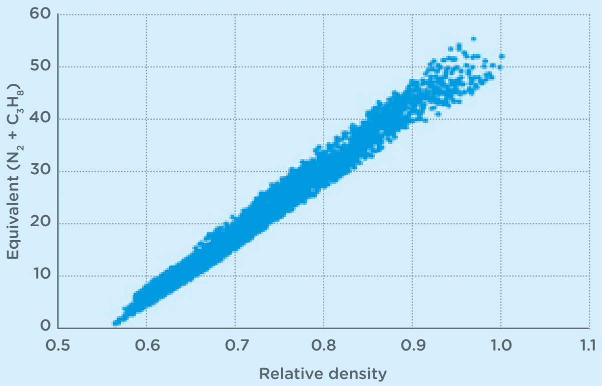


**Fig. 78** Demonstration that RD is a good proxy for equivalent ($N_2 + C_3H_8$)



The abscissa in the current Interchangeability Diagram is based on the propane and nitrogen content of the equivalent mixture[54]. However, an alternative approach adopted within Europe is to plot WI against RD. This offers has a number of advantages:

- Simplification – reduction of composition to an equivalent mixture is not required.
- Harmonisation with European practice.

The EASEE-gas specification sets interchangeability limits solely in terms of WI and RD, so limits can be compared directly.

Replotting the Interchangeability Diagram in terms of WI and RD has only a minor impact on the diagram because RD is a good proxy for equivalent Nitrogen ($N_2$) and Propane ($C_3 H_8$) – this can be seen by a plot of the two terms for a series of hypothetical gas compositions selected by Monte-Carlo methods – see Figure 78. The hypothetical compositions were selected to reflect GB natural gases that were both compliant and non-compliant with the requirements of the GS(M)R.

Figure 79 shows the modified Interchangeability diagram resulting from employing RD as the abscissa. Superimposed on the diagram are the EASEE-gas interchangeability limits in WI and RD. The diagram also shows the location of the stage 1 and 2 test gases and the stage 3 trial gases within the various boundaries. Note these gases are above GS(M)R normal upper limit and sit within the emergency envelope of GS(M)R.

**Fig. 79** Modified natural gas interchangeability diagram showing stage 3 gas positions

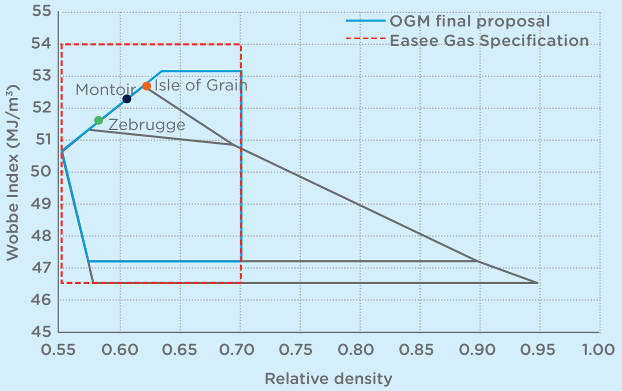


Figure 80 again depicts the GS(M)R, EASEE-gas and proposed Oban limits, but this contains the location of the globally available LNG within the various boundary limits. It illustrates the headroom below the EASEE-gas limits and how extending the upper WI limit to 53.25 MJ/m³ would accommodate most of globally available LNG without the requirement for processing, whilst satisfying appliance performance and safety considerations.

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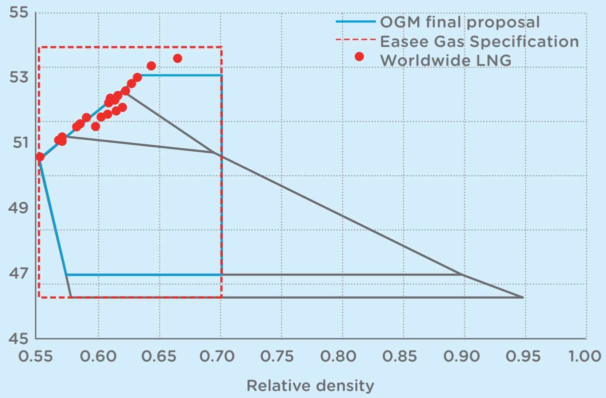
[54] The equivalent mixture is a hypothetical mixture of methane, propane, nitrogen and hydrogen that has the same Wobbe index as that of the gas under consideration.

**Fig. 80** Modified interchangeability diagram showing position of globally available LNG



The following proposals are therefore made to the interchangeability requirements of the GS(M)R:

**Incomplete combustion factor (ICF) is removed as a requirement**
The ICF parameter was introduced by Dutton because test results indicated a small dependence of flue gas $CO/CO_2$ ratio upon equivalent ($N_2$ + $C_3H_8$). In practice, this dependency is quite small over the range of interest (around 0 – 18%, corresponding to a relative density range of 0.55 – 0.70). Subsequent testing by the GASQUAL consortium and by KIWA in this project have confirmed that for today's appliances, WI as a sole parameter is appropriate provided RD is limited to no more than around 0.70.

ICF was derived by Dutton from the performance of instantaneous water heaters; these appliances (together with the radiant gas fire) were commonly found in most homes in the 1970s and generally generated flue gas $CO/CO_2$ ratios that doubled when WI was increased by approximately 1.5 MJ/m³. Such appliances are now rare and today's 'equivalent' appliance is the central heating/hot water boiler. Such appliances do not show such severe sensitivity to WI: KIWA testing of a combi boiler with partially premixed burner suggests doubling of flue gas $CO/CO_2$ ratios only occurs when WI is increased by 3.0 MJ/m³. As a result, Dutton's relationship for calculating ICF from composition over-predicts true ICF for today's appliances.

ICF is simply a measure of how flue gas $CO/CO_2$ ratio increases as WI increases and takes no account of flue gas CO content. Today's appliances tend to operate with much lower flue gas CO content and the GASQUAL consortium, for instance, characterised appliance performance by a combination of flue gas CO content and increase as WI increased.

**The upper WI limit is increased from 51.41 MJ/m³ to 53.25 MJ/m³**
This is the key finding from the project and is based on the findings of the laboratory, in-premises and field testing of a wide range of appliances.

The WI limit of 51.41 MJ/m³ arose from the selection of ICF limit of 0.48 by Dutton because this value corresponds approximately to the WI limit of 51.20 MJ/m³ that was in use by the British Gas Corporation following a survey of GB appliances carried out in 1978.

**Sooting Index is replaced by relative density**
Dutton's basis for limiting equivalent ($N_2$ + $C_3H_8$) was based on limiting sooting associated with higher density gases and the Sooting Index limit value of 0.6 is based on visual assessment of the discolouration of ceramic radiants of gas fires commonly in use at the time. Sooting at this level is not a safety consideration and becomes a concern only when considering excessive deposition – in the flues of flame-effect fires, for instance. Testing in this project and by the GASQUAL consortium shows that limiting relative density to 0.70 limits propensity for significant sooting.

It is worth pointing out that the relative density limit of 0.70 generally represents a stricter limitation compared with the SI limitation of the GS(M)R. Most natural gases have relative density lower than 0.70 and only some associated natural gases or heavily-enriched gases would be affected.

**No change to the Lower WI limit**
The lower WI value of 47.20 MJ/m³ was originally proposed by Dutton on the basis heat service considerations, i.e. heat output from instantaneous water heaters (and to a lesser extent gas fires and cookers) led to consumer complaints if WI falls by more than 5% of the reference gas[55].

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[55] Note that reduction of WI to 95% of the reference gas corresponds to 48.18 and not 47.2 MJ/m³. Dutton's discussion of heat service limitation in the IGEM communication contains a number of discrepancies that are not readily interpreted.

**No evidence of deterioration** in appliance performance was found after one full year operation on gas outside of GS(M)R limits.

## Road map for GB roll-out *cont.*

The low emergency limit of the GS(M)R permits WI as low as 46.50 MJ/m³ to be conveyed in order to prevent a gas supply emergency and this limit value corresponds to the limit value for lift index of 1.16, which was established by visual assessment of flame detachment from the burners of cooker hobs.

No change in the lower WI limit is proposed at the current time, although there is scope for revision should assessment of future gas quality scenarios incorporating unconventional and renewable gases require this.

**No change to the hydrogen limit**

Prior to 1996 the British Gas Corporation employed a normal limit for hydrogen content of 10% (mol/mol), based on the consideration by Dutton of earlier work carried out in the 1970s. The limit was proposed by Dutton in anticipation of an imminent arrival of Substitute Natural Gases (SNGs) manufactured from petroleum feedstocks. In practice SNGs have not figured in GB energy mix to date and for the coming into force of the GS(M)R in 1996, hydrogen was set at an arbitrarily low value of 0.1 mol%. This removed the influence of hydrogen on calculation of WI, ICF and SI, effectively converting Dutton's three-dimensional 'interchangeability volume' into the current two-dimensional interchangeability diagram.

No change in the hydrogen limit is proposed at the current time, although there is scope for revision should assessment of future gas quality scenarios incorporating unconventional and renewable gases, together with hydrogen injection into natural gas grid, require this.

Figure 81 shows therefore the Modified Interchangeability Diagram resulting from the proposed changes discussed in the previous section. The majority of gases of Group H of the Second Gas Family sit within the boundary designated by the blue line. The arrows illustrate deviation from limits as follows:

A: High WI/low RD gases. Generally, these are not feasible, unless blending with low-density hydrogen is carried out (or significant helium is present, in which case its economic value would suggest extraction of helium prior to combustion).

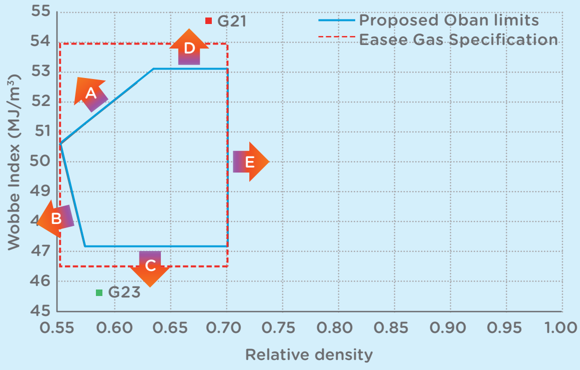
B: Low WI/low RD gases. Generally, these are not feasible, unless addition of low-density gases such as hydrogen is carried out (or significant helium is present).

C: Low WI gases. Generally, these are gases containing significant inerts (e.g. nitrogen, carbon dioxide) and little higher hydrocarbons. Some natural gases such as those from Morecambe bay and some biomethanes and coal bed methanes would fall into this category. Some shale gases may contain significant inerts and may also fit in this category.

D: High WI gases. Typically, these are likely to be a limited number LNG supplies, although some pipeline gases from Norwegian North Sea fields might fall into this category. Some ballasting with nitrogen would be required.

E: High density gases. Typically, this would be limited to: associated natural gases containing significant C2+ content; heavily enriched biogases (i.e. containing significant carbon dioxide – not biomethanes) and LPG-air mixtures (not employed in GB).

**Fig. 81** Modified natural gas interchangeability diagram



### 4. Transfer GS(M)R to IGEM Standard

An IGEM Gas Quality Standard working group should be established, based on representation from the whole GB Industry to consider evidence and determine the appropriateness of a new upper Wobbe Index Limit of 53.25 MJ/m³. If the Gas Quality Working Group supports a change to the gas quality requirements specified in GS(M)R Schedule 3, this should take the form of an IGEM Standard, simplifying the process for further changes to be accommodated within this area of the industry.

Following a number of meetings with IGEM, DECC, OFGEM and the HSE a structure has been agreed in principle, by the industry, that will oversee the transfer of schedule 3 of GS(M)R to an industry produced standard. This will support the rollout of the Oban findings and other work into GB. Simultaneously a wider review of the GS(M)R will be undertaken to ensure much needed changes are incorporated into the revised legislation at the same time.

### Why an IGEM standard

An IGEM standard is regularly reviewed and amended and has the confidence of industry and government agencies. Incorporating Schedule 3 into an IGEM standard provides a robust approach with the flexibility of allowing the specification to be appropriately developed as and when new evidence emerges. The review of IGEM standards follows a peer review process which involves wide industry consultation. This flexibility will benefit the consumer and the industry as the nature of the composition of the gas being consumed by GB customers' changes. As innovation and diversity of supply continues this would present GB with a robust, flexible, appropriate and future proofed mechanism.

### IGEM Gas Quality standard working group

This group and associated sub groups should compose subject matter experts from across the gas industry and other key stakeholders. The group should be an umbrella gas quality working group that initially considers the gas quality changes proposed in the Oban (Opening up the Gas Market) project, and then subsequently evaluates, identifies and facilitates projects toward gas quality changes. It will create a database of evidence in support of changes. It will potentially identify a number of offshoot projects, subject to a materiality and Cost benefit assessment.

The objectives of the working group are:

- Set up of a core group to drive the production of the standard and ensure appropriate representation from across the industry and supply chain.
- Identify and map relevant industry groups and bodies.
- Identify links and necessary representation for these both in GB and in the EU.
- Set up of sub groups (where required) which will examine the specific potential effects of a change in GS(M)R on the supply chain, industry, customers and asset owners.
- Develop database of current and previous studies into gas quality.
- Production of an IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.
- Evaluate, identify and facilitate projects toward future gas quality changes.
- Successful completion of the review process of the IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.
- Agreement and approval of the IGEM standard covering GB gas quality specification in order to facilitate a change from GS(M)R.

### IGEM role

IGEM should take the lead in establishing and facilitating the core working group developing the standard for gas quality. This will involve engagement and consultation with industry, mapping of industry groups and identifying links and necessary representation both in GB and in the EU. The core group will comprise key stakeholders and subject matter experts on matters relating to schedule 3 of GS(M)R. IGEM will develop and maintain an evidence database of all relevant studies and projects, both previous and current.

## 5. Review CO guidance message

A key learning from the project is that around 6% of GB appliances are likely at risk or immediately dangerous currently. Gas Quality in the range proposed presents a very small component of CO risk from appliances.

The project has shown that the importance of CO safety lies predominantly with the effective maintenance of appliances, with the correct installation of a CO alarm being treated as a secondary safeguard, rather than as the sole preventative measure.

While CO alarms, when installed correctly, are effective at raising the alarm in the event of a CO leak, they are reactionary rather than preventative. Whereas effective maintenance means that an appliance limits CO exposure, by taking effective measures where required during an inspection, the CO alarm could only highlight that a leak has already occurred.

In order to address this finding, it is recommended a review of CO awareness campaigns to ensure focus is targeted in areas that offer the most cost effective and real risk reductions i.e. appliance maintenance, servicing and replacement.

Furthermore, the optimum frequency and nature of appliance servicing should be reviewed and discussed between the gas distribution, appliance industries and IGEM gas quality standard working group in order to inform CO campaigns. Opportunities to effectively reduce pre-existing CO risk and improve appliance performance should also be explored with the relevant governmental and regulatory bodies.

Although not exhaustive, a number of options range from a focused CO campaign, targeted appliance inspection and replacement via scrappage schemes, to mandated periodic appliance servicing. These measures would have to be proportionate to the reduction in risk they could achieve.

### 6. Permanent GS(M)R Exemptions for the SIUs

SGN own and operate four mainland SIUs (Scottish Independent Undertakings) in Oban, Wick, Thurso and Campbeltown. These are discrete networks that are not connected to the main gas grid, rather supplied by regasified LNG. Historically, LNG for the four mainland SIU's has been obtained from any one of four LNG liquefaction facilities across GB, namely Glenmavis, Partington, Denyvor Arms and Avonmouth. In recent years, Partington and Denyvor Arms have closed and in July 2010 National Grid LNG advised SGN of their doubt regarding the long-term viability of the LNG plant at Glenmavis due to the age and condition of critical equipment.

In December 2010 SGN was notified that the liquefier had failed, causing LNG production to cease and that liquefaction facilities at Avonmouth would be the single source of compliant LNG supply for the SIU's. The originally selected Compressed Natural Gas (CNG) solution in 2011 was not viable and contingency LNG storage facilities were installed in Provan. In early 2013, National Grid announced that its Avonmouth LNG facility would be closing in 2018, therefore leaving SGN with no GS(M)R compliant supply option for the SIU's post 2018. Following an exhaustive review of multiple options, originally initiated when Glenmavis was due to close, it was determined that the most viable (in the time permitted) was to install nitrogen ballasting facilities at the four mainland SIU sites. Thus providing flexibility to procure LNG from any of the European truck loading LNG terminals and ballast the LNG to GS(M)R specification.

**Fig. 82** SGN's Mainland Scottish Independent Undertakings

In parallel with this, in 2013 SGN received funding for this ambitious project (OGM) to assess the potential to widen the permissible Wobbe range under GS(M)R.

In December 2013 National Grid LNG announced they were going to expedite the closure of the Avonmouth facility to April 2016. The ballasting could not be ready on all sites until 2018. At this point in time, the OGM project was progressing well and the likelihood of its success significantly increased.

Following the comprehensive appliance testing and inspection programme in Oban, an exemption was granted by the HSE to allow SGN to supply rich WI gas in Oban in 2014. In parallel to the development of the ballasting solution, the learning from the OGM project, in terms of appliance inspection, was applied to the remaining mainland SIU's. Exemptions for all SIU's has now been granted until April 2018. It is recommended that from 2018 onwards the exemptions are made permanent based upon the learning of this project.

# Further works

The following recommendations for further work are made as part of the Road Map for GB roll out.

1. Study on the impact of gas quality changes on industry and large commercial gas fired equipment.
2. Study on the impact of gas quality changes on the National Transmission System.
3. Report on findings from wider SIU appliance inspections.

**1. Impact on industrial and large commercial gas fired equipment**

Large commercial and industrial appliances were out with the scope of this project as there are no such appliances located within the Oban network. Whilst it is broadly accepted that industrial and commercial gas fired equipment is more tolerant due to investment in more sophisticated process control, certain production processes could be affected by gas quality changes.

Appropriate evidentiary requirements should be identified and projects scoped by the IGEM Gas Quality Standard working group. This should include a commercial impact analysis both of the change and the cost of delay.

Industrial and commercial gas-fired equipment are designed to tolerate to a wider range of WI and calorific value. In general, installed equipment for industrial use has more sophisticated burner types and process controls. Burner types may include:

- Air blast burners.
- Diffusion flame or post aerated burners with no premixing of gas and air.
- Nozzle mix burners.
- Pulse combustors.
- Catalytic burners.

It is acknowledged, there are a number of industrial processes that could be sensitive to a change towards gas with a higher WI such as:

- Furnaces with controlled atmospheres.
- Ceramics and glazing processes.
- Gas engines.
- Direct fired textile processes.

From a safe operation perspective, there are few concerns amongst manufacturers and industrial users alike, however it is recognised that the consequences in lost production or heating services could be significant to individual customers who may be affected by gas quality changes.

The impacts of a change in WI on gas fired Combined Cycle Power Plants is variable and very much depends on the quality and hydrocarbon contents of the gas used. Use of higher WI gases that are outside the acceptable gas quality band for a particular turbine could lead to operational issues such as, but not limited to, combustion dynamics, increased emissions including NOx, decreased component life and the change in fuel characteristics could potentially lead to substantial load swings.

Experience has shown that the combustion system of gas turbines is impacted by variations in fuel quality. A number of research studies to identify robust combustion system configurations that are capable of reliable operation with variable gas quality have been undertaken over the years.

Gas turbines are usually designed to operate without significant impact on performance with WI gases that are typically +/- 10% of their optimum design criterion.

The current WI band for GB specification gas is 47.20 > 51.41 MJ/m$^3$, so turbines designed to work with natural gas in GB would have a WI design criterion of 49.30 MJ/m$^3$ (+/- 10%) which gives an allowable swing of 4.9 MJ/m$^3$. This is comfortably within the current GB gas specification but although they are capable of accepting quite wide variations in gas quality most generating companies would require either automation via control instrumentation or prior notice and manual intervention to allow optimisation of the machines.

If not already fitted there are various instrumentation packages available that allow gas turbines to operate on a wider range of gas quality whilst maintaining optimum performance and exhaust emission levels, these systems allow greater flexibility in fuel specification and hence would enable power generators to leverage cost reduction due to reduced processing costs at the Gas/LNG reception terminals.

Most manufacturers offer upgrades for their generator packages that have the ability to automatically accept a wide and rapid variation in WI whilst protecting the operational boundaries of the gas turbine and optimising its performance. These systems require no manual intervention and achieve fuel flexibility throughout the operating envelope of the machine. They would typically allow systems to accommodate a 20% swing in WI and a rate of change in excess of 18% per minute.

With dynamic control systems it is possible to effectively change Gas Turbine control settings to adequately compensate for measured changes in fuel composition, two examples are given below.

Where WI is the critical feature controlled fuel heating and variable Vane technology can be used to effectively modify the WI in response to a change in gas composition, for example there is a system available called Opflex Balance auto tune which utilises a high speed Wobbe meter and fuel heating in conjunction with variable vane technology to effectively and continuously optimise system behaviour.

On the same lines one manufacturer has a system called Integrated Fuel Characterisation which as above incorporates a high speed Wobbe meter, fuel heating and variable vane technology to modify the combustion characteristics of its Gas Turbines.

Both systems can be fitted from new with retrofit solutions available for most turbines currently in service. These systems help mitigate the risk associated with gas composition variations but as always operators need to be aware of these developments to ensure that potential variations in fuel gas composition are properly considered.

A number of manufacturers supply instruments and telemetry such with various instruments that could be used in power generation control systems.

In understanding potential issues with power generation and industrial uses, SGN carried out engagement with a number of organisations. For the purposes of this report, specific details of site operation efficiency and capacity are considered commercially sensitive therefore we have not referenced or included the detail discussed.

Thus anecdotally, a substantial widening of WI allowed under GS(M)R should not be an issue for power generators in the UK using gas turbines to generate electricity. Most sites would require some upgrade work, mostly software with some older sites requiring upgrades to telemetry and instrumentation, especially if within day changes to gas quality were likely to be experienced.

This should initially take the form of a detailed review of prior studies worldwide, some of which have been identified through Marcogaz Gas Quality Working group. Any gaps in understanding the effect should be identified with the relevant representations, such as ICOM and Energy UK, and subsequently a programme of in-situ testing should be carried out.
A number of older designs of industrial gas appliances incorporate partially premixed burners, where the natural gas is mixed with a sub-stoichiometric quantity of air at the injector and then additional combustion air diffused into the flame after its emergence from the burner ports. These burners tend to show a relatively flat response of CO emissions with WI variations i.e. CO emissions do not increase quickly as WI increases or decreases.

Fully pre-mixed burners using gas/air ratio controls effectively ‘meter’ precise quantities of natural gas and air into the appliance (at a fixed gas/air ratio) and no additional excess air permitted. Previous studies and the OGM project have shown that, depending on the Wobbe Index of initial adjustment, fully pre-mixed appliance performance can be sensitive to WI variations and CO emissions can rise as the WI of the gas supplied changes.

The OGM project has demonstrated that fully pre-mixed burners, which have been initially adjusted at a WI of 50.72 MJ/m$^3$ (G20), are shown to operate satisfactorily at the gas ‘Oban limit’ WI range i.e. 47.20-53.25 MJ/m$^3$.

However, it has not yet been confirmed that this also applies for large-scale Industrial and Commercial gas equipment.

It is recommended that further analysis is required to understand the impact of the change to Wobbe limits proposed. This should be co-ordinated through the proposed Gas Quality standard working group umbrella project.

**2. Impact on National Transmission System**
National Grid Gas Transmission (NGGT) is conducting a project[56] to understand the likely impact of different gas specifications on existing and future National Transmission System (NTS) assets and operations. The risks and impacts to the NTS asset capability due to a change in WI need to be identified, qualified and quantified. Of particular consideration is the % ethane content, as anecdotally it can behave differently above 12% in terms of hazardous areas and pipeline/storage failure characteristics.

The initial phase of the project will concentrate on the identification of assets, processes and operations that may be impacted by a change in the specification of GB gas quality in respect to all NTS assets.

An assessment will be carried out to qualify and quantify the risk and impact on specific performance of key NTS asset types that will be impacted by a change in specification. Where an adverse impact is identified, the risk will be quantified and where remedial action is possible, an estimation of outline cost will be provided. For emissions, the cost of remedial action will focus on those assets selected on highest risk and priority as advised by NGGT.

The results of the project should be reviewed by the IGEM Gas Quality Standard working group.

**3. Report on findings from wider SIU appliance inspections**
In December 2015 National Grid LNG announced that Avonmouth liquefaction facility was closing in April 2016. Avonmouth was the only facility left in GB that can supply GS(M)R compliant LNG to the SIUs.

SGN was planning to construct Nitrogen ballasting facilities in the SIUs, however these could not be commissioned in all four SIU sites until 2018 and hence SGN would not able to supply GS(M)R compliant gas to these sites until 2018.

A project was therefore undertaken by SGN to seek an exemption to GS(M)R by the HSE in order to supply high Wobbe Index LNG from Europe or Isle of Grain until such time that the ballasting facilities were installed.

The exemption application used the work already carried out in Oban under the ‘Opening up the Gas Market’ project as a blueprint for obtaining an exemption. Results from the OGM in Oban demonstrated that gas appliances correctly installed, serviced and operated can safely burn gas with WI up to 53.25 MJ/m³.

With this in mind and given the tight timescale until April 2016, it has was agreed with industry experts (Dave Lander Consulting and Kiwa) that the best approach to obtaining an exemption was to inspect all 5,981 appliance installations in the remaining SIUs to confirm that they are installed, serviced and operated correctly, and rectify where necessary. The work was also necessary to generate the required evidence base to support formal application to the HSE for GS(M)R exemption from gas quality limits in the SIUs until 2018.

An exemption level of 53.25 MJ/m³ for each mainland SIU was subsequently approved by the HSE in April 2016. The exemptions are due to expire in 2018.

It is suggested that a full report detailing the findings of the appliance inspections is produced. This will add to the evidence produced from Oban to support the insight in to GB appliance health.

Data pertaining to CO alarms was captured that included a check for the existence of alarms in rooms with gas appliances and also whether or not the alarm  was fully functional and correctly installed.

This additional data should form part of this report to give an insight into the effectiveness of CO alarms installed in customers properties. This will support the data provided by ‘The Carbon Monoxide – Be Alarmed!’ campaign run by Energy UK on behalf of British Gas, EDF Energy, E.ON, npower, Scottish Power and SSE, in partnership with the Dominic Rodgers Trust[57].

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[56] http://www.smarternetworks.org/NIA_PEA_PDF/NIA_NGGT0094_4114.pdf
[57] http://www.co-bealarmed.co.uk/about/

# Appendices

# Appendix 1 – references to literature

3 DNV GL Demographic Analysis of Oban for Gas Testing, 2013.

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40 https://www.gassaferegister.co.uk/media/1774/tb_001_-_gas_industry_unsafe_situation_procedure_-giusp-_edition-71.pdf

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48 Rail Safety and Standards Board Guidance on the use of cost-benefit analysis when determining whether a measure is necessary to ensure safety so far as is reasonably practicable July 2014 http://www.rssb.co.uk/risk-analysis-and-safety-reporting/risk-analysis/taking-safe-decisions/taking-safe-decisions-safety-related-cba

52 Health and Safety Executive. 'A Guide to the Gas Safety (Management Regulations'. HSE Books ISBN 978 0 7176 1159 1.

53 B.C.Dutton. 'A new dimension to gas interchangeability'. IGEM Communication 1246, 50th Autumn Meeting. 1984.

56 http://www.smarternetworks.org/NIA_PEA_PDF/NIA_NGGT0094_4114.pdf

# Appendix 2 – extract from BS 7967: 2015 – (Combustion Performance Action Levels)

## Guide for the use of electronic portable combustion gas analysers for the measurement of carbon monoxide in dwellings and the combustion performance of domestic gas-fired appliances

| | | $CO/CO_2$ ratio | |
|---|---|---|---|
| **Appliance type** | | **Current** | **Appliances with gas-air ratio control** |
| Back boiler unit | Boiler unit | 0.0080 | 0.0040 |
| | In combination with fire* | N.A.* | – |
| Central heating boiler | | 0.0080 | 0.0040 |
| Circulator | | 0.0100 | – |
| Combination boiler | | 0.0080 | 0.0040 |
| Gas fire | Open-flue (type B) | 0.0200 | – |
| | Room sealed (type C) live fuel effect | 0.0200 | |
| | Other room-sealed (type C) | 0.008 | |
| | Flueless (type A) | 0.0010 | |
| Water heater – flued and flueless | | 0.0200 | |
| Warm air heater | | 0.0080 | 0.0040 |
| Flueless cookers | Cooker oven (domestic & commercial) | 0.0080 | – |
| | Cooker hob (domestic & commercial) | Visual inspection of flames (value of 0.01 used for this project | |
| | Cooker grill (CE marked – domestic & commercial) | 0.0100 | |
| | Cooker grill (non CE marked – domestic & commercial) | Value of 0.01 used for this project | |
| Range oven (flued) | | 0.0200 | |
| Tumble drier | Flued | 0.0100 | |
| | Flueless | 0.0010 | |
| Commercial catering | All types (except hob, oven grill, wok) | Value of 0.01 used for this project | – |

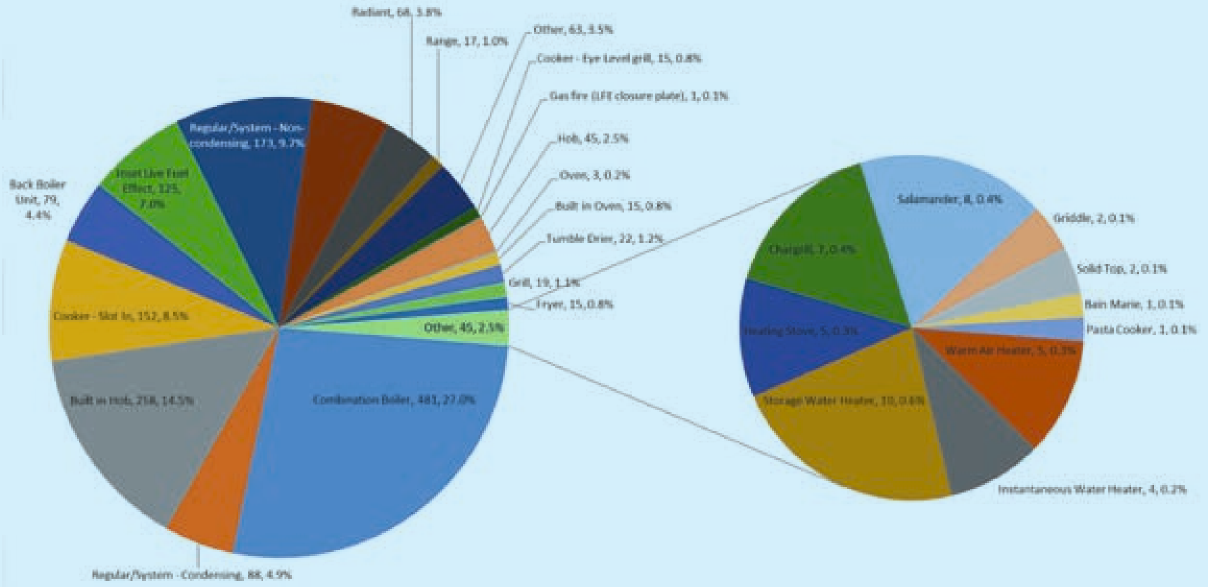
*not used – for the purposes of this test program BBU and firefront are tested separately

# Appendix 3 – list of British and European testing standards

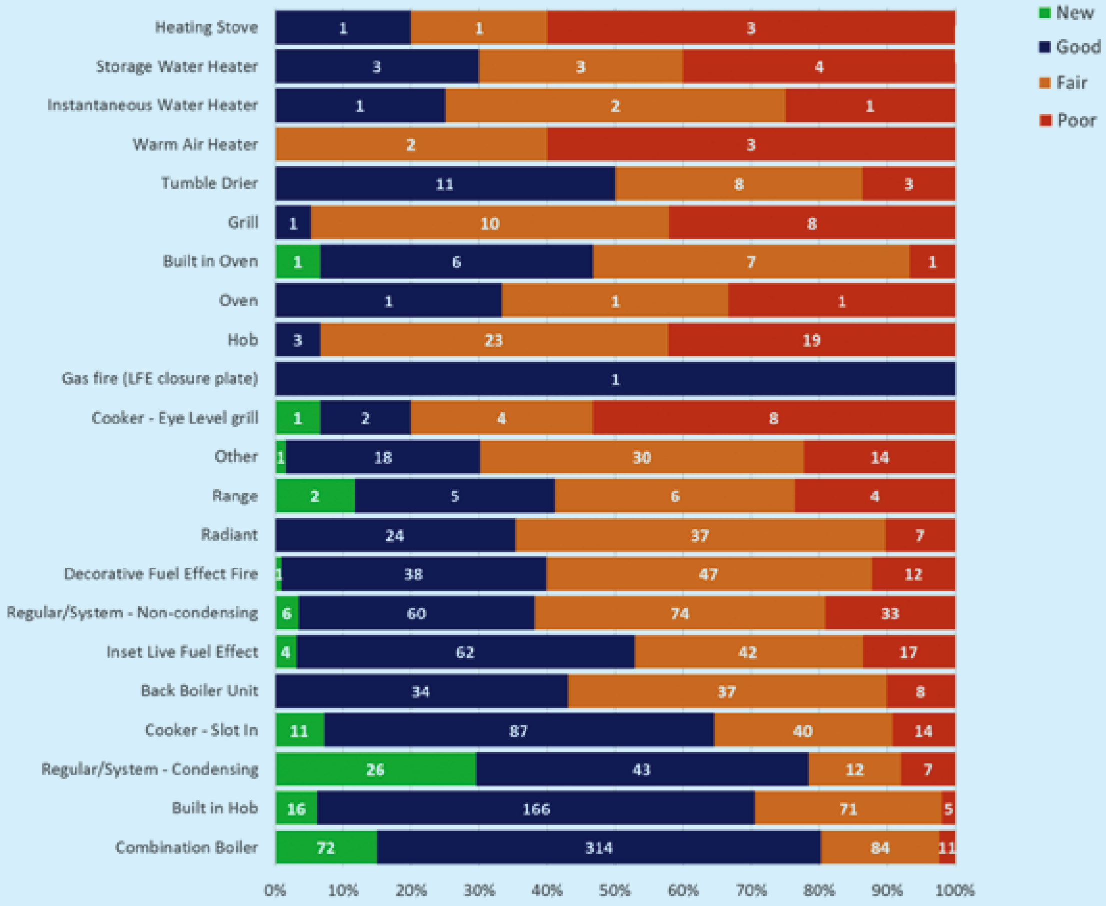
| Appliance type | Test standard |
|---|---|
| Local space heaters (gas fires) | BS EN 509:2000 +A1: 2003 +A2: 2004 – Decorative fuel-effect gas appliances.<br>BS EN 613:2001 + A1: 2003 +C1: 2008 – Independent gas-fired convection heaters.<br>BS 7977-1:2009+A1:2013 – Specification for safety and rational use of energy of domestic gas appliances. Radiant/convectors. |
| Domestic cooking appliances | BS EN 30-1-1:2008+A3:2013 – Domestic cooking appliances burning gas. Safety. General. |
| Commercial catering appliances | BS EN 203-1:2014 – Gas heated catering equipment. General safety rules. |
| Central heating and combination boilers | BS EN 15502-1:2012 – Gas-fired heating boilers. General requirements and tests.<br>BS EN 15502-2-1:2012 – Gas-fired central heating boilers. Specific standard for type C appliances and type B2, B3 and B5 appliances of a nominal heat input not exceeding 1000 kW.<br>BS 7977-2:2003 – Specification for safety and rational use of energy of domestic gas appliances. Combined appliances. Gas fire/back boiler. |
| Shell boiler with forced draught burner | BS EN 303-3:1999 – Heating boilers. Gas-fired central heating boilers. Assembly comprising a boiler body and a forced draught burner.<br>BS EN 303-7:2006 – Heating boilers. Gas-fired central heating boilers equipped with a forced draught burner of nominal heat output not exceeding 1000 kW. |

# Appendix 4 – appliance health by appliance type

## Appliance type population – Oban

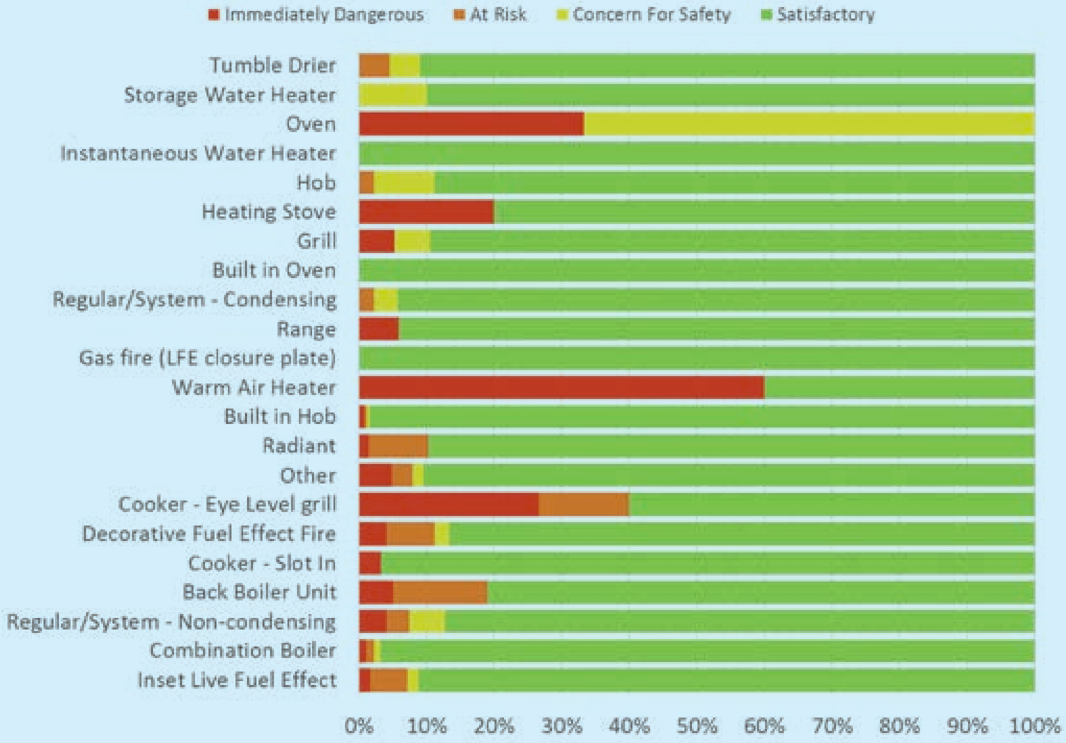


## Condition by appliance type – Oban

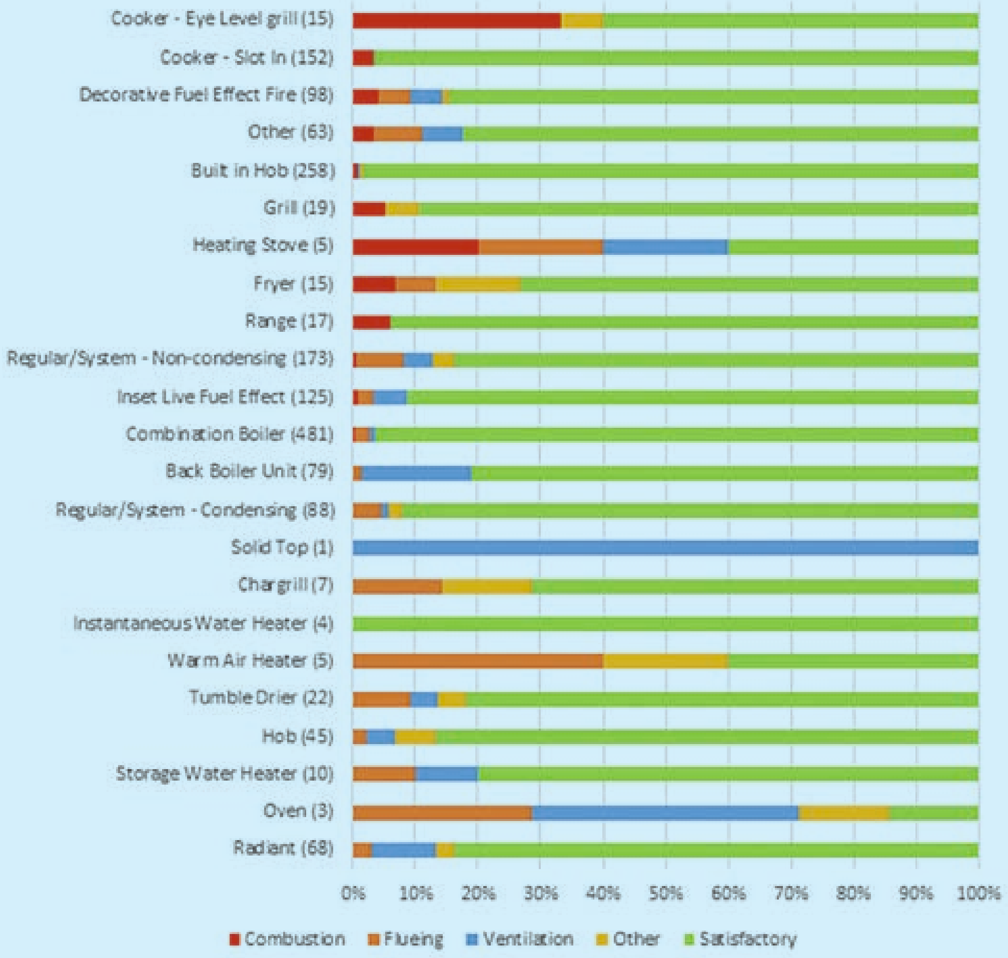


# Appendix 4 – appliance health by appliance type *cont.*

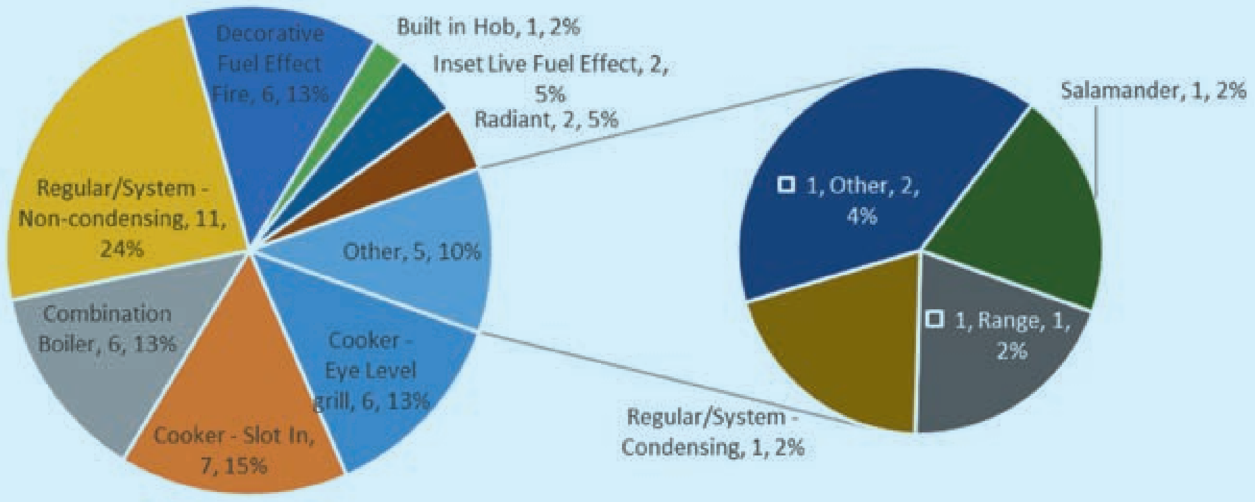
Unsafe situations by appliance type – Oban



Unsafe situations (fault classification) by appliance type



Appliances replaced by appliance type – Oban



# Appendix 5 – reasons for appliance replacement

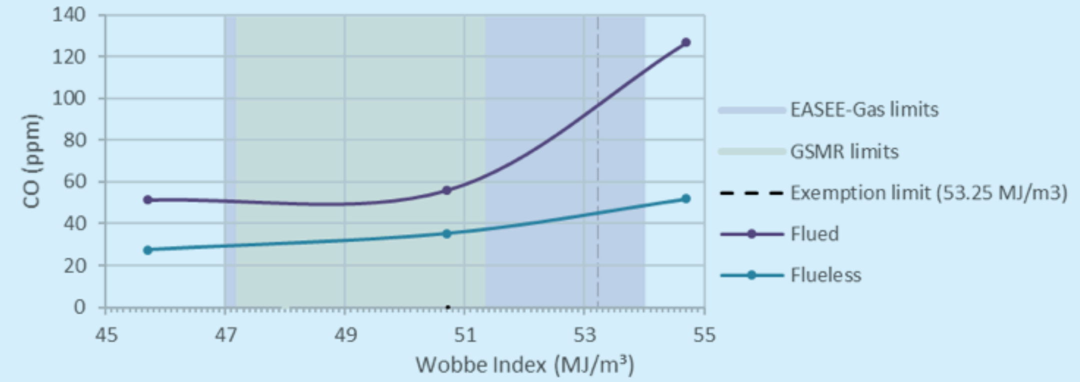
| Burner ID | Appliance condition | Unsafe situation | Appliance category | Appliance type | Burner category | Flue type | Reason for replacement |
|---|---|---|---|---|---|---|---|
| 14196 | Fair | S | Central heating boilers | Combination boiler | Boilers | FBF | Appliance general faults |
| 14235 | Poor | CS | Central heating boilers | Combination boiler | Boilers | FBF | Flue fault |
| 14585 | Poor | ID | Central heating boilers | Combination boiler | Boilers | OF | Flue fault |
| 14627 | Poor | AR | Central heating boilers | Combination boiler | Boilers | FF | Not tested – flue and ventilation faults |
| 14671 | Fair | S | Central heating boilers | Combination boiler | Boilers | BF | Appliance general faults |
| 15060 | Fair | ID | Central heating boilers | Combination boiler | Boilers | FBF | Multiple appliance faults and combustion fault G20 |
| 15878 | Poor | AR | Central heating boilers | Regular/system – condensing | Boilers (gas/air ratio) | FF | Combustion fault G20 |
| 13804 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Combustion fault G20 |
| 14107 | Fair | ID | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Not tested – multiple appliance faults |
| 14191 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | BF | Appliance faults and flue fault |
| 14281 | Poor | AR | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Not tested – multiple appliance faults |
| 14332 | Poor | AR | Central heating boilers | Regular/system – non-condensing | Boilers | BF | Combustion fault G20 |
| 14574 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Combustion fault G20 |
| 14584 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | BF | Not tested – multiple appliance faults |
| 14945 | Poor | AR | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Flue fault |
| 15217 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | BF | Combustion fault G20 |
| 15220 | Poor | CS | Central heating boilers | Regular/system – non-condensing | Boilers | BF | Flue fault |
| 15534 | Poor | ID | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Appliance faults and combustion fault G20 |
| 15181 | Poor | CS | Central heating boilers | Regular/system – non-condensing | Boilers | OF | Flue fault |

| Burner ID | Appliance condition | Unsafe situation | Appliance category | Appliance type | Burner category | Flue type | Reason for replacement |
|---|---|---|---|---|---|---|---|
| 15819 | Poor | S | Commercial cooking | Salamander | Commercial grill | FL | Combustion fault G20 |
| 14611 | Poor | ID | Domestic cooking | Built in hob | Hob | FL | Combustion fault G20 |
| 13894 | Poor | AR | Domestic cooking | Cooker – eye level grill | Hob | FL | Not tested – multiple appliance faults |
| 14043 | Poor | ID | Domestic cooking | Cooker – eye level grill | Grill | FL | Combustion fault G20 |
| 14143 | Poor | ID | Domestic cooking | Cooker – eye level grill | Grill | FL | Combustion fault G20 |
| 14313 | Fair | ID | Domestic cooking | Cooker – eye level grill | Grill | FL | Not tested – multiple appliance faults |
| 14396 | Poor | ID | Domestic cooking | Cooker – eye level grill | Grill | FL | Combustion fault G20 |
| 16012 | Poor | AR | Domestic cooking | Cooker – eye level grill | Grill | FL | Combustion fault G20 |
| 13735 | Poor | S | Domestic cooking | Cooker – slot In | Grill | FL | Combustion fault G20 |
| 13793 | Poor | ID | Domestic cooking | Cooker – slot In | Grill | FL | Combustion fault G20 |
| 13859 | Poor | ID | Domestic cooking | Cooker – slot In | Grill | FL | Combustion fault G20 |
| 14242 | Poor | ID | Domestic cooking | Cooker – slot In | Hob | FL | Combustion fault G20 |
| 14504 | Fair | ID | Domestic cooking | Cooker – slot In | Hob | FL | Combustion fault G20 |
| 15123 | Poor | ID | Domestic cooking | Cooker – slot In | Hob | FL | Not tested – multiple appliance faults |
| 15353 | Poor | S | Domestic cooking | Cooker – slot In | Grill | FL | Not tested – multiple appliance faults |
| 14416 | Poor | ID | Domestic cooking | Range | Grill | FL | Combustion fault G20 |
| 15349 | Poor | AR | Other | Other | Boilers | FF | Combustion fault G20 |
| 15625 | Poor | S | Other | Other | Boilers | BF | Not tested – multiple appliance faults |
| 13922 | Fair | S | Space heating | Decorative fuel effect fire | Flued space heater | OF | Multiple appliance faults and flue fault |
| 14065 | Fair | AR | Space heating | Decorative fuel effect fire | Flued space heater | BF | Combustion fault G20 |
| 14768 | Poor | CS | Space heating | Decorative fuel effect fire | Flued space heater | OF | Appliance faults and flue fault |
| 15029 | Fair | AR | Space heating | Decorative fuel effect fire | Flued space heater | OF | Combustion fault G20 |
| 15644 | Poor | S | Space heating | Decorative fuel effect fire | Flued space heater | BF | Combustion fault G20 |
| 15821 | Poor | S | Space heating | Decorative fuel effect fire | Flued space heater | OF | Not tested – multiple appliance faults |
| 15262 | Poor | S | Space heating | Inset live fuel effect | Flued space heater | OF | Not tested – multiple appliance faults |
| 15820 | Poor | AR | Space heating | Inset live fuel effect | Flued space heater | OF | Combustion fault G20 |
| 13759 | Poor | AR | Space heating | Radiant | Flued space heater | OF | Not tested – multiple appliance faults |
| 14553 | Poor | AR | Space heating | Radiant | Flued space heater | OF | Not tested – multiple appliance faults |

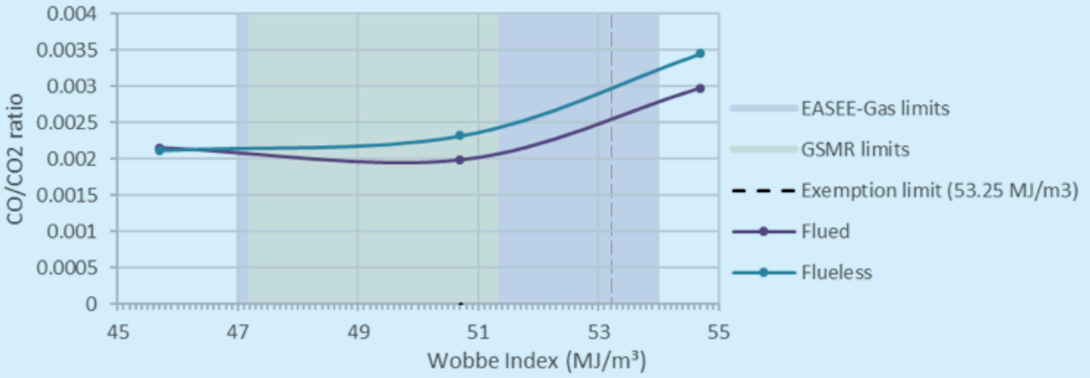
# Appendix 6 – combustion results by appliance burner type

### Average flued and flueless appliance CO emissions ppm and CO/CO$_2$ results for test gases G23, G20 and G21

Average CO results vs Wobbe Index by flued and flueless appliances

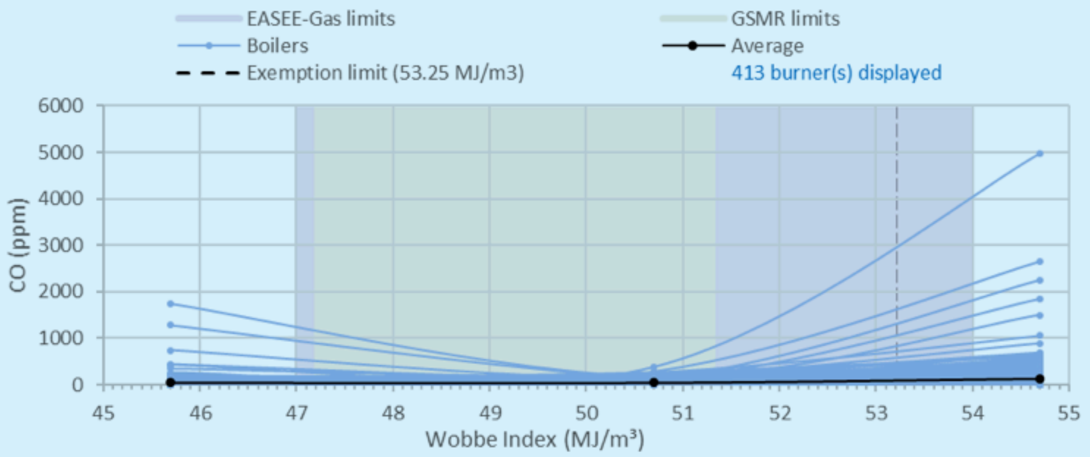


Average CO/CO$_2$ ratio results vs Wobbe Index by flued and flueless appliances

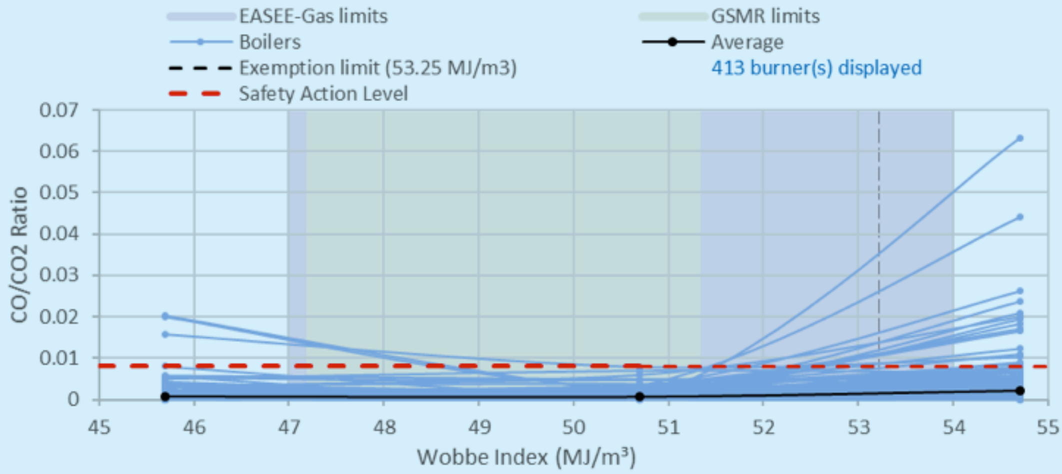


### Appliance type CO ppm and CO/CO$_2$ results for test gases G23, G20 and G21

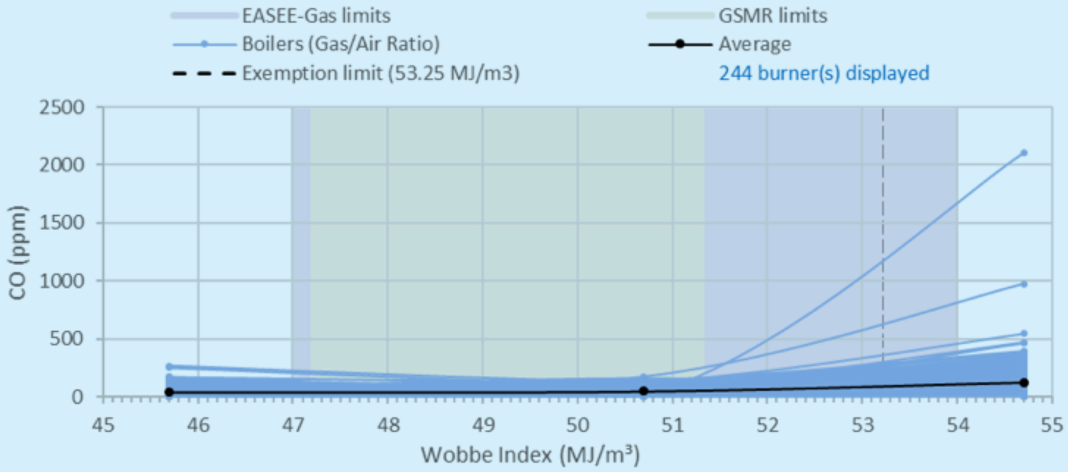
Boilers CO ppm



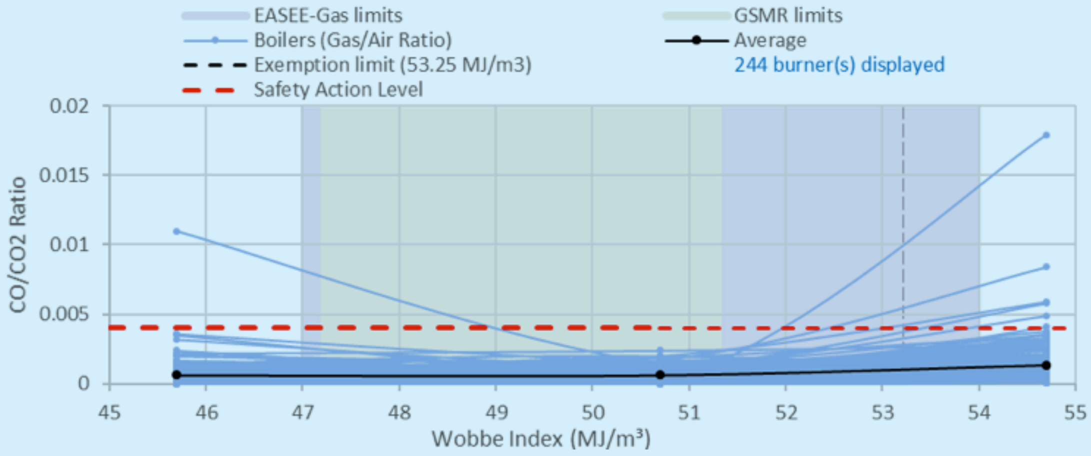
Boilers CO/$CO_2$ ratio



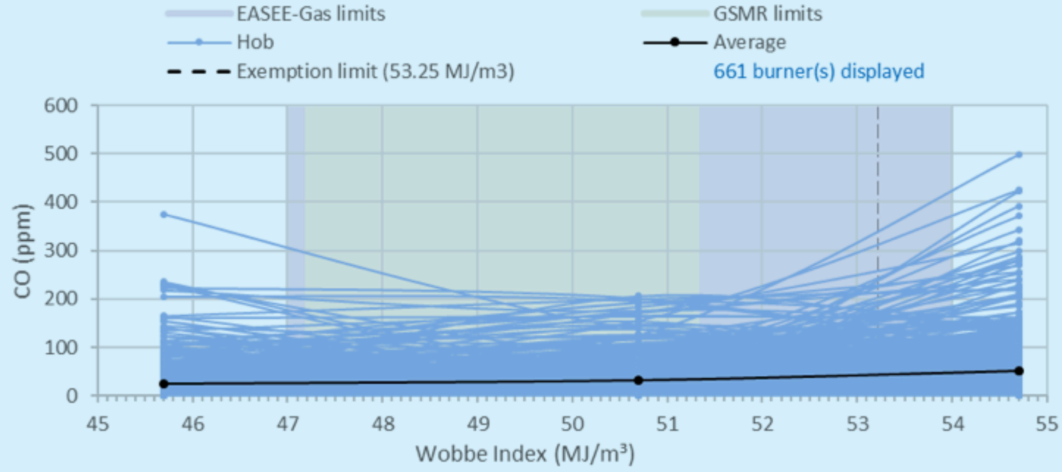
Boilers (air/gas ratio) CO ppm



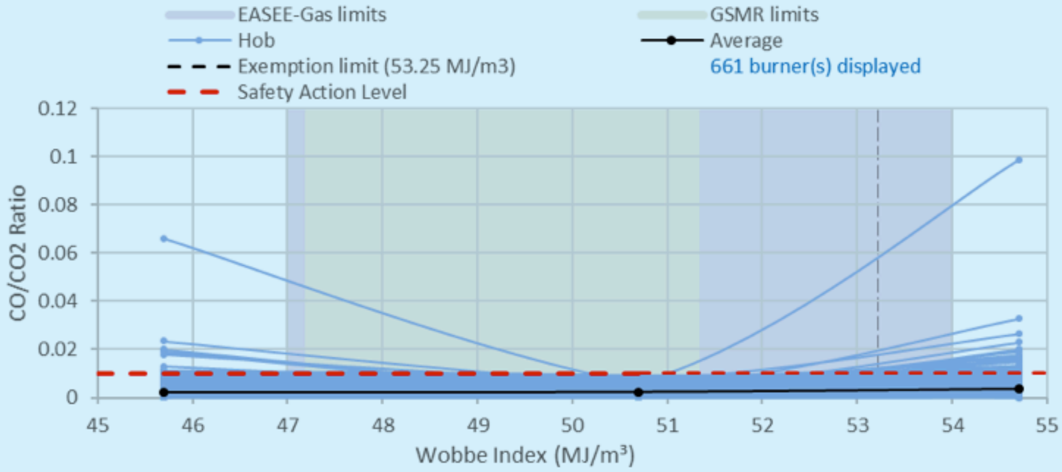
Boilers (air/gas ratio) CO/$CO_2$ ratio



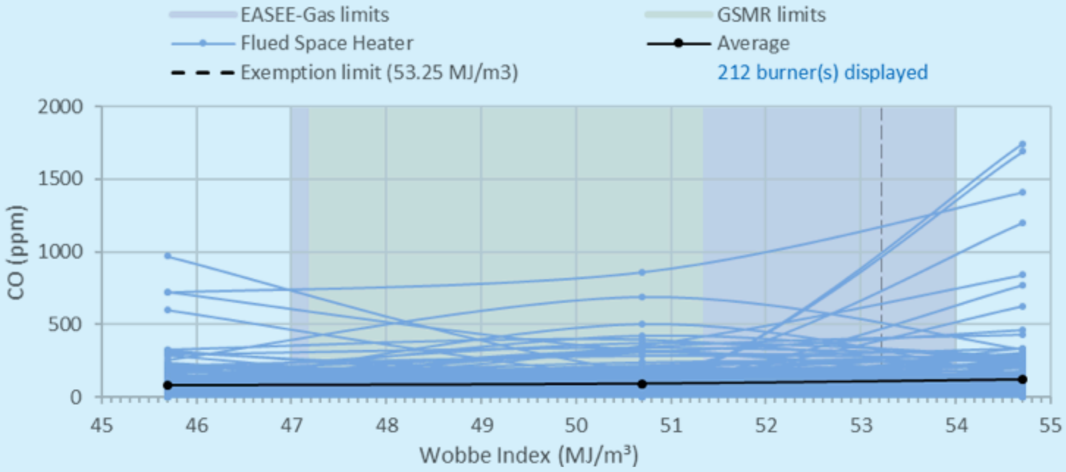
Hobs CO ppm



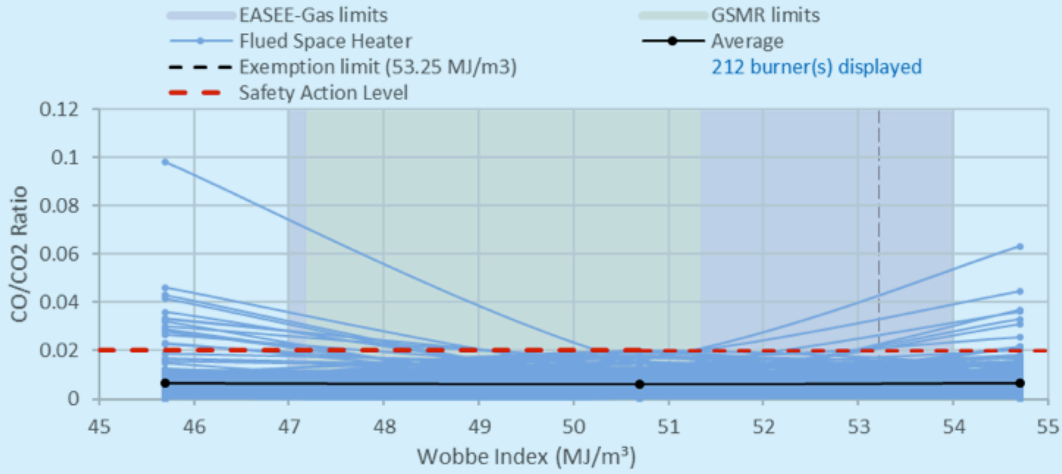
Hobs CO/$CO_2$ ratio



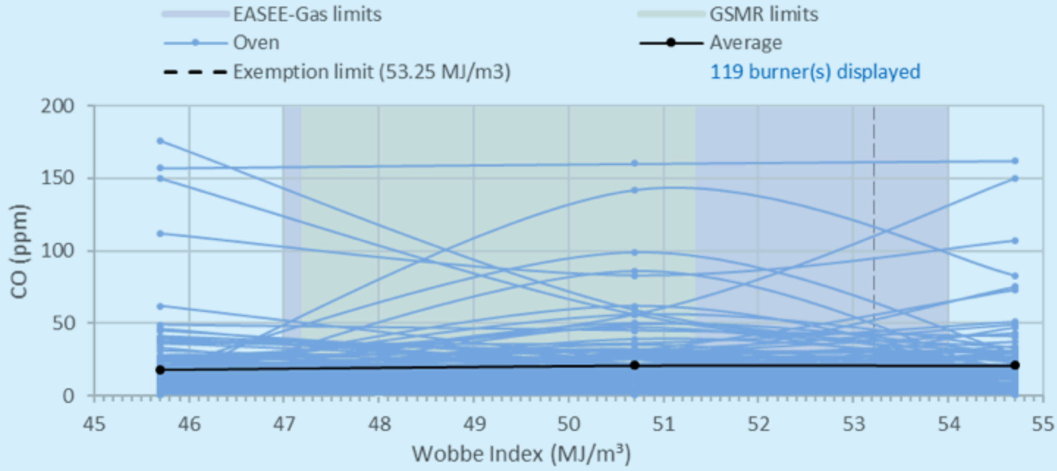
Flued space heater CO ppm



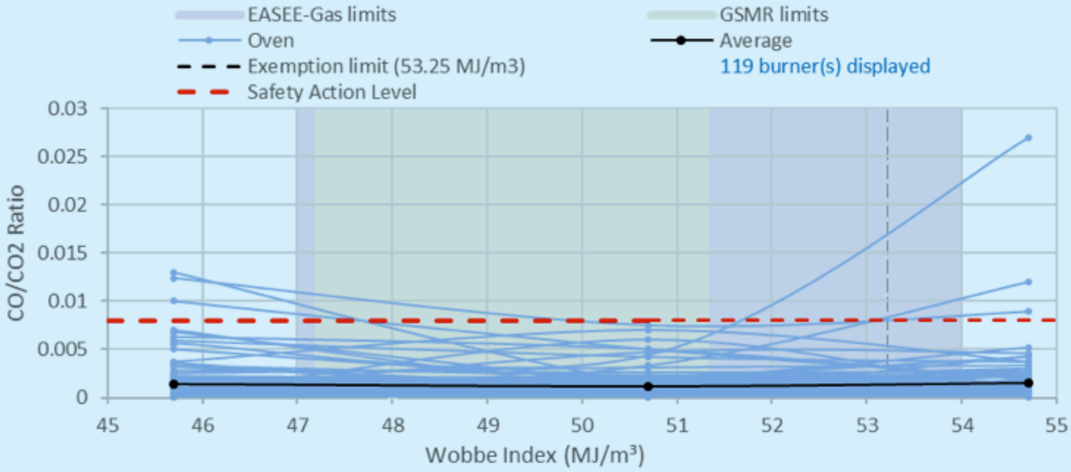
Flued space heater CO/$CO_2$ ratio



Ovens CO ppm

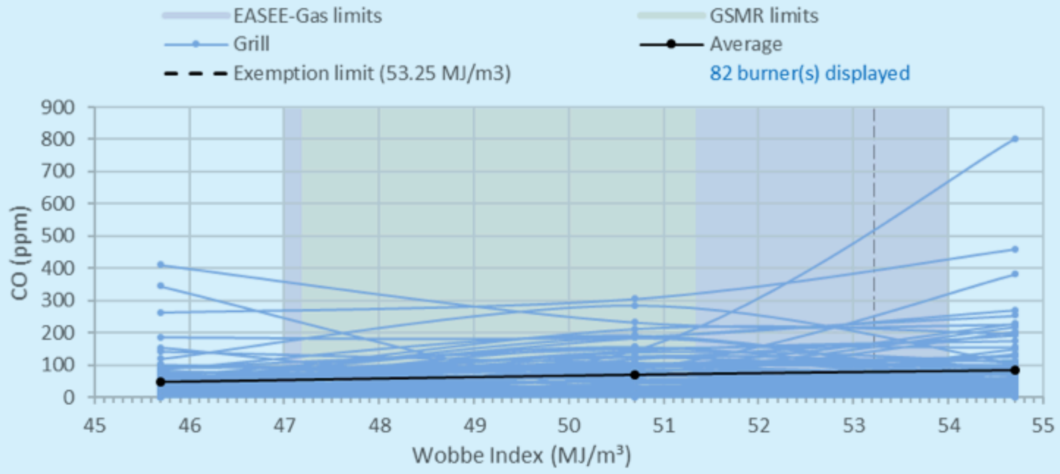


Ovens CO/$CO_2$ ratio

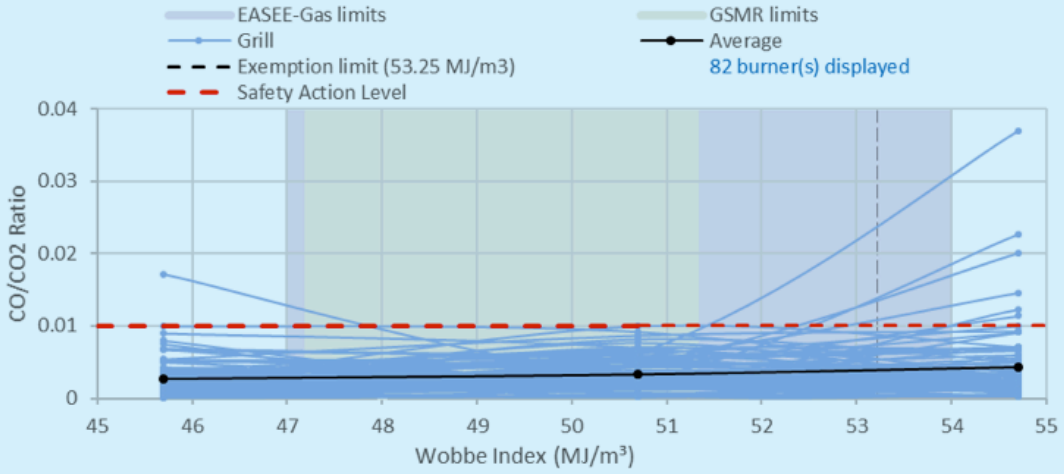


# Appendix 6 – combustion results by appliance burner type *cont.*

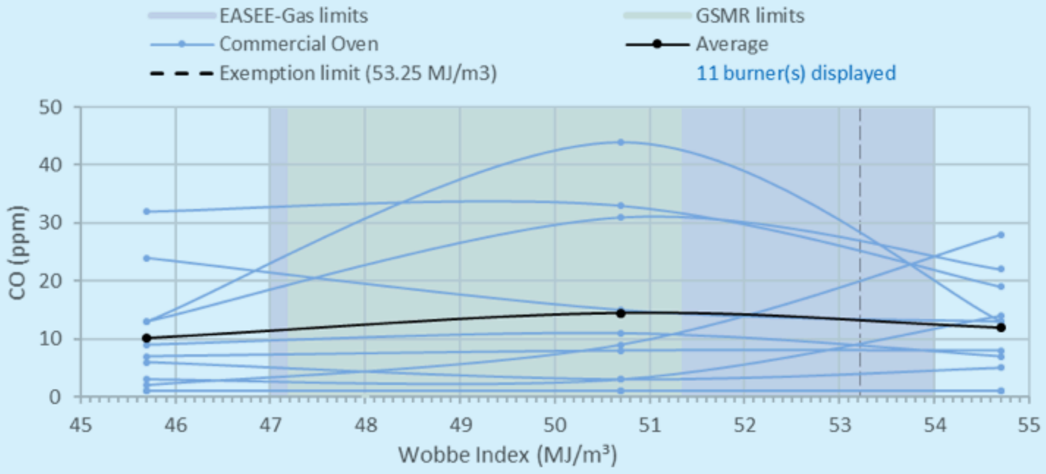
Grills CO ppm



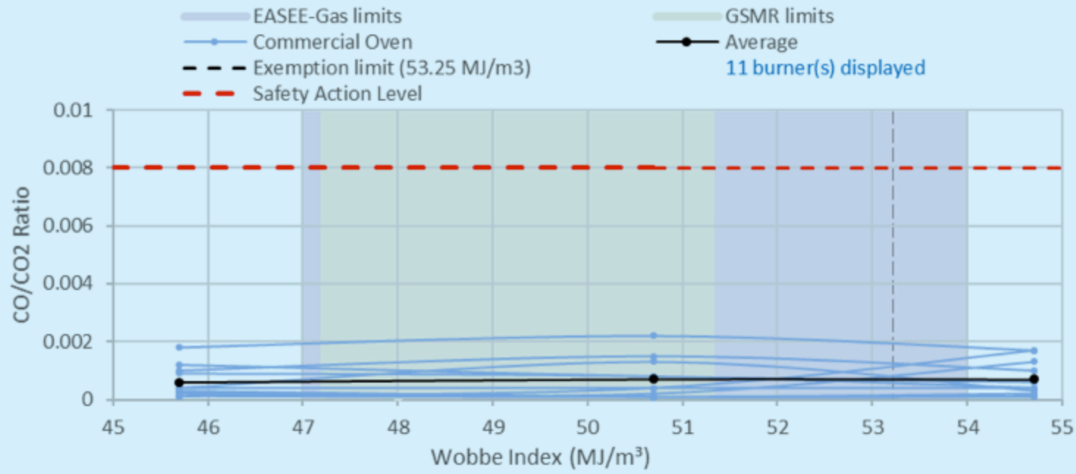
Grills CO/$CO_2$ ratio



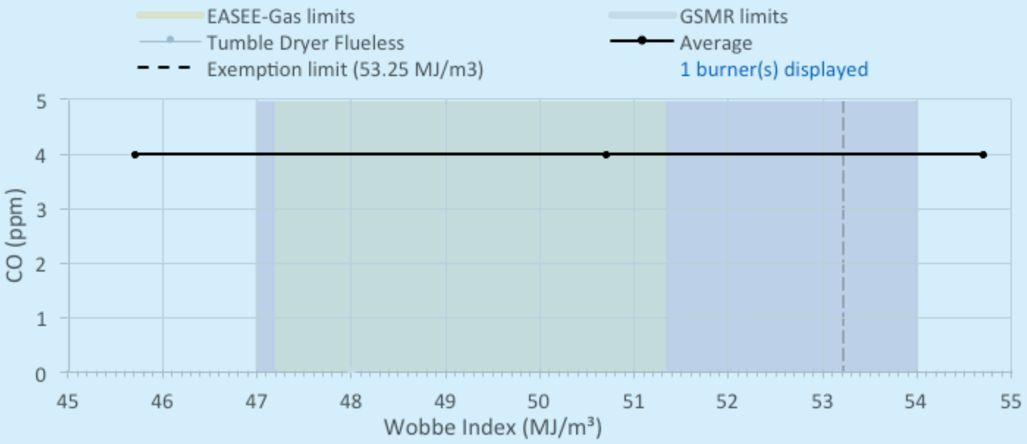
Commercial ovens CO ppm



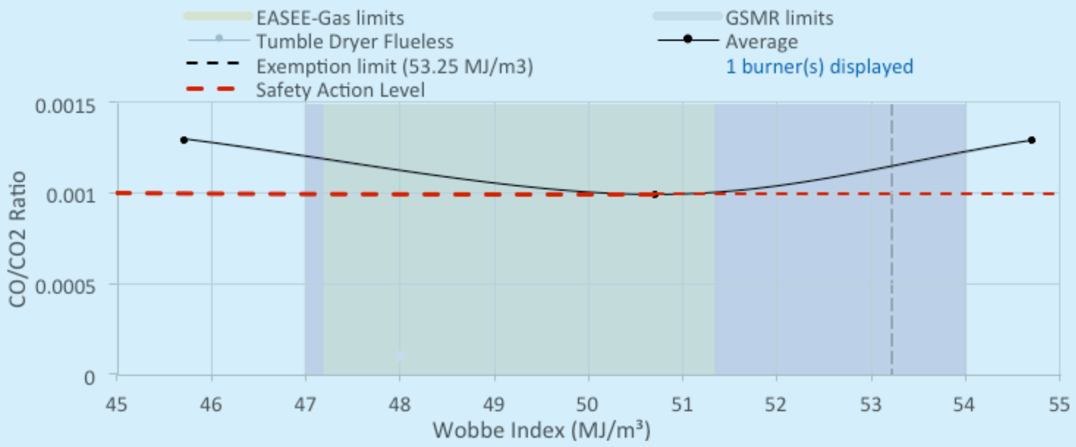
Commercial ovens $CO/CO_2$ ratio



Commercial hob CO ppm

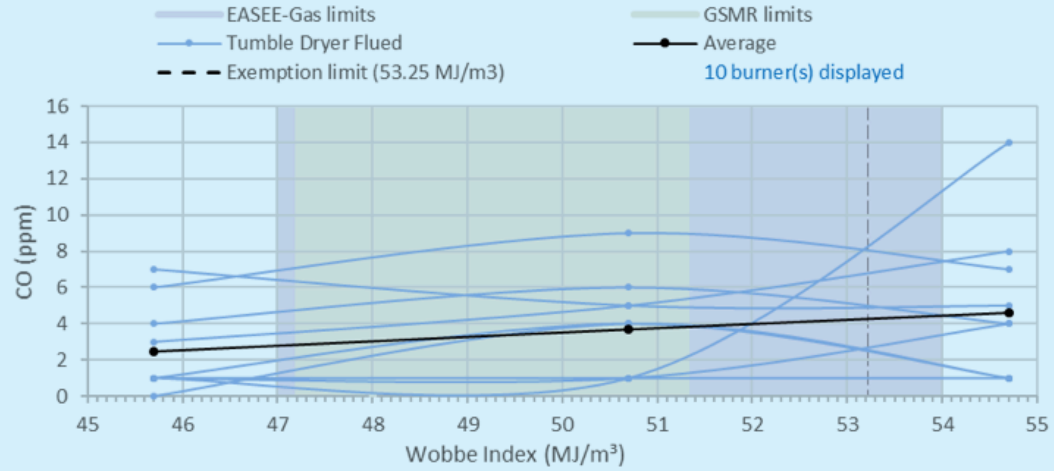


Commercial hob $CO/CO_2$ ratio

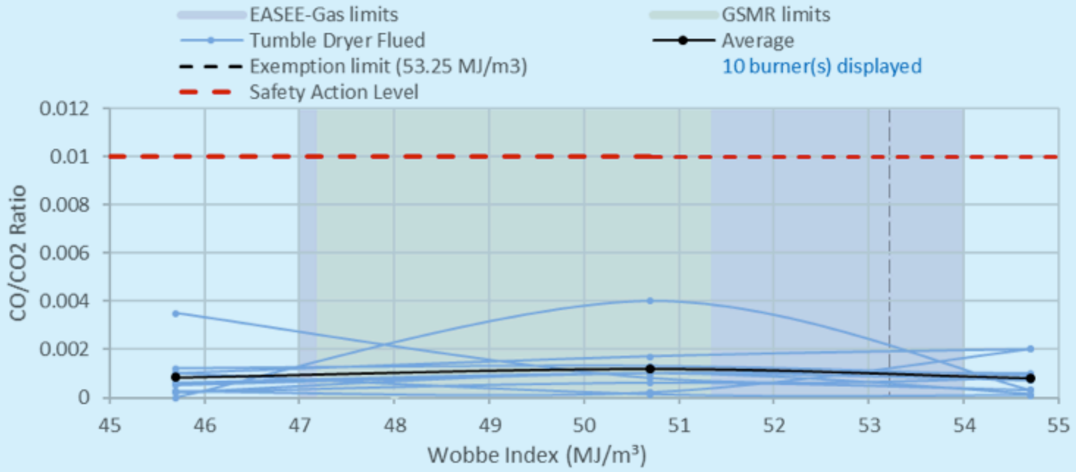


# Appendix 6 – combustion results by appliance burner type *cont.*

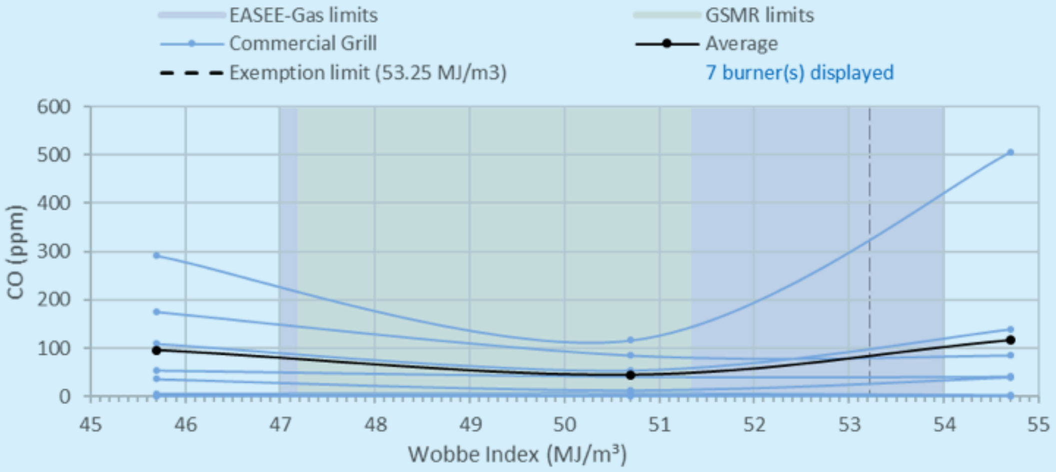
Tumble dryer flued CO ppm



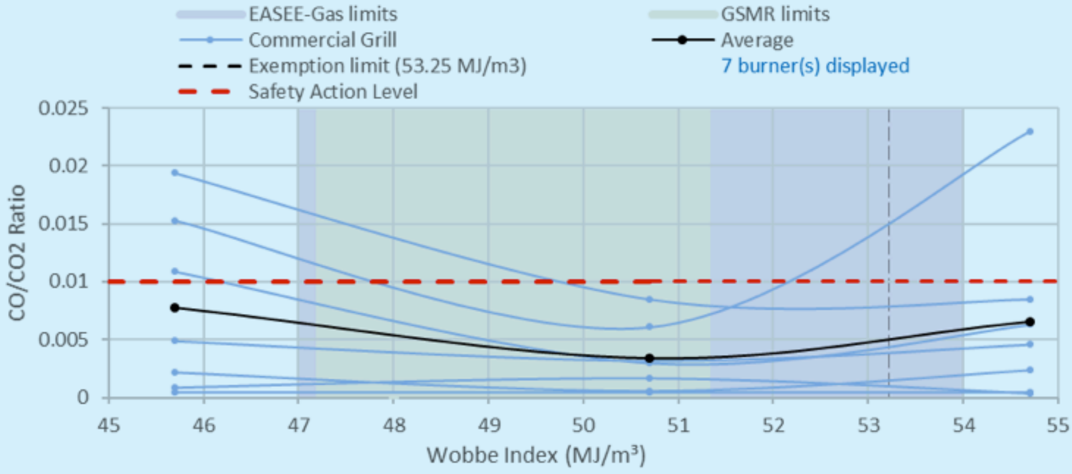
Tumble dryer flued CO/CO$_2$ ratio



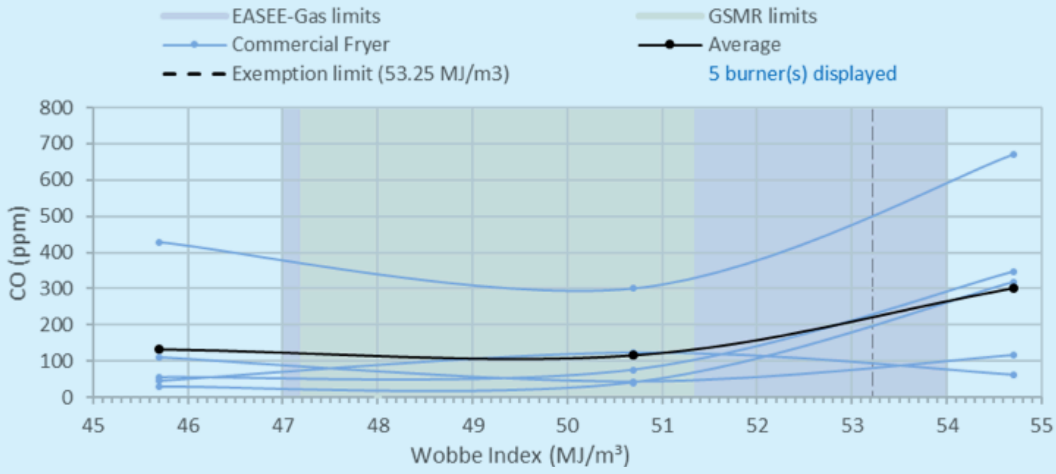
Commercial grill CO ppm



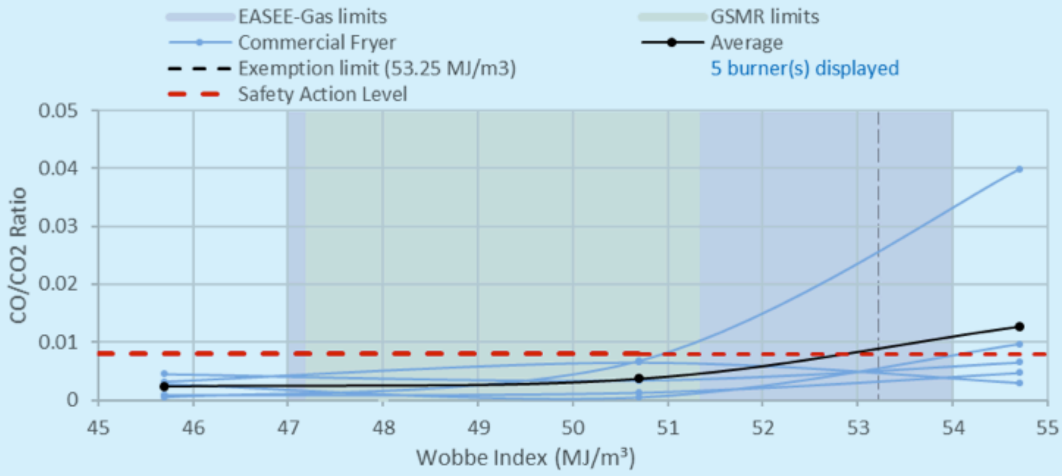
Commercial grill CO/CO$_2$ ratio



Commercial fryer CO ppm

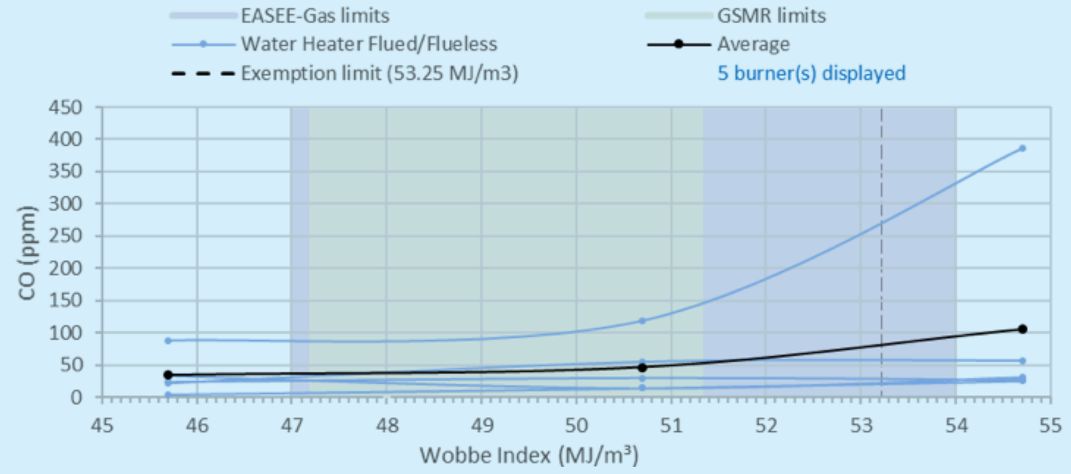


Commercial fryer CO/CO$_2$ ratio

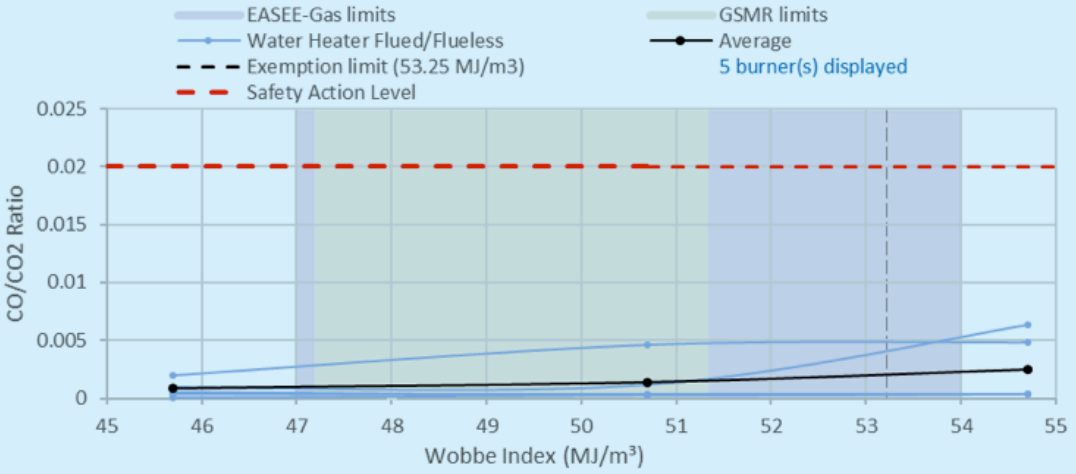


# Appendix 6 – combustion results by appliance burner type *cont.*

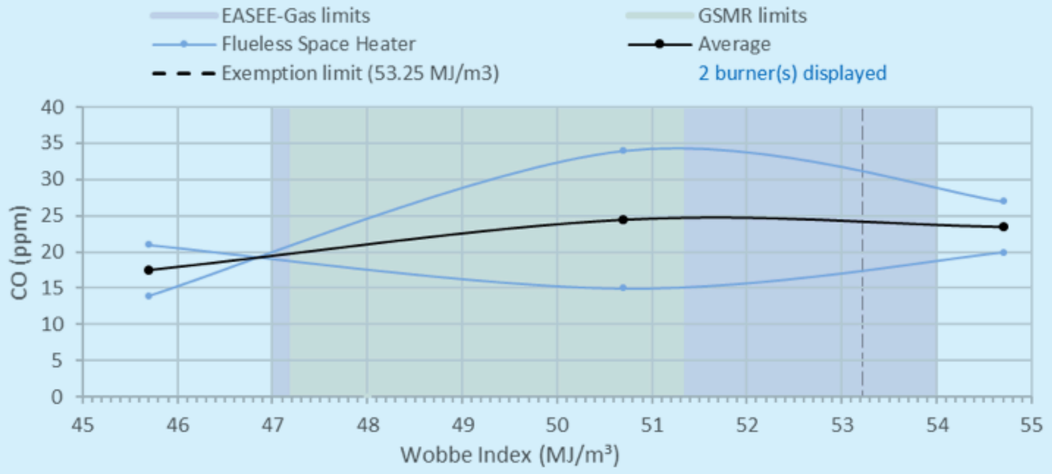
Water heater flued and flueless CO ppm



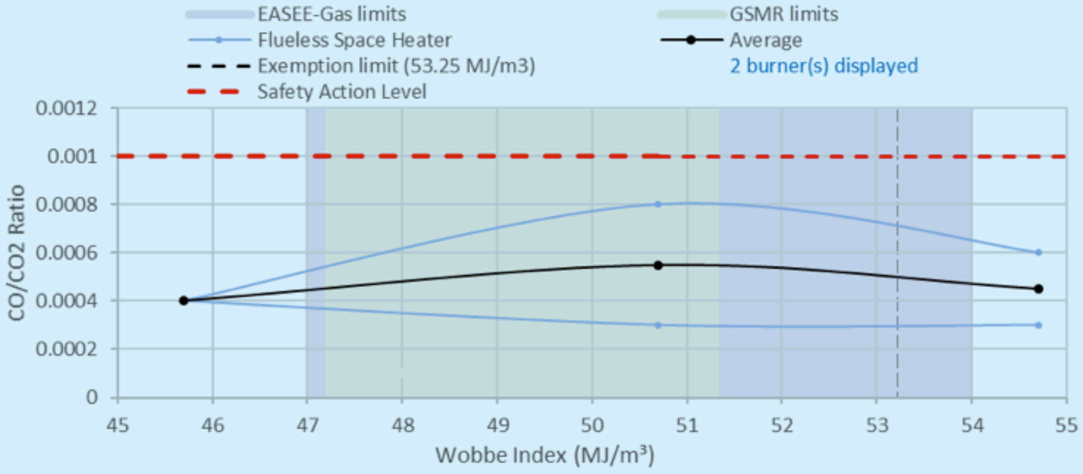
Water heater flued and flueless CO/$CO_2$ ratio



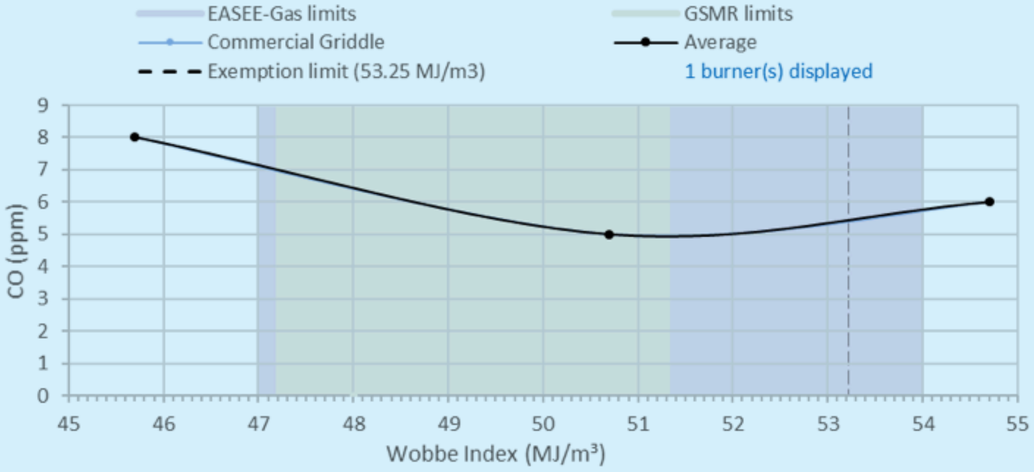
Flueless space heater CO ppm



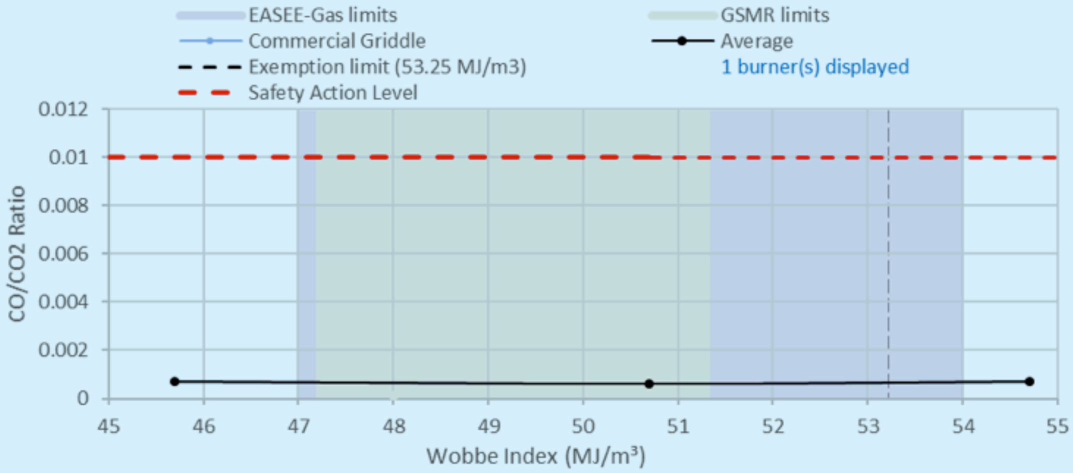
Flueless space heater CO/CO$_2$ ratio



Commercial griddle CO ppm

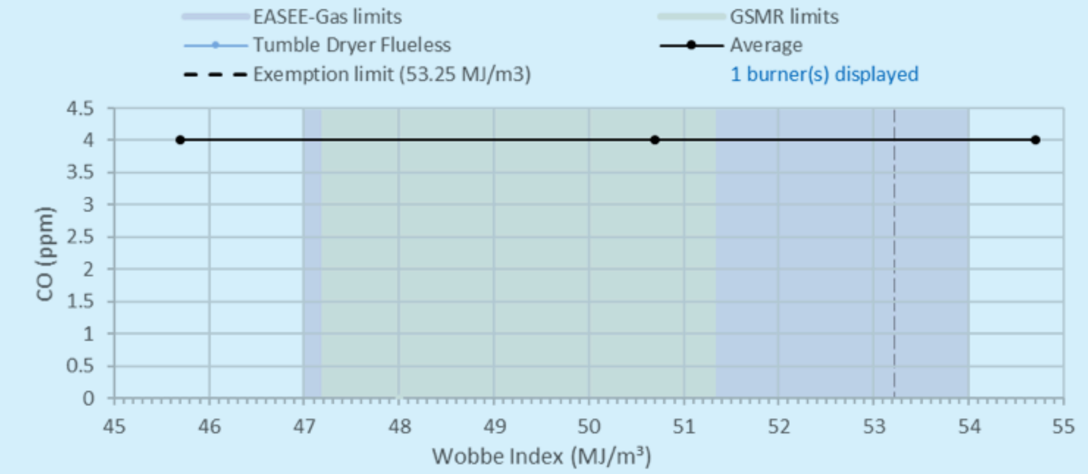


Commercial griddle CO/CO$_2$ ratio

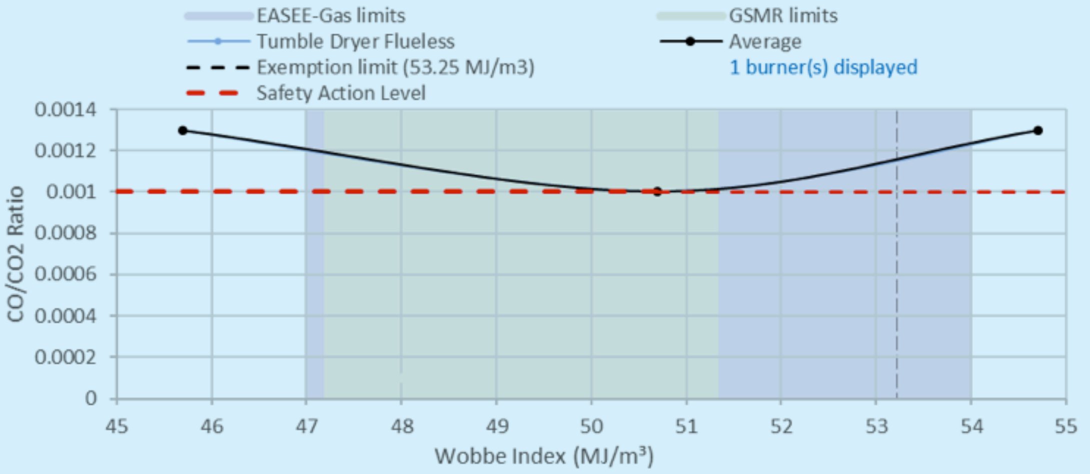


# Appendix 6 – combustion results by appliance burner type *cont.*

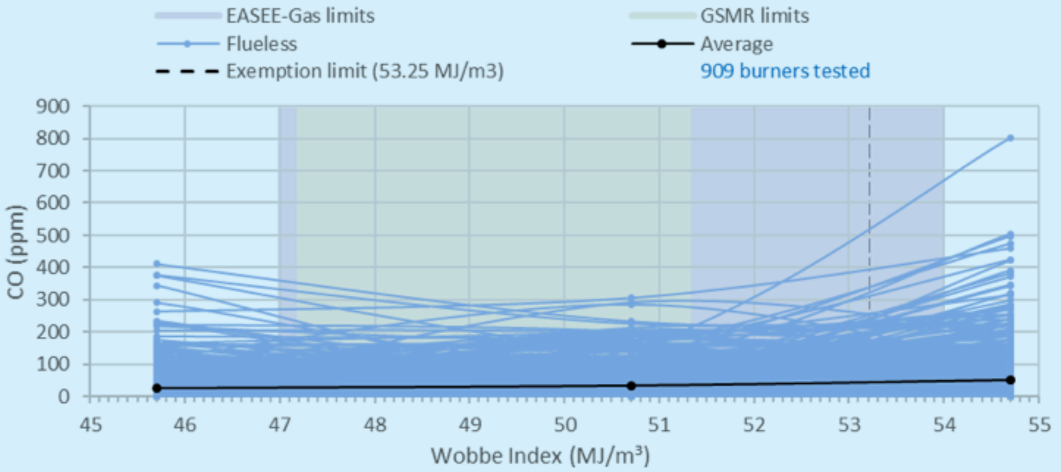
Tumble dryer flueless CO ppm



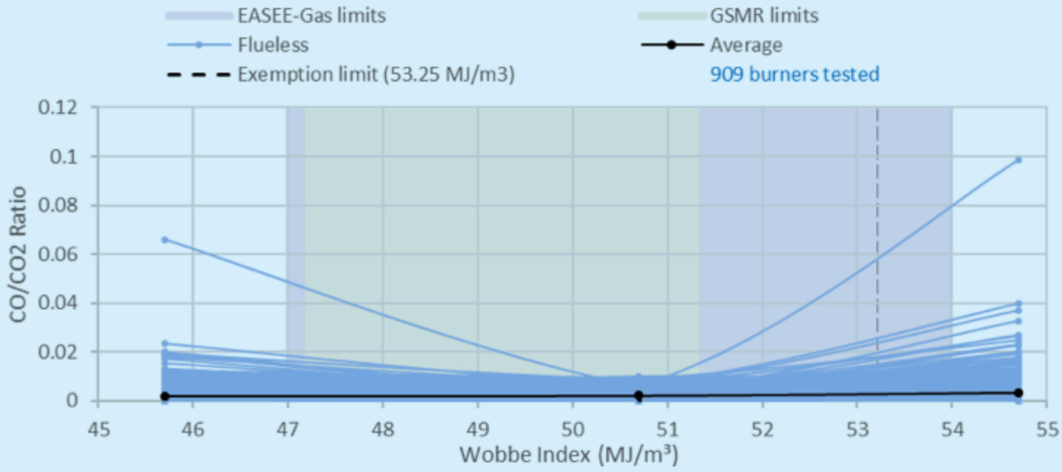
Tumble dryer flueless CO/CO$_2$ ratio



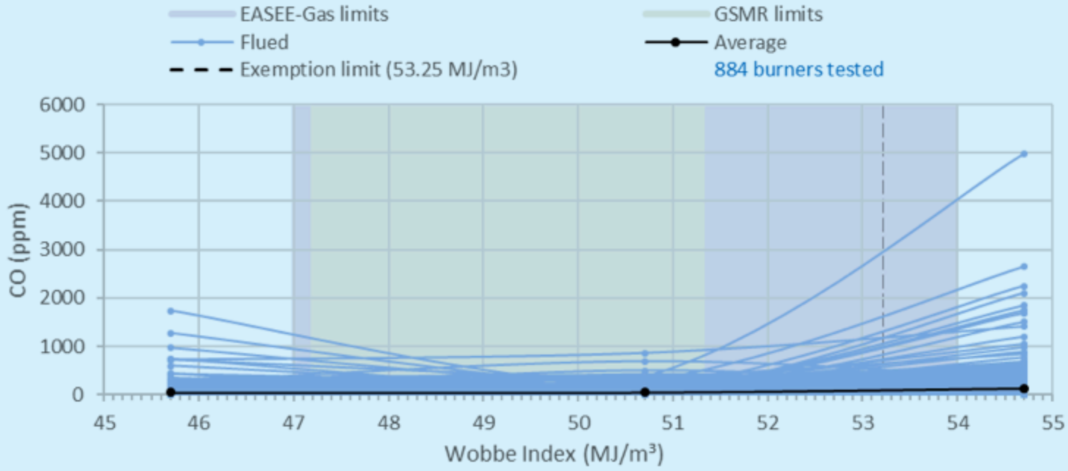
All flueless CO ppm



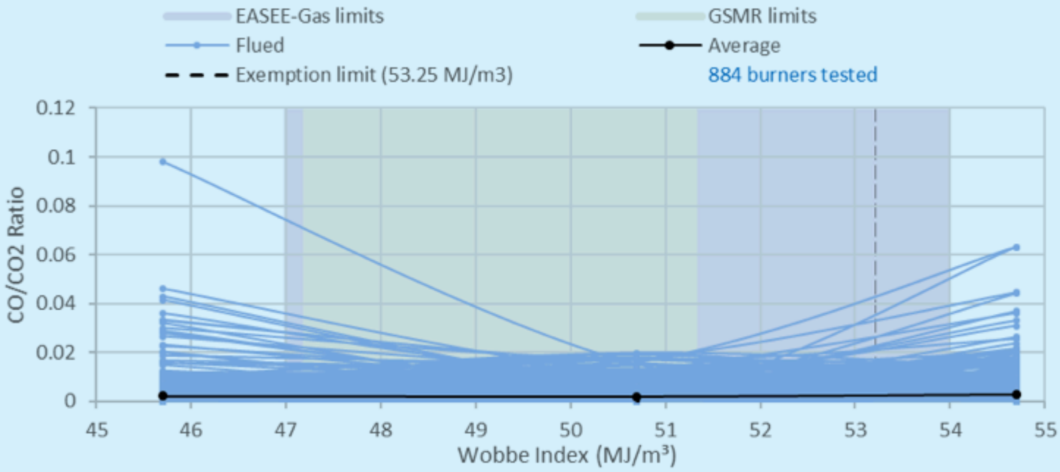
All flueless CO/CO$_2$ ratio



All flued CO ppm



All flued CO/CO$_2$ ratio



# Appendix 7 – summary of CO/$CO_2$ action level results by appliance burner type

| Appliance burner type | Safety action level | Gas | Below | Above | Total | Below | Above |
|---|---|---|---|---|---|---|---|
| Boilers | 0.0080 | G23 | 415 | 3 | 418 | 99.28% | 0.72% |
| | | G20 | 414 | 4 | | 99.04% | 0.96% |
| | | G21 | 400 | 18 | | 95.69% | 4.31% |
| | | 53.25 | 402 | 16 | | 96.17% | 3.83% |
| Boilers (gas/air ratio) | 0.0040 | G23 | 245 | 2 | 247 | 99.19% | 0.81% |
| | | G20 | 242 | 5 | | 97.98% | 2.02% |
| | | G21 | 240 | 7 | | 97.17% | 2.83% |
| | | 53.25 | 241 | 6 | | 97.57% | 2.43% |
| Commercial fryer | 0.0100 | G23 | 5 | 0 | 5 | 100.00% | 0.00% |
| | | G20 | 5 | 0 | | 100.00% | 0.00% |
| | | G21 | 4 | 1 | | 80.00% | 20.00% |
| | | 53.25 | 4 | 1 | | 80.00% | 20.00% |
| Commercial griddle | 0.0100 | G23 | 1 | 0 | 1 | 100.00% | 0.00% |
| | | G20 | 1 | 0 | | 100.00% | 0.00% |
| | | G21 | 1 | 0 | | 100.00% | 0.00% |
| | | 53.25 | 1 | 0 | | 100.00% | 0.00% |
| Commercial grill | 0.0100 | G23 | 4 | 5 | 9 | 44.44% | 55.56% |
| | | G20 | 7 | 2 | | 77.78% | 22.22% |
| | | G21 | 6 | 3 | | 66.67% | 33.33% |
| | | 53.25 | 6 | 3 | | 66.67% | 33.33% |
| Commercial hob | 0.0100 | G23 | 20 | 1 | 21 | 95.24% | 4.76% |
| | | G20 | 19 | 2 | | 90.48% | 9.52% |
| | | G21 | 16 | 5 | | 76.19% | 23.81% |
| | | 53.25 | 17 | 4 | | 80.95% | 19.05% |
| Commercial oven | 0.0080 | G23 | 12 | 1 | 13 | 92.31% | 7.69% |
| | | G20 | 11 | 2 | | 84.62% | 15.38% |
| | | G21 | 12 | 1 | | 92.31% | 7.69% |
| | | 53.25 | 12 | 1 | | 92.31% | 7.69% |
| Flued space heater | 0.0200 | G23 | 203 | 25 | 228 | 89.04% | 10.96% |
| | | G20 | 212 | 16 | | 92.98% | 7.02% |
| | | G21 | 208 | 20 | | 91.23% | 8.77% |
| | | 53.25 | 208 | 20 | | 91.23% | 8.77% |
| Flueless space heater | 0.0010 | G23 | 2 | 0 | 2 | 100.00% | 0.00% |
| | | G20 | 2 | 0 | | 100.00% | 0.00% |
| | | G21 | 2 | 0 | | 100.00% | 0.00% |
| | | 53.25 | 2 | 0 | | 100.00% | 0.00% |
| Grill | 0.0100 | G23 | 85 | 7 | 92 | 92.39% | 7.61% |
| | | G20 | 82 | 10 | | 89.13% | 10.87% |
| | | G21 | 79 | 13 | | 85.87% | 14.13% |
| | | 53.25 | 78 | 14 | | 84.78% | 15.22% |

| Appliance burner type | Safety action level | Gas | Below | Above | Total | Below | Above |
|---|---|---|---|---|---|---|---|
| Hob | 0.0100 | G23 | 673 | 26 | 699 | 96.28% | 3.72% |
| | | G20 | 661 | 38 | | 94.56% | 5.44% |
| | | G21 | 642 | 57 | | 91.85% | 8.15% |
| | | 53.25 | 655 | 44 | | 93.71% | 6.29% |
| Oven | 0.0080 | G23 | 117 | 5 | 122 | 95.90% | 4.10% |
| | | G20 | 119 | 3 | | 97.54% | 2.46% |
| | | G21 | 117 | 5 | | 95.90% | 4.10% |
| | | 53.25 | 117 | 5 | | 95.90% | 4.10% |
| Tumble dryer flued | 0.0100 | G23 | 9 | 0 | 9 | 100.00% | 0.00% |
| | | G20 | 9 | 0 | | 100.00% | 0.00% |
| | | G21 | 9 | 0 | | 100.00% | 0.00% |
| | | 53.25 | 9 | 0 | | 100.00% | 0.00% |
| Tumble dryer flueless | 0.0010 | G23 | 0 | 1 | 1 | 0.00% | 100.00% |
| | | G20 | 1 | 0 | | 100.00% | 0.00% |
| | | G21 | 0 | 1 | | 0.00% | 100.00% |
| | | 53.25 | 0 | 1 | | 0.00% | 100.00% |
| Water heater flued/flueless | 0.0200 | G23 | 5 | 0 | 5 | 100.00% | 0.00% |
| | | G20 | 5 | 0 | | 100.00% | 0.00% |
| | | G21 | 5 | 0 | | 100.00% | 0.00% |
| | | 53.25 | 5 | 0 | | 100.00% | 0.00% |

# Appendix 8 – extract from BS 7967 Part 5: 2010

| **Health effects of CO on adult human beings** | | | |
|---|---|---|---|
| **CO** | **PPM** | **Effects on adults** | **Saturation of CO in blood stream** |
| 0.01 | 100 | Slight headache in 2-3 hrs | 13 |
| 0.02 | 200 | Mild headache, dizziness, nausea and tiredness after 2-3 hrs | 20-30 |
| 0.04 | 400 | Frontal headache and nausea after 1-2 hrs; risk to life if over 3 hr exposure | 36 |
| 0.08 | 800 | Severe headaches, dizziness, convulsions within 45 mins; unconsciousness and death possible within 2-3 hrs | 50 |
| 0.16 | 1600 | Headache, dizziness, nausea within 20 min; collapse, unconsciousness and death possible 1-2 hrs | 68 |
| 0.32 | 3200 | Headache, dizziness, nausea within 5-10 min; collapse, unconsciousness and death possible 15 min | 70-75 |
| 0.64 | 6400 | Severe symptoms within 1-2 min; death within 15 mins | 80 |
| 1.28 | 12800 | Immediate symptoms; death within 1–3 min | 85-90 |

# Appendix 9 – CO exposure model

**Description of the exposure model employed for further assessment of carbon monoxide levels.** Dave Lander, 05/05/2016

## 1. Introduction

Laboratory testing of gas appliances as part of the Network Innovation Competition Project ‘Opening up the Gas Market’ has highlighted a need to assess the impact of release of increased levels of carbon monoxide by flueless appliances. The approach applied here is similar to that commonly employed in environmental risk assessment, an example of which can be seen at the US Dept. of Energy’s Risk Assessment Information System (RAIS) website[1].

When conducting an environmental risk assessment the overall aim is to assess and quantify the risk to the environment presented by a particular activity. If the risk exceeds a minimum acceptable value, then mitigation actions are assessed and implemented. The approach can be summarised in three steps:

a. A ‘Source-Pathway-Receptor’ conceptual model of exposure is set out. The conceptual model clarifies the assumptions about the Source (i.e. how a particular pollutant arises), The Receptor (i.e. the environment/entity that is exposed to the pollutant and for which impact is assessed) and the Pathway (i.e. how the pollutant is transported from the Source to the Receptor).

b. Based on the stated assumptions and boundaries of the conceptual model, a mathematical exposure model is derived. The exposure model permits assessment of the average concentration of pollutant to which the Receptor is likely to be exposed.

c. Health Criteria Values (HCVs) are obtained for the pollutant, based on expert assessment reported in the literature.

## 2. The conceptual model

Table 1 below sets out the main assumptions regarding a conceptual model of exposure to carbon monoxide from combustion of high Wobbe index natural gas in a domestic cooking environment.

In the approach used by RAIS, identification of Chemicals of Potential Concern (COPCs) is carried out at an earlier stage so as to limit the number of chemicals for which risk assessment is carried out. In this instance carbon monoxide is the only COPC that is assessed.

## 3. The exposure model

The exposure model employed here is essentially the same exposure model as that employed by both Afsset[2] and the UK Environment Agency[3] for calculating the average exposure concentration of pollutants associated with biomethane conveyed in gas distribution systems. In the case of the biomethane risk assessment, there are more COPCs, whereas for this assessment only carbon monoxide is considered.

Conceptual model of exposure to carbon monoxide from high Wobbe index natural gas

| | Assumption | Notes |
|---|---|---|
| Source: | Natural gas of high Wobbe index is conveyed to a consumer’s premises. | The gas conveyed within the gas pipeline is therefore considered to be of high Wobbe index. |
| Pathway: | A single pathways is considered:<br>Inhalation of carbon monoxide released whilst a gas cooker hob is in use. | A gas cooker hob is assumed to be the most common unflued gas appliance.<br>Alternative exposure pathways could be considered, however, it is expected that such releases would give rise to lower concentrations at the Receptor. |
| Receptor: | Human acute and chronic exposure through inhalation during cooking operations. | It is assumed that cooking is carried out in a separate, typical domestic kitchen by adults. Children and the elderly are assumed to be present. Human health impacts only are considered; impacts on other entities in the environment (e.g. water courses, wildlife, etc.) are not considered. |

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[1] US Department of Energy. Risk Assessment Information System. https://rais.ornl.gov/ (Accessed March 2016).

[2] Risques sanitaires du biogas. Evaluation des risques sanitaires lies a l'injection de biogas dans le reseau de gaz naturel. Avis de l Afsset. Rapport d'expertise collective. S008.

[3] Environment Agency. ‘Draft Quality Protocol for biomethane: Environmental Risk Assessment’. May 2012.

The exposure model is based on a room of volume **V** into which the pollutant is introduced. The model assumes that the room is well mixed and is ventilated by a supply of fresh air supplied at **n** room changes per hour.

The pollutant is assumed to be released during two cooking operations that each comprise three phases: a short ignition phase, a combustion (i.e. cooking) phase and a post-combustion phase. The cooking operations are assumed to last one hour each and exposure occurs during the cooking operation and for a further one hour following the cooking operation.

Three types of pollutant can be released during each cooking operation:

a) Through release during the ignition phase of pollutants that are present in the unburnt natural gas but are destroyed during the combustion phase ('destructed' pollutants). Destructed pollutants are assumed to be released only during the ignition phase and after ignition the pollutant concentration decays as a function of the ventilation rate. For this study carbon monoxide is assumed not to be present in the unburnt natural gas, so ignition-phase releases are ignored.

b) Through release during the ignition phase of pollutants that are present in the unburnt biomethane but are **not** destroyed during the combustion phase ('undestructed' pollutants). Undestructed pollutants are assumed to be released during the ignition and combustion phases and only after combustion does the pollutant concentration decay as a function of the ventilation rate. Again, for this study carbon monoxide is assumed not to be present in the unburnt natural gas, so this source of release is ignored.

c) Through release during the combustion phase of pollutants that are not present in the biomethane, but are formed as combustion products ('combustion product' pollutants). Combustion product pollutants are assumed to be released only during the combustion phase and after combustion the pollutant concentration decays as a function of the ventilation rate. Carbon monoxide formed during combustion is treated as a combustion product pollutant.

### 4. Nomenclature

| | | |
|---|---|---|
| Ct | concentration of pollutant in room at time t | mg.m-3 |
| Cg | concentration of pollutant in flue gas | mg.m-3 |
| n | ventilation rate (room changes per hour) | h-1 |
| qi | rate of release of pollutant during ignition phase | mg.h-1 |
| qc | rate of release of pollutant during combustion phase | mg.h-1 |
| t | time | h |
| ti | ignition time | h |
| tstart | time of start of exposure | h |
| tend | time of end of exposure | h |
| V | volume of room | $m^3$ |

### 5. Continuous releases

For continuous releases of a pollutant into a perfectly-mixed room the concentration of pollutant at time t may be expressed as

**Equation 1**

$$C_t = \frac{q}{nV}\left(1 - e^{-nt}\right) + C_0 e^{-nt}$$

The concentration of pollutant rises from the initial concentration C0 at time **t** and increases with time, stabilising at a value and time that is dictated by the rate of release, q, the volume of the room, **V**, and the ventilation rate, **n**.

The average concentration of pollutant during a continuous release is given by integrating equation 1 over the exposure period tstart to tend.

**Equation 2**

$$C_{ave} = \frac{\int_{t_{start}}^{t_{end}} \left(\frac{q}{nV}\left(1 - e^{-nt}\right) + C_{t_{start}}{}_{-}\, e^{-nt}\right).dt}{\left(t_{end} - t_{start}\right)}$$

Which can be shown to be

**Equation 3**

$$C_{ave} = \frac{\left[\frac{q}{nV}\left(t_{end} - t_{start}\right) + \frac{\left(C_{t_{start}} - \frac{q}{nV}\right)}{n}\left(1 - e^{-n\left(t_{end} - t_{start}\right)}\right)\right]}{\left(t_{end} - t_{start}\right)}$$

## 6. Decay in concentration following cessation of release

If the release of pollutant into the room is ceased **q** – and hence the first term in equation 1 – becomes zero and the concentration of pollutant at time **t** may be expressed as

**Equation 4**

$$C_t = C_{t_{cessation}} e^{-n\left(t - t_{cessation}\right)}$$

Where $C_{t_{cessation}}$ is the pollutant concentration at the time that release ceases. The average concentration of pollutant during the decay period is given by integrating equation 4 over the exposure period

**Equation 5**

$$C_{ave} = \frac{\int_{t_{start}}^{t_{end}} C_{t_{start}} e^{-nt}.dt}{\left(t_{end} - t_{start}\right)}$$

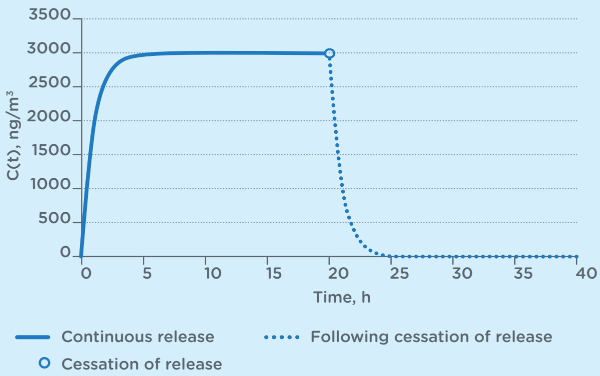
Which can be shown to be

**Equation 6**

$$C_{ave} = \frac{\left[\frac{C_{t_{start}}}{n}\left(1 - e^{-n\left(t_{end} - t_{start}\right)}\right)\right]}{\left(t_{end} - t_{start}\right)}$$

The diagram below illustrates the continuous release and decay periods.

Concentration of continuously-released pollutant



Note that equation 1 and 4 – and 3 and 6 – are essentially equivalent (equations 4 and 6 cover the case of zero release rate, **q**).

## 7. Average concentrations

The three phases of each cooking operation are therefore combinations of the one or more continuous releases in which average concentration is given by one or more equations of form 3, followed by a decay in concentration in which average concentration is given by an equation of form 6. These are given in the table below for each pollutant type and each phase in turn:

| Pollutant | Cooking operation | Phase | Model parameters |
|---|---|---|---|
| Combustion product | 1 | Ignition | N/A |
| | | Combustion | $q_c$ = 0.15 X $C_g$ (mg/h); V=17m$^3$; n=0.5; $t_{start}$=5s; $t_{end}$=1h5s |
| | | Decay | $C_{tstart}$ = $C_{tend}$ for combustion phase (mg/m$^3$); V=17m$^3$; n=0.5; $t_{start}$=1h5s; $t_{end}$=2h5s |
| | 2 | Ignition | N/A |
| | | Combustion | $q_c$ = 0.15 X $C_g$ (mg/h); V=17m$^3$; n=0.5; $t_{start}$=7h5s; $t_{end}$=8h5s |
| | | Decay | $C_{tstart}$ = $C_{tend}$ for combustion phase (mg/m$^3$); V=17m$^3$; n=0.5; $t_{start}$=8h5s; $t_{end}$=9h5s |

Three exposure concentrations for carbon monoxide can be established:

a. The peak concentration that is seen during a 24 hour period. In practice this is the concentration of carbon monoxide immediately prior to cessation of the second cooking operation (because there is generally an extremely low concentration of residual carbon monoxide in the room at the start of the second operation).

b. The average concentration over the two 2-hour cooking/post combustion exposure periods.

c. The average concentration over a 24 hour period.

These three concentrations can be compared with the following carbon monoxide health criteria values:

| | | |
|---|---|---|
| EH40 (LTEL) | ppm mol/mol | 36.76 |
| EH40 (STEL) | ppm mol/mol | 245.08 |

### 8. Exposure model spreadsheet

The exposure model can employ either analytical integration, i.e. equation 3, or numerical integration of equation 1 for calculation of average contaminant concentration over the desired exposure period.

# Appendix 10 – analysis of CO emissions by flue type

This appendix shows the CO emissions recorded for the entire appliance/burner populations that were tested on all 3 test gases plotted across the WI test range. A quadratic function has been used to interpolate the values at WI of 53.25 MJ/m³. Note the x-axis is limited to 54 MJ/m³. Threshold values were allocated to a green, amber and red zone for different flue types. For all burners, irrespective of flue type, the vast majority fall into the green zone which can be considered as normal operation. The amber zone captures the results that are 2 times greater than the green threshold. The amber zone could be interpreted that the burner may be in need of attention i.e. service etc. The red zone indicates that the burners are producing high levels of CO for that flue type. It should be stressed that burners falling into either the amber or red zone do not necessarily constitute a risk and may even still pass the $CO/CO_2$ action level criteria. As the number of burners that fall into the amber or red zones only account for a very small percentage of the overall appliance population a limited y-axis from 0 to 5% has been used in the charts that follow that show:

1. Room sealed has the most number of burners in the red zone (1.05%) at a WI of 53.25 MJ/m³ of the total room sealed population, however as already discussed it is most unlikely that flue products would enter the room as the products or combustion are discharged to outside.

2. Open flued has the lowest numbers of burners in the red zone (0.4%) at a WI of 53.25 MJ/m³. The majority of these appliance are now fitted with an ASD that would shut of the appliance should CO start to enter the room.

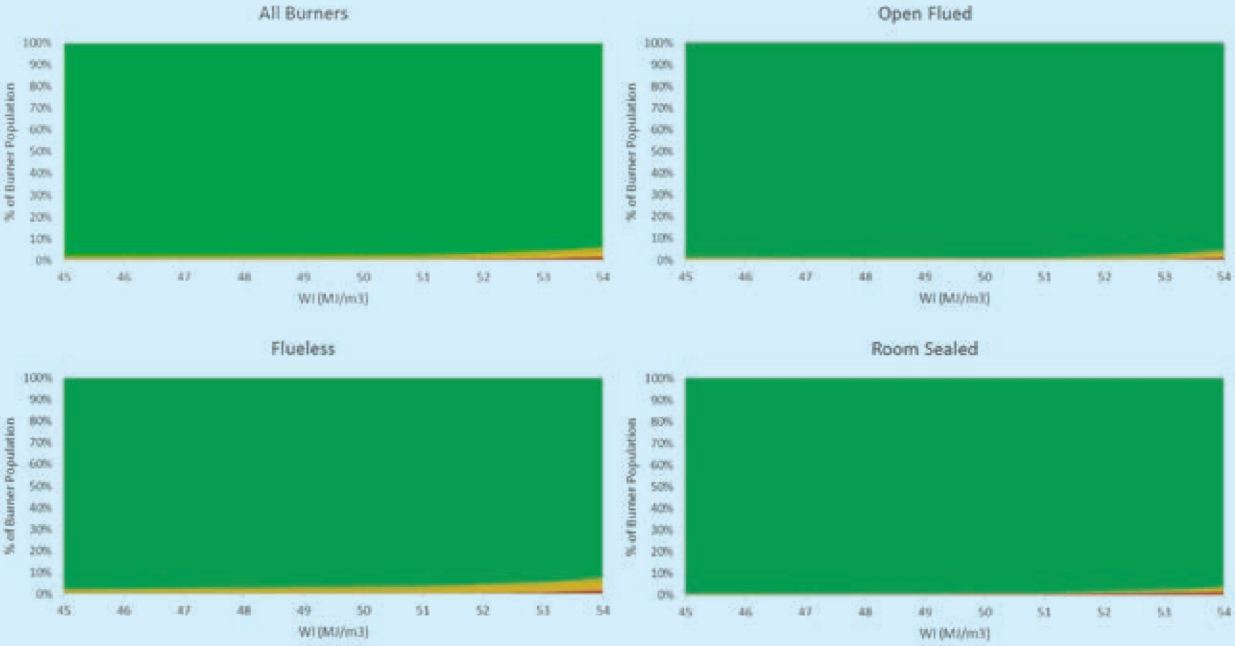
3. Flueless type has the most number of burners in the amber zone (1.0%) at a WI of 53.25 MJ/m³ but as previously discussed these burners are of low input rate and when correctly installed with adequate ventilation and proper use, would not be considered to pose a risk.

Key for red, amber and green charts

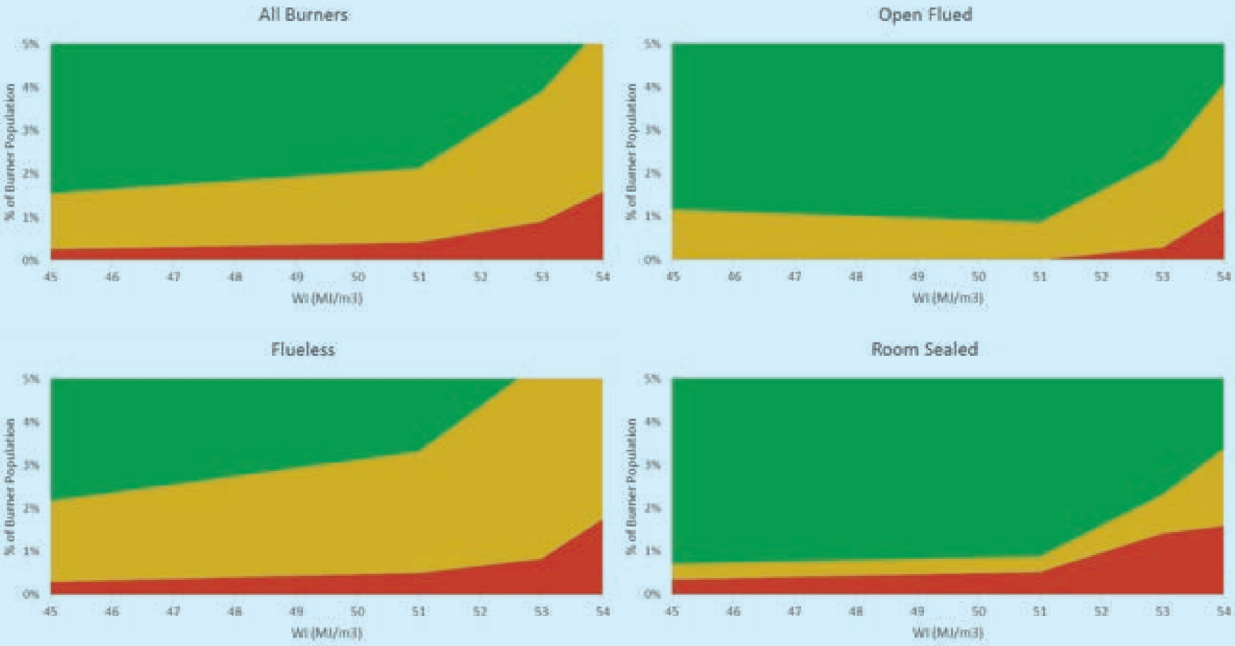
| | Threshold values (CO ppm) | | |
|---|---|---|---|
| **Flue type** | **Green<br>Low CO** | **Amber<br>Med CO** | **Red<br>High CO** |
| Flueless | 0 to <201 | 201 to < 401 | >401 |
| Open flued | 0 to <501 | 501 to < 1001 | >1001 |
| Room sealed | 0 to <501 | 501 to < 1001 | >1001 |

# Appendix 10 – analysis of CO emissions by flue type *cont.*

Percentage of total Burner population failing into red, amber and green zones



Percentage of total Burner population failing into red, amber and green zones (exploded view)



# Glossary

| Abbreviation | Term |
|---|---|
| ALARP | As Low As Reasonably practicable |
| ASD | Atmospheric Safety Device |
| BBU | Back Boiler Unit |
| BEIS | Department for Business Energy and Industrial Strategy |
| BERR | The Department for Business, Enterprise and Regulatory Reform |
| BIS | Department for Business Innovation and Skills |
| BS | British Standard |
| $C_3H_8$ | Propane |
| CBA | Cost Benefit Analysis |
| CE | European Conformity |
| CEN | The European Committee of Standardisation |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COSHH | Control of Substances Hazardous to Health |
| CV | Calorific Value |
| DAF | Dry Air Free |
| DECC | Department of Energy and Climate Change |
| DNV GL | Technical advisor to the energy industry |
| EASEE | European Association for the Streamlining of Energy Exchange |
| EU | European Union |
| FWACV | Flow weighted Average Calorific Value |
| GAD | Gas Appliance Directive |
| GB | Great Britain |
| GDN | Gas Distribution Network |
| GEOTER | GAS (Calculation of Thermal Energy) Regulations |
| GS(M)R | Gas Safety (Management) Regulations |
| HHIC | Heating and Hot Water Industry Council |
| HSE | Health & Safety Executive |
| ICF | Incomplete Factor |
| IGEM | Institution of Gas Engineers and Managers |
| IGU | International Gas Union |
| KIWA | Kiwa Gastec |
| LCNI | Low Carbon Network and Innovation |
| LNG | Liquefied Natural Gas |
| MJ/$m^3$ | Megajoule per Cubic Meter |
| $N_2$ | Nitrogen |
| NEC | Network Emergency Co-ordinator |
| NBP | National Balancing Point (GB) |
| NIC | Network Innovation Competition |
| NOx | Oxides of Nitrogen |
| OGM | Opening up the Gas Market |
| PPM | Parts Per Million |
| PPR | Project Progress Report |
| QRA | Quantified Risk Assessment |
| RD | Relative Density |
| SDRC | Successful Delivery Reward Criteria |
| SI | Sooting Index |
| SIU | Scottish Independent Undertaking |
| SMSP | System Marginal Sell Price |
| UK | United Kingdom |
| VPF | Value of preventing a fatality |
| WI | Wobbe Index |
| WWU | Wales and the West Utilities |
| ZEE | Zeebrugge (Belgium) |

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