TRACEABILITY AND UNCERTAINTY ANALYSIS FOR A CALIBRATION PROCESS FOR FLOWMETERS, USING CORIOLIS FLOWMETERS AS REFERENCE

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Abstract: A flow meter manufacturer has recently developed a new system for calibrating its flow instruments. This system is based on the use of Coriolis flow meters as intermediate transfer standards. This new system is referred to as the Transfer Standard Method or TSM.

This paper and presentation will review the test data used to establish the validity of the Coriolis-based TSM, and will describe the process layout and design of the new TSM flow calibration stands. The focus of the paper, however, will be on traceability of the calibrations to national standards and on the uncertainty analysis for the TSM flow stands.

The working mass standards in the MMI (Micro Motion, Inc.) Primary Stand laboratory are traceable to Japanese and United States of America national standards. These working mass standards are used to calibrate and verify the scales of the MMI Primary Stand. The MMI Primary Stand is used to calibrate the reference meters. The reference meters are placed into service in TSM stands.

The uncertainty analysis can be split into four main parts:

A. Uncertainty of the scales in the MMI Primary Stand
B. Uncertainty of the MMI Primary Stand (Best Measurement Capability of the MMI Primary Stand)
C. Uncertainty of the reference meters, calibrated on the primary stand
D. Uncertainty of the TSM stand (Best Measurement Capability of TSM stand).

This paper and presentation explain, step by step, the uncertainty calculations from scale to flowmeter under test. The end result of this analysis, for worst case conditions, is a Best Measurement Capability of the TSM system of 0.013% on mass and 0.020% on volume.

Keywords: Coriolis, traceability, uncertainty, transfer standard, flow meter, best measurement capability

1. INTRODUCTION

The three purposes of this paper are:

- To discuss flowmeter calibration stand requirements and data used by the flowmeter manufacturer to support the development of the TSM (transfer standard method) calibration stand and to describe how the new TSM calibration stands operate.
- To review traceability for the new TSM calibration stands.
- To describe the TSM stand uncertainty analysis.

2. FLOWMETER CALIBRATION STAND REQUIREMENTS

The calibration requirements for the manufacturer's flowmeter calibration stands include:

- Uncertainty of < 0.033% mass. (This value of stand uncertainty is required in order to achieve a 3 times capability when calibrating flowmeters that have specified reference accuracy of 0.10%.)
- Mass and volumetric calibration
- Straight run for velocity type meters
- Readily automated
- Minimum calibration time
- Low maintenance
- Worldwide consistency

3. FEASIBILITY STUDY

The calibration technologies considered included gravimetric SSF (standing start-finish), gravimetric diverter and small volume prover. The TSM design was developed after collecting and reviewing data from the manufacturer's CMF series Coriolis sensors. The data was collected by using a special calibration on the manufacturer's standard CMF series flowmeters. The data for figure 1 were obtained using a gravimetric SSF calibration stand and the manufacturer's CMF type sensor, size CMF050. The sensor's normal full-scale flow rate is 56.7 kg/min with a maximum flow rate of 113 kg/min. The data shown in figure 1 comprise a total of 325 separate and independent flow batches and weigh scale measurements. Similar data was collected for other sizes of CMF sensors.

The history of the stability of the CMF series sensors "flow calibration factor" is excellent. The flow calibration factors for a number of sensors have been recorded for 4 or more years and there is no change in the flow calibration factors within the uncertainty of the flowmeter calibration process. Stability of the flow calibration factor for CMF series sensors is an active area of continuing study.

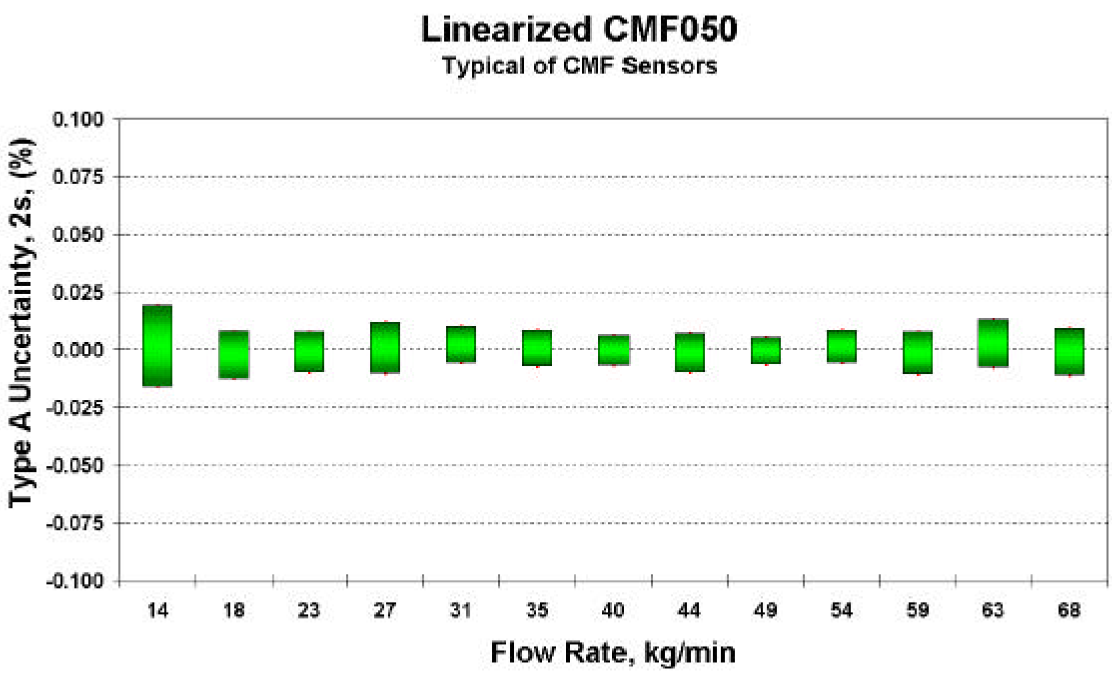

Figure 1
Typical TSM RM type A Uncertainty

Note that the data shown in figure 1 (as well as all further references to performance of Coriolis meters throughout this paper) are from standard production MMI (Micro Motion, Inc.) Elite meters. The only thing special about these meters is their calibration; their design and fabrication are, in all other respects, identical to all other MMI Elite meters.

The data shown in figure 1 support that, over a range of flow rates, standard CMF sensors can be calibrated, with linearization, to a very low type A uncertainty (repeatability), much better than the meter's standard reference specification for flow, 0.10 %. These specially calibrated sensors are then used as the RM (reference meter(s)) in the TSM flowmeter calibration stands.

4. TSM OPERATION

Figure 2 is a simplified P&ID (process & instrument diagram) of the TSM design. Different TSM calibration stands with different flow rate capabilities are all of a similar design. All TSM stands use pneumatically powered clamping systems, which facilitate rapid installation of the UUT (unit under test – refers to the meter(s) being calibrated and adjusted). The flow meters called RM (reference meters) and QCM (quality check meter) on each TSM stand are identical in size and calibration. For some meter technologies, the UUT can be more than one sensor installed in series.

The UUT is calibrated and adjusted to the RM. When verifying a meter's performance, after determining its flow calibration factor, the TSM calibration stand with its automated programming checks the UUT's low flow performance by comparing it to that of one of the in-line reference meters smaller than itself. Each time a reading is obtained from the UUT, the RM and QCM meters are also read. This is one of the key features of the TSM stand design: The QCM provides a continuous, real time, first level check on the calibration process for the UUT and on the stability of the RM, as well as on other potentially confounding effects such as entrained air and leakage.

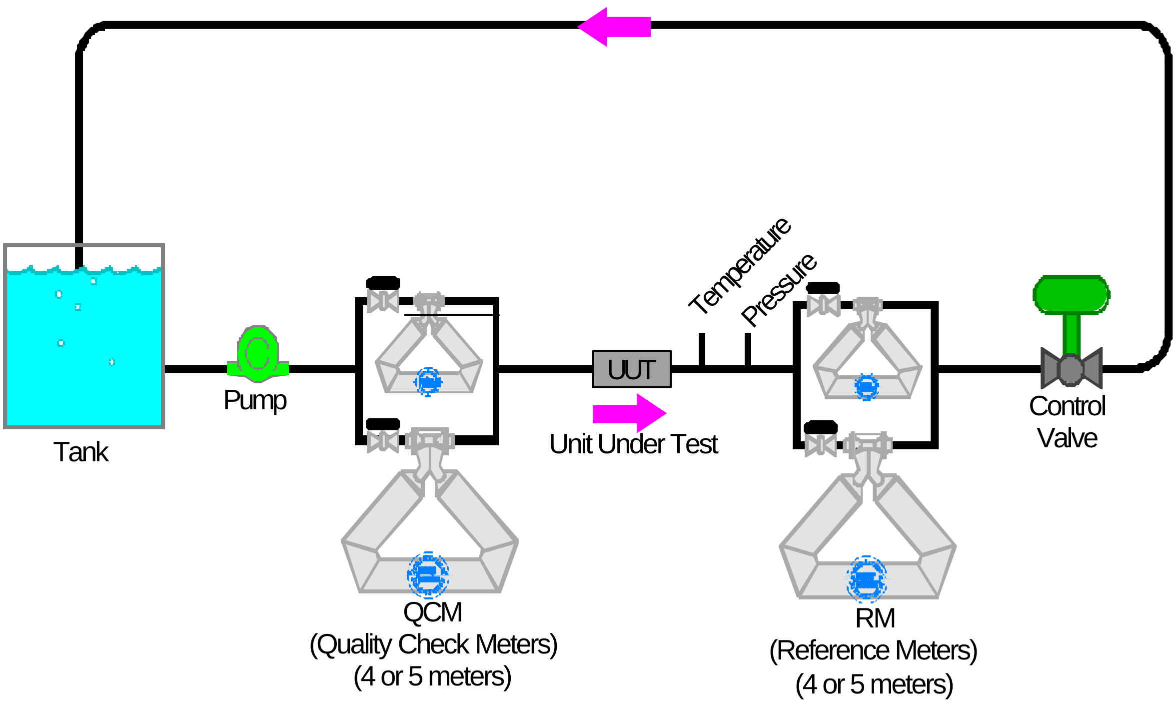

Figure 2
Simplified P &ID for a TSM Flowmeter Calibration Stand

5. TRACEABILITY

5.1 Calibration Traceability for TSM Stands

The uncertainty of the TSM calibration process is traced to national standards through a chain of successive measurements (figure 3). The USA traceable mass standards are used for calibration of the MMI Primary Stand scales. (The words, box 1, box 2, box 3 and box 4 shown on the traceability diagram, figure 3, are not a part of the traceability chain but are there as a convenience to use for reference in other parts of this paper.) NMI - VSL (Physical Standards Laboratory of the Netherlands) has approved this method for generating traceability for the MMI TSM stands (reference 1).

The RM meters (figure 2) are the reference standards in the TSM calibration stand, and they are calibrated on the MMI Primary Stand (figure 3, box 2). The MMI Primary Stand uses three high-precision scales for the calibration of the RM and QCM meters, in order to cover the full range of required flow rates.

All links in the traceability chain are renewed periodically. All TSM meters are returned to the MMI Primary Stand on a regular basis for verification.   The scales on the MMI Primary Stand are validated with the MMI mass standards. The MMI working mass standards traceable to NIST (National Institute of Science and Technology) are returned to the State of Colorado for calibration every year.

The calibration of all temperature, pressure and barometric equipment for all MMI flowmeter stands are verified on a regular basis with standards traceable to NIST.

5.2 Multi-path Traceable Verification for TSM Process

Two sets of reference mass standards are maintained on site for verification of the three scales of the MMI Primary Stand (figure 4). One set of mass standards is traceable to USA national standards and the other set is traceable to Japanese national standards. The scale calibrations with their correction curves are verified using both the USA-traceable and the Japan-traceable mass standards.

Both sets of the reference masses follow similar paths through third parties to be traceable to their respective national standards. The NIST traceable mass standards are calibrated by the State of Colorado. The NRLM (National Research Laboratory of Metrology) traceable mass standards are calibrated by JQA (Japan Quality Assurance Institute). The State of Colorado and JQA perform the calibration of the MMI mass standards by comparison to their working standards, which in turn are traceable to their resident primary standards, which are then traceable to the respective national standards

6. MEASUREMENT ASSURANCE

As stated earlier, the first level of measurement assurance is provided by the QCM meters, which are an integral part of each TSM stand. The automated checking of the RM flow measurement against the QCM flow measurement that occurs for each data point provides an on-line, continuous verification of the RM by an equivalent check standard.

A second level of measurement assurance utilizes so-called “gold” meters. These gold meters (which are also standard Micro Motion Elite meters) constitute another type of check standard, and a set of them are permanently located and maintained at each MMI facility with TSM stands and in the laboratory where the MMI Primary Stand is located. The gold meters provide measurement assurance for the overall TSM process by regularly verifying them in the UUT sections of the TSM stands and the MMI Primary Stand. These gold meters are always re-verified without making adjustments to them, so that the data collected serves as a measure of the variation over time of the TSM or MMI Primary Stand. The gold meters used for the MMI Primary Stand are also used in the same capacity on several other flow facilities that reside in the MMI Engineering laboratory, thus providing an ILC (inter-laboratory comparison).

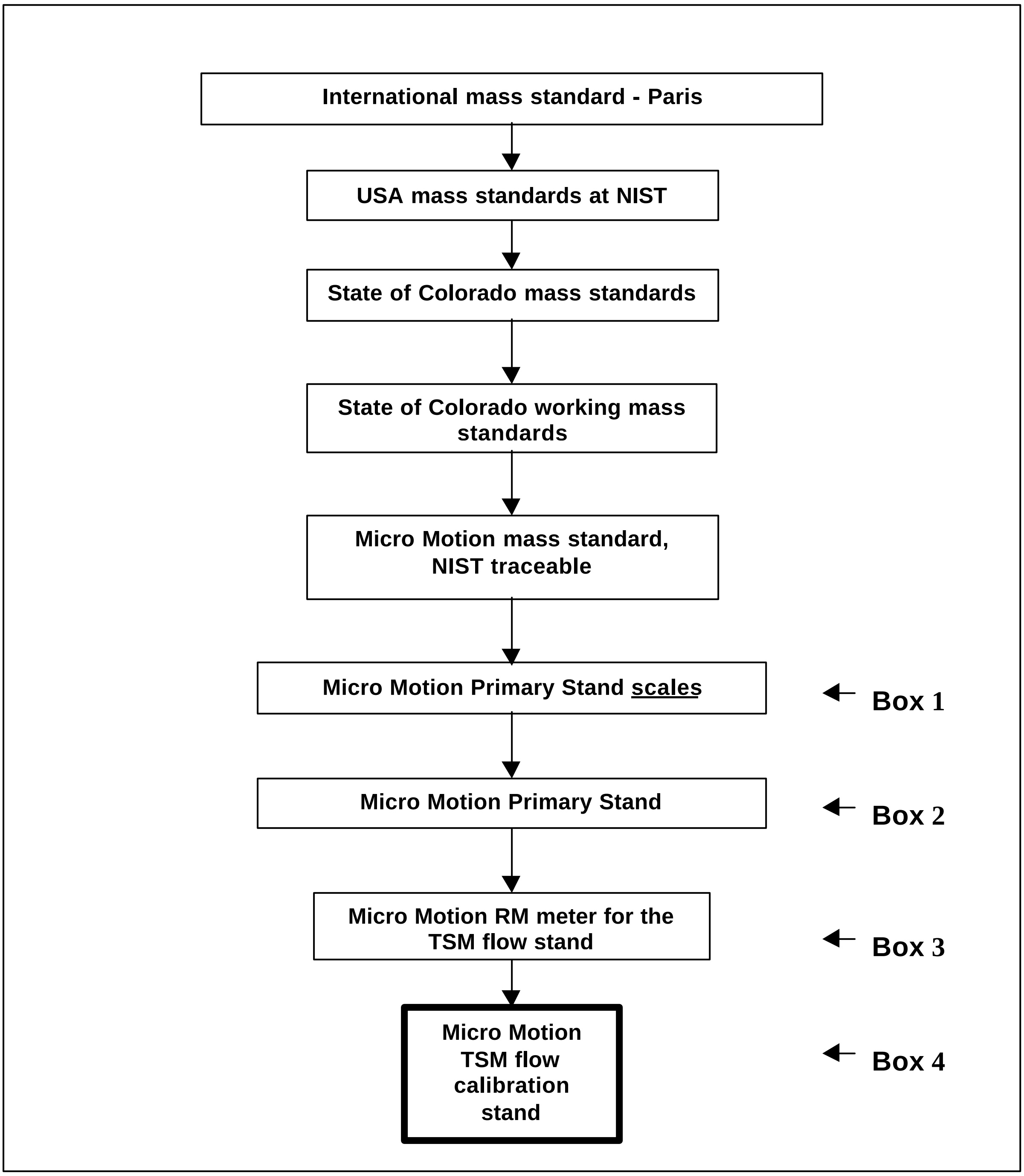

Figure 3
Calibration Traceability for TSM Stands

A third method for measurement assurance is a broader ILC that includes several TSM and gravimetric flowmeter calibration stands. In this case, the scales of the gravimetric stands are calibrated using a different set of NIST traceable working standards, not the same ones used to calibrate the scales for the MMI Primary Stand.

An even broader ILC, which would include multiple TSM stands and some national flow standards laboratories, is being planned.

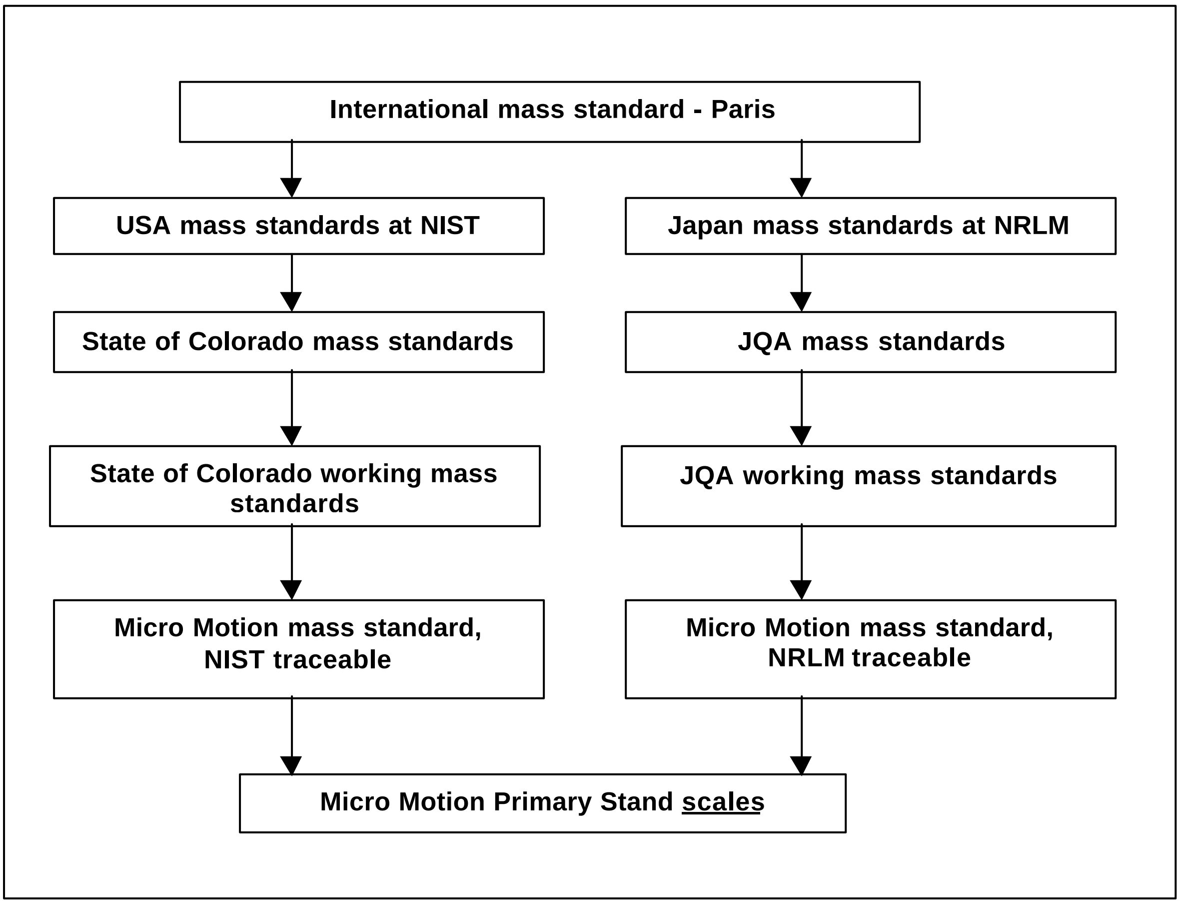

Figure 4
Multi-path Traceable Verification for TSM Process

7. UNCERTAINTY ANALYSIS

7.1 General

Definitions:

- The word uncertainty in this paper means "expanded uncertainty" (> 95% confidence).
- BMC (Best Measurement Capability) refers to the lowest uncertainty of measurement at which a flow meter calibration stand can operate, in the hypothetical situation that the UUT in the stand is perfect (i.e., the UUT's type A uncertainty is zero).

This analysis is guided by:

- GUM (Guide to the Expression of the Uncertainty in Measurement). The total uncertainty for any application is calculated as the root of the sum of the squares (RSS) combination of each of the individual contributions to that application's uncertainty. Reference 2.
- Uncertainty Analysis of stand 4 at MMI/Veenendaal, NL, as performed by NMi-VSL. Reference 3.
- Calculation of Liquid-mass (in vacuo) out of Weighing Scale Indication and its Related Uncertainty. Reference 4.

The uncertainty analysis for the Micro Motion TSM flow calibration stand, consists of four parts:

a) Uncertainty of the scale - part of the MMI Primary Stand (Figure 3, Box 1)
b) Uncertainty of the MMI Primary Stand (BMC, mass, Figure 3, Box 2)
c) Uncertainty of the reference meter (Figure 3, Box 3)
d) Uncertainty of the TSM flowmeter calibration stand (BMC, mass and volume, Figure 3, Box 4)

7.2 Uncertainty of the scales, in the mean, of the MMI Primary Stand (Figure 3, Box 1)

The three high-precision scales used in the MMI Primary Stand have been optimized for best performance in the following ways:

- The liquid container is centrally located on the weighing scale platform so the water weight is uniformly spread with no eccentric loads.
- The scales are only used with increasing loads to avoid hysteresis effects.
- The scales are installed indoors so ambient temperature changes are minimal.
- When the container is drained, it is always drained completely.

In addition the MMI Primary Stand incorporates the following capabilities:

- Online air density determination during scale and RM calibration.
- Online water density determination during RM calibration.

All mass standards used have known density and density uncertainty, as specified on their calibration certificates.

These subjects are considered when determining the uncertainty of the scale, and since the scales are used in the traceability chain, "uncertainty in mean" is calculated.

7.2.1 Type A Uncertainty in the Mean of the Scales (Figure 3, Box 1)

An appropriate minimum batch size was selected for each of the three scales in the MMI Primary Stand (2, 200, and 1500 lbs, respectively, for the small, medium, and large scales on this stand). Repetitive measurements were made at these minimum batch sizes across the full range of each scale in accordance with section 7.2. These data were then analyzed to establish the type A uncertainty in the mean for each scale:

$$U_{AM-SCALES} = {}^{2s}\!/_{\sqrt{n}}$$

= The type A uncertainty in the mean for each scale. (Equal to the type A uncertainty in the single measurement (repeatability) divided by the square root of n, the number of measurements.)

Typically, a hundred or more individual measurements were used in the calibration process for each scale.

Table 1 Type A uncertainty in the mean of the scales

	Small Scale	**Medium Scale**	**Large Scale**
Minimum Batch (lbs.)	2	200	1500
$U_{AM-SCALES}$	0.0052 %	0.0033 %	0.0080 %

7.2.2 Type B Uncertainty of the Scales (Figure 3, Box 1)

Type B uncertainty is frequently referred to as systematic uncertainty or bias.

The mass is calculated from the scale indication during the scale calibration as follows:
Mass = scale-indication x WSF
WSF = Weigh Scale Factor (reference 4) = 0.999876 (average WSF during scale calibration)

Four sources of type B uncertainty influence the mass indicated by the scales:

a) U_{B1} = Uncertainty of the mass standards (0.002%, from certificates).

b) U_{B2} = Uncertainty related to the resolution of the scale readout and the scale sensitivity. The controlling factor between these two items is the scale readout, and the uncertainty of it is determined using a rectangular distribution (0.0058 % to 0.0077 %). Reference 4.

c) U_{B3} = Uncertainty of the air density during scale calibration, due to the equipment used and varying ambient conditions (1%, confidence level > 95%).

d) U_{B4} = Uncertainty of the density of the mass standards used for scale calibration (5 %).

Table 2 Type B uncertainty of the scales

Uncertainty Source	**Calculation Method**	**Small Scale (Percent)**	**Medium Scale (Percent)**	**Large Scale (Percent)**
Mass Standards	$U_{B1}S1$	0.002 x 1	0.002 x 1	0.002 x 1
Scale Readout	$U_{B2}S2$	0.0058 x 1	0.0058 x 1	0.0077 x 1
Air Density	$U_{B3}S3$	1.0 x 0.00012	1.0 x 0.00012	1.0 x 0.00012
Mass Standard Density	$U_{B4}S4$	5.0 x 0.00003	5.0 x 0.00003	5.0 x 0.00003
$U_{BT-SCALES}$		0.0061	0.0061	0.0080

Notes

a) U_{B2} is for minimum batch quantity.

b) *S*1 to *S*4 are sensitivity coefficients, the influence factors of the uncertainty source on the scale indications (reference 4).

7.2.3 Combined Uncertainty in the Mean for the Scales (Figure 3, Box 1)

This uncertainty value, $U_{CM-SCALE}$, is calculated as the RSS combination of type A and type B uncertainties of the scales, per sections 7.2.1 and 7.2.2 above.

Table 3 Combined uncertainty in the mean for the scales

	Small Scale (Percent)	**Medium Scale (Percent)**	**Large Scale (Percent)**
$U_{AM-SCALE}$	0.0052	0.0033	0.0080
$U_{BT-SCALE}$	0.0061	0.0061	0.0080
$U_{CM-SCALE}$	0.0080	0.0069	0.0113

7.3 BMC of MMI Primary Stand (Figure 3, Box 2)

The mass of the liquid, measured with the TSM RM meter, is calculated as follows:
Mass = Scale indication x WSF x BVC
WSF = Weigh Scale Factor (See section 7.2.2)
BVC = Buoyancy Vapor Correction (reference 4) = 1.000994 (average BVC during RM calibration)

The BMC for mass of the MMI Primary Stand ($BMC_{PRIMARY\ STAND-MASS}$) is influenced by five parameters, and these are again combined in an RSS fashion:

a) U_5 = the combined uncertainty in the mean of the scale (0.0069 to 0.0113 %, *S5* =1).

b) U_6 = uncertainty related to air density during operation (1.0 %, *S6* = 0.001).

c) U_7 = uncertainty related to liquid density during operation. The uncertainty of the liquid density is 0.015% in section 7.6. This value is for the density of the water in the pipe near the UUT. What is needed is the density of the water in the tank. The density uncertainty was increased to allow for 1/2 degree C temperature difference between the pipe and scale tanks (0.020 %, *S7* = 0.001).

d) U_8 = uncertainty, caused by the "transfer point", based on a maximum of 1 mm variation from the mean and a rectangular distribution (0.0088 % to 0.0015 %, *S8* = 1). Reference 3.

e) U_9 = uncertainty related to the minimum number of pulses of RM (0.0025 %, *S9* = 1).

Table 4 BMC of MMI Primary Stand

Uncertainty Source	**Calculation Method**	**Small Scale (Percent)**	**Medium Scale (Percent)**	**Large Scale (Percent)**
Scales	U_5 S5	0.0080 x 1	0.0069 x 1	0.0113 x 1
Air Density	U_6 S6	1 x 0.001	1 x 0.001	1 x 0.001
Liquid Density	U_7 S7	0.020 x 0.001	0.020 x 0.001	0.020 x 0.001
Transfer Point	U_8 S8	0.0088 x 1	0.0037 x 1	0.0015 x 1
Pulses	U_9 S9	0.0025 x 1	0.0025 x 1	0.0025 x 1
$BMC_{PRIMARY\ STAND-MASS}$		0.0122	0.0083	0.0117

Notes:

a) *S5* to *S9* are sensitivity coefficients, the influence factors of the uncertainty source on the $BMC_{PRIMARY\ STAND-MASS}$. (reference 4)

7.4 Uncertainty of TSM Reference Meters, Calibrated on MMI Primary Stand (Figure 3, Box 3)

BMC in mass of the MMI Primary Stand is now known, per the previous section. Next, the uncertainty of the RM's that are calibrated on this stand (U_{CM-RM}) is determined by the RSS combination of this value with the type A uncertainty of the TSM RM's themselves. Figure 1 shows an example of the data used for this analysis.

From figure 1 the type A uncertainty of the RM's (U_{AM-RM}) is less than $\left(\frac{0.020}{\sqrt{25}}\right)$ = 0.0040 %, since 25 measurements were made at each individual flow rate.

Then $U_{CM-RM} = \sqrt{U_{AM-RM}{}^2 + BMC_{PRIMARY STAND-MASS}{}^2}$

Since the $BMC_{PRIMARYSTAND-MASS}$ is different for each scale, there could be a TSM RM uncertainty dependent on scale used. This paper will only calculate the worst case, as follows.

$$U_{CM-RM} = \sqrt{(0.0040)^2 + (0.0122)^2}$$ = 0.0128 %

7.5 BMC of TSM Stand, Mass (Figure 3, Box 4)

When an RM is installed in the TSM stand, then its uncertainty is part of the calculation of the Best Measurement Capability of the TSM stand. The TSM method is based on steady state flow, no uncertainty is introduced due to the transfer point because there is no transfer point. However, there is instead a different component to the BMC of the TSM stand due to the number of pulses counted during each measurement, and the uncertainty associated with this process.

Therefore the BMC in mass of the TSM stand ($BMC_{TSM-MASS}$) is determined from the combined RSS uncertainty of the RM meter (U_{CM-RM}), per section 7.4 above, and the uncertainty related to the number of pulses used. The minimum number of pulses used in all TSM stand measurements is 50,000. Hence, we get

$$BMC_{TSM-MASS} = \sqrt{U_{CM-RM}^{\ 2} + U_{Pulses}^{\ 2}} = \sqrt{(0.0128)^2 + (0.0020)^2} = \mathbf{0.013\ \%}$$

7.6 BMC of TSM Stand, Volume (Figure 3, Box 4)

The BMC of the TSM stand in volume ($BMC_{TSM-VOLUME}$) can be calculated from $BMC_{TSM-MASS}$ and uncertainty of the water density,$U_{rT\,density}$. Measurements on the system have shown the bias between the system water supply and NIST samples to be constant. The water density uncertainty analysis includes an Anton-Paar densitometer, a certified water sample from NIST with its uncertainty analysis, samples from of the TSM system water, water temperature measurements, and water pressure measurement and sampling factors. All together, the uncertainty analysis for water density includes eight items. These eight items and their uncertainties are modeled after work completed by NMi on a gravimetric stand at MMI, Veenendaal, NL (reference 3). These eight influences, as before, are combined in an RSS fashion to determine the uncertainty of the density determination, $U_{rT\,density}$. This information is summarized in Table 5.

Table 5 Uncertainty Analysis for Water Density

	Contribution to Uncertainty (Percent)
Uncertainty of the sample from the national laboratory used to calibrate the Anton-Paar	0.00100
Resolution uncertainty of the Anton-Paar on national laboratory sample	0.01000
Resolution uncertainty of the Anton-Paar on TSM system water sample	0.01000
Basic uncertainty of the PTB equations for density of water	0.00050
Uncertainty of the calibration of the temperature device	0.00420
Uncertainty due the sampling techniques of the temperature	0.00210
Uncertainty of the calibration of the pressure device	0.00046
Uncertainty due to the sampling techniques of the pressure	0.00046
$U_{rT\,density}$	**0.01500**

Finally, $U_{rT\,density}$ is combined with $BMC_{TSM-MASS}$ from section 7.5 to calculate the BMC of the TSM stand on volume, $BMC_{TSM-VOLUME}$, as follows:

$$BMC_{TSM-VOLUME} = \sqrt{BMC_{TSM\ Mass}^{\ 2} + U_{rT\ density}^{\ 2}} = \sqrt{(0.0131)^2 + (0.0150)^2} = \mathbf{0.020}\ \%$$

8. CONCLUSION

The end result of this analysis, from the previous two sections of this paper, is a Best Measurement Capability of the TSM system of 0.013% on mass and 0.020% on volume. These values, even for the worst case conditions they represent, show that the BMC's of the TSM stands well exceed the target performance of 0.033% for calibration stand capability established in section 2 of this paper. Micro Motion has applied to the Dutch Accreditation Council RvA (RAAD VOOR ACCREDITATIE) in March 2000, for accreditation of the MMI Primary Stand. The accreditation process is continuing at this time.

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