PRESENTATION OF THE HANDBOOK OF UNCERTAINTY CALCULATIONS
- FISCAL METERING STATIONS

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1. ABSTRACT

A new *Handbook* [1] for uncertainty calculations on fiscal metering stations is presented. The *Handbook* has been developed by Christian Michelsen Research AS (CMR) on behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM) and the Norwegian Petroleum Directorate (NPD).

The aim of the *Handbook* is to secure a more uniform uncertainty evaluation of fiscal metering stations. The *Handbook* provides a practical introduction to uncertainty calculations based on the principles and terminology defined by the ISO-publication Guide to the expression of uncertainty in measurement [2]. Furthermore, the *Handbook* contains a comprehensive evaluation of two specific fiscal oil and gas metering stations. The uncertainty calculations are implemented in two software programs that are described and included as a part of the *Handbook*.

2. INTRODUCTION

2. Uncertainty in measurement

The fiscal measurement of oil and gas in the North Sea must be in accordance with NPD regulation [3]. This requires that an uncertainty analysis of a fiscal metering system must be performed according to “recognised standards”.

In practise, different methods for evaluation of measurement uncertainties are used. In 1995 the International Organisation for Standardisation (ISO) published the Guide to the expression of uncertainty in measurement [2]. The document is commonly referred to as the Guide. The overall objective of the Guide has been to establish an internationally accepted method for estimating measurement uncertainty, and to provide guidelines for the calculation procedure and the reporting of the results. In addition, the Guide has introduced some new terms and suppressed some traditional terminology to standardise the concepts so that “everyone speaks the same language” and agrees on how uncertainties should be quantified.

It should be noted that the Guide at present is an ISO recommendation and not a standard. However, the standard published in 1997 by the European co-operation for Accreditation of Laboratories (EAL) [4], is in conformity with the Guide. Previously, ISO 5168 [5] - [6] has been used for reference when calculating uncertainties on gas metering stations, and the principles have also to some extent been applied in uncertainty calculations on oil metering stations. However, ISO-5168 and the ISO-Guide are based on significant different views on measurement uncertainty [7], and ISO-5168 was revised and reduced to a technical report in April 1999 [8].

The Guide comprises a theoretical and a mathematical approach to the field of uncertainty calculations, and it provides detailed procedures for performing uncertainty calculations in general. The *Handbook*, however, provides a more practical approach to the field of uncertainty calculations, where the principles of the Guide are applied to an oil- and a gas fiscal metering station. The intention is further to simplify, and to some extent standardise, the uncertainty evaluation of fiscal oil and gas metering stations.

2.2 The Handbook

In 1994 the Norwegian Society for Oil and Gas Measurement (NFOGM) initiated the establishment of a workgroup with the scope of work: "Uncertainty calculations of flow measurements in the oil and gas industry". Based on the previous work at CMR on uncertainty calculations [9]-[13], the workgroup invited CMR to propose a project for completion of the work. In 1997 CMR therefore proposed a project for developing a *Handbook* for uncertainty calculations of fiscal metering stations. The project was initiated and financially supported by NFOGM and NPD in 1998.

The *Handbook* includes uncertainty calculations and analysis of the two fiscal metering stations. This analysis reveals the uncertainties that must be included in the calculations and which are negligible. Two programs have been developed in Microsoft Excel 97 for performing uncertainty calculations on these two metering stations. The programs are part of the *Handbook*, which also serves as a user manual.

The functional relationships and measurement procedures used in fiscal metering stations to calculate the standard volume flow rate (oil) or the mass flow rate (gas) are vital for the uncertainty evaluation. Thus, the necessary functional relationships and procedures are described and outlined along with references in the *Handbook*. The *Handbook* may therefore to some extent serve as a measurement *Handbook* for fiscal metering stations. The *Handbook* is separated in two parts; one part covers the uncertainty calculations and evaluation, and a second part contains the user manuals for the software programs.

By practical use of the *Handbook*, the reader should have gained sufficient knowledge about uncertainty analysis to secure proper application of, and to fully exploit, the calculation programs. The user should then also be able to perform similar uncertainty evaluations on other kinds of instrument and measurement systems.

A reference group comprising six metering specialists has reviewed the *Handbook* and the calculation programs in order to secure the quality of the final product

3. UNCERTAINTY ANALYSIS

3.1 Scope of work

The fiscal metering stations evaluated in the *Handbook* are intended to be typical, and consist of equipment most widely used in the North Sea. The equipment of the metering stations evaluated is listed in Table 1 and Table 2. The fiscal oil metering station is based on turbine meter measurements and pipe proving, and is based on use of *K-factor* and volume correction factors in determination of the standard volume flow rate. The fiscal gas metering station is based on orifice plate measurements, and includes an on-line (by-pass) installation of the density transducer with optional correction of density from by-pass conditions to line conditions.

Table 1 Equipment list for the evaluated fiscal oil metering station.

Measurement	**Instrument**
Volume flow rate	Turbine Meter / Pipe Prover (general type)
Temperature	Rosemount 3144 Temperature Transmitter Class A (EN 60751) Temperature Element
Static Pressure	Rosemount 3051P Pressure Transmitter
Density	Solatron Model 7835 Liquid Density Transducer

Table 2 Equipment list for the evaluated fiscal gas metering station.

Measurement	**Instrument**
Mass flow rate	Orifice Meter (general type)
Temperature	Rosemount 3144 Temperature Transmitter Class A (EN 60751) Temperature Element
Differential Pressure	Rosemount 3051P Differential Pressure Transmitter
Static Pressure	Rosemount 3051P Pressure Transmitter
Density	Solatron Model 7812 Gas Density Transducer

In section 3.3 a sample of an uncertainty analysis of the Solatron 7835 Liquid Density Transducer is shown, while the *Handbook* covers the other transducers.

3.2 Calculation and evaluation

The Guide [2] procedure for calculating and evaluating uncertainties has been applied consistently throughout the *Handbook*. The Guide procedure includes establishment of the equations for mathematically combining the standard uncertainties based on the functional relationship between the measurand and the input quantities. This means that the sensitivity of the quantity in question with respect to the different input measurements can be taken into account through calculated sensitivity coefficients. The Guide offers a universal method for uncertainty analysis where the standard uncertainties are transferable. This means that the result of an uncertainty calculation can be used directly in a subsequent uncertainty evaluation, which makes the measurements taken at different times and at different places comparable.

The *Handbook* contains complete calculations of the uncertainties of the different primary variables, such as temperature, absolute pressure, differential pressure and density. The primary variables, with their calculated uncertainties, are further used with the functional relationships and measurement procedures of the metering stations to calculate the combined uncertainties of the flow rates. The functional relationships and measurement procedures, which are described in the *Handbook*, are according to measurement standards, such as [14]-[23]. Thus, the *Handbook* may to some extent be used as a guide for fiscal metering stations.

Based on the algorithms and measurement procedures defined in the standards, uncertainty budgets have been established. Uncertainty budgets provide means for evaluating the uncertainties of the input quantities, as well as evaluating their influence on the combined uncertainties of the calculated results.

3.3 Example of uncertainty analysis

An example of uncertainty analysis of the liquid density measured by the Solatron 7835 Liquid Density Transducer [24] is given in Section 3.3.1. The measured liquid density is pressure and temperature corrected according to specific algorithms, which are outlined in the Appendix. In this example the density meter is mounted on-line (in a by-pass), downstream the turbine meter. The by-pass installation would normally require a separate correction for the pressure and temperature deviations between the by-pass and line conditions. This installation effect is described in Section 3.3.2.

3.3.1 Liquid density transducer uncertainty

To calculate the uncertainty of the measured density, the functional relationships for both the primary density measurement and the pressure and temperature corrections are required. Furthermore, the model uncertainties that are attached to the corrections themselves must also be included, since they are not ideal corrections but e.g. derived from experimental tests. The functional relationships and the correction procedures for the Solatron 7835 Liquid Density Transducer are briefly described in the Appendix, while the *Handbook* [1] treats the subject in fully details.

An uncertainty budget for the density transducer can be established using the procedure of the Guide. The uncertainty budget is very useful when comparing the magnitude of the different uncertainty contributions, and it may reveal if some of the uncertainties can be neglected in order to simplify the uncertainty calculations. Such a sample uncertainty budget for the liquid density measurement is shown in Table 3.3. This uncertainty budget is only briefly described here, while the *Handbook* [1] presents detailed uncertainty budgets for all the transducers in the oil and gas metering stations as specified by Table 1 and Table 2.

The combined standard uncertainty $u_c(\rho)$ of the measurand (liquid density) equals the positive square root of the combined standard variance. Standard uncertainty is the uncertainty of a result of a measurement expressed as one standard deviation. The combined standard variance $u_c^2(\rho)$ is calculated as follows[1]:

$$u_c^2(\rho) = \sum_i (S_i^2 \cdot u_i^2) \qquad (1)$$

where

S_i - sensitivity coefficient of input quantity i
u_i - standard uncertainty of the input quantity i

The sensitivity coefficients are obtained from the partial derivatives of the functional relationship with respect to the different input quantities of interest (e.g., temperature and pressure). An example of how to calculate the sensitivity coefficients is illustrated in the Appendix.

Input quantities that contribute to the combined standard uncertainty of the liquid density are given in Table 3.3 along with sample values.

The transducer uncertainty[2] and the uncertainties due to stability[3] and repeatability are given in the technical manual for the liquid density transducer [24].

The measured density is pressure and temperature corrected according to the algorithms given in the technical manual (cf. Appendix). The uncertainties of the pressure and temperature measurements (P, T) must therefore also be included in the calculation of the combined uncertainty. In the Appendix the expressions for the sensitivity coefficients are derived based on the correction algorithms.

The pressure and temperature correction procedure is empirical and not ideal. An imperfect correction introduces an extra uncertainty (model uncertainty) that must be included in the uncertainty budget. Hence, the uncertainties of the pressure and temperature corrections are included in Table 3.3 as “temperature effect” and “pressure effect”. These model uncertainties are given in the technical manual for the liquid density transducer.

The expanded uncertainty $U(\rho)$ of the final density estimate, ρ, can be evaluated by multiplying the combined standard uncertainty by a coverage factor, k, on the basis of the level of confidence required for the interval r ± $U(\rho)$. Assuming a normal distribution of ρ, and requiring a level of confidence close to 95%, yields k_{95} =1.96 ª 2.0. Thus, the expanded uncertainty at 95% confidence level[4] is given by

$$U(\rho) = k_{95} \cdot u_c(\rho) \qquad (2)$$

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[1] *If, however, some of the input quantities are correlated then covariance terms have to be included in Eq., see the Guide [2] or the Handbook [1] for fully details.*
[2] *The uncertainty due to the transducer includes calibration reference uncertainty*
[3] *The uncertainty due to stability is based on a yearly calibration interval and represents the drift (increasin /decreasing offset) in the readings with time.*
[4] *A confidence level of 95% corresponds to two standard deviations.*

Table 3.3 Sample uncertainty budget for the Solatron 7835 Liquid Density Transducer.

Measurand: Liquid Density			**Value at operating condition: 776 kg/m^3**		
Input quantity	**Estimate**	**Standard Uncertainty**	**Sensitivity Coefficient**	**Standard Variance**	**Expanded Uncertainty ($k_{95} = 2$)**
Transducer	-	0.0750 kg/m^3	1	$5.625 \cdot 10^{-3}$	
Stability	-	0.0750 kg/m^3	1	$5.625 \cdot 10^{-3}$	
Repeatability	-	0.0100 kg/m^3	1	$1.0 \cdot 10^{-4}$	
Temperature effect	-	0.11250 kg/m^3	1	$1.266 \cdot 10^{-2}$	
Pressure effect	-	0.03030 kg/m^3	1	$9.181 \cdot 10^{-4}$	
T	65 °C	0.056 °C	0.01580 kg/m^3/°C	$7.83 \cdot 10^{-7}$	
P	20.2 barg	0.08 bar	0.0101 kg/m^3/bar	$6.53 \cdot 10^{-7}$	
Combined variance			$u_c^2(\rho)$	0.02493	**U(ρ)**
Combined standard uncertainty:			$u_c(\rho)$	0.158 kg/m^3	**0.32 kg/m^3**

It is evident from Table 3.3 that the pressure and temperature measurements (P, T) have negligible influence on the combined uncertainty compared to the other contributors. However, the uncertainty of the temperature correction (Temperature effect) is the largest contributor and it is actually larger than the uncertainty of the transducer itself. Thus, the uncertainty due to the temperature correction cannot be neglected from the uncertainty budget.

3.3.2 Installation effects

If the liquid density transducer is mounted in a by-pass loop (on-line measurements), a pressure and temperature deviation between the line and by-pass loop will occur. This effect must be included in the combined uncertainty of the liquid density measurement.

The IP Petroleum Measurement Manual, Part VII, Density [21] gives guidelines for on-line installations of liquid density meters. Maximum pressure and temperature deviations for different HC liquids, that will cause a change in liquid density of 0.03% are given in the IP manual. For stabilised crude oil of 850 kg/m^3, the maximum differences in pressure and temperature are 4 bar and 0.4°C respectively [21], and these maximum deviations will each cause a change in the liquid density of 0.03%. The temperature and pressure coefficients of the quoted crude oil are 0.0007 g/ml/°C and 0.00007 g/ml/bar, respectively. The coefficients may change with operating conditions, and the uncertainties are in this case assumed to have a rectangular distribution rather than a normal distribution[5]. The uncertainties caused by P and T deviations are not considered to be purely random, but will also contain systematic effects. Ideally the systematic effect should be corrected for, but in practise they may be hard to evaluate and quantify.

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[5] *The pressure gradient is expected to be negative, while the sign of the temperature gradient depends on the ambient temperature. It is therefore assumed that the quoted uncertainty of 0.03% of reading represents endpoints of a uniform or rectangular probability distribution of the density. The standard uncertainty due to P and T deviations can then be computed as (0.0003/÷3)◊r rather than (0.0003/k_{95})◊r for a normal (Gaussian) distribution. Assuming a rectangular distribution gives a conservative estimate, which represents the "worst case" scenario.*

For this sample calculation, these coefficients are used for the liquid density of 776 kg/m^3, even if they are only valid for a crude oil with density equal to 850kg/m^3. In a real case, however, one must document the real deviation in temperature and pressure caused by the by-pass installation at the actual operating conditions, and further how this influence the liquid density measurement. I.e., the values of the temperature and pressure coefficients should be determined for the specific oil.

Table 3.4 Sample uncertainty budget for the Solatron 7835 Liquid Density Transducer including the uncertainty due to 4 bar pressure and 0.4°C temperature differences between the line and by-pass loop.

Measurand: Liquid Density			**Value at operating condition: 776 kg/m^3**		
Input quantity	**Estimate**	**Standard Uncertainty**	**Sensitivity Coefficient**	**Standard Variance**	**Expanded Uncertainty ($k_{95} = 2$)**
Transducer	-	0.0750 kg/m^3	1	$5.625 \cdot 10^{-3}$	
Stability	-	0.0750 kg/m^3	1	$5.625 \cdot 10^{-3}$	
Repeatability	-	0.0100 kg/m^3	1	$1.0 \cdot 10^{-4}$	
Temperature effect	-	0.11250 kg/m^3	1	$1.266 \cdot 10^{-2}$	
Pressure effect	-	0.03030 kg/m^3	1	$9.181 \cdot 10^{-4}$	
T	65 °C	0.056 °C	0.01580 kg/m^3/°C	$7.83 \cdot 10^{-7}$	
P	20.2 barg	0.08 bar	0.0101 kg/m^3/bar	$6.53 \cdot 10^{-7}$	
Temperature deviation	0.4°C	0.1344 kg/m^3	1	$1.807 \cdot 10^{-2}$	
Pressure deviation	4 bar	0.1344 kg/m^3	1	$1.807 \cdot 10^{-2}$	
Combined variance			$u_c^2(\rho)$	0.06107	**$U(\rho)$**
Combined standard uncertainty:			$u_c(\rho)$	0.247 kg/m^3	**0.49 kg/m^3**

From the uncertainty budget in Table 3.4 it can be inferred that the installation effects (the pressure and temperature deviations between line and by-pass) are the main uncertainty contributors. It is here demonstrated that the uncertainties due to the by-pass installation give a significant contribution to the combined uncertainty of the liquid density measurement, and must therefore be evaluated carefully.

3.4 Documentation

The *Handbook* briefly describes the documentation requirements regarding uncertainty calculations. According to the ISO-Guide [2], Chapter 7, all the information necessary for a re-evaluation of the measurement should be available to others who may need it.

This puts strong requirements on the documentation of the uncertainty evaluation and analysis. This means that it must be verified that the functional relationships applied in the evaluation in the *Handbook*, equals the functional relationships actually implemented for the transducer or metering station in question.

Furthermore, documentation in form of uncertainty budgets (with background documentation of the algorithms and input quantities) like the ones presented in the *Handbook*, are suggested as a clear and straightforward way to present uncertainty calculations. These kinds of uncertainty budgets also provide powerful means for evaluation of the influence of different input quantities on the combined uncertainty.

4. THE EMU-99 SOFTWARE TOOLS

Based on the conclusions from the calculations and evaluations in the *Handbook*, two Excel programs have been developed for performing uncertainty evaluations of the fiscal oil and gas metering stations. The programs, which also are parts of the *Handbook*, are made in Microsoft Excel 97 and are used as normal workbooks in Excel.

The EMU-99 (Evaluation of Metering Uncertainties) programs may as well be applied to other instruments than listed in Table 1 and Table 2. However, the user must then evaluate and verify that the type of uncertainty specifications and the functional relationships incorporated in the EMU-programs are valid for the alternative instrument. Furthermore, the user must verify that the evaluations and conclusions made in the *Handbook* regarding the instrument in question are also applicable to the alternative instrument. If the above requirements are verified and documented, the user may change the default uncertainty values and confidence levels in the programs according to the data sheets of the alternative transmitters in order to calculate the uncertainty of the metering station for alternative instrumentation.

The programs contain only the input quantities found to be significant regarding the uncertainty calculation, thus minimising the amount of data needed and simplifying the calculations. The user may easily change input quantities, such as the operating conditions of the metering stations, in order to simulate the influence of changes in input quantities on various combined uncertainties of the metering stations that the programs calculate and display.

4.1 Output from the program

The outputs from the program may be used as supplement to the documentation of the uncertainty calculations, and as means for analysing the influence of different operating conditions on the combined uncertainty of the metering station. This may be well suited for people working with the design of new metering stations, and for renewal and re-evaluation of older metering stations.

The input data to the programs must be properly documented, and the functional relationships and default values implemented in the program must also be verified.

One of the output features is a graph presenting the combined relative expanded uncertainty of e.g. the mass flow rate of the gas metering station (or the standard volume flow rate of the oil metering station).

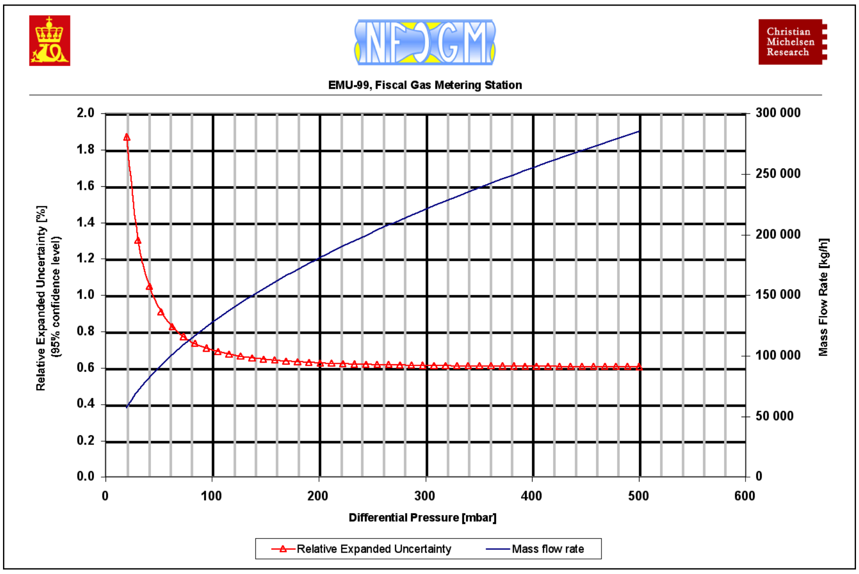
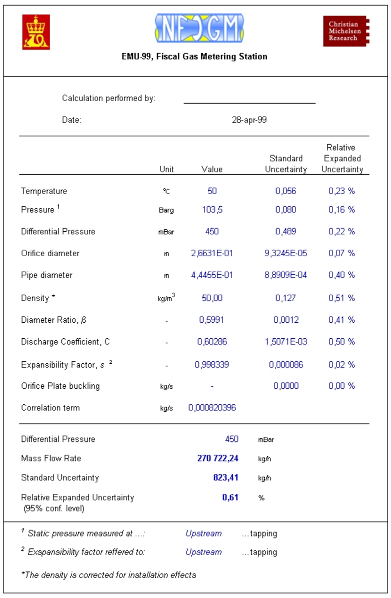


Figure 4.1 Typical output from the EMU-99, Fiscal Gas Metering Station, program presenting the relative combined expanded uncertainty and the standard mass flow rate vs. the differential pressure across the orifice.

Furthermore, a simple uncertainty summary report is generated by the program, which presents the most relevant information from the uncertainty calculation. The display of the uncertainty summary report is shown in Figure 4.2, and this may e.g. be used when varying some of the input quantities to study their influence on the combined uncertainty of the flow rate (in this case the mass flow rate).



EMU-99, Fiscal Gas Metering Station

Calculation performed by: ____________________

Date: 28-apr-99

	Unit	Value	Standard Uncertainty	Relative Expanded Uncertainty
Temperature	°C	50	0,056	0,23 %
Pressure [1]	Barg	103,5	0,080	0,16 %
Differential Pressure	mBar	450	0,489	0,22 %
Orifice diameter	m	2,6631E-01	9,3245E-05	0,07 %
Pipe diameter	m	4,4455E-01	8,8909E-04	0,40 %
Density *	kg/m^3	50,00	0,127	0,51 %
Diameter Ratio, β	-	0,5991	0,0012	0,41 %
Discharge Coefficient, C	-	0,60286	1,5071E-03	0,50 %
Expansibility Factor, ε [2]	-	0,998339	0,000086	0,02 %
Orifice Plate buckling	kg/s	-	0,0000	0,00 %
Correlation term	kg/s	0,000820396		

Differential Pressure	450	mBar
Mass Flow Rate	**270 722,24**	kg/h
Standard Uncertainty	**823,41**	kg/h
Relative Expanded Uncertainty (95% conf. level)	**0,61**	%

[1] *Static pressure measured at ...:* *Upstream* ...tapping

[2] *Exspansibility factor reffered to:* *Upstream* ...tapping

**The density is corrected for installation effects*

Figure 4.2 The uncertainty summary report display from the EMU-99, Fiscal Gas Metering Station program.

5 CONCLUSION AND FURTHER WORK

The major intention of the *Handbook* is to simplify, and to some extent standardise, the calculation of uncertainties of fiscal metering stations.

The *Handbook* may also be basis for courses on uncertainty calculations and lectures on uncertainty calculations and evaluations. It may even be used as a metering *Handbook* for oil and gas fiscal metering stations, while it covers the functional relationships and gives a brief overview of the instrumentation of such metering stations.

Further extension of the *Handbook* to also cover parallel metering runs, gas chromatography, ultrasonic metering stations and other transducers for measurement of primary variables like temperature, density and pressure are desirable. However, first the *Handbook* will be published and feedback based on practical use of the *Handbook* will be collected. A future revision is meant to include updates based on this feedback in addition to other possible extensions.

6. REFERENCES

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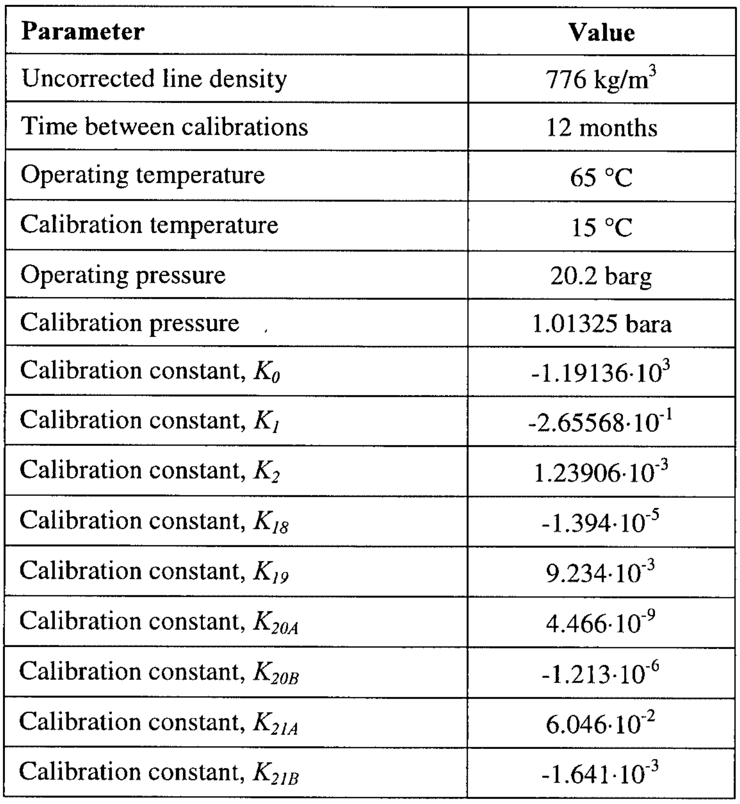
Appendix

This appendix contains the functional relationships on which the uncertainty budgets in Table 3.3 are based. For even more detailed coverage of the calculation and evaluation, please refer to the “”*Handbook* of uncertainty calculations – fiscal metering stations” [1]

Table A.1 The values used in the sample calculation in Table 3.3.



Parameter	**Value**
Uncorrected line density	776 kg/m^3
Time between calibrations	12 months
Operating temperature	65 °C
Calibration temperature	15 °C
Operating pressure	20.2 barg
Calibration pressure	1.01325 bara
Calibration constant, K_0	$-1.19136 \cdot 10^{3}$
Calibration constant, K_1	$-2.65568 \cdot 10^{-1}$
Calibration constant, K_2	$1.23906 \cdot 10^{-3}$
Calibration constant, K_{18}	$-1.394 \cdot 10^{-5}$
Calibration constant, K_{19}	$9.234 \cdot 10^{-3}$
Calibration constant, K_{20A}	$4.466 \cdot 10^{-9}$
Calibration constant, K_{20B}	$-1.213 \cdot 10^{-6}$
Calibration constant, K_{21A}	$6.046 \cdot 10^{-2}$
Calibration constant, K_{21B}	$-1.641 \cdot 10^{-3}$

The uncertainties in the data sheet for the Solatron 7835 Liquid Density Transducer [24] are given at 95% confidence level. The Solatron 7835 Liquid Density Transducer is based on the vibrating cylinder principle, where the output is a periodic time of the vibrations. This periodic time is then related to the density according to:

$$D = K_0 + K_1 \cdot \tau + K_2 \cdot \tau^2 \tag{3}$$

where

D - uncorrected density [kg/m^3]
K_0 - constant from the calibration certificate
K_1 - constant from the calibration certificate
K_2 - constant from the calibration certificate
t - periodic time [ms]

The calibration constants, K_0, K_1 and K_2, are determined at a given calibration temperature (normally 20 °C) and pressure (normally 1.01325 bara).

If the transducer operates at temperatures other than the calibration temperature, a correction of the calculated density must be made for optimal performance. The temperature correction is performed according to:

$$D_T = D \cdot \left(1 + K_{18} \cdot \left(T - T_{cal}\right)\right) + K_{19} \cdot \left(T - T_{cal}\right) \tag{4}$$

where

D_T - temperature corrected density [kg/m^3]
D - uncorrected density [kg/m^3] from Eqn. 3.
K_{18} - constant from the calibration certificate
K_{19} - constant from the calibration certificate
T - operating temperature [°C]
T_{cal} - calibration temperature [°C]

If the transducer operates at pressures other than the calibration pressure, a second correction for pressure must also be applied, and this correction is performed according to:

$$D_{PT} = D_T \cdot \left(1 + K_{20} \cdot \left(P - P_{cal}\right)\right) + K_{21} \cdot \left(P - P_{cal}\right) \tag{5}$$

where

D_{PT} - pressure (and temperature) corrected density [kg/m^3]
D_T - temperature corrected density [kg/m^3] from Eqn. 4.
K_{20} - constant from the calibration certificate
K_{21} - constant from the calibration certificate
P - operating pressure [bar]
P_{cal} - calibration pressure [bar]

The constants, $K2_0$ and $K2_1$, are given as a function of the line pressure and the calibration pressure:

$$\begin{aligned} K_{20} &= K_{20A} + K_{20B} \cdot (P - P_{cal}) \\ K_{21} &= K_{21A} + K_{21B} \cdot (P - P_{cal}) \end{aligned} \tag{6}$$

where

K_{20A} - constant from the calibration certificate
K_{20B} - constant from the calibration certificate
K_{21A} - constant from the calibration certificate
K_{21B} - constant from the calibration certificate

The functional relationships to be applied are given in Eqn. 4, 5 and 6. The functional relationship for temperature and pressure corrected density then becomes:

$$\begin{aligned} D_{PT} = &\{K_0 + K_1 \cdot \tau + K_2 \cdot \tau^2 \cdot (1 + K_{18} \cdot (T - T_{cal})) + K_{19} \cdot (T - T_{cal})\} \cdot \\ &(1 + K_{20} \cdot (P - P_{cal})) + K_{21} \cdot (P - P_{cal}) \end{aligned} \tag{7}$$

The sensitivity of the temperature and pressure corrected density, with respect to the temperature and pressure respectively, can then be found by partial differentiating Eqn. 7.

$$S_{D_{PT}\_T} = \frac{\partial D_{PT}}{\partial T} \tag{8}$$

$$S_{D_{PT}\_P} = \frac{\partial D_{PT}}{\partial P} \tag{9}$$

The changes between line and calibration temperature and pressure used in the calculations are 45°C and 20.2 bar, respectively.