




**Client** Staffordshire Crystal Ltd.  
 Unit 14 Pedmore Road Ind. Estate  
 Brierley Hill  
 West Midlands  
 DY5 1TJ

### Part 1: Executive Summary

## Report for the Periodic Monitoring of Emissions to Air.

<b>Site</b>	<b>Brierley Hill</b>
<b>Plant</b>	<b>Furnace</b>
<b>Sampling Date</b>	<b>28th January 2016</b>
<b>Report Date</b>	<b>25th February 2016</b>
<b>Job Number</b>	<b>71962p1r0</b>
<b>Permit Number</b>	<b>PB/98 Variation 200839393</b>

<b>Report Prepared by:</b>	<b>Print</b>	<b>Michelle Edwards</b>
	<b>MCERTS No.</b>	<b>MM05 659</b> <b>Level 2 TE: 1,2,3,4</b>

<b>Report Approved by:</b>	<b>Sign</b>	
	<b>Print</b>	<b>Derek Myers</b>
	<b>MCERTS No.</b>	<b>MM02 115</b> <b>Level 2 TE: 1,2,3,4</b>



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 Bordesley Green Trading Estate  
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Tel: 0161 4323286  
 Company Registration No SC070429

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## Monitoring Objectives

The monitoring was undertaken to check compliance with authorised emission limits.

All monitoring procedures were carried out to the MCERTS requirements under the Exova (UK) Ltd quality system to ISO 17025: 2005.

Monitoring was undertaken for the listed emissions from the following sampling positions:

Sampling Location	Emission
Furnace	Particulates Lead Oxygen

## Special Monitoring Requirements

There were no special requirements for this monitoring campaign.

## Summary Of Methods

Emission	Method number	Method standard
Gas velocity and volume flow	TPM/01A	BS EN ISO 16911-1:2013
Particulate	MM0004	BS EN 13284-1 : 2002
Water vapour	MM0010	BS EN 14790 : 2005
Oxygen	MM0002	BS EN 14789 : 2005
Lead	MM0007	BS EN 14385 : 2004

## Summary Of Results

The table presents the atmospheric emissions from the tests undertaken on behalf of **Staffordshire Crystal Ltd.**  
The results were measured from the sample positions downstream of the arrestment plant.

Emission at Brierley Hill Furnace	Sampling Time			Emission Result mg/m <sup>3</sup> *	Authorised Limit mg/m <sup>3</sup> *	Uncertainty +/- mg/m <sup>3</sup> *	Detection Limit mg/m <sup>3</sup> *	Mass Emission g/h
	Date	Start	End					
s Particulate	28/01/16	14:53	15:33	23.9	20	22.8	13.3	5.8
s Total heavy metals, Pb	28/01/16	13:54	14:34	1.03	5	1.4347	0.0137	0.30

* at reference conditions	Stack Gas Weight 29.00 Kg/kmol	0 °C 101.3 kPa	Dry Gas Oxygen	13	%
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Where applicable

Oxides of nitrogen results are expressed as nitrogen dioxide  
TOC results are expressed as total carbon

Throughout Report:

\* Reference conditions (see above)  
\*\* Analysis not required  
ND Non detectable  
s - Subcontracted laboratory analysis

Nm<sup>3</sup> 273 K, 101.3 kPa  
# - UKAS accredited only  
## - Not Accredited  
N/A Not applicable

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor k=2, providing a 95% confidence level. The uncertainty evaluation has been carried out in accordance with UKAS requirements.



All tests included in this report are accredited under UKAS and MCERTS accreditation schemes unless otherwise stated.  
Opinions and interpretations expressed herein are outside the scope of MCERTS and UKAS accreditation.



## Operating Information

The table below shows details of the operating information on each sampling date for: **Furnace**

Date	Process type	Process duration	Fuel	Feedstock	Abatement	Load
28/01/2016	Glass Furnace	Batch	Natural Gas	Glass	None	Normal operation

No CEMs installed on the emission point.

## Comments & Monitoring Deviations

A waste gas homogeneity test to BS EN 15259:2007 (MID) is not required:-  
The homogeneity test is not applicable to duct areas less than 1m<sup>2</sup>.

All monitoring was performed in accordance with the relevant procedures.

The sampling location is a vertical duct.

Due to restrictions caused by the temporary scaffold provided for access, sampling could only be undertaken from one horizontal sample port, achieving only single point sampling.

Due to the small platform size the sampling train was leak checked and then the probe removed and re-assembled to allow it to be inserted in the stack.

The particulate monitoring was within the required 95 to 115 % isokinetic rate as stated in BS EN 13284-1: 2002

The velocity and temperature profile at the sampling location met the requirements of BS EN 13284-1: 2002.

The calculated particulate emission level was greater than the control blank.

The impinger efficiency check for lead was not performed because the measured emission was less than 30% of the emission limit value.

When the results are expressed as non-detected the mass emissions are calculated from the detection limit and therefore they are worst case results.




Part 2: Supporting Information

Report for the Periodic Monitoring of Emissions to Air.

<b>Client</b>	Staffordshire Crystal Ltd.
<b>Site</b>	Brierley Hill
<b>Plant</b>	Furnace
<b>Sampling Date</b>	28th January 2016
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## APPENDIX 1

## Emission Monitoring Procedures And Instrumentation

### Gas velocity and temperature

Documented in-house procedure TPM01/A to the main procedural requirements of BS EN ISO 16911-1:2013. Velocity and temperature measurements are performed using a calibrated Pitot tube, a calibrated pressure differential reading device and a calibrated thermocouple. Velocity and possible flow deviation measurements are carried out at selected, representative points in the gas stream.

### Water vapour

Documented in-house procedure MM0010 to the main procedural requirements of BS EN 14790:2005. A measured volume of gas is extracted from the gas stream through a moisture trapping unit. The mass gain of moisture trapped is divided by the volume of gas sampled to determine the mass concentration of water vapour. For water saturated stacks the temperature of the gas stream is measured and the water vapour concentration is determined using liquid-gas equilibrium tables. Sampling points are selected in accordance with the findings of any BS EN 15259 assessment.

### Total particulate matter

Documented in-house procedure MM0004 to the main procedural requirements of BS EN 13284-1:2002. Stack gases are extracted from representative sampling points at isokinetic flow rates through a sharp-edged nozzle. Particulate matter is collected on a pre-weighed filter conditioned at 180°C. Deposits upstream of the filter are also recovered and weighed. The increase of mass of the filter and mass collected upstream of the filter is divided by the volume sampled to determine the mass concentration.

### Oxygen

Documented in-house procedure MM0002 to the main procedural requirements of BS EN 14789:2005. Continuous analysis using probe, sample line, gas conditioning system, and a paramagnetic, zirconium cell, or electrochemical cell analyser. The analytical equipment detailed above is calibrated before and during the tests using certified gas mixtures of nitrogen and oxygen. Sampling points are selected in accordance with the findings of any BS EN 15259 assessment.

### Lead

Documented in-house procedure MM0007 to the main procedural requirements of BS EN 14385:2004. A substantial metered volume of gas is sampled isokinetically through a sharp edged nozzle dedicated heated probe, filter, and chilled impinger train containing appropriate hydrogen peroxide/nitric acid and sulphuric acid/potassium permanganate solutions, and subsequent Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) analysis.



## Sampling Project Personnel Competency And Expiry Dates

		MCERTS No	Level 1	Level 2	TE1	TE2	TE3	TE4
Report prepared by:	Michelle Edwards	MM05 659	-	30/06/2017	31/12/2017	31/12/2019	30/06/2018	29/02/2020
Report authorised by:	Derek Myers	MM02 115	-	30/09/2017	31/05/2018	30/11/2018	30/11/2018	30/11/2018
Team leader:	Michelle Edwards	MM05 659	-	30/06/2017	31/12/2017	31/12/2019	30/06/2018	29/02/2020
Team leader:	Aidan Wrynn	MM08 921	-	31/05/2017	31/05/2017	31/11/2018	30/11/2017	30/06/2018

## Equipment References

Equipment	Reference Number
Probe	15
Nozzles	AQ153
Stack Thermocouple	AQ173
Gas Analyser	AQ354
Regulator	AQ901
Timer / Stopwatch	AQ308
Barometer	AQ343
Pitot	AQ102
Callipers	CV24
Tape Measure	AQ278
Impinger Thermocouple	TV34
Sample Rate Calculation Equipment	Laptop
Thermometer	AQ126
Manometer	AQ126
Balance	AQ090
Weights	AQ090a & AQ090b

## Subcontracted Analysis

Exova (UK) Ltd has, with your approval, used the following sub-contracted laboratories for the laboratory analyses referenced below:

Laboratory:	<b>Scientific Analysis Laboratories</b>
Parameters:	Lead - Internal method, ICPMS BS EN 14385 Particulates - Internal method, Gravimetric
Accreditation:	UKAS Accredited testing laboratory number 1549

## APPENDIX 2

Date	28/01/2016
Time	13:15
Pitot Cp	0.82

Barometric pressure	100.5	kPa
Duct static pressure	0.00	kPa
Stack Area	0.126	m <sup>2</sup>
Oxygen	20.6	%

Stack Diameter (circular)	0.40	m
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Point	Traverse Line	Depth cm	ΔP mmH <sub>2</sub> O	T °C	Angle °	velocity m/s	Traverse Line	Depth cm	ΔP mmH <sub>2</sub> O	T °C	Angle °	velocity m/s
1	A						B					
2	A						B					
3	A	5.0	14.9	49	<15	13.4	B					
4	A	7.1	17.5	48	<15	14.5	B					
5	A	10.0	19.1	49	<15	15.2	B					
6	A	14.2	19.2	49	<15	15.3	B					
7	A	25.8	19.0	50	<15	15.2	B					
8	A	30.0	18.9	50	<15	15.2	B					
9	A	32.9	19.0	50	<15	15.2	B					
10	A	35.0	21.6	50	<15	16.2	B					
11	A						B					
12	A						B					

Average Pitot DP	18.60	mmH <sub>2</sub> O
Average Temperature	322.5	K
Average Velocity	15.0	m/s
Average volumetric flow rate	1.89	m <sup>3</sup> /s at stack conditions
Average volumetric flow rate	1.59	m <sup>3</sup> /s (wet STP)
Average volumetric flow rate	1.57	m <sup>3</sup> /s (dry STP)
Average volumetric flow rate	0.06	m <sup>3</sup> /s (dry, STP, reference oxygen concentration)

**Sampling plane requirements Re: BS EN 13284-1:2001 5.2**

a	Angle of gas flow less than 15° with regard to duct axis	YES
b	No local negative flow	YES
c	Minimum pitot greater than 5Pa	YES
d	Ratio of highest to lowest local gas velocity less than 3:1	YES
	Minimum local gas velocity	13.4
	Maximum local gas velocity	16.2
	Ratio of highest to lowest local gas velocity	1.21

**Moisture Determination BS EN 14790:2005**

	Volume m <sup>3</sup>	Temp °C	Pressure mbar
Meter start	2970.302	16	1005
Meter end	2971.248	20	1005
Meter Yd	0.974		
Gas volume	0.858		

Impinger	1	2	3	4	5
Mass start (g)	719.7	655.4	730.0	816.3	198.0
Mass End (g)	720.5	657.9	731.5	819.4	198.1
Total Mass collected (g)	8.0				

Water vapour content (% v/v)	1.1
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If water droplets are present in the gas, the water vapour content is calculated using BS EN 14790 Annex A

N/A % v/v

**Preliminary Velocity Traverse & Moisture Data**



Blank Filter Weight		Weight Collected	
Filter No. 448	71962/8	0.0001	g
Washings	71962/7	0.0003	g
Total		0.0004	g

Filter Weight Test 1		Weight Collected	
Filter No. 399	71962/10	0.0001	g
Washings	71962/9	0.0008	g
Total		0.0009	g

Particulate Emission Results		Blank	
Detection Limit		13.30	mg/m <sup>3*</sup>
Particulate Emission		10.64	mg/m <sup>3*</sup>

Particulate Emission Results		Test 1	
Detection Limit		13.30	mg/m <sup>3*</sup>
Particulate Emission		23.94	mg/m <sup>3*</sup>

Laboratory	SAL	
Method N° & Accreditation Status	Gravimetric	UKAS
Date of analysis	10/02/2016	

Reference Gas Details					
Species	Units	Value	Cylinder Reference		
Nitrogen	%	99.999	VC174989		
Oxygen	%	20.93	Dry Ambient Air		
Calibration Details		Initial Time	13:52	Final Time	16:00
	Units	Initial Zero	Initial Span	Final Zero	Final Span
Oxygen	%	0.00	20.89	0.20	20.86

### Total Particulate Matter - Emission Results

Probe/Pitot ID No	15/ AQ102	Nozzle Diameter (d)	5.993	mm
Pitot Calibration Factor (Cp)	0.82	In-stack Filtration	N	Y/N
Probe liner material	Titanium	Leak check OK	Y	Y/N
Gas Calibration Factor (Y)	0.974	Meter ID No	AQ126	
Barometric Pressure	kPa 100.5	Initial Gas Meter Reading	2970.302	m³
Duct static Pressure	kPa 0.00	Final Gas Meter Reading	2971.248	m³
Date	28/01/2016	Sampled Vol, Dry at Meter	0.946	m³
Start Time	hh:min 13:54	Sampled Vol, Dry STP	0.860	Nm³
End Time	hh:min 14:34	Moisture content of stack gas	1.1	% v/v
Sampling Duration	hh:min 00:40	Isokinetic	102.5	%

Impinger	1	2	3	4	5
Initial mass (g)	719.7	655.4	730.0	816.3	198.0
Final mass (g)	720.5	657.9	731.5	819.4	198.1

Sample Point Number	Line	Sampling Time hh:min	Pitot Reading (h) mm w.g	Temperatures				Orifice Pressure (Dh) mm w.g
				Sample Gas Temperature (Ts) °C	Meter Temperature (Tm) °C	Probe Temperature °C	Filter Temperature °C	
4	A	13:54	18.2	48	16	175	175	51.1
		13:59	18.0	48	17	180	176	50.6
		14:04	18.2	48	18	180	180	51.1
		14:09	18.2	48	18	176	180	51.1
		14:14	18.2	48	19	180	180	51.1
		14:19	18.2	48	20	180	180	51.5
		14:24	18.2	48	20	180	180	51.5
		14:29	17.8	48	20	180	180	50.0
	End	14:34						
Averages			18.1	48.0	18.5	178.9	178.9	51.0

Average velocity	14.80	m/s
Average flow rate	1.86	m³/s
Average flow rate	0.08	m³/s*

Heavy Metals - Sampling Data

Date	28/01/2016
Start time	13:54
Finish time	14:34
Sample volume Nm <sup>3</sup> (dry gas)	0.860

HEAVY METALS	Impinger mass	
Impinger 1,2 & wash	230	g
Impinger 3 & wash	140	g

Measured moisture concentration	1.14	% v/v
Measured oxygen concentration	20.59	%

HEAVY METALS	Filter Analysis 71962/6	Particulate Phase Emission	Impinger 1 & 2 Analysis 71962/4	Vapour phase Emission Impinger 1 & 2	Impinger 3 Analysis 71962/5	Vapour phase Emission Impinger 3	Detection Limit	Efficiency % Trapped In impinger 3	Total Emission
Units	µg	mg/m <sup>3</sup> *	µg/l	mg/m <sup>3</sup> *	µg/l	mg/m <sup>3</sup> *	mg/m <sup>3</sup> *	%	mg/m <sup>3</sup> *
Lead (Pb)	41	0.91994	15	0.07741	9.7	0.03047	0.01371	N/A	1.027825

TOTAL HEAVY METALS Particulate Phase & Vapour Phase	Total Emission mg/m <sup>3</sup> *	Detection Limits mg/m <sup>3</sup> *	Total Emission As % ELV
Total heavy metals, Pb	1.0278	0.0137	20.6

Numbers in bold indicate detection limits

Reference Gas Details					
Species	Units	Value	Cylinder Reference		
Nitrogen	%	99.999	VC174989		
Oxygen	%	20.93	Dry Ambient Air		
Calibration Details		Initial Time	13:52	Final Time	16:00
	Units	Initial Zero	Initial Span	Final Zero	Final Span
Oxygen	%	0.00	20.89	0.00	20.86

Metals excluding Mercury

Laboratory	SAL	
Method N <sup>o</sup> & Accreditation Status	ICPMS BS EN 14385	UKAS
Date of analysis	10/02/2016	

## Heavy Metals - Emission Results

Date	28/01/2016
Start time	13:54
Finish time	14:34
Sample volume Nm <sup>3</sup> (dry gas)	0.860

HEAVY METALS	Impinger mass	
Impinger 1,2 & wash	230	g
Impinger 3 & wash	180	g

Measured moisture concentration	1.14	% v/v
Measured oxygen concentration	20.59	%

HEAVY METALS	Filter Analysis 71962/3	Particulate Phase Emission	Impinger 1 & 2 Analysis 71962/1	Vapour phase Emission Impinger 1 & 2	Impinger 3 Analysis 71962/2	Vapour phase Emission Impinger 3	Detection Limit	Efficiency % Trapped In impinger 3	Total Emission
Units	µg	mg/m <sup>3</sup> *	µg/l	mg/m <sup>3</sup> *	µg/l	mg/m <sup>3</sup> *	mg/m <sup>3</sup> *	%	mg/m <sup>3</sup> *
Lead (Pb)	0.5	0.01122	<b>0.3</b>	0.00000	<b>0.3</b>	0.00000	0.01398	N/A	0.011219

TOTAL HEAVY METALS Particulate phase & Vapour phase	Total Emission mg/m <sup>3</sup> *	Detection Limits mg/m <sup>3</sup> *	Total Emission As % ELV
Total heavy metals, Pb	<b>0.0140</b>	0.0140	0.3

Numbers in bold indicate detection limits

Metals excluding Mercury

Laboratory	SAL	
Method N <sup>o</sup> & Accreditation Status	ICPMS BS EN 14385	UKAS
Date of analysis	10/02/2016	

## Heavy Metals - Field Blank Emission Results



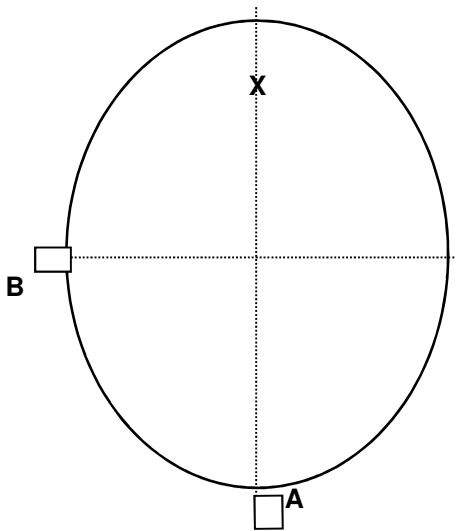
## APPENDIX 3

## Diagram Of The Sampling Location

Diagram of sampling points across the cross section of the duct (not to scale).

Traverse length = 0.40 m

Point	% of D	Location cm
4	87.5	35.0



## General Calculations

### Stack area:

$$\text{Area of a circle} = \frac{\pi \cdot D^2}{4}$$

D = Diameter (m)  
 $\pi = 3.142$

### Pressure conversion:

1mmH<sub>2</sub>O = 0.00980665 kPa  
 1mmH<sub>2</sub>O = 9.80665 Pa  
 1 mar = 0.1 kPa

### Water vapour concentration:

From reference calculations (taken from BS EN 14790):

$$V_{WC(\%)} = \frac{\frac{m_{WC} \cdot V_{mol(std)}}{M_w}}{\frac{m_{WC} \cdot V_{mol(std)}}{M_w} + V_{m(std)}} \times 100$$

VWC (%) = Water vapour content on wet basis, in volume % (m<sup>3</sup> of water vapour in m<sup>3</sup> of wet gas)  
 Vm(std) = Dry gas volume measured, corrected to standard conditions (m<sup>3</sup>)  
 mWC = Mass of water collected in the impingers (g)  
 Mw = Molecular weight of water, 18.01534 rounded to 18 (g/mol)  
 Vmol(std) = Molar volume of water at standard conditions = 0.0224 (m<sup>3</sup>/mol)

### Gas meter volume at standard conditions (STP)

From reference calculations (taken from BS EN 14790):

$$V_{m(std)} = y_d \times (V_2 - V_1) \times \frac{T_{std}}{T_m} \times \frac{P_m}{P_{std}}$$

Vm(std) = Dry gas meter volume at standard conditions (m<sup>3</sup>)  
 y<sub>d</sub> = Gas meter calibration coefficient  
 (V<sub>2</sub>-V<sub>1</sub>) = Dry gas meter volume at actual conditions (m<sup>3</sup>)  
 T<sub>m</sub> = Actual Temperature (K)  
 T<sub>std</sub> = Standard temperature (273 K)  
 p<sub>m</sub> = Absolute pressure at the gas meter (kPa)  
 p<sub>std</sub> = Standard gas pressure (101.3 kPa)

### Isokenetic Ratio (%):

From reference calculations (taken from EA TGN M2):

$$\text{IsokeneticRatio}(\%) = \frac{\text{Velocity at the sampling nozzle}}{\text{Velocity of the stack gas}} \times 100$$

### Estimating Measurement Uncertainty

Uncertainty estimates are calculated using the general rule of uncertainty propagation. Guidance is taken from publications including UKAS document M3003 and ISO 20988:2007.

## Flow Calculations

### Velocity:

From reference calculations (taken from ISO 10780):

$$\bar{v} = KC \sqrt{\frac{T_s \Delta p}{P_e M_s}}$$

$\bar{v}$  = Average velocity (m/s)

$C$  = velocity calculation constant = 129

$T_s$  = Average stack temperature (K)

$M_s$  = Molar mass of gas; assume 29 kg/kmol unless the molar mass is < 27 kg/kmol or > 31 g/kmol

$K$  = Pitot calibration coefficient

$P_e$  = Absolute gas pressure (kPa)

$\Delta p$  = Average pitot tube pressure differential (kPa)

### Volume flow rate

From reference calculations (taken from ISO 10780):

$$q_{va} = \bar{v}A$$

$q_{va}$  = Average flow rate (m<sup>3</sup>/s)

$\bar{v}$  = Average velocity (m/s)

$A$  = Stack cross-sectional area (m<sup>2</sup>)

### Volume flow rate corrected for moisture

From reference calculations (taken from BS ISO 9096):

$$q_m = q_{va} \frac{(100 - H_a)}{(100 - H_m)}$$

$q_m$  = Corrected volume flowrate (m<sup>3</sup>/s)

$q_{va}$  = Volume flow rate at actual conditions (m<sup>3</sup>/s)

$H_a$  = Moisture at actual conditions (%volume)

$H_m$  = Reference moisture (%volume)

### Volume flow rate corrected for temperature and pressure

From reference calculations (taken from BS ISO 9096):

$$q_m = q_{va} \frac{(T_m P_a)}{(T_a P_m)}$$

$q_m$  = Corrected volume flowrate (m<sup>3</sup>/s)

$q_{va}$  = Volume flow rate at actual conditions (m<sup>3</sup>/s)

$T_a$  = Temperature at actual conditions (K)

$T_m$  = Reference Temperature (K)

$p_a$  = Absolute gas pressure at actual conditions (kPa)

$p_m$  = Reference pressure (kPa)

### Volume flow rate corrected for oxygen

From reference calculations (taken from BS ISO 9096):

$$q_m = q_{va} \frac{(20.9 - O_{2,ref})}{(20.9 - O_{2,m})}$$

$q_m$  = Corrected volume flowrate (m<sup>3</sup>/s)

$q_{va}$  = Volume flow rate at actual conditions (m<sup>3</sup>/s)

$O_{2,m}$  = Actual oxygen concentration (%)

$O_{2,ref}$  = Reference oxygen concentration (%)

## Concentration Calculations

### Concentration:

From reference calculations (taken from BS EN 13284-1):

$$c = \frac{m}{V}$$

$c$  = Concentration  
 $m$  = Mass of substance  
 $V$  = Volume sampled

### Mass Emission

$$\text{Mass emission} = c \times q_m$$

$c$  = Concentration  
 $q$  = Volume flow rate

### Concentration corrected for oxygen:

From reference calculations (taken from BS ISO 9096):

$$c_m = c_a \times \frac{20.9 - O_{2,ref}}{20.9 - O_{2,a}}$$

$c_m$  = Concentration at reference conditions  
 $c_a$  = Actual concentration  
 $O_{2, ref}$  = Reference oxygen (%)  
 $O_{2, a}$  = Actual Oxygen (%)

### Concentration corrected for moisture:

From reference calculations (taken from BS ISO 9096):

Convert wet gas to dry gas

$$c_{dry} = c_{wet} \times \frac{100}{100 - H_a}$$

Convert dry gas to wet gas

$$c_{wet} = c_{dry} \times \frac{100 - H_a}{100}$$

$c_{wet}$  = Concentration wet gas  
 $c_{dry}$  = Concentration dry gas  
 $H_a$  = Water vapour content (%vol)

### Conversion of parts per million (ppm) to mg/m<sup>3</sup>

From reference calculations (taken from EA TGN M2):

$$\text{Concentration}(mg / m^3) = \frac{\text{Concentration}(ppm) \times \text{molecular weight}(g)}{\text{molar volume}(l) \text{ at a given temperature}}$$

molar volume at 273K = 22.4 litres

### When Converting TOC

$$\text{Concentration}(mg / m^3) = \frac{\text{Concentration}(ppm) \times \text{molecular weight of carbon in span gas}(g)}{\text{molar volume}(l) \text{ at a given temperature}}$$

molar volume at 273K = 22.4 litres

## Calculation of Uncertainty Estimates - Manual Monitoring Techniques

$$C_m = \frac{Q_m}{V_{std}}$$

$$V_{std} = V_{T.p} \times \frac{T_{std}}{T} \times \frac{P}{P_{std}}$$

Where:

$C_m$	=	the measured concentration	in	mg/m <sup>3</sup>
$Q_m$	=	mass concentration collected in absorber solution and filter	in	mg
$v_s$	=	the volume of the sample solution	in	l
$V_{std}$	=	volume sampled at standard conditions	in	m <sup>3</sup>
$T_m$	=	mean temperature of gas meter	in	K
$T_{std}$	=	standard temperature	=	273K
$p=p_{rel}+P_{atm}$	=	absolute pressure = gas meter pressure + atmospheric pressure	in	kPa
$P_{std}$	=	standard pressure	=	101.325 kPa
$V_{T.p}$	=	volume sampled as indicated by the gas meter	in	m <sup>3</sup>

Expression for calculation of the combined uncertainty of the measured concentration

$$\frac{u^2(C_m)}{(C_m)^2} = \frac{u^2(Q_m)}{(Q_m)^2} + \frac{u^2(v_s)}{(v_s)^2} + \frac{u^2(V_{std})}{(V_{std})^2}$$

Expression for calculation of the combined uncertainty of the gas volume

$$V_{std} = V_{T.p} \times \frac{T_{std}}{T_m} \times \frac{P}{P_{std}}$$

Assuming that uncertainties associated with the standard quantities  $T_{std}$  and  $P_{std}$  are negligible

Expression for calculation of the combined uncertainty of the measured concentration

$$\frac{u^2(C_m)}{(C_m)^2} = \frac{u^2(Q_m)}{(Q_m)^2} + \frac{u^2(v_s)}{(v_s)^2} + \frac{u^2(V_{T.p})}{(V_{T.p})^2} + \frac{u^2(T)}{(T)^2} + \frac{u^2(p_{rel})}{(p)^2} + \frac{u^2(p_{atm})}{(p)^2}$$

$$u(C_m) = \sqrt{\left( \frac{u^2(Q_m)}{(Q_m)^2} + \frac{u^2(v_s)}{(v_s)^2} + \frac{u^2(V_{T.p})}{(V_{T.p})^2} + \frac{u^2(T)}{(T)^2} + \frac{u^2(p_{rel})}{(p)^2} + \frac{u^2(p_{atm})}{(p)^2} \right)} \times (C_m)^2$$

Overall expanded uncertainty (k = 2)

$$U(C_m) = u(C_m) \times k$$

Uncertainty of the measured concentration at oxygen reference concentration

$$u(C_{m,O_2,ref}) = \sqrt{\left( \frac{u^2(Q_m)}{(Q_m)^2} + \frac{u^2(v_s)}{(v_s)^2} + \frac{u^2(V_{T.p})}{(V_{T.p})^2} + \frac{u^2(T)}{(T)^2} + \frac{u^2(p_{rel})}{(p)^2} + \frac{u^2(p_{atm})}{(p)^2} + \frac{u^2(O_{2,meas,dry})}{(21 - O_{2,meas,dry})^2} \right)} \times (C_{m,O_2,ref})^2$$

Where:

$u(C_{m,O_2,ref})$	=	uncertainty associated with the mass concentration at O <sub>2</sub> reference concentration	in	mg/m <sup>3</sup>
$C_{m,O_2,ref}$	=	mass concentration at O <sub>2</sub> reference concentration	in	mg/m <sup>3</sup>
$O_{2,meas}$	=	O <sub>2</sub> measured concentration	in	% volume
$u((O_{2,meas})_{dry})$	=	uncertainty associated to the measured O <sub>2</sub> concentration	in	% (relative to O <sub>2,meas</sub> )

## Calculation of Uncertainty Estimates - Instrumental Monitoring Techniques

### Model equation

$$C_{ppm} = C_{reading} + Corr_{fit} + Corr_{0,dr} + Corr_{s,dr} + Corr_{rep} + Corr_{adj} + \sum_{i=1}^n Corr_{inf} + Corr_{int}$$

Where:

$C_{ppm}$	=	concentration in ppm	$Corr_{rep}$	=	correction of repeatability of measurement
$C_{NO,reading}$	=	concentration given by analyser	$Corr_{adj}$	=	correction of adjustment
$Corr_{fit}$	=	correction of lack of fit	$Corr_{inf}$	=	correction of influence quantities
$Corr_{0,dr}$	=	correction of zero drift	$Corr_{int}$	=	correction of interferences
$Corr_{s,dr}$	=	correction of span drift			

### Calculation of partial uncertainties

$$u(Corr_{fit}) = \frac{\left( \frac{X_{fit,max}}{100 \times range} \right)}{\sqrt{3}} \quad \text{Where: } X_{fit,max} \text{ is the maximum allowable deviation from linearity}$$

Expressed as % of the range and calculated by applying a rectangular probability distribution

$$u(Corr_{0,dr}) = \frac{X_{0,dr}}{\sqrt{3}} \quad u(Corr_{s,dr}) = \frac{X_{s,dr}}{\sqrt{3}}$$

$$u(Corr_{rep}) = \max(S_{0,rep}; S_{s,rep}) = S_{rep} \quad \text{Where: } S_{r,0} \text{ is the standard uncertainty at zero level, } S_{r,s} \text{ is the standard uncertainty at span level}$$

$$u(Corr_{adj}) = u(Corr_{loss}) + u(Corr_{cal}) \quad \text{Where: } u(Corr_{loss}) \text{ is the uncertainty due to losses in sample line, } u(Corr_{cal}) \text{ is the uncertainty due to losses in sample line}$$

$$u(Corr_{loss}) = \frac{C_{j,loss}}{\sqrt{3}} \quad \text{Where: } C_{j,loss} \text{ is the concentration of sample loss at span level}$$

$$u(Corr_{cal}) = \frac{U_{cal}}{2} \quad \text{Where: } U_{cal} \text{ is the expanded uncertainty of the calibration gas}$$

$$u(Corr_{int}) = c_j \sqrt{\frac{(x_{j,max} - x_{j,adj})^2 + (x_{j,min} - x_{j,adj})^2 + (x_{j,max} - x_{j,min})^2}{3}} \quad \text{Where: } c_j \text{ is the sensitivity coefficient of the influence quantity, } x_{j,min} \text{ is the minimum value of the influence quantity during monitoring, } x_{j,max} \text{ is the maximum value of the influence quantity during monitoring, } x_{j,adj} \text{ is the value of the influence quantity during adjustment}$$

$$u(Corr_{int}) = \frac{c_j}{Int_{j,test}} \sqrt{\frac{Int_{j,max}^2 + Int_{j,min} \times Int_{j,max} + Int_{j,min}^2}{3}}$$

and

$$u(\Sigma Corr_{int}) = \max[S_{int,p}; S_{int,n}] \quad \text{Where: } c_j \text{ is the sensitivity coefficient of the interferent j, } Int_{j,test} \text{ is the concentration of the interferent j used to determine } c_j, Int_{j,min} \text{ is the minimum value of the interferent j quantity during monitoring, } Int_{j,max} \text{ is the maximum value of the interferent j quantity during monitoring, } Int_{j,adj} \text{ is the concentration of the interferent j in the cal gas used to adjust the analyser, } S_{int,p} \text{ is the sum of interferences with positive impact, } S_{int,n} \text{ is the sum of interferences with negative impact}$$

### Combined uncertainty

$$u(C_{ppm}) = \sqrt{u^2(Corr_{fit}) + u^2(Corr_{0,dr}) + u^2(Corr_{s,dr}) + u^2(Corr_{rep}) + u^2(Corr_{s,vf}) + u^2(Corr_{a,press}) + u^2(Corr_{temp}) + u^2(Corr_{volt}) + u^2(Corr_{adj}) + S_{int}^2}$$

Overall expanded uncertainty (k = 2)  $U(C_m) = u(C_m) \times k$

### Uncertainty of NOx measurements

$$u(C_{NOx,conv}) = \frac{C_{NOx} \times R \times \eta}{\sqrt{3}} \quad \text{Where: } C_{NOx} \text{ is the concentration of NOx measured by the analyser, } R \text{ is the ratio of NO:Nox in the stack gas, } \eta \text{ is the NOx converter efficiency}$$

### Combined uncertainty NOx measurements

$$u(C_{NOx,stack}) = \sqrt{u^2(Corr_{fit}) + u^2(Corr_{0,dr}) + u^2(Corr_{s,dr}) + u^2(Corr_{rep}) + u^2(Corr_{s,vf}) + u^2(Corr_{a,press}) + u^2(Corr_{temp}) + u^2(Corr_{volt}) + u^2(Corr_{adj}) + S_{int}^2 + u^2(Corr_{NOx,conv})}$$

### Uncertainty of mass concentration at oxygen reference concentration

$$u(C_{O_2,ref}) = \sqrt{u^2(Corr_{fit}) + u^2(Corr_{0,dr}) + u^2(Corr_{s,dr}) + u^2(Corr_{rep}) + u^2(Corr_{s,vf}) + u^2(Corr_{a,press}) + u^2(Corr_{temp}) + u^2(Corr_{volt}) + u^2(Corr_{adj}) + S_{int}^2 + \left( \frac{u^2(O_{2,meas,dry})}{(21 - O_{2,meas,dry})^2} \right)}$$

Where:

$u(C_{O_2,ref})$	=	uncertainty associated with the mass concentration at O <sub>2</sub> ref. concentration	in	mg/m <sup>3</sup>
$C_{O_2,ref}$	=	mass concentration at O <sub>2</sub> reference concentration	in	mg/m <sup>3</sup>
$O_{2,meas}$	=	O <sub>2</sub> measured concentration	in	% volume
$u(O_{2,meas,dry})$	=	uncertainty associated to the measured O <sub>2</sub> concentration	in	% (relative to O <sub>2</sub> meas)

## APPENDIX 4



## Uncertainty Estimate For The Measurement Of Total Particulate Matter

### Total Particulate Matter

Symbol	Mass concentration of TPM	Units
$C_m$	1.28	mg/m <sup>3</sup>
$C_m$ at $O_2$ ref	23.94	mg/m <sup>3</sup>

Filter	0.10	mg
Washings	0.80	mg

Symbol	Reference Oxygen	Units
$O_{2,ref}$ (0=No Correction)	13	%

Symbol	Daily emission limit value	Units
DELV	20.0	mg/m <sup>3</sup>

#### Mass of Particulate

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u(\text{calBal})$	Calibration	0.1180	mg	Normal	2	1	0.0590	
$u(\text{repBal})$	Repeatability Filter	0.0110	mg	Normal	1	2	0.0220	
$u(\text{repBal})$	Repeatability Washings	0.0300	mg	Normal	1	2	0.0600	
$u(\text{driftBal})$	Drift	0.0312	mg	Rectangular	$\sqrt{3}$	1	0.0180	
$u(\text{resBal})$	Resolution	0.0050	mg	Rectangular	$\sqrt{3}$	1	0.0029	
$u(\text{aceBal})$	Residual acetone	0.0400	mg	Normal	2	1	0.0200	
$u(\text{buoBal})$	Air buoyancy	0.0015	mg	Normal	1	1	0.0015	
$u(\text{mass})$	Combined Uncertainty	-	-	Normal	-	-	0.0911	
$u(\text{mass})/\text{mass}$	Relative	0.900	mg	-	-	-	0.0710	
							$u(\text{mass})^2/\text{mass}^2$	0.005040

$U(W_m)$	Expanded Combined Weighing Uncertainty As Percentage of DELV $k=2$	$\pm$	0.91	%
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#### Volume of sampled gas

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u(\text{cal}V_{T,p})$	Calibration	0.0034	m <sup>3</sup>	Normal	2	1	0.0017	
$u(\text{rep}V_{T,p})$	Repeatability	0.0004	m <sup>3</sup>	Normal	1	1	0.0004	
$u(\text{drift}V_{T,p})$	Drift	0.0019	m <sup>3</sup>	Rectangular	$\sqrt{3}$	1	0.0011	
$u(\text{res}V_{T,p})$	Resolution	0.0002	m <sup>3</sup>	Rectangular	$\sqrt{3}$	1	0.0001	
$u(V_{T,p})$	Combined Uncertainty	-	-	Normal	-	-	0.0021	
$u(V_{T,p})/V_{T,p}$	Relative	0.701	m <sup>3</sup>	-	-	-	0.0030	
							$u(V_m)^2/V_m^2$	0.000009

#### Temperature of the DGM

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u(\text{cal}T_m)$	Calibration	1.0	K	Normal	2	1	0.5000	
$u(\text{cal}T_m)$	Calibration	1.0	K	Normal	2	1	0.5000	
$u(\text{res}T_m)$	Resolution	0.1	K	Rectangular	$\sqrt{3}$	1	0.0577	
$u(\text{drift}T_m)$	Drift	1.0	K	Rectangular	$\sqrt{3}$	1	0.5774	
$u(T_m)$	Combined Uncertainty	-	-	Normal	-	-	0.9147	
$u(T_m)/T_m$	Relative	296.3	K	Normal	-	-	0.0031	
							$u(T_m)^2/T_m^2$	0.000010

#### Atmospheric Pressure

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u(P_{\text{atm}})$	Metrological Office	300	Pa	Normal	$\sqrt{3}$	1	173	
$u(P_{\text{atm}})$	Combined Uncertainty	-	-	Normal	-	-	173	
$u(P_{\text{atm}})/P$	Relative	100500	-	Normal	-	-	0.0017	
							$u(P_{\text{atm}})^2/P^2$	0.000003

#### Relative DGM Pressure

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u(P_{\text{rel}})$	DGM Pressure	40	Pa	Normal	1	1	40	
$u(P_{\text{rel}})$	Combined Uncertainty	-	-	Normal	-	-	40	
$u(P_{\text{rel}})/P$	Measured pressure	100829	-	-	-	-	0.0004	
							$u(P_{\text{rel}})^2/P^2$	0.000002

#### Oxygen reference concentration

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	$c_i$	$U_i$	
$u((O_2, \text{meas})_{\text{dry}})_{\text{rel}}$	Measurement of oxygen	0.20	%	Normal	1	1	0.2000	
	Uncertainty of oxygen correction	-	-	-	-	-	0.4664	
	Measured Oxygen	20.6	%	-	-	-	$u(O_{\text{rel}})^2/O^2$	0.217565

#### Measurement uncertainty

$u(C_m)$	Combined Standard Uncertainty			$\pm$	0.13	mg/m <sup>3</sup>
$u(C_m)$ at ref $O_2$	Combined Standard Uncertainty			$\pm$	11.42	mg/m <sup>3</sup>

#### Expanded uncertainty expressed with a level of confidence of 95%, $k=2$

$U(C_m)$	Expanded Combined Uncertainty	$k = 2$		$\pm$	0.26	mg/m <sup>3</sup>
$U(C_m, \text{rel})$	Expanded Combined Uncertainty	$k = 2$		$\pm$	20.1	%
$U(C_m, \text{rel}, \text{ELV})$	Expanded Combined Uncertainty	$k = 2$		$\pm$	1.3	%

#### Expanded uncertainty at oxygen reference conditions expressed with a level of confidence of 95%, $k=2$

$U(C_m)$ at ref $O_2$	Expanded Combined Uncertainty	$k = 2$		$\pm$	22.85	mg/m <sup>3</sup>
$U(C_m, \text{rel})$ at ref $O_2$	Expanded Combined Uncertainty	$k = 2$		$\pm$	1780.5	%
$U(C_m, \text{rel}, \text{ELV})$ at ref $O_2$	Expanded Combined Uncertainty	$k = 2$		$\pm$	114.2	%

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor ( $k = 2$ ), providing a level of confidence of approximately 95%. The uncertainty evaluation has been carried out in accordance with UKAS requirements.

## Uncertainty Estimate For The Measurement Of Heavy Metals

## Total Mass Concentration Of Metals - Lead

Symbol	Total mass concentration of Lead	Units
Cm	0.05324	mg/m3
Cm at O2 ref	1.02782	mg/m3

## Mass of heavy metals in filter digest

	Qmf (mg)	LODmf	u(Qmf) % (k = 2)	u(Qmf)/Qmf	u(Qmf) <sup>2</sup> /Qmf <sup>2</sup>
Lead (Pb)	41.000	0.500	23.000	0.115	0.013

## Concentration of heavy metals absorption solution

	Qm (mg/l)	LODm	u(Qm) % (k = 2)	u(Qm)/Qm	u(Qm) <sup>2</sup> /Qm <sup>2</sup>
Lead (Pb)	15.000	0.300	20.500	0.103	0.011

## Volume of sampled gas

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(calVT.p)	Calibration	0.0028	m3	Normal	1.000	1.000	0.003
u(driftVT.p)	Drift	0.0027	m3	Rectangular	$\sqrt{3}$	1.000	0.002
u(resVT.p)	Resolution	0.0002	m3	Rectangular	$\sqrt{3}$	1.000	0.000
u(VT.p)	Combined Uncertainty	-	-	Normal	-	-	0.003
u(VT.p)/VT.p	Relative uncertainty	0.860	m3	-	-	-	0.004
						u(Vm) <sup>2</sup> /Vm <sup>2</sup>	0.000014

## Temperature of the DGM

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(calTm)	Calibration	1.0	K	Normal	2.000	1.000	0.500
u(calTcm)	Calibration	1.0	K	Normal	2.000	1.000	0.500
u(resTm)	Resolution	0.5	K	Rectangular	$\sqrt{3}$	1.000	0.289
u(Tm)	Combined Uncertainty	-	-	Normal	-	-	0.764
u(Tm)/Tm	Relative uncertainty	292	K	Normal	-	-	0.003
						u(Tm) <sup>2</sup> /Tm <sup>2</sup>	0.000007

## Atmospheric Pressure

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(Patm)	Metrological Office	300	Pa	Normal	1.000	1.000	300
u(Patm)	Combined Uncertainty	-	-	Normal	-	-	300
u(Patm)/P	Relative uncertainty	100500	-	Normal	-	-	0.003
						u(Patm) <sup>2</sup> /P <sup>2</sup>	0.000009

## Relative DGM Pressure

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(Prel)	Manometer	40	Pa	Normal	1.000	1.000	40.000
u(Prel)	Combined Uncertainty	-	-	Normal	-	-	40.000
u(Prel)/P	Relative uncertainty	101001	-	Normal	-	-	0.0004
						u(Prel) <sup>2</sup> /P <sup>2</sup>	0.0000002

## Volume (mass) of Absorption Solution

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(repsv)	Repeatability	0.13	g (ml)	Normal	1.000	1.000	0.130
u(calvs)	Calibration (Tare)	0.10	g (ml)	Rectangular	1.000	1.000	0.100
u(drsv)	Drift	0.10	g (ml)	Rectangular	1.000	1.000	0.100
u(resvs)	Resolution	0.05	g (ml)	Rectangular	$\sqrt{3}$	1.000	0.029
u(vs)	Combined Uncertainty	-	-	-	-	-	0.194
u(vs)/vs	Relative uncertainty	230	-	Normal	-	-	0.0008
						u(vs) <sup>2</sup> /vs <sup>2</sup>	0.0000007

## Oxygen reference concentration

Symbol	Source of Uncertainty	Value	Units	Probability Distribution	Divisor	ci	Ui
u(O <sub>2</sub> ,meas)dry)rel	Measurement of oxygen	0.28	%	Normal	1	1	0.282
	Uncertainty of oxygen correction	-	-	-	-	-	0.6807
	Measured Oxygen	20.6	%	-	-	u(Orel) <sup>2</sup> /O <sup>2</sup>	0.4633163

u(Cm)rel	Overall Combined Uncertainty	mg/m3	Total Lead	±	0.0082
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U(Cm)rel	Expanded Combined Uncertainty	mg/m3	Total Lead	k = 2	±	0.0164
U(Cm,rel)	Expanded Combined Uncertainty	% of ELV	Total Lead	k = 2	±	0.3

u(Cmrel) at ref O2	Expanded Combined Uncertainty	mg/m3	Total Lead	k = 2	±	1.435
U(Cm,rel)	Expanded Combined Uncertainty	% of ELV	Total Lead	k = 2	±	0.3

The reported expanded uncertainty is based on a standard uncertainty multiplied by a coverage factor (k = 2), providing a level of confidence of approximately 95%.

The uncertainty evaluation has been carried out in accordance with UKAS requirements.