TYPICAL MEASUREMENT UNCERTAINTY IN GAS FLOW MEASURED BY GFS2102 GRAVIMETRIC FLOW STANDARD

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FOREWARD

The GFS2102 is a fully automated gravimetric flow standard designed to supply primary gas flow measurements from 0.2 to 200 mg/s. This system supports primary traceability at DH Instruments, Inc (DHI) and other laboratories by a method that is directly traceable to mass and time.

This technical note is provided to assist metrologists using GFS2102 in formulating an uncertainty analysis for their primary flow measurements. Unlike other uncertainty analysis technical notes published by DHI, this document does not provide a fixed product specification for various ranges of mass flow each defined in a specific table. Instead, it provides examples of uncertainties in the form of tables at different mass flow rates defining typical measurement uncertainty in an amount of mass depleted from the reference cylinder.

INTRODUCTION

This technical note is a product uncertainty analysis that can be used as an example for any GFS2102 delivered by DHI. The analysis is performed by defining conservative environmental and operational limits that predict worse case conditions in a primary laboratory. All uncertainties are calculated based on the recommendations given in the GUM[1].

A unique feature of the GFS2102 is its ability automatically AutoZero and re-calibrate the mass balance before and during mass depletion tests. Thanks to this feature, many uncertainties are reduced to small changes in influences from their state when the AutoZero or re-calibration occurred. This leaves only the influences from the fundamental measurands of mass and time.

Another characteristic of a GFS2102 is that the beginning and ending measurements in mass are made dynamically at the same nominal flow rate. This reduces uncertainties that must be included in a system in which ramping flow rate up and down are required.

At the end of this document there are four uncertainty tables for three separate mass flow rates covering the range of the GFS2102. These can be used as uncertainty examples for the user of the GFS2102 and also are used to justify the typical flow measurement uncertainty defined in this document.

CALCULATIONS

Mass Flow [2]

The fundamental equation for mass flow is simple in the respect it is just mass [m] per time [t].

1) $$q_m = \frac{m_U}{t_d}$$

2) $$t_d = t_{(i)} - t_{(0)}$$

3) $$m_u = abs\left|m_{f(i)} - m_{f(0)}\right|$$

4) $$m_f = m_i + m_{bc} - m_d$$

where

q_m	=	Mass flow	[kg/s]
m_u	=	Mass change over a specified duration	[kg]
t_d	=	Duration of mass depletion	[s]
$t_{(0)}$	=	Time stamp at first reading	[s]
$t_{(i)}$	=	Time stamp when next reading is taken	[s]
$m_{f(0)}$	=	Fully compensated mass at start	[kg]
$m_{f(i)}$	=	Fully compensated mass reading	[kg]
m_i	=	Uncompensated mass reading	[kg]
m_{bc}	=	Reference cylinder buoyancy correction	[kg]
m_d	=	Balance drift correction	[kg]

The corrections shown to calculate the fully compensated mass value (m_f) are for the changes in buoyancy conditions of the bottle assembly from the time of a tare and the drift of the balance as is determined by the AMH-GFS2102 reference mass.

AutoZero correction

In the GFS2102 the AMH-GFS2102 is used as an automated single mass loader to detect and correct the drift (m_d) of the balance for longer gas depletions. The correction accounts for changes in air density that could change the amount of force created by the reference mass accelerated by local gravity between the initial AutoZero and consecutive AutoZeros.

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5) $$m_d = m_\Delta - m_T \frac{\rho_1 - \rho_2}{\rho_m}$$

where

m_T	=	True mass value of the reference	[kg]
m_Δ	=	Balance reading	[kg]
ρ_1	=	Air density at the initial AutoZero	[kg/m^3]
ρ_2	=	Air density at AutoZero	[kg/m^3]
ρ_m	=	Density of the reference mass	[kg/m^3]

Bottle Assembly Buoyancy Correction

The bottle assembly buoyancy correction (m_{bc})is used to account for changes in buoyant force created by changes in the air density and also changes in the volume of the bottle with respect to temperature and pressure changes. The calculation is iterative with m_{bc} starting at zero until m_{bc} does not change by more than 0.01 mg, or with 10 maximum iterations.

6) $$m_{bc} = 0$$

7) $$m_{btl} = m_i + m_{bc} + m_d$$

8) $$P_b = \frac{T_{IR} P_N \left(m_{btl} - m_{b0}\right)}{1000 T_N V_{\text{int}} \rho_{g\,(P_N, T_N)}}$$

9) $$V_{CR} = V_{ext}\left(1 + \lambda P_b\right)\left(1 + 3\alpha\left(T_{IR} - T_N\right)\right)$$

10) $$m_{bc} = 1000\left[V_{CR}\rho_{air}(P, T_C, H) + V_{acc}\rho_{air}(P, T_P, H)\right]$$

where

m_{btl}	=	Uncorrected instantaneous bottle mass	[kg]
m_i	=	Balance reading	[kg]
P_b	=	Reference cylinder pressure	[Pa]
T_{IR}	=	Reference cylinder temperature	[K]
P_N	=	Standard pressure 101325 Pa	[Pa]
m_{b0}	=	Evacuated reference cylinder mass	[kg]
T_N	=	Standard temperature	[K]
V_{int}	=	Reference cylinder internal volume	[m^3]
ρ_g	=	Density of test gas at standard conditions (Pn,Tn)	[kg/m^3]
V_{ext}	=	Reference cylinder external volume	[m^3]
V_{CR}	=	Corrected Reference cylinder external volume	[m^3]
λ	=	Elastic deformation coefficient of the ref cylinder	[Pa^{-1}]
α	=	Thermal expansion coefficient of the ref cylinder	[°C^{-1}]
V_{acc}	=	External volume of regulator assembly	[m^3]

ρ_{air} = Air density at ambient humidity and pressure, and temperature surrounding either the reference cylinder or the regulator assembly (T_C and T_P respectively). [kg/m^3]

ENVIRONMENTAL AND SYSTEM LIMITS

The uncertainties in this technical note are calculated based on defined environmental and system limits. In the case of a GFS2102, it is not range of ambient conditions that is required, but the amount of change in the ambient conditions over a complete GFS2102 depletion. Though the changes depend on the control of these parameters in the user's lab, listed are typical worse case changes in the environment surrounding the GFS2102 components that are sensitive to changes in buoyancy.

Environmental Limits

Ambient pressure:	± 1 kPa
Ambient temperature:	-5 to + 0.5 °C change
Ambient humidity:	-5 to + 10 %RH change

System Requirements

The main system requirement is that AutoZero (for both zero and slope) be used as needed to make balance drift negligible. The AutoZero frequency needed to meet this requirement is dependent upon the environmental conditions and the individual balance used.

It is assumed that the reference cylinder's temperature does not drop low enough to condense the surrounding air. The system cannot account for mass collected on the reference cylinder due to condensation. The infrared temperature sensor is used to measure the temperature of the cylinder and GFSTools software provides a warning if the temperature of the bottle approaches the dew point of the surrounding air to avoid making measurements in condensing conditions.

Finally, an assumption is made that the DHI LCM is used to monitor all ambient condition sensors and that the sensors calibrations are up to date.

Gas Media Requirements

This uncertainty analysis does not assume any specific gas characteristics. However, for reasons of safety, the GFS2102 manual should be referenced for gases that cannot be measured with the GFS2102.

Because GFS2102 measures the amount of mass depleted in the reference bottle, the composition of the gas does not significantly effect the result. However the purity of the gas may very well be a significant uncertainty in the device under test.

UNCERTAINTIES

In this section all known uncertainties are listed and explained. For each uncertainty the type (A or B), sensitivity, type of distribution and the standard uncertainty are given. At the end of this section some uncertainties are listed for special consideration. These are not included in the example uncertainty tables, but may be relevant depending on the test device being calibrated by the GFS2102.

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Time [t_d]

Durations of gas depletions are measured with the DHI LCM (laboratory conditions monitor) on board frequency counter. The LCM provides a time stamp on mass measurements obtained directly from the balance. This avoids any latency that may occur from the computer's operating system.

The uncertainty in this function of the LCM is conservative and can almost be considered negligible. There are no corrections on the time value so the uncertainty is only in the time that is read. The stated uncertainty is ± 0.01% of reading with at least 95% confidence.

Type of uncertainty:	relative type B
Sensitivity:	1% of reading/% of reading
Distribution:	considered normal
Standard uncertainty:	0.005%

Reference mass [m_T]

The reference mass used with the AMH-GFS2102 is a nominal 2kg mass with an uncertainty of $\pm 1 \times 10^{-5}$ in mass using a coverage factor of 2. The reference mass is used to calibrate the balance span before a test is run. This uncertainty is considered to be insignificant compared to the other major influences defined in this analysis.

Depleted mass [m_U]

The depleted mass is the difference between the fully compensated mass value determined at the start of the test and when a reading is obtained. It is important to understand that the compensation is performed the same way on the first reading as it is for subsequent readings. This means that any uncertainties contributed by the ambient sensors on the GFS are limited only to the change in those conditions between the start of the test and when a reading is taken. Uncertainties from constants, such as gas properties for Air, are also minimized.

There are a number of sensors or measured values used to determine separate ambient conditions for the reference cylinder and the regulator assembly. Only the values that change from the first reading to the next are considered to contribute uncertainty. These are listed with their sensitivity with respect to the mass value.

<u>Reference cylinder temperature</u>

The IR probe used to detect temperature of the air around the bottle to warn the user of possible condensation is also used to assist in the calculation of the reference cylinder pressure. (ref equation 8). The uncertainty is high, ± 3 °C using a coverage factor of 2, but the sensitivity to mass is very low.

Type of uncertainty:	type B
Sensitivity:	0.02mg/°C
Distribution:	considered normal
Standard uncertainty:	1.5°C

<u>Ambient temperature of air surrounding reference cylinder</u>

To compensate for the changes in buoyancy of the reference cylinder, the temperature and humidity of the air surrounding the reference cylinder is measured by one of the two TH probes connected to the LCM. Again, only the uncertainty in the difference between the first reading in the test and each subsequent reading needs to be considered. Therefore only the characteristics of repeatability and resolution for those measurements are used to assign uncertainty.

For the TH probe temperature repeatability and resolution account for approximately ± 0.2 °C, using a coverage factor of 2. This may be considered a rectangular distribution as the specification is from product literature.

Type of uncertainty:	type B
Sensitivity:	6.5 mg/°C
Distribution:	rectangular
Standard uncertainty:	0.11°C

<u>Ambient humidity of air surrounding reference cylinder</u>

As with temperature, the uncertainty contributed by the TH humidity sensor is only dependent upon the repeatability characteristics of the sensor and the resolution. A conservative estimate based on the manufacturer's specifications is ± 3% RH using a coverage factor of 2.

Type of uncertainty:	type B
Sensitivity:	0.17 mg/%RH
Distribution:	rectangular
Standard uncertainty:	1.7%RH

<u>Ambient pressure of air surrounding reference cylinder</u>

The sensor used to measure ambient pressure is specified to have repeatability and resolution of ± 50 Pa using a coverage factor of 2.

Type of uncertainty:	type B
Sensitivity:	0.04mg/Pa
Distribution:	rectangular
Standard uncertainty:	29 Pa

<u>Ambient temperature of air surrounding regulator assembly</u>

A separate TH sensor is used to measure the temperature of the air surrounding the regulator assembly. The uncertainty is the same as the temperature sensor that is used to measure the air surrounding the reference cylinder, but the sensitivity is lower because it applies to the volume of the regulator instead of the larger volume of the reference cylinder.

Type of uncertainty:	type B
Sensitivity:	0.46mg/°C
Distribution:	rectangular
Standard uncertainty:	0.11°C

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Ambient humidity of air surrounding regulator assembly

The same sensor that is used to measure humidity of the air surrounding the reference cylinder is used to estimate the humidity of the air surrounding the regulator assembly. The sensitivity is lower because it is applied to the volume of the regulator assembly which is smaller than the reference cylinder, but its uncertainty is the same.

Type of uncertainty:	type B
Sensitivity:	0.02 mg/%RH
Distribution:	rectangular
Standard uncertainty:	1.7%RH

Ambient pressure of air surrounding regulator assembly

The same ambient pressure that is read to determine the density of the air surrounding the reference cylinder is used to determine the density of the air surrounding the regulator assembly. The uncertainty is the same in pressure but the sensitivity is lower due to the fact the regulator mass is lower.

Type of uncertainty:	type B
Sensitivity:	0.0012 mg/Pa
Distribution:	rectangular
Standard uncertainty:	29 Pa

Gas properties

Gas properties of air are used to calculate the density of air. As with the other uncertainties assigned to the sensors that are used to measure air density, the absolute uncertainty in gas density cancels. The main difference is that the gas properties do not have an uncertainty contributed by non-repeatability. Therefore the only uncertainty is the difference in the calculations when ambient conditions changed significantly. This uncertainty, using a coverage factor of 2, can be estimated at ± 0.001% of the air density measured, or nominally ± 0.000012 kg/m^3 based on the ambient limits shown in the beginning of this document.

Type of uncertainty:	type B
Sensitivity:	1558.72 g/kg/m^3
Distribution:	considered normal
Standard uncertainty:	0.000006 kg/m^3

Mass Balance

The balance used in a GFS2102 is a Mettler XP2004S precision balance. The uncertainties associated with the balance are resolution, repeatability, linearity, rate of change and the AutoZero correction.

Resolution

Resolution for the XP2004S is 0.1 mg. Using the rules of the GUM, one standard uncertainty is equal to resolution divided by the square root of 12.

Type of uncertainty:	type B
Sensitivity:	1mg/mg
Distribution:	rectangular
Standard uncertainty:	0.03mg

Balance Linearity

The specification of linearity for the XP2004S from the operator's manual is ± 1 mg. However this is over the entire range of the balance. Since only 1/10th of the range is ever used the linearity was experimentally determined using DHI reference masses in the region the balance is used. The results show that, using a coverage factor of 2, the uncertainty is approximately ± 0.37 mg, or 0.19 mg at k=1. Since it was experimentally determined it is listed as a type A uncertainty.

Type of uncertainty:	type A
Sensitivity:	1mg/mg
Distribution:	considered normal
Standard uncertainty:	0.19 mg

Repeatability

The specification for repeatability from the operator's manual of the XP2004S is ± (0.08 mg + 9 x 10-9 of reading). This is approximately 0.28 mg at 2000 grams. As with linearity, repeatability was determined experimentally using DHI reference masses. The uncertainty observed is ± 0.48 mg at k=2 providing 1 standard uncertainty of 0.24 mg which is consistent with the manufacturer's specification .

Type of uncertainty:	type A
Sensitivity:	1mg/mg
Distribution:	rectangular
Standard uncertainty:	0.24 mg

Rate of change of mass

When the GFS2102 is depleting gas, there is a limitation as to how fast the balance can be read. The XP2004S can provide a mass sample 23 times per second. The rate of change of mass is defined by the GFS2102 range of 0.2 to 200 mg/s. The worse case update from the balance at a rate of 200 mg/s is at a minimum value of 8.7 mg. In the best case, at 0.2 mg/s this value is reduced proportionally to 0.0087 mg. This uncertainty is very similar to resolution in that there is a rectangular distribution that defines the probability of the value being correct and is then defined as 2.5 mg and 0.0025 mg respectively at one standard uncertainty. This uncertainty can then be defined as a function of flow rate at value of 1.25% of flow rate. Note that this is a fixed value in mg, no matter how long the test runs as long as flow rate remains constant.

Type of uncertainty:	type B
Sensitivity:	0.0125 mg/mg/s
Distribution:	rectangular
Standard uncertainty:	1.25% of flow rate

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AutoZero

The uncertainty due to drift of the balance during a test can effectively be eliminated using the AutoZero function. But the AutoZero function is dependent upon the changing environmental conditions defined in equation 5. Again, since the balance is tared, the uncertainty is only due to changes in the environmental conditions, i.e. if an ideal situation existed and the ambient parameters did not change, there would not be an uncertainty added. However it is likely that the AutoTare function would be used most often in tests of long duration where ambient conditions can change.

The external PRT read by the LCM is used to measure the temperature of the air surrounding the reference mass. The internal pressure and humidity sensor are used to measure ambient pressure and humidity respectively. Table 1 below lists the uncertainties contributed by the sensors to this correction based on the worse case environmental changes over the duration of a GFS depletion.

Table 1. Typical uncertainties in reference mass buoyancy correction

	Ux, k=1	Sens [mg/x]	Um[mg]
Pressure	25	3.01E-09	0.08
Temperature	0.05	1.12E-06	0.06
Humidity	1.7	2.60E-08	0.04

Type of uncertainty: type B
Sensitivity: see table 1
Distribution: considered normal
Standard uncertainty: see table 1

SPECIAL CONSIDERATIONS

Calibration of molbloc-S and molbloc-L

When calibrating molbloc-S and molbloc-L sonic nozzle and laminar flow based flow transfer standards, the method of comparison varies depending upon flow rate. Below 20 mg/s (1 Nl min^{-1}) a totalization of mass by the molbloc is used to compare to the GFS2102. Above 20 mg/s the speed at which a molbloc can totalize produces an uncertainty that is significant relative to the uncertainty in the GFS2102. At greater than 20 mg/s an average flow must be used.

The uncertainty in the average flow depends upon the stability of the flow, therefore any additional uncertainty can be calculated by a standard deviation of the flow values read by a molbloc. In practice, because of the good flow control provided by the MFC-CB and MFC and the fact that flow can be stabilized before GFS2102 begins to take readings, the uncertainty is not normally significant.

The difference of uncertainties between low and high flow rates

When considering the uncertainties for a GFS2102 the limits defined in this document for environmental changes are considered typical, but are actually the typical worse case condition observed, i.e at higher flows where cooling of the bottle is the most significant. For lower flow rates, the uncertainties may be significantly reduced because the cooling of the reference cylinder and regulator assembly is minimal.

In the case of lower flow rates the depletion times are much longer. Normally this means there is a greater chance that environmental condition around the reference cylinder and the regulator assembly will change significantly. The conditions during a test can be reviewed in a GFS Tools data file and could be used to define the uncertainties contributed by changing environmental conditions.

UNCERTAINTY TABLES

The uncertainty tables that follow are examples of four separate mass flow rates, each given with two separate depletion amounts. Based on the results of the eight separate combined and expanded uncertainties, a typical mass flow uncertainty is given as an equation dependent upon average mass flow rate and the amount of mass depleted.

There is some correlation between the uncertainties listed because the same sensors are used for different corrections in the GFS model. For example, for ambient measurements that are critical to the uncertainty of the GFS, the values read from the same pressure and humidity sensors are used in three separate calculations.

The tables identify the uncertainties and give each ones value in its own units, sensitivity coefficient and value in mg. The uncertainties are combined and expanded to a level of k=2. The correlation coefficients are not shown. The combined uncertainty is calculated by summing the correlated uncertainties in pressure and humidity, then included as one uncertainty in the final combination, i.e. there ends up being one uncertainty for pressure and one for humidity.

REFERENCES

[1] Guide To The Expression Of Uncertainty In Measurement; ISO/TAG4/WG3, 1994

[2] GFS2101 Operational and Maintenance Manual, June 2006.

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UNCERTAINTY TABLES – Typical Mass Flow Uncertainty [mg/s]: ± [(3 mg + 0.035 mg/g depletion) + 1.25% of change of mass per second]/ depleted mass.

	mass flow rate 0.2 mg/s 5 gram depletion				mass flow rate 0.2 mg/s 10 gram depletion			
Uncertainties	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)
(uncorrelated)		[mg/Ux]	[mg]	[mg]		[mg/Ux]	[mg]	[mg]
Time	0.00005	5000		0.25	0.00005	10000		0.50
Reference cylinder temperature	1.5	0.02		0.03	1.5	0.02		0.03
Ambient temperature reference cylinder	0.11	6.5		0.72	0.11	6.5		0.72
Reference mass buoyancy - temperature	0.05	1.12		0.06	0.05	1.12		0.06
Ambient temperature regulator assembly	0.11	0.46		0.05	0.11	0.46		0.05
Gas properties	0.000006	1559		0.01	0.000006	1559		0.01
Resolution	0.03	1		0.03	0.03	1		0.03
Balance Linearity	0.19	1		0.19	0.19	1		0.19
Repeatability	0.24	1		0.24	0.24	1		0.24
(correlated)								
Ambient pressure reference cylinder	29	0.040	1.16		29	0.040	1.16	
Ambient pressure regulator assembly	29	0.0012	0.03		29	0.0012	0.03	
Reference mass buoyancy - pressure	29	0.0030	0.09	1.28	29	0.0030	0.09	1.28
Ambient humidity reference cylinder	1.7	0.17	0.29		1.7	0.17	0.29	
Ambient humidity regulator assembly	1.7	0.020	0.03		1.7	0.020	0.03	
Reference mass buoyancy - humidity	1.7	0.026	0.04	0.37	1.7	0.026	0.04	0.37
	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]
Rate of change of mass	0.2	0.0125		0.00	0.2	0.0125		0.00
Combined		**0.031%**	**rdg**	**1.57 mg**		**0.016%**	**rdg**	**1.63 mg**
Combined and expanded		**0.063%**	**rdg**	**3.13 mg**		**0.033%**	**rdg**	**3.25 mg**

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	mass flow rate 10 mg/s 5 gram depletion				mass flow rate 10 mg/s 20 gram depletion			
Uncertainties	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)
(uncorrelated)		[mg/Ux]	[mg]	[mg]		[mg/Ux]	[mg]	[mg]
Time	0.00005	5000		0.25	0.00005	20000		1.00
Reference cylinder temperature	1.5	0.02		0.03	1.5	0.02		0.03
Ambient temperature reference cylinder	0.11	6.5		0.72	0.11	6.5		0.72
Reference mass buoyancy - temperature	0.05	1.12		0.06	0.05	1.12		0.06
Ambient temperature regulator assembly	0.11	0.46		0.05	0.11	0.46		0.05
Gas properties	0.000006	1559		0.01	0.000006	1559		0.01
Resolution	0.03	1		0.03	0.03	1		0.03
Balance Linearity	0.19	1		0.19	0.19	1		0.19
Repeatability	0.24	1		0.24	0.24	1		0.24
(correlated)								
Ambient pressure reference cylinder	29	0.040	1.16		29	0.040	1.16	
Ambient pressure regulator assembly	29	0.0012	0.03		29	0.0012	0.03	
Reference mass buoyancy - pressure	29	0.0030	0.09	1.28	29	0.0030	0.09	1.28
Ambient humidity reference cylinder	1.7	0.17	0.29		1.7	0.17	0.29	
Ambient humidity regulator assembly	1.7	0.020	0.03		1.7	0.020	0.03	
Reference mass buoyancy - humidity	1.7	0.026	0.04	0.37	1.7	0.026	0.04	0.37
	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]
Rate of change of mass	10	0.0125		0.13	10	0.0125		0.13
Combined		**0.031% rdg**		**1.57 mg**		**0.009% rdg**		**1.85 mg**
Combined and expanded		**0.063% rdg**		**3.14 mg**		**0.018% rdg**		**3.69 mg**

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	mass flow rate 100 mg/s 20 gram depletion				mass flow rate 100 mg/s 50 gram depletion			
Uncertainties	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)	Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)
(uncorrelated)		[mg/Ux]	[mg]	[mg]		[mg/Ux]	[mg]	[mg]
Time	0.00005	20000		1.00	0.00005	50000		2.50
Reference cylinder temperature	1.5	0.02		0.03	1.5	0.02		0.03
Ambient temperature reference cylinder	0.11	6.5		0.72	0.11	6.5		0.72
Reference mass buoyancy - temperature	0.05	1.12		0.06	0.05	1.12		0.06
Ambient temperature regulator assembly	0.11	0.46		0.05	0.11	0.46		0.05
Gas properties	0.000006	1559		0.01	0.000006	1559		0.01
Resolution	0.03	1		0.03	0.03	1		0.03
Balance Linearity	0.19	1		0.19	0.19	1		0.19
Repeatability	0.24	1		0.24	0.24	1		0.24
(correlated)								
Ambient pressure reference cylinder	29	0.040	1.16		29	0.040	1.16	
Ambient pressure regulator assembly	29	0.0012	0.03		29	0.0012	0.03	
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Reference mass buoyancy - humidity	1.7	0.026	0.04	0.37	1.7	0.026	0.04	0.37
	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]
Rate of change of mass	100	0.0125		1.25	100	0.0125		1.25
Combined		**0.011%**	**rdg**	**2.23 mg**		**0.006%**	**rdg**	**3.19 mg**
Combined and expanded		**0.022%**	**rdg**	**4.45 mg**		**0.013%**	**rdg**	**6.39 mg**

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Uncertainties	mass flow rate 200 mg/s, 20 gram depletion: Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)	mass flow rate 200 mg/s, 50 gram depletion: Ux - k=1	Sensitivity	Um (correlated)	Um (uncorrelated)
(uncorrelated)		[mg/Ux]	[mg]	[mg]		[mg/Ux]	[mg]	[mg]
Time	0.00005	20000		1.00	0.00005	50000		2.50
Reference cylinder temperature	1.5	0.02		0.03	1.5	0.02		0.03
Ambient temperature reference cylinder	0.11	6.5		0.72	0.11	6.5		0.72
Reference mass buoyancy - temperature	0.05	1.12		0.06	0.05	1.12		0.06
Ambient temperature regulator assembly	0.11	0.46		0.05	0.11	0.46		0.05
Gas properties	0.000006	1559		0.01	0.000006	1559		0.01
Resolution	0.03	1		0.03	0.03	1		0.03
Balance Linearity	0.19	1		0.19	0.19	1		0.19
Repeatability	0.24	1		0.24	0.24	1		0.24
(correlated)								
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Ambient humidity reference cylinder	1.7	0.17	0.29		1.7	0.17	0.29	
Ambient humidity regulator assembly	1.7	0.020	0.03		1.7	0.020	0.03	
Reference mass buoyancy - humidity	1.7	0.026	0.04	0.37	1.7	0.026	0.04	0.37
	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]	mass flow rate [mg/s]	Sensitivity [mg/(mg/s)]		Um [mg]
Rate of change of mass	200	0.0125		2.50	200	0.0125		2.50
Combined		**0.016%**	**rdg**	**3.11 mg**		**0.008%**	**rdg**	**3.86 mg**
Combined and expanded		**0.031%**	**rdg**	**6.21 mg**		**0.015%**	**rdg**	**7.72 mg**

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NOTES

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