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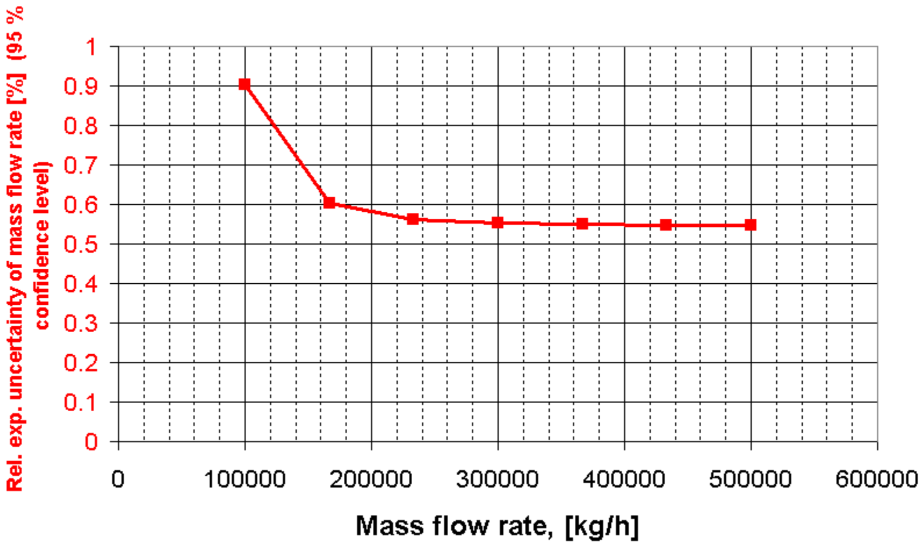
HANDBOOK OF UNCERTAINTY CALCULATIONS

Fiscal Orifice Gas and Turbine Oil Metering Stations



Revision 2, March 2003

Handbook of Uncertainty Calculations
Fiscal Orifice Gas and Turbine Oil Metering Stations

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Prepared for

The Norwegian Society for Oil and Gas Measurement (NFOGM)
The Norwegian Petroleum Directorate (NPD)
The Norwegian Society of Chartered Engineers (NIF)

by:

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Christian Michelsen Research AS

The *Handbook* and the Excel programs *EMU – Orifice Fiscal Gas Metering Station, Version 2.0* and *EMU – Turbine Fiscal Oil Metering Station, Version 2.0,* are freeware and can be downloaded from the NFOGM web pages www.nfogm.no.

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PREFACE

Norwegian regulations relating to measurement of petroleum for fiscal purposes and for calculation of CO_2 tax require that the overall measurement uncertainty be documented to be within defined limits. However, the different methods used gave different results. A consistent, standardised method of uncertainty estimation was required, so that different measurement systems could be directly compared.

In 1992 the *Guide to the expression of uncertainty in measurement* was published, revised and updated in 1995. This report is establishing general rules for evaluating and expressing uncertainty in measurement, intended for a broad scope of measurement areas. It is commonly referred to as ”*the Guide*”. The report was jointly developed by the International Organisation of Standardisation (ISO), the International Electrotechnical Commission (IEC), the International Organisation of Legal Metrology (OIML) and the International Bureau of weights and Measurement (BIPM).

The Norwegian Petroleum Directorate (NPD) and the Norwegian Society for Oil and Gas Measurement (NFOGM), together with Christian Michelsen Research (CMR), felt that a user-friendly handbook together with a spreadsheet based upon the principles laid down in *the Guide* would satisfy the need for a modern method of uncertainty estimation in the field of oil and gas measurement.

First revision was published in 1999.

A revision to include comments from users and to get a more flexible and up to date document was initiated by NFOGM, and financed by NFOGM and The Norwegian Society of Chartered Engineers (NIF).

Christian Michelsen Research had the resources and competence to update the handbook.

The same reference group consisting of six persons with a broad and varied competence from oil and gas measurement has again evaluated and commented the handbook. The reference group consisted of:

Eide, John, Holta & Håland
Folkestad, Trond, Norsk Hydro
Frøystein, Hans Arne, The Norwegian Metrology and Accreditation Service
Malde, Erik, ConocoPhillips
Moestue, Håkon, Norsk Hydro
Sakariassen, Reidar, MetroPartner

We wish to express our thanks to the project leader at CMR, Eivind O. Dahl, and to the members of the reference group for their contribution to this handbook.

March, 2003

Norwegian Society for Oil and Gas Measurement
ConocoPhillips

Svein Neumann

TABLE OF CONTENTS

Orifice Fiscal Gas Metering Station

1. INTRODUCTION

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 [Lunde P. *et al.*, 1997][Midttveit Ø. & Nilsson J., 1997] [Midttveit Ø. *et al.*, 1998], the workgroup invited CMR to present a project proposal to complete the work of the workgroup. In 1997 CMR therefore proposed a project for developing the first handbook for uncertainty calculations of fiscal metering stations.

The project was initiated and financially supported by NFOGM and the Norwegian Petroleum Directorate (NPD) in 1998, and the first revision of the "Handbook of uncertainty calculations - Fiscal metering stations" [Dahl *et al.*, 1999] was published in 1999. That handbook concentrated on fiscal oil metering stations based on a turbine flow meter, and fiscal gas metering stations based on an orifice flow meter. As a further development with respect to fiscal gas metering stations, a follow-up project was initiated between the same partners for developing a handbook of uncertainty calculations for gas metering stations which are based on a flow calibrated multipath ultrasonic gas flow meter [Lunde & Frøysa, 2002].

On basis of user experiences with the first handbook of uncertainty calculations [Dahl *et al.*, 1999] and the work with the latest handbook on multipath ultrasonic gas flow meters, the partners in June 2002 decided to review the first handbook for turbine oil and orifice gas fiscal metering stations. The update was made to correct for some minor errors found in the handbook document and uncertainty calculation programs and to add functionality and flexibility to the uncertainty calculation programs.

1.1 Background

The fiscal measurement of oil and gas in the North Sea must be in accordance with the Norwegian Petroleum Directorate (NPD) regulations [NPD, 2001a], which require that an uncertainty analysis of a fiscal metering system must be in accordance with "recognised standards". In practise, different methods for evaluation of measurement uncertainties are used. The various methods have some kind of root-sum-square calculation as the basis, but the evaluation and combination of the individual uncertainty contributions from the basic measurements differ.

In 1995 the International Organisation for Standardisation (ISO) published the "Guide to the expression of Uncertainty in Measurement" [ISO, 1995a]. The document is commonly referred to as the *GUM*. The overall objective of the *GUM* 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 *GUM* 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 uncertainty should be quantified.

It should be noted that the *GUM* 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) [EAL-R2, 1997], is in conformity with the *GUM*. Previously, ISO-5168:1978 [ISO, 1978], 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-5168:1978 and the ISO-*GUM* were based on significantly different views on measurement uncertainty, and ISO-5168:1978 was therefore first revised in 1989 (ISO/DIS 5168 [ISO, 1989]) but later reduced to a technical report (ISO-TR 5168 [ISO, 1998]). A new international standard committee was then established to revise the 5168 document, and published a draft standard ISO/CD 5168 [ISO, 2000] in November 2000 and a final draft for voting ISO/DIS 5168 in March 2002 [ISO, 2002].

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

1.2 About the *Handbook*

The handbook covers uncertainty analysis and calculations of two metering stations; a turbine fiscal oil metering station and an orifice fiscal gas metering station. Through a detailed assessment of the metering stations, a theoretical and practical guideline for analysis and calculation of the metering stations is given. The analysis further reveals which uncertainties must be included in the calculations and which may be considered negligible. Two programs have also been made (Microsoft Excel 2000) for performing uncertainty calculations on these two metering stations. The programs are part of the handbook, which also serves as a user manual for these programs.

As the functional relationships and measurement procedures used in calculation of standard volume flow rates (oil) or mass flow rates (gas) are important to the uncertainty evaluation, the required functional relationships and procedures are given together with references in the *Handbook*. The *Handbook* may therefore to some extent serve as a measurement handbook for fiscal metering stations.

Chapter 2 provides a general introduction to the fundamentals of uncertainty calculations, where Sections 2.1 and 2.2 covers the basic terminology and symbols used in evaluation of metering uncertainties, respectively. In Section 2.3 the theoretical principles for performing uncertainty calculations according to the *GUM* are briefly described, while Section 2.4 describes how to document the calculations according to the *GUM*.

By understanding Chapter 2 the reader should have gained sufficient knowledge about uncertainty evaluations in general to secure proper application of and 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.

The handbook is further divided into two main chapters covering the uncertainty analysis and calculations of each metering station, and two chapters serving as user manuals for the uncertainty calculation programs. The uncertainty calculation for the turbine oil fiscal metering station is covered in Chapter 3 while the user manual for the corresponding uncertainty calculation program is covered in Chapter 4. Chapter 5 covers the uncertainty calculation for the orifice gas fiscal metering station and Chapter 6 is the user manual for the uncertainty calculation program.

1.3 About the new revision of the *Handbook*

In this Section the major updates of the present revision of the *Handbook* are briefly described.

The previous version of this *Handbook* [Dahl *et al.*, 1999] formed basis for development of the *Handbook of uncertainty calculations - USM Fiscal Gas Metering Stations* [Lunde & Frøysa, 2002] (hereafter denoted the *USM Handbook).* In relation with this work, most of the previous version of this *Handbook* was reviewed in detail and the gas metering station part in particular. The EMU[1] program layouts and implementations were also reviewed and an improved and more flexible layout was developed for the program *EMU - USM Fiscal Gas Metering Station*. Among others, the new EMU program supports more flexible graphical presentations of calculated uncertainties, and allows the user to more freely choose to use different transmitters (pressure, temperature, density) than the previous versions. The user may also more easily add own uncertainty contributions at the different parts of the metering station than before if one finds this desirable. Introducing a miscellaneous uncertainty contribution to each of the relevant uncertainty budgets enables this, and may among others be used to account for acceptance tolerances if desired.

As part of the work with the *USM Handbook* a review of the terminology regarding uncertainty calculations in general was made. On this basis one has introduced some changes to the terminology used in the NFOGM handbooks in order to establish a terminology that is applicable to any technology without risking confusion with terminology related to measurement technologies.

A major part of the present revision has therefore concerned an update of the terminology to adapt to the terminology used in the *USM Handbook*, and upgrade of the EMU programs to include the latest options with respect to flexibility.

All functional relationships and uncertainty calculations have been reviewed and verified in detail, both in the *Handbook* and in the EMU programs. The *Handbook* has been updated according to the latest versions of standards, regulations and data sheets, and the new revision complies with the new NPD regulations that entered into force on January 1st, 2002 [NPD, 2001a] and the new ISO-5167 standard published on February 24th [ISO, 2003].

The authors have also received feedback from users of the *Handbook* regarding some text and calculation errors found in the previous *Handbook* document and in the EMU programs. This has comprised a major part of the present revision in order to correct errors and to achieve a more user friendly and applicable handbook.

A more specific list of major corrections made to the *Handbook* document and programs is given in the following:

[1] The abbreviation *EMU* is short for “Evaluation of Metering Uncertainty”.

Handbook:

- Chapter 2 regarding the fundamentals of uncertainty calculations have been updated and revised on basis of the work performed in relation with the *USM Handbook* [Lunde & Frøysa, 2002].
- Changes have been made to the layout of the uncertainty budgets in the *Handbook* and the EMU programs.
- Adapted the terminology to the *USM Handbook* [Lunde & Frøysa, 2002].
- Changed the way of referencing literature
- Small changes have been made to the document layout.
- Changes have been made to the Chapter divisions to achieve a more logical and self-explaining document.
- The uncertainty evaluations of the Rosemount 3051P and 3144 pressure and temperature transmitters, and the Solartron 7812 and 7835 gas and liquid densitometers, have been reviewed and slightly extended.
- The density Velocity of Sound (VOS) correction has been reviewed in detail and is now handled differently, see Section 3.4.
- Added equations (5.31) and (5.32) on page 172 which were left out in the previous update of the *Handbook*.
- The functional relationship for the expansibility factor, and the model uncertainties given for the expansibility factor and the discharge coefficient have been updated according to the recently published ISO 5167 [ISO, 2003] standard.

EMU programs:

- More flexible EMU programs, where the user more freely may choose to use other equipment than used in the examples in the *Handbook* and EMU programs. The user may now specify the uncertainty of each instrument at either an overall or a detailed level.
- A separate cell for instrument type has been added to the worksheets in the EMU programs to allow the user more easily include information/descriptions of the instruments being evaluated.
- The “Upper Range Limit” (URL) specification in the static and differential pressure worksheets is no longer limited by a fixed range of URLs to be selected from a list, but may be freely set by the user.
- A fixed range of values no longer limits the specification of K0 and K1 for the reference density calculation.
- Added a “miscellaneous” uncertainty contribution in each uncertainty budget in the EMU programs to allow the user to more easily define and add own uncertainty contributions.

- New graphical plotting functionality and flexibility is built into the EMU programs, and the plotted values are also available in tabulated form.
- The relative expanded uncertainty of the gas density in the "*Density*" worksheet in the *EMU - Orifice Fiscal Gas Metering Station* program is now calculated in terms of Kelvin (previously it was calculated in terms of Celsius).
- The optional use of "Density installation correction" in the "*Density*" worksheet in the *EMU - Orifice Fiscal Gas Metering Station* program has been removed. The "density installation correction" is now handled differently, see Section 3.4. The *"Density"* worksheet in the *EMU - Orifice Fiscal Gas Metering Station* is now implemented in a slightly different way than in the previous version of the *Handbook.*
- An error relating to the propagation of uncertainty from the "*Density*" worksheet to the calculation of combined expanded uncertainty for the gas the metering station has been corrected.
- The effect of atmospheric pressure variations on the static pressure measurements has been included in both metering stations.
- Descriptions of the colour coding in the EMU programs have been included.

1.4 About the EMU-programs

As a part of the present revision of the *Handbook*, the two Excel programs *EMU - Turbine Fiscal Oil Metering Station* and *EMU - Orifice Fiscal Gas Metering Station* has also been revised[2]. The programs are implemented in Microsoft Excel 2000 and are opened as normal workbooks in Excel.

It has been the intention that the EMU programs to some extent shall be self-explaining. However, Chapters 4 and 6 in the *Handbook* gives an overview of the programs and serves as a user manual. In addition, Chapter 3 and 4.11 of the *Handbook* provides guidelines for specifying input parameters and uncertainties to the programs through practical examples. This may be useful to read together with running the programs for the first time. At each "input cell" in the program a comment is also given with reference to the relevant section(s) of the Handbook in which some information and help about the required input can be found. As

[2] In the previous revision of this *Handbook* [Dahl *et al.*, 1999], the two Excel programs were named *EMU - Fiscal Gas Metering Station* (for gas metering stations based on orifice plate), and *EMU - Fiscal Oil Metering Station* (for oil metering stations based on a turbine meter). Hence, the programs are now renamed *EMU - Orifice Fiscal Gas Metering Station* and *EMU - Turbine Fiscal Oil Metering Station*, respectively, in order to more clearly separate them from the recently published program *EMU - USM Fiscal Gas Metering Station* program [Lunde & Frøysa, 2002].

delivered, the program is "loaded" with the input parameters and uncertainties used for the example calculations given in Chapters 3 and 5.

The *EMU - Turbine Fiscal Oil Metering Station* program calculates the expanded and relative expanded uncertainties of a Turbine meter based oil metering station for standard volume flow rate, Q. The *EMU - Orifice Fiscal Gas Metering Station* program calculates the expanded and relative expanded uncertainties of an Orifice meter based gas metering station for actual mass flow rate, q_m.

In addition to calculation/plotting/reporting of the expanded uncertainty of the metering stations and the individual equipment of the stations, the Excel program can be used to calculate, plot and analyse the relative importance of the various contributions to the uncertainty budgets for the actual instruments of the metering stations (using bar-charts), such as:

- Pressure transmitter (static and/or differential)
- Temperature element / transmitter
- Densitometer
- Flow calibration
- The metering stations in total

In the programs the uncertainties of the primary (density, pressure and temperature) measurements can each be specified at two levels:

(1) ***"Overall level":*** The user specifies the combined standard uncertainty of the density, pressure or temperature estimates directly as input to the program. It is then left to the user to calculate and document these combined standard uncertainties. This option is general, and covers any method of obtaining the uncertainties of the primary measurements (measurement or calculation)[3].

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[3] The "overall level" options may be of interest in several cases, such as e.g.:
- If the user wants a "simple" and quick evaluation of the influence of the standard uncertainties of the primary measurements on the expanded uncertainty of the metering station,
- In case of a different installation of the densitometers (e.g. in-line) or a different densitometer functional relationship
- In case the input used at the "detailed level" does not fit sufficiently well to the type of input data / uncertainties which are relevant for the pressure transmitter or temperature element/transmitter at hand.

(2) ***"Detailed level":*** The combined standard uncertainties of the density, pressure and temperature are calculated in the program from more basic input for the different transmitters provided by the instrument manufacturer and calibration laboratory.

In Table 1.1 and Table 1.2 the optional levels of specification of the input uncertainties are shown for the Turbine oil and Orifice gas metering stations, respectively.

Table 1.1 Uncertainty model contributions, and optional levels for specification of input uncertainties to the program EMU - Turbine Fiscal Oil Metering Station.

Uncertainty contribution	**Overall level**	**Detailed level**
Pressure measurement uncertainty	✓	✓
Temperature measurement uncertainty	✓	✓
Density measurement uncertainty	✓	✓
Turbine meter measurement uncertainty	✓	
Flow calibration uncertainty (Prover)	✓	
Volume correction factors / Density conversion model		✓
Signal communication and flow computer calculations	✓	

Table 1.2 Uncertainty model contributions, and optional levels for specification of input uncertainties to the program EMU - Orifice Fiscal Gas Metering Station.

Uncertainty contribution	**Overall level**	**Detailed level**
Pressure measurement uncertainty (static)	✓	✓
Differential pressure measurement uncertainty	✓	✓
Temperature measurement uncertainty	✓	✓
Density measurement uncertainty	✓	✓
Compressibility factor uncertainties		✓
Signal communication and flow computer calculations	✓	

In the NPD regulations it is stated that the total uncertainty of the measurement system shall be documented, and an uncertainty analysis shall be prepared for the measurement system within a 95 % confidence level [NPD, 2001a]. The *GUM* [ISO, 1995a] also put requirements to such documentation, cf. Section 2.4.

With reference to the *Handbook*, and provided the user of the program on basis of manufacturer information or another source can document the figures used for the input uncertainties to the EMU programs, the expanded uncertainties calculated by the EMU programs may be used in documentation of metering station uncertainties.

It is emphasised that for traceability purposes the inputs to the program must be documented by the user, cf. Section 2.4. The user must also document that the calculation procedures and functional relationships implemented in the program (cf. Chapters 3 and 5) are in conformity with the ones actually applied in the fiscal metering station being evaluated[4].

1.5 Acknowledgements

The present revision of the Handbook has been worked out on behalf of the Norwegian Society for Oil and Gas Measurement (NFOGM) and the Norwegian Society of Chartered Engineers (NIF).

We greatly acknowledge the useful discussions and input from the technical reference group, consisting of (in arbitrary order) Reidar Sakariassen (Metropartner), John Magne Eide (JME Consultants, representing Holta & Håland), Erik Malde (ConocoPhillips), Trond Folkestad (Norsk Hydro), Håkon Moestue (Norsk Hydro) and Hans Arne Frøystein (Norwegian Metrology and Accreditation Service).

We also highly acknowledge the useful discussions and inputs received from Inge Hommedal (Holta & Håland Instruments AS) and Svein Neumann (ConocoPhillips).

[4] If the "overall level" options of the programs are used, the programs should cover a wide range of situations met in practice. However, note that in this case possible correlations between the estimates that are specified at the "overall level" are not accounted for. In cases where such correlations are important, the influence of the covariance term on the expanded uncertainty of the metering station should be investigated.

2. FUNDAMENTALS OF UNCERTAINTY EVALUATION

The NPD regulations [NPD, 2001a] and the NORSOK I-104 [NORSOK, 1998a] and NORSOK I-105 [NORSOK, 1998b] standards refer to the *GUM* (*Guide to the expression of uncertainty in measurement)* [ISO, 1995a][5] as the "accepted norm" with respect to uncertainty analysis. The uncertainty model and the uncertainty calculations reported here are therefore based primarily on the "*GUM*".

A brief outline of the *GUM* terminology used in evaluating and expressing uncertainty is given in Section 2.1. A list of important symbols used in the *Handbook* for expressing uncertainty is given in Section 2.2. The *GUM* procedure used here for evaluating and expressing uncertainty is summarized in Section 2.3, as a basis for the description of the uncertainty model and the uncertainty calculations. Requirements for documentation of the uncertainty calculations are described in Section 2.4.

2.1 Terminology for evaluating and expressing uncertainty

Precise knowledge about the definitions of the terms used in the *Handbook* is important in order to perform the uncertainty calculations with - preferably - a minimum possibility of misunderstandings.

Consequently, the definitions of some selected terms regarding uncertainty calculations that are used in the present *Handbook*, or are important for using the *Handbook,* are summarized in Table 2.1. References are also given to the source documents in which further details may be given. For definition of terms in which symbols are used, the symbol notation is defined in Section 2.2.

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5 The *GUM* was prepared by a joint working group consisting of experts nominated by BIPM, IEC, ISO and OIML, on basis of a request from the CIPM. The following seven organizations supported the development, which was published in their name: BIPM, IEC, IFCC, ISO, IUPAC, IUPAP and OIML.

The abbreviations are: CIPM: Comité International des Poids et Mesures, France (International Committee for Weights and Measures); BIPM: Bureau International des Poids et Mesures, Sévres Cedex, France (International Bureau of Weights and Measures); IEC: International Electrotechnical Commission, Genève, Switzerland; IFFC: International Federation of Clinical Chemistry, Nancy, France; ISO: International Organization for Standardization Genève, Switzerland; IUPAC: International Union of Pure and Applied Chemistry, Oxford, UK; IUPAP: International Union of Pure and Applied Physics, Frolunda Sweden; IOML: International Organization of Legal Metrology, Paris, France.

For additional definitions of relevance, cf. e.g. the *VIM* [ISO, 1993], and the *GUM*, Appendices E and F [ISO, 1995a][6].

Table 2.1 Definitions of some terms regarding uncertainty calculations.

Type of term	**Term**	**Definition**	**Reference**
Quantities and units	Output quantity, y	In most cases a measurand y is not measured directly, but is determined from M other quantities $x_1, x_2, ..., x_M$ through a functional relationship, $y = f(x_1, x_2, ..., x_M)$	*GUM*, §4.1.1 and §4.1.2, p. 9
	Input quantity, x_i,	An *input quantity*, x_i (i = 1, ..., M), is a quantity upon which the *output quantity*, y, depends, through a functional relationship, $y = f(x_1, x_2, ..., x_M)$. The input quantities may themselves be viewed as measurands and may themselves depend on other quantities.	*GUM*, §4.1.2, p. 9
	Value (of a quantity)	Magnitude of a particular quantity generally expressed as a unit measurement multiplied by a number.	*VIM*, §1.18. *GUM*, §B.2.2, p. 31
	True value (of a quantity)	Value consistent with the definition of a given particular quantity. *VIM* notes (selected): 1. This is a value that would be obtained by a perfect measurement. 2. True values are by nature indeterminate. *GUM* comment: The term "true value" is not used, since the terms "value of a measurand" (or of a quantity) and the term "true value of a measurand" (or of a quantity) are viewed as equivalent, with the word "true" to be redundant. *Handbook* comment: Since a true value cannot be determined, in practice a conventional true value is used (cf. the *GUM*, p. 34).	*VIM*, §1.19 *GUM*, §3.1.1, p. 4. *GUM*, §3.2.3, p. 4. *GUM*, §D.3.5, p. 41.
Quantities and units (contd.)	Conventional true value (of a quantity)	Value attributed to a particular quantity and accepted, sometimes by conventions, as having an uncertainty appropriate for a given purpose. *VIM* note (selected): "Conventional true value" is sometimes called **assigned value**, **best estimate** of the value, **conventional value** or **reference value**.	*VIM*, §1.20 *GUM*, §B.2.4, p. 32
Measurements	Measurand	Particular quantity subject to measurement.	*VIM*, §2.6 *GUM*, §B.2.9
	Influence quantity	Quantity that is not the measurand, but that affects the result of measurement.	*VIM*, §2.7 *GUM*, §B.2.10, pp. 32-33.

6 Note that a number of documents are available in which the basic uncertainty evaluation philosophy of the *GUM* is interpreted and explained in more simple and compact manners, for practical use in metrology. Some documents which may be helpful in this respect are [Taylor and Kuyatt, 1994], [NIS 3003, 1995], [EAL-R2, 1997], [EA-4/02, 1999], [Bell, 1999] and [ISO/DIS 5168, 2002].

Type of term	Term	Definition	Reference
Measurement results	Result of measurement	Value attributed to a measurand, obtained by measurement. *VIM* notes: 1. When a result is given, it should be made clear whether it refers to: - the indication, - the uncorrected result, - the corrected result, and whether several values are averaged. 2. A complete statement of the result of a measurement includes information about the uncertainty of measurement.	*VIM*, §3.1 *GUM*, §B.2.11, p. 33
	Indication (of a measuring instrument)	Value of a quantity provided by a measuring instrument. *VIM* notes (selected): 1. The value read from the display device may be called the **direct indication**; it is multiplied by the instrument constant to give the indication. 2. The quantity may be the measurand, a measurement signal, or another quantity to be used in calculating the value of the measurand.	*VIM*, §3.2
	Uncorrected result	Result of a measurement before correction for systematic error.	*VIM*, §3.3 *GUM*, §B.2.12, p. 33
	Corrected result	Result of a measurement after correction for systematic error.	*VIM*, §3.4 *GUM*, §B.2.13, p. 33
	Correction	Value added algebraically to the uncorrected result of a measurement to compensate for systematic error. *VIM* notes: The correction is equal to the negative of the estimated systematic error. Since the systematic error cannot be known perfectly, the compensation cannot be complete. *Handbook* comment: If a correction is made, the correction must be included in the functional relationship, and the calculation of the combined standard uncertainty must include the standard uncertainty of the applied correction.	*VIM*, §3.15. *GUM*, §B.2.23, p. 34
	Correction factor	Numerical factor by which the uncorrected result of a measurement is multiplied to compensate for systematic error. *VIM* note: Since the systematic error cannot be known perfectly, the compensation cannot be complete. *Handbook* comment: If a correction factor is applied, the correction must be included in the functional relationship, and the calculation of the combined standard uncertainty must include the standard uncertainty of the applied correction factor.	*VIM*, §3.16 *GUM*, §B.2.24, p. 34

Type of term	**Term**	**Definition**	**Reference**
Measurement results (contd.)	Accuracy of measurement	Closeness of the agreement between the result of a measurement and a true value of the measurand. *VIM* notes: Accuracy is a qualitative concept. The term "precision" should not be used for "accuracy". *Handbook* comment: Accuracy should not be used quantitatively. The expression of this concept by numbers should be associated with (standard) uncertainty.	*VIM*, §3.5 *GUM*, §B.2.14, p. 33
	Repeatability	Closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. *VIM* notes: 1. These conditions are called repeatability conditions. 2. Repeatbility conditions include: - the same measurement procedure, - the same observer, - the same measuring instrument, used under the same conditions, - the same location, - repetition over a short period of time. 3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results.	*VIM*, §3.6 *GUM*, §B.2.15, p. 33.
	Reproducibility	Closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement. *VIM* notes: 1. A valid statement of reproducibility requires specification of the conditions changed. 2. The changed conditions may include: - principle of measurement, - method of measurement, - observer, - measuring instrument, - reference standard, - location, - conditions of use, - time. 3. Repeatability may be expressed quantitatively in terms of the dispersion characteristics of the results. 4. Results are here usually understood to be corrected results.	*VIM*, §3.7 *GUM*, §B.2.16, p. 33
	Experimental standard deviation	A quantity characterizing the dispersion of the results, for a series of measurements of the same measurand.	*VIM*, §3.8; *GUM*, § B.2.17, p. 33
	Uncertainty of measurement	Parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand.	*VIM*, §3.9. *GUM*, §2.2.4, p. 2-3. *GUM*, §B.2.18, p. 34. *GUM*, Annex D
	Error (of measurement)	Result of a measurement minus a true value of the measurand.	*VIM*, §3.10. *GUM*, §B.2.19, p. 34
	Deviation	Value minus its reference value.	*VIM*, §3.11

Type of term	Term	Definition	Reference
Measurement results (contd.)	Relative error	Error of a measurement divided by a true value of the measurand.	*VIM*, §3.12. *GUM*, §B.2.20, p. 34.
	Random error	Result of a measurement minus the mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions. *VIM* notes: 1. Random error is equal to error minus systematic error. Because only a finite number of measurements can be made, it is possible to determine only an estimate of random error.	*VIM*, §3.13. *GUM*, §B.2.21, p. 34.
	Systematic error	Mean that would result from an infinite number of measurements of the same measurand carried out under repeatability conditions minus the true value of the measurand. *VIM* notes: Systematic error is equal to error minus random error. Like true value, systematic error and its causes cannot be completely known. For a measuring instrument, see "bias".	*VIM*, §3.14 *GUM*, §B.2.22, p. 34.
Characterisation of measuring instruments	Nominal range	Range of indications obtainable with a particular setting of the controls of a measuring instrument. *VIM* note (selected): 1. Nominal range is normally stated in terms of its lower and upper limits.	*VIM*, §5.1
	Span	Modulus of the difference between the two limits of nominal range. *VIM* note: 1. In some fields of knowledge, the difference between the greatest and smallest value is called **range**.	*VIM*, §5.2
	Measuring range, Working range	Set of values of measurands for which the error of a measuring instrument is intended to lie within specified limits	*VIM*, §5.4
	Resolution (of a displaying device)	Smallest difference between indications of a displaying device that can be meaningfully distinguished. *VIM* note (selected): 1. For a digital displaying device, this is the change in the indication when the least significant digit changes by one step.	*VIM*, §5.12
	Drift	Slow change of metrological characteristic of a measuring instrument.	*VIM*, §5.16
	Accuracy of a measuring instrument	Ability of a measuring instrument to give responses close to a true value. *VIM* note: 1. "Accuracy" is a qualitative concept.	*VIM*, §5.18 *GUM*, §B.2.14, p. 33
	Error (of indication) of a measuring instrument	Indication of a measuring instrument minus a a true value of the corresponding input quantity. *VIM* note (selected): 1. This concept applies mainly where the instrument is compared to a reference standard.	*VIM*, §5.20 *GUM*, §B2.2.19, p. 34; Section 3.2

Type of term	Term	Definition	Reference
Characterisation of measuring instruments (contd.)	Datum error (of a measuring instrument)	Error of a measuring instrument at a specified indication of a specified value of the measurand, chosen for checking the instrument.	*VIM*, §5.22
	Zero error (of a measuring instrument)	Datum error for zero value of the measurand.	*VIM*, §5.23
	Bias (of a measuring instrument)	Systematic error of the indication of a measuring instrument. *VIM* note: 1. The bias of a measuring instrument is normally estimated by averaging the error of indication over an appropriate number of repeated measurements.	*VIM*, §5.25 *GUM*, §3.2.3 note, p. 5
	Repeatability (of a measuring instrument)	Ability of a measuring instrument to provide closely similar indications for repeated applications of the same measurand under the same conditions of measurement.	*VIM*, §5.27
Statistical terms and concepts	Random variable	A variable that may take any of the values of a specified set of values, and with which is associated a probability distribution.	*GUM*, §C.2.2, p. 35
	Probability distribution (of a random variable)	A function giving the probability that a random variable takes any given value or belongs to a given set of values.	*GUM*, §C.2.3, p. 35
	Variance	A measure of dispersion, which is the sum of the squared deviations of observations from their average divided by one less than the number of observations. *GUM* note (selected): 1. The sample standard deviation is an unbiased estimator of the population standard deviation.	*GUM*, §C.2.20, p. 36.
	Standard deviation	The positive square root of the variance. *GUM* note: 1. The sample standard deviation is a biased estimator of the population standard deviation.	*GUM*, §C.2.12, p. 36; §C.2.21, p. 37; §C.3.3, p. 38.
	Normal distribution		*GUM*, §C.2.14, p. 34
	Estimation	The operation of assigning, from the observations in a sample, numerical values to the parameters of a distribution chosen as the statistical model of population from which this sample is taken.	*GUM*, §C.2.24, p. 37
	Estimate	The value of an estimator obtained as a result of an estimation. *Handbook* comment: 1. Estimated value of a quantity, obtained either by measurement, or by other means (such as by calculations).	*GUM*, §C.2.26, p. 37.

Type of term	Term	Definition	Reference
	Input estimate, and output estimate	An estimate of the measurand, y, denoted by $\hat{y}$, is obtained from the functional relationship $y = f(x_1, x_2, ..., x_M)$ using input estimates, $\hat{x}_1$, $\hat{x}_2$, ..., $\hat{x}_M$ for the values of the M quantities $x_1, x_2, ..., x_M$. Thus the output estimate, which is the result of the measurement, is given by $\hat{y} = f(\hat{x}_1, \hat{x}_2, ..., \hat{x}_M)$. *Handbook* comment: 1. The symbols used here are those used in this *Handbook*, cf. Section 2.4.	*GUM*, §4.1.4, p. 10.
Statistical terms and concepts (contd.)	Sensitivity coefficient	Describes how the output estimate y varies with changes in the values of an input estimate, x_i, $i = 1, \ldots, M$.	*GUM*, §5.1.3, p.19; 5.1.4, p. 20
	Coverage factor, k:	Numerical factor used as a multiplier of the combined standard uncertainty in order to obtain an expanded uncertainty.	*GUM*, §2.3.6, p. 3. *GUM*, §G.1.3, p. 59.
	Level of confidence		*GUM*, Annex G, pp. 59-65.
	Standard uncertainty	Uncertainty of the result of a measurement expressed as standard deviation	*GUM*, §2.3.1, p. 3. *GUM*, Chapter 3, pp. 9-18.
	Combined standard uncertainty	The standard uncertainty of the result of a measurement, when that result is obtained from the values of a number of other quantities, is termed *combined standard uncertainty*, and denoted u_c. It is the estimated standard deviation associated with the result, and is equal to the positive square root of the combined variance obtained from all variance and covariance components.	*GUM*, §3.3.6, p. 6. *GUM* §4.1.5, p. 10.
	Expanded uncertainty	Quantity defining an interval about the result of a measurement that may be expected to encompass a large fraction of the distribution of values that could reasonably be attributed to the measurand.	*GUM*, §2.3.5, p. 3. *GUM* §6.1.2, p. 23. *GUM* Chapter 5, pp. 23-24.
	Systematic effect	The effect of a recognized effect of an influence quantity. Note: By [NIS 81, 1994, p. 4], contributions to uncertainty arising from systematic effects are described as "those that remain constant while the measurement is being made, but can change if the measurment conditions, method or equipment is altered".	*GUM*, §3.2.3, p. 5
	Random effect	The effect of unpredictable or stochastic temporal and spatial variations of influence quantities.	*GUM*, §3.2.2, p. 5
	Linearity	Deviation between a calibration curve for a device and a straight line.	[NPD, 2001a]
	Type A evaluation (of uncertainty)	Method of evaluation of uncertainty by the statistical analysis of series of observations.	*GUM*, §2.3.2, p. 3
	Type B evaluation (of uncertainty)	Method of evaluation of uncertainty by means other than the statistical analysis of series of observations, e.g. by engineering/scientific judgement.	*GUM*, §2.3.3, p. 3
Miscellaneous	Functional relationship, f	In most cases a measurand y is not measured directly, but is determined from M other quantities $x_1, x_2, ..., x_M$ through a functional relationship, $y = f(x_1, x_2, ..., x_M)$	*GUM*, §4.1.1 and §4.1.2, p. 9

2.2 Symbols for expressing uncertainty

In general, the following symbols are used in the present *Handbook* for expressing quantities and uncertainties:

$\hat{x}_i$: an *estimated value* (or simply an *estimate*) of an input quantity, x_i,
$\hat{y}$: an *estimated value* (or simply an *estimate*) of an output quantity, y,

$u(\hat{x}_i)$: the *standard uncertainty* of an input estimate, $\hat{x}_i$,
$u_c(\hat{y})$: the *combined standard uncertainty* of an output estimate, $\hat{y}$,

$U(\hat{y})$: the *expanded uncertainty* of an output estimate, $\hat{y}$:

$$U(\hat{y}) = k \cdot u_c(\hat{y}),$$

E_x : the *relative standard uncertainty* of an input estimate, $\hat{x}_i$:

$$E_x = \frac{u(\hat{x}_i)}{|\hat{x}_i|}$$

E_y : the *relative combined standard uncertainty* of an output estimate[7], $\hat{y}$:

$$E_y = \frac{u_c(\hat{y})}{|\hat{y}|}$$

With four exceptions (see Table 2.2 and points (1)-(4) below), the symbols used for expression of uncertainty are those used by the *GUM* [ISO, 1995a, §4.1.5 and §6.2.1], see also [Taylor and Kuyatt, 1994], [EAL-R2, 1997], [EA-4/02, 1999], [ISO/DIS 5168, 2002].

(1) With respect to the symbols used for *a quantity and the estimate value of the quantity*, the "conventions" of the *GUM* are not followed exactly, mainly for practical reasons[8]. Here, both capital and small letters are used for input

[7] For simplicity in notatation, and since it should not cause confusion here, the same symbol, E_y, is used for both types of relative (i.e., percentage) standard uncertainties; i.e., relative standard uncertainty, and relative combined standard uncertainty. In each case it will be noted in the text which type of relative uncertainty that is in question.

[8] In the *GUM* [ISO, 1995, Section 3.1, pp. 9-10], a quantity and an estimate value for the quantity are denoted by capital and small letters, respectively (such as "*X*" and "*x*", respectively) (cf. Note 3 to §4.1.1). (Cf. also [NIS 3003, 1995, pp. 16-17).
This notation is considered to be impractical for the present Handbook. For example, in physics, engineering and elsewhere the temperature is uniformly denoted by *T*, while in e.g. the USM community a transit time is commonly denoted by *t* (cf. e.g. [ISO, 1997]). This is one of several examples where this notation is considered to be impractical.
Moreover, also in the *GUM*, the "*GUM* conventions" are not used consequently. For example, in the illustration examples [ISO, 1995, Annex H, cf. p. 68], the same symbol has been used for a quantity and its estimate, for simplicity in notation.

quantities, in order to enable use of common and well-established terminology in USM technology (cf. e.g. [ISO, 1997]) and physics in general, involving both capital and small letters as symbols for input/output quantities. To distinguish between a quantity and the estimate value of the quantity, the above-defined terminology has thus been chosen (with the symbol "$\hat{x}$" (the "hat notation") to denote the estimate value of the quantity "*x*").

(2) With respect to *relative uncertainties*, no specific symbol was used in the *GUM*, other than a notation of the type $u_c(\hat{y})/|\hat{y}|$ (for the relative combined standard uncertainty of an output estimate, $\hat{y}$) [ISO, 1995a, §5.1.6, p. 20]. This notation has been used also in [ISO/DIS 5168, 2002]. However, for the present document, a simpler symbol than $u_c(\hat{y})/|\hat{y}|$ has been found to be useful, or even necessary, to avoid unnecessary complexity in writing the expressions for the relative expanded uncertainties. "E_y" is the symbol for relative uncertainty used by e.g. [ISO, 1997]; [ISO 5168:1978], and has been adopted here[9,10].

(3) With respect to the symbol "$U(\hat{y})$, the use of simply "*U*" has been recommended by the *GUM*. In the present document that would lead to ambiguity, since expanded uncertainties of two output estimates are considered in this document: $\hat{q}_v$ and $\hat{q}_m$, cf. Chapters 3 and 4.11. Hence, the symbols $U(\hat{q}_v)$ and $U(\hat{q}_m)$ are used for these to avoid confusion.

(4) With respect to the symbols used for *dimensional (absolute)* and *dimensionless (relative) sensitivity coefficients*, the *GUM* has recommended use of the symbols c_i and c_i^*, respectively. These symbols are used also by [ISO/DIS 5168, 2002]. However, this NFOGM Handbook series also covers USM metering stations where the well-established notation *c* is used for the sound velocity (VOS). To avoid confusion, the symbols s_i and s_i^* are therefore used in the NFOGM Handbook series for the dimensional (absolute) and dimensionless (relative) sensitivity coefficients of the output estimate $\hat{y}_i$ to the input estimate $\hat{x}_i$.

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9 By [EAL-R2, 1997], the notation $w(\hat{x}) = u(\hat{x})/|\hat{x}|$ has been used for the relative standard uncertainty of an estimate $\hat{x}$ (cf. their Eqn. (3.11)). [Taylor and Kuyatt, 1994] has proposed to denote relative uncertainties by using a subscript "*r*" for the word "relative", i.e., $u_r(\hat{x}) \equiv u(\hat{x})/|\hat{x}|$, $u_{c,r}(\hat{y}) \equiv u_c(\hat{y})/|\hat{y}|$ and $U_r \equiv U/|\hat{y}|$ for the relative standard uncertainty, the relative combined standard uncertainty, and the relative expanded uncertainty, respectively (cf. their §D1.4).

10 The "E_y" - notation for relative uncertainties was used also in [Lunde *et al.*, 1997; 2000a].

In Table 2.2, the symbol notation used in the *Handbook* is summarized and compared with the symbol notation recommended by the *GUM*.

Table 2.2 Symbol notation used in the Handbook *in relation to that recommended by the* GUM.

Term	**GUM symbol**	**Handbook symbol**	**Deviation ?**
Input quantity & estimate value of the input quantity Output quantity & estimate value of the output quantity	Capital and small letters, respectively (" X_i " and " x_i ") Capital and small letters, respectively ("Y" and "y")	“ $\hat{x}_i$ ” denotes the estimate value of the input quantity “ x_i ” “ $\hat{y}$ ” denotes the estimate value of the output quantity “y”	Yes
Standard uncertainty of an input estimate	$u(x_i)$	$u(\hat{x}_i)$	No
Combined standard uncertainty of an output estimate	$u_c(y)$	$u_c(\hat{y})$	No
Relative standard uncertainty of an input estimate Relative combined standard uncertainty of an output estimate	$\frac{u(x_i)}{\lvert x_i \rvert}$ $\frac{u_c(y)}{\lvert y \rvert}$	$E_{x_i} = \frac{u(\hat{x}_i)}{\lvert \hat{x}_i \rvert}$ $E_y = \frac{u_c(\hat{y})}{\lvert \hat{y} \rvert}$	Yes
Expanded uncertainty	U	$U(\hat{y})$	Yes / No
Relative expanded uncertainty	$\frac{U}{\lvert y \rvert}$	$\frac{U(\hat{y})}{\lvert \hat{y} \rvert}$	No
Dimensional (absolute) sensitivity coefficients Dimensionless (relative) sensitivity coefficients	c_i c_i^*	s_i s_i^*	Yes

2.3 Procedure for evaluating and expressing uncertainty

The procedure used here for evaluating and expressing uncertainty is the procedure recommended by the *GUM* [11] [ISO, 1995a, Chapter 7], given as[12]:

1. The (mathematical) *functional relationship* is expressed between the measurand, y, and the input quantities, x_i, on which y depends: $y = f(x_1, x_2, ..., x_M)$, where M is the number of input quantities (in accordance with the *GUM*, Chapter 7, §1). The function, f, should preferably contain every quantity, including all corrections and correction factors, that can contribute significantly to the uncertainty of the measurement result.

2. $\hat{x}_i$, the *estimated value* of the input quantity, x_i, is determined, either on the basis of a statistical analysis of a series of observations, or by other means (in accordance with the *GUM*, Chapter 7, §2)[13].

3. The *standard uncertainty* $u(\hat{x}_i)$ of each input estimate $\hat{x}_i$ is evaluated; either as Type A evaluation of standard uncertainty (for an input estimate obtained from a statistical analysis of observations), or as Type B evaluation of standard uncertainty (for an input estimate obtained by other means), in accordance with the *GUM*, Chapter 7, §3 (cf. also the *GUM*, Chapter 3; [EAL-R2, 1997], [EA-4/02, 1999]).

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11 Other documents of interest in this context are e.g. [Taylor and Kuyatt, 1994], [NIS 3003, 1995], [EAL-R2, 1997], [EA-4/02, 1999], [Bell, 1999] and [ISO/DIS 5168, 2002], which are all based on (and are claimed to be consistent with) the *GUM*. However, the *GUM* is considered as the authoritative text.

12 The *GUM* procedure is here given in our formulation. The substance is meant to be the same, but the wording may be different in some cases. In case of possible inconsistency or doubt, the text given in Chapter 7 of the *GUM* is authoritative.

13 With respect to the estimated value of a quantity x_i (input or output), the "hat" symbol, $\hat{x}_i$, is used here, to distinguish between these. Cf. Section 2.2.

If the uncertainty of the input estimate $\hat{x}_i$ is given as an expanded uncertainty, $U(\hat{x}_i)$, this expanded uncertainty may be converted to a standard uncertainty by dividing with the coverage factor, *k*:

$$u(\hat{x}_i) = \frac{U(\hat{x}_i)}{k} \tag{2.1}$$

For example, if $U(\hat{x}_i)$ is given at a 95 % confidence level, and a normal probability distribution is used, k = 2. If the confidence level is 99 %, and a normal probability distribution is used, k = 3. If the confidence level is 100 %, and a rectangular probability distribution is used, converting to standard uncertainty is done by using $k = \sqrt{3}$. When an expanded uncertainty is given as a specific number of standard deviations, the standard uncertainty is achieved by dividing the given expanded uncertainty with the specific number of standard deviations.

4. *Covariances* are evaluated in association with input estimates that are *correlated*, in accordance with the *GUM*, Chapter 7, §4 (cf. also the *GUM*, Section 4.2). For two input estimates $\hat{x}_i$ and $\hat{x}_j$, the covariance is given as

$$u(\hat{x}_i, \hat{x}_j) = u(\hat{x}_i)u(\hat{x}_j)r(\hat{x}_i, \hat{x}_j) \qquad (i \neq j), \tag{2.2}$$

where the degree of correlation is characterised by $r(\hat{x}_i, \hat{x}_j)$, the correlation coefficient between $\hat{x}_i$ and $\hat{x}_j$ (where $i \neq j$ and $|r| \leq 1$). The value of $r(\hat{x}_i, \hat{x}_j)$ may be determined by engineering judgement or based on simulations or experiments. The value is a number between -1 and 1, where $r(\hat{x}_i, \hat{x}_j) = 0$ represents uncorrelated quantities, and $|r(\hat{x}_i, \hat{x}_j)| = 1$ represents fully correlated quantities

5. The *result of the measurement* is to be calculated in accordance with the *GUM*, Chapter 7, §5. That is, the estimate, $\hat{y}$, of the measurand, *y*, is to be calculated from the functional relationship, *f*, using for the input quantities the estimates $\hat{x}_i$ obtained in Step 2.

6. The *combined standard uncertainty*, $u_c(\hat{y})$, of the measurement result (output estimate), $\hat{y}$, is evaluated from the standard uncertainties and the covariances associated with the input estimates, in accordance with the *GUM*, Chapter 7, §6 (cf. also the *GUM*, Chapter 4).

$u_c(\hat{y})$ is given as the positive square root of the combined variance $u_c^2(\hat{y})$,

$$u_c^2(\hat{y}) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(\hat{x}_i) + 2\sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(\hat{x}_i, \hat{x}_j), \tag{2.3}$$

where N is the number of input estimates $\hat{x}_i$, $i = 1, \ldots, N$, and the partial derivatives are the sensitivity coefficients, s_i, i.e.

$$s_i \equiv \frac{\partial f}{\partial x_i}. \tag{2.4}$$

7. The *expanded uncertainty U* is determined by multiplying the combined standard uncertainty, $u_c(\hat{y})$, by a coverage factor, k, to obtain

$$U = k \cdot u_c(\hat{y}) \tag{2.5}$$

on basis of the level of confidence required for the uncertainty interval $\hat{y} \pm U$, in accordance with the *GUM*, Chapter 7, §7 (cf. also the *GUM*, Chapter 5 and Annex G).

For example, if U is to be given at a 95 % confidence level, and a normal probability distribution is assumed, k = 2. If the confidence level is 99 %, and a normal probability distribution is used, k = 3. If the confidence level is 100 %, and a rectangular probability distribution is supposed, $k = \sqrt{3}$.

In the EMU programs, the coverage factor k is set to k = 2, cf. Section 1.2, corresponding to a level of confidence of 95.45 % in case of a normal probability distribution of the output estimate, $\hat{y}$ [14].

[14] Note that a coverage factor of k = 2 produces an interval corresponding to a level of confidence of 95.45 % while that of k = 1.96 corresponds to a level of confidence of 95 %. The calculation of intervals having specified levels of confidence is at best only approximate. The *GUM* justifiably emphasises that for most cases it does not make sense to try to distinguish between e.g. intervals having levels of confidence of say 94, 95 or 96 %, cf. Annex G of the *GUM*. In practice, it is therefore recommended to use k = 2 which is assumed to produce an interval having a level of confidence of approximately 95 %. This is also in accordance with NPD regulations [NPD, 2001a].

8. The result of the measurement (the output estimate), $\hat{y}$, is to be *reported*, together with its expanded uncertainty, *U*, and the method by which *U* has been obtained, in accordance with the *GUM*, Chapter 7, §7 (cf. also the *GUM*, Chapter 6).

This includes documentation of the value of each input estimate, $\hat{x}_i$, the individual uncertainties $u(\hat{x}_i)$ which contribute to the resulting uncertainty, and the evaluation method used to obtain the reported uncertainties of the output estimate as summarised in steps 1 to 7.

Table 3.5 in Chapter 3.2.2 on page 38 show a typical uncertainty budget used for documentation of the calculated expanded uncertainties.

The above procedure (given by steps 1-8), recommended by the *GUM*, serves as a basis for the uncertainty calculations reported in Chapters 3 and 4.11 and the EMU programs described in Chapter 4 and 6.

In the NPD regulations [NPD, 2001a] the uncertainties are specified as relative expanded uncertainties, at a 95 % confidence level (assuming a normal probability distribution), with k = 2.

In the formulas that are implemented in the EMU programs, the input standard uncertainties, combined standard uncertainties, and the expanded uncertainties, are in many cases expressed as *relative* uncertainties, defined as

$$\frac{u(\hat{x}_i)}{|\hat{x}_i|}, \qquad \frac{u_c(\hat{y})}{|\hat{y}|}, \qquad \frac{U}{|\hat{y}|}, \tag{2.6}$$

respectively.

2.4 Documentation of uncertainty evaluation

According to the *GUM* [ISO, 1995a, Chapter 6], all the information necessary for a re-evaluation of the measurement should be available to others who may need it.

In Chapter 6.1.4 of the *GUM* it is stated that one should:

(1) Describe clearly the methods used to calculate the measurement result and its uncertainty from the experimental observations and input data,
(2) List all uncertainty components and document fully how they were evaluated,
(3) Present the data analysis in such a way that each of its important steps can be readily followed and the calculation of the reported result can be independently repeated if necessary,
(4) Give all corrections and constants used in the analysis and their sources.

The present *Handbook* together with the *EMU* programs should fill essential parts of the documentation requirements (1)-(4) above. A printout of the worksheets used for uncertainty evaluation of the measurand in question, together with the "*Report*" worksheet and the mathematical expressions given in Chapters 3 and 4.11, may be used in a documentation of the uncertainty evaluation of the metering station.

In addition, the user of the program must also document the uncertainties used as input to the program. Such documentation may be calibration certificates, data sheets, manufacturer information or other specifications of the metering station.

For uncertainty calculations on fiscal metering stations this requires that every quantity input to the calculations should be fully documented with its value (if needed), and its uncertainty, together with the confidence level and probability distribution. Furthermore, it must be documented that the functional relationships used in the uncertainty calculation programs following the *Handbook* are equal to the ones actually implemented in the metering station. An uncertainty evaluation report should be generated, containing the uncertainty evaluations and copies of (or at least reference to) the documentation described above.

3. TURBINE FISCAL OIL METERING STATION

The present chapter gives a description of a typical Turbine meter based fiscal oil metering station, serving as basis for the uncertainty model of such metering stations. This chapter includes a brief description of metering station methods and equipment as well as the functional relationships of the metering station (Section 3.1), the temperature, pressure and density instruments (Sections 3.2, 3.3, 3.4, respectively) and models for liquid and steel correction factors and conversion of line density to standard density (Sections 3.5 and 3.6, respectively).

In this *Handbook,* the combined expanded uncertainty of the standard volume flow rate, *Q*, of a turbine fiscal oil metering station is calculated. For further calculations of e.g. mass flow rate on basis of this primary value, please refer to the NORSOK I-105 standard [NORSOK, 1998b]. The recently published *Handbook of Water Fraction Metering* [Dahl et. *al.*, 2001] may also be of relevance.

An Excel program, *EMU - Turbine fiscal oil metering station,* has also been developed for calculation of the combined expanded uncertainty of the standard volume flow rate of turbine fiscal oil metering stations. This program is described in Chapter 4, which servers as a user manual to the program. It is recommended to read chapter 3 and 4 in parallel for better overview.

3.1 Description of a Turbine fiscal oil metering station

A turbine meter consists of a turbine wheel that rotates proportional to the volume flow rate through the meter, and by counting the number of revolutions the volume flow rate can be found. The turbine meter is calibrated in situ with a Prover and a known reference volume. From this calibration a *K-Factor* is established that relates the rotation of the turbine wheel (number of pulses counted) to a given volume. Figure 3.1 shows a typical fiscal oil metering station.

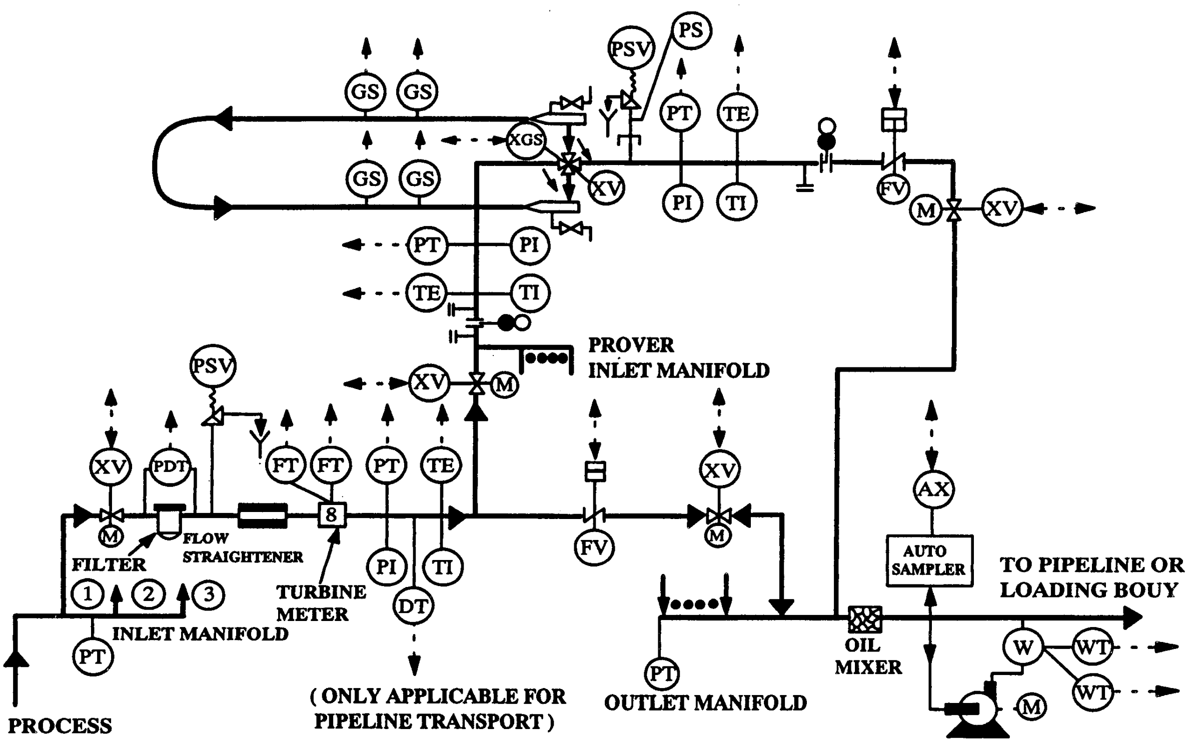

Figure 3.1 A typical turbine fiscal oil metering station [NPD, 1997]

According to NPD regulations [NPD, 2001a] the temperature and pressure shall be measured in each of the metering tubes. When metering oil, the temperature and pressure shall also be measured at the inlet and outlet of the pipe Prover. The density shall be measured in each of the metering pipes, or by two densitometers mounted at the inlet or outlet of the metering station in such a manner that they provide representative density.

Pressure and temperature shall be measured as close as possible to the densitometer. The densitometer is often mounted in a by-pass loop that is normally equipped with dedicated pressure and temperature transmitters for use with the density measurement[15] [Sakariassen, 2002]. The complete set of density and dedicated temperature and pressure measurements then forms basis for calculation of density at standard reference conditions, cf. Section 3.6. In some cases, however, metering stations may not be equipped dedicated pressure and/or temperature transmitters located close to the densitometer (e.g. in a by-pass loop). This is normally based on an assumption of only small deviations between the conditions at the densitometer location (e.g. in a by-pass) and in the metering run. One must then as an alternative use the line pressure and/or temperature measurements as estimates for the pressure

[15] The Solartron 7835 liquid densitometer is equipped with an internal temperature measurement, but this may not be calibrated as a separate unit and is therefore not used in fiscal metering stations for density corrections or calculation of standard reference density.

and temperature at the densitometer location. These must then be used for densitometer corrections (temperature and pressure compensation of the density measurement, cf. Section 3.4.1) and calculation of density at standard reference conditions (cf. Section Section 3.6). In these cases one must include an additional uncertainty contribution to the pressure and temperature estimates to account for potential deviation in pressure and temperature between line and densitometer location[16] (see Sections 3.2 and 3.3).

The complete metering station, including measurement of temperature, pressure and density values, is first calibrated and then the same instrumentation is used to perform the actual measurements. When performing such relative measurements the uncertainties are significantly reduced compared to absolute measurements, and systematic uncertainty contributions are compensated for in the calibration.

3.1.1 Measurement uncertainty requirements according to NPD regulations

According to NPD regulations [NPD, 2001a], the total measurement uncertainty of the metering station shall be within ±0.30% of standard volume using 95% confidence level.

The NPD regulations further impose additional requirements set for a turbine fiscal oil metering station in terms of measurement uncertainties, see Table 3.1. Please refer to [NPD, 2001a] for the complete set of requirements also including linearity and repeatability limitations. One should also confer the Guidelines to the NPD regulations [NPD, 2001b] for details.

Table 3.1 Measurement uncertainty requirements of loop and components according to NPD regulations [NPD, 2001a]. All uncertainties specified with 95% confidence level.

Component	Loop uncertainty limits	Component uncertainty limits
Prover volume	NA	0.04% for all four volumes
Turbine meter	1 pulse of 100000 (0.001%)	0.25% for the working range: (10:1)
Pressure measurement	0.30% of measured value	0.10% of measured value
Temperature measurement	0.30 °C	0.20 °C
Density measurement	0.50 kg/m^3	0.30 kg/m^3

[16] The dedicated pressure and temperature measurements for use in pressure and temperature correction of the density measurement and calculation of standard reference density are implemented as separate worksheets (“P-density” and “T-density”) in the EMU program.

3.1.2 Instrumentation and operating conditions

The Turbine fiscal oil metering station evaluated in the present *Handbook* consists of the equipment listed in Table 3.2, as specified by NFOGM, NPD and CMR to be widely used instrumentation on Turbine fiscal oil metering stations. With respect to the Turbine meter and flow computer no specific equipments are considered.

Operating conditions, etc., used for the present uncertainty evaluation example[17] are given in Table 3.3.

Table 3.2 The evaluated Turbine fiscal gas metering station instrumentation.

Measurement	Instrument
Turbine meter	Not specified.
Prover	Not specified.
Flow computer	Not specified.
Pressure (gauge), P	Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a].
Temperature, T	Pt 100 element: according to EN 60751 tolerance A [NORSOK, 1998a]. Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2002a].
Density, ρ	Solartron Model 7835 Liquid Density Transducer [Solartron, 2001b].

Table 3.3 Operating conditions for the Turbine meter fiscal oil metering station being evaluated (example).

Conditions	Quantity	Value
Operating	Line pressure, P (gauge)	18.0 barg
	Line temperature, T	65 ^{o}C (= 338.15 K)
	Ambient (air) temperature, T_{air}	0 ^{o}C
	Base pressure, Pb_a	101.325 kPa
	Equilibrium vapour pressure, Pe_a	101.325 kPa
Proving	Line pressure, P (gauge)	18.0 barg
	Line temperature, T	65 ^{o}C (= 338.15 K)
	Average pressure at Prover inlet and outlet, P_{pa}	18.0 barg
	Average temperature at Prover inlet and outlet, T_{pa}	65 ^{o}C (= 338.15 K)
Densitometer	Density, ρ	776.0 kg/m^3
	Temperature, T_d	63 ^{o}C [18]

[17] As for the *USM Handbook* [Lunde & Frøysa, 2002], the ambient temperature has been set to 0 ^{o}C to achieve a worst-case calculation of ambient temperature effects on the temperature and pressure transmitters.

[18] Temperature deviation between line and densitometer conditions may be as large as 7-8 ^{o}C [Sakariassen, 2001]. A representative value may be about 10 % of the temperature difference

	Pressure, P_d (gauge)	17.5 barg
	Calibration temperature, T_c	20 ^{o}C
	Calibration pressure, P_c	1.01325 bar
Turbine meter	Number of meter pulses during proving, *Mrp*	90092
Prover	Base volume of Prover	28.646 m^3
Pressure transmitter	Ambient (air) temperature at calibration	20 ^{o}C
Temperature transm.	Ambient (air) temperature at calibration	20 ^{o}C

3.1.3 Functional relationship

3.1.3.1 Standard volume flow rate

The measurement of standard volume flow rate using Turbine fiscal oil metering stations can be described by the functional relationship:

$$Q = \frac{MR_m}{K} \cdot C_{tsm} \cdot C_{psm} \cdot C_{tlm} \cdot C_{plm} \cdot 3600 \quad [m^3/h] \tag{3.1}$$

where

Q	standard volume flow rate [m^3/h]
MR_m	pulse counted per second during metering [pulses/min]
K	*K-Factor* [pulses/m^3]
C_{tlm}	volume correction factor for the effect of temperature on the liquid during metering (line conditions)
C_{plm}	volume correction factor for the effect of pressure on the liquid during metering (line conditions)
C_{tsm}	volume correction factor for the effect of temperature on Turbine steel
C_{psm}	volume correction factor for the effect of pressure on Turbine steel

It is important to notice that the volume correction factors in Eqn. (3.1) are not equal in magnitude to the volume correction factors applied in Section 3.1.3.2, Eqn. (3.4). The functional relationships are the same, but the conditions will differ from the values measured during the proving sequence.

Furthermore, the volume correction factors C_{tsm} and C_{psm} are given in the NORSOK I-105 standard [NORSOK, 1998b], where it is stated that the "accuracy" of these

between densitometer and ambient (air) conditions. Here, 2 ^{o}C deviation is used as a moderate example.

formulas must be evaluated before implementation[19]. However, the formulas are not specified with any traceability, model uncertainty or criteria for evaluation, and hence it may be interpreted as optional to exclude these corrections from the calculations (see also Section 3.5.5). According to [Ullebust, 1998] the C_{tsm} and C_{psm} correction factors are normally omitted when stable operating conditions are achieved during calibration (proving), and when the conditions during metering do not deviate significantly from the conditions during calibration. The volume correction factors C_{tsm} and C_{psm} are therefore not included in the calculations or evaluations in this handbook, and if the user decides to use them, their contribution to the combined uncertainty in standard volume flow rate must be included in the calculations in the *EMU - Turbine Fiscal Oil Metering Station* program as a miscellaneous effect. The functional relationship for the standard volume flow rate to be evaluated in this document then becomes:

$$Q = \frac{MR_m}{K} \cdot C_{tlm} \cdot C_{plm} \cdot 3600 \quad [\mathrm{m^3/h}] \tag{3.2}$$

By writing the volume correction factors in Eqn. (3.2) directly in terms of their input quantities, correlation between these input quantities are avoided[20]. The model uncertainties of the volume correction factors must be included separately. However, there will be correlation's due to the common input quantities *T, P,* MR_m and the volume correction factors and the standard density that are applied both in the calculation of the *K-factor* and *Q*.

Later in Section 3.8 it will be shown that the uncertainty contribution from the density at standard conditions on the *K-factor* is very small (see Section 3.8), and may therefore in fact be neglected from the uncertainty calculation of the *K-factor*. Hence, with a negligible influence on the K-factor uncertainty, the contribution of the standard density to the covariance term will become even smaller and the standard density is therefore neither required to be included in the covariance term of the standard volume flow rate.

The functional relationship for the covariance term for the standard volume flow rate may then be expressed as:

---

[19] Previously, these volume correction factors were given in the NPD regulations [NPD, 1997], but have been left out in the regulations that entered into force January 1st, 2002 [NPD, 2001a]. In the new regulations it is rather in more general ways referred to "recognized standards", and NORSOK I-105 is one of the explicitly named "recognized standards".

[20] Eqn. (3.2) has not been written with all volume correction factors given in terms of input quantities, as this would become a rather large and complex expression. Computational aids should be used in order to avoid typing errors.

$$
\text{Covariance} = 2 \cdot \left\{
\begin{aligned}
& \frac{\partial \text{Q}}{\partial T_{m\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial T_{m\_proving}} \right) \cdot u(T_{m\_metering}) \cdot u(T_{m\_proving}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial P_{m\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial K - \text{Factor}}{\partial P_{m\_proving}} \right) \cdot u(P_{m\_metering}) \cdot u(P_{m\_proving}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial MR_{m}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial MR_{p}} \right) \cdot u(MR_{m}) \cdot u(MR_{p}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial C_{tlm\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{tlm\_proving}} \right) \cdot u(C_{tlm\_metering}) \cdot u(C_{tlm\_proving}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial C_{tlm\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{tlp}} \right) \cdot u(C_{tlm\_metering}) \cdot u(C_{tlp}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial C_{plm\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{plm\_proving}} \right) \cdot u(C_{plm\_metering}) \cdot u(C_{plm\_proving}) \cdot 1 \\
& + \frac{\partial \text{Q}}{\partial C_{plm\_metering}} \cdot \left(\frac{\partial \text{Q}}{\partial K - factor} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{plp}} \right) \cdot u(C_{plm\_metering}) \cdot u(C_{plp}) \cdot 1
\end{aligned}
\right\} \qquad (3.3)
$$

For further details, please refer to the example calculation in Section 3.9.

3.1.3.2 K-factor

In order to obtain a *K-Factor* referred to standard conditions, the physical volume of the Prover and the volume of the liquid in the Prover must be corrected to standard conditions. This is performed using the steel volume correction factors (Cf. Sections 3.5.3 and 3.5.4) and the liquid volume correction factors (Cf. Sections 3.5.1 and 3.5.2) for the Prover. The number of pulses counted by the Turbine meter also depends on the volume of the liquid passing through the Turbine meter. Hence, the liquid volume correction factors[21] obtained for the Turbine meter during the proving sequence must therefore also be applied in order to relate the number of counted pulses to standard conditions.

Furthermore, the volume correction factor used to correct for temperature effects on the liquid requires the liquid density at standard conditions. Hence, it is also required to convert the line density to density standard conditions, which is covered in Section 3.6.

The functional relationship for the *K-Factor* corrected to standard conditions is given as:

$$
\text{K} = \frac{MRp \cdot (C_{tsm} \cdot C_{psm}) \cdot (C_{tlm} \cdot C_{plm})}{BV \cdot (C_{tsp} \cdot C_{psp}) \cdot (C_{tlp} \cdot C_{plp})} \qquad (3.4)
$$

[21] Regarding the steel correction factors for the turbine meter Cf. Section 3.5.5.

where

K	*K-factor* relating the number of pulses to a given volume [pulses/m^3]
MRp	number of pulses counted during the proving period [pulses]
BV	base volume of Prover [m^3]
C_{tsp}	volume correction factor for the effect of temperature on Prover steel
C_{psp}	volume correction factor for the effect of pressure on Prover steel
C_{tsm}	volume correction factor for the effect of temperature on Turbine steel
C_{psm}	volume correction factor for the effect of pressure on Turbine steel
C_{tlp}	volume correction factor for the effect of temperature on the liquid in the Prover
C_{plp}	volume correction factor for the effect of pressure on the liquid in the Prover
C_{tlm}	volume correction factor for the effect of temperature on the liquid in the Turbine meter
C_{plm}	volume correction factor for the effect of pressure on the liquid in the Turbine meter

As discussed with regards to the functional relationship for the standard volume flow rate in Sections 3.1.3.1 and 3.5.5, the volume correction factors C_{tsm} and C_{psm} is not included in the calculations in this handbook. If the user decides to use them, their contributions to the combined uncertainty of the *K-factor* must be included in the calculations in the *EMU - Turbine Fiscal Oil Metering Station* program as a miscellaneous effect.

The functional relationship for the *K-factor* to be evaluated in this document then becomes:

$$\mathrm{K-Factor} = \frac{MRp \cdot \left(C_{tlm} \cdot C_{plm}\right)}{BV \cdot \left(C_{tsp} \cdot C_{psp}\right) \cdot \left(C_{tlp} \cdot C_{plp}\right)} \qquad (3.5)$$

Depending on the MR_p/BV value, the uncertainties of the volume correction factors will be subjected to rather large sensitivity coefficients when calculating the combined uncertainty of the *K-Factor*. However, the uncertainties become correlated since some of the volume correction factors are calculated from the same models (like e.g. C_{tlp} and C_{tlm}). In the example calculations presented in Section 3.8 it will be seen that these covariance terms to a large extent will cancel the uncertainties of the volume correction factors. Hence, the combined uncertainty decreases when the covariance terms are included.

One way to avoid most of the covariance terms due to correlation of the input quantities is to write all the volume correction factors in terms of input quantities in the functional relationship in Eqn. (3.4), hence expanding Eqn. (3.4)[22]. Then only the correlation of volume correction factor model uncertainties will remain, and an expression for the covariance term may be established for these correlated model uncertainties:

$$\text{Covariance} = 2 \cdot \left\{ \begin{aligned} & \frac{\partial \text{K} - \text{Factor}}{\partial C_{tlm}} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{tlp}} \cdot u(C_{tlm}) \cdot u(C_{tlp}) \cdot r(C_{tlm}, C_{tlp}) \\ & + \frac{\partial \text{K} - \text{Factor}}{\partial C_{plm}} \cdot \frac{\partial \text{K} - \text{Factor}}{\partial C_{plp}} \cdot u(C_{plm}) \cdot u(C_{plp}) \cdot r(C_{plm}, C_{plp}) \end{aligned} \right\} \tag{3.6}$$

The correlation coefficient $r(C_{tlm},C_{tlp})$ in Eqn. (3.6) indicates the covariance between the two volume correction factors and takes values between -1 and 1. It is a parameter that must be evaluated by means of engineering judgement, and since the models are equal and the values of the input quantities are almost equal in magnitude and uncertainty, $r(C_{tlm},C_{tlp})$ may be considered to unity for both the C_{plm} and C_{tlm} terms.

In addition to the uncertainties due to MR_p, *BV* and the volume correction factors, uncertainty due to linearity and repeatability of the turbine meter must be included in the combined uncertainty of the K-factor. The NPD regulations [NPD, 2001a] set definite requirements to the repeatability and linearity of the turbine meter measurements.

Repeatability is defined in the *VIM* [ISO, 1993] as "the precision under repeatability conditions", and repeatability conditions are "where independent test results are obtained with the same method on identical test items in the same laboratory by the same operator using the same equipment within short intervals of time". The NPD regulations [NPD, 2001a] (§8) requires that the repeatability of the turbine meter shall be less than 0.04% (band) in the working range (10:1) during Factory Acceptance Tests (FAT). When calibrated with a prover, 5 consequent single calibrations shall be within a band of 0.05 % of average calibration factor (§25). See the NPD regulations [NPD, 2001a] for more details.

Linearity is defined by NPD [2001a] as "the deviation between a calibration curve for a device and a straight line". The NPD regulation requires that the linearity of turbine meters shall not exceed 0.50% in the working range (10:1), and in the reduced

[22] Eqn. (3.1) has not been written with all volume correction factors given in terms of input quantities, as this would become a rather large and complex expression. Computational aids should be used in order to avoid typing errors.

working range (5:1) where the turbine will be mainly operated, the linearity error shall not exceed 0.25%.

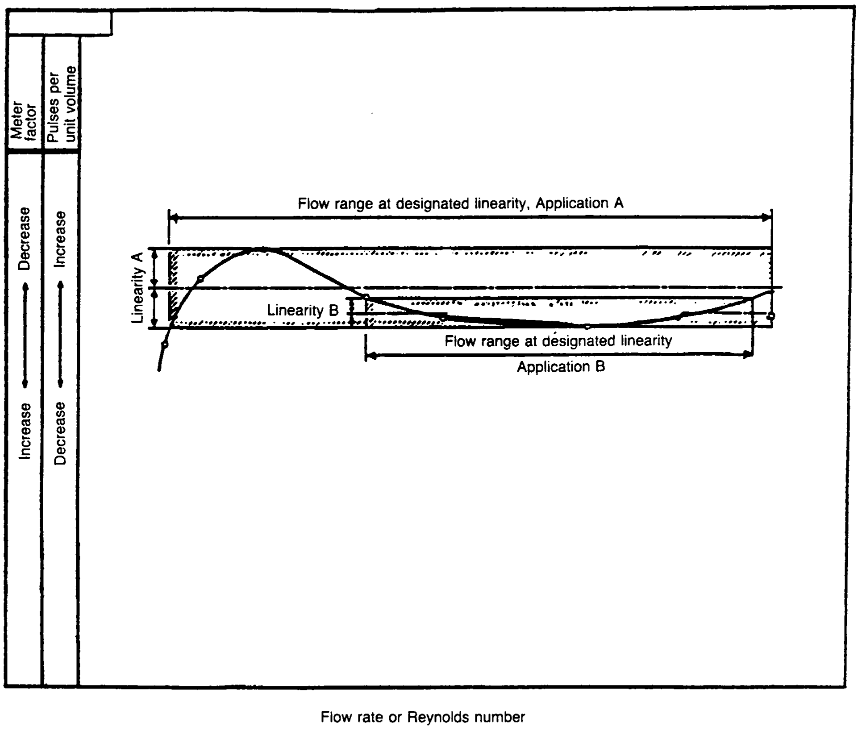

Figure 3.2 *Linearity of the* K-factor. *The term linearity regarding turbine meters and* K-Factors *are defined in API MPMS Chapter 5 [API, 1987].*

Figure 3.2 shows how to calculate the linearity of the *K-Factor*. A straight line is placed at the average of all the *K-Factors*, and the deviation from this straight line is calculated for each test point to find the deviation from the straight line. The largest deviation of the test points then becomes the uncertainty due to linearity.

The uncertainties due to the repeatability and the linearity are given as relative expanded uncertainties referred to the average *K-Factor*. These expanded uncertainties must therefore be converted to standard uncertainties before they are applied in the uncertainty calculations. This means that the (average) *K-Factor* must be known prior to the uncertainty evaluation. To convert these relative expanded uncertainties to standard uncertainties, normal distributions with 95% confidence level shall be used.

The sensitivity coefficients for the *K-factor* are derived by partial differentiating the expression in Eqn. (3.4) with respect to the individual input quantities. If as suggested here the correction factors are written directly in terms of input quantities to avoid covariance terms, this will cause the calculation of the sensitivity coefficients of the input quantities of Eqn. (3.4) to become rather large. The partial differentiations must therefore be accomplished using computational aids. This approach has been selected by CMR in this handbook, and also forms the basis of the calculations implemented in the *EMU - Turbine fiscal oil metering station* program (see Chapter 4).

More details regarding the volume correction factors, C_{iii}, are given in Section 3.5, while example uncertainty calculations of the uncertainty due to the flow calibration (Proving to determine the *K-factor*) and the combined expanded uncertainty in standard volume flow rate is covered in Sections 3.8 and 3.9, respectively.

3.2 Line temperature measurement

As described in Section 1.4, the uncertainty of the temperature transmitter can in the program *EMU - Turbine Fiscal Oil Metering Station* be specified at two levels (cf. also Chapter 4):

(1) ***"Overall level":*** The user gives $u_c(\hat{T})$ directly as input to the program. It is left to the user to calculate and document $u_c(\hat{T})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the liquid temperature measurement.

(2) ***"Detailed level":*** $u_c(\hat{T})$ is calculated in the program from more basic input uncertainties for the temperature element / transmitter provided by the instrument manufacturer and calibration laboratory

The following discussion concerns the "Detailed level". As for the pressure measurement, it has been found convenient to base the user input to the program on the type of data that are typically specified for common temperature transmitters used in North Sea fiscal metering stations.

The temperature loop considered here consists of a Pt 100 or 4-wire RTD element and a smart temperature transmitter, installed either as two separate devices, or as one unit [NORSOK, 1998a; §5.2.3.5]. The Pt 100 temperature element is required as a minimum to be in accordance with EN 60751 tolerance A [EN, 1995]. By [NORSOK, 1998a; §5.2.3.5], the temperature transmitter and the Pt 100 element shall be calibrated as one system. A 3-wire temperature element may be used if the temperature element and transmitter are installed as one unit, where the Pt 100 element is screwed directly into the transmitter.

The signal is transferred from the temperature transmitter using a HART protocol, i.e. the “digital accuracy” is used.

The temperature transmitter chosen by NFOGM, NPD and CMR to be used in the present *Handbook* for the example uncertainty evaluation of Chapter 4 is the Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2001], cf. Table 3.2 and Figure 3.3. The Rosemount 3144 transmitter is widely used in the North Sea when upgrading existing fiscal oil metering stations and when designing new metering stations. This transmitter is also chosen for the layout of the temperature transmitter user input to the program *EMU - Turbine Fiscal Oil Metering Station*.

Figure 3.3 The Rosemount 3244 Temperature Transmitter (example). © 2000 Rosemount Inc. Used by permission [Rosemount, 2002b].

Figure 3.3 shows a typical temperature transmitter with an integrated Pt-100 temperature element. However, the temperature transmitter is often installed remote from the Pt-100 temperature element with a 4-wire cable between the transmitter and the element.

The measurement principle and functional relationship of RTDs is described e.g. in [ISO/CD 15970, 1999]. However, as the element/transmitter is calibrated and given a specific “accuracy” in the calibration data sheet, no functional relationship is actually used here for calculation of the uncertainty of the temperature measurements. The functional relationship is only internal to the temperature element/transmitter, and the uncertainty due to the functional relationship is included in the calibrated “accuracy” of the element/transmitter.

3.2.1 Functional relationship

The combined standard uncertainty of the temperature measurement, $u_c(\hat{T})$, can be given as input to the program *EMU - Turbine Fiscal Oil Metering Station* at two levels: “Overall level” and “Detailed level”, cf. Section 1.4.

As the “Overall level” is straightforward, only the “Detailed level” is discussed in the following. The uncertainty model for the temperature element/transmitter is quite general, and applies to e.g. the Rosemount 3144 Temperature Transmitter used with a Pt 100 element, and similar transmitters.

At the “Detailed level”, $u_c(\hat{T})$ may be given as[23]

$$\begin{aligned} u_c^2(\hat{T}) = {} & u^2(\hat{T}_{elem,transm}) + u^2(\hat{T}_{stab,transm}) + u^2(\hat{T}_{RFI}) + u^2(\hat{T}_{temp}) + u^2(\hat{T}_{stab,elem}) \\ & + u^2(\hat{T}_{vinbration}) + u^2(\hat{T}_{power}) + u^2(\hat{T}_{cable}) + u^2(\hat{T}_{misc}) \end{aligned} \tag{3.7}$$

where [Rosemount, 2001]:

$u(\hat{T}_{elem,transm}) \equiv$ standard uncertainty of the temperature element and temperature transmitter, calibrated as a unit.

$u(\hat{T}_{stab,transm}) \equiv$ standard uncertainty of the stability of the temperature transmitter, with respect to drift in the readings over time.

$u(\hat{T}_{RFI}) \equiv$ standard uncertainty due to radio-frequency interference (RFI) effects on the temperature transmitter.

$u(\hat{T}_{temp}) \equiv$ standard uncertainty of the effect of temperature on the temperature transmitter, for change of gas temperature relative to the temperature at calibration.

$u(\hat{T}_{stab,elem}) \equiv$ standard uncertainty of the stability of the Pt 100 4-wire RTD temperature element. Instability may relate e.g. to drift during operation, as well as instability and hysteresis effects due to oxidation and moisture inside the encapsulation, and mechanical stress during operation.

---

23 In accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001], the sensitivity coefficients have been assumed to be equal to 1 throughout Eqn. (3.12). Note that this is a simplified approach. An alternative and more correct approach would have been to start from the full functional relationship of the temperature measurement, and derive the uncertainty model according to the recommendations of the *GUM* [ISO, 1995a].

$u(\hat{T}_{vibration}) \equiv$ standard uncertainty due to vibration effects on the temperature transmitter.

$u(\hat{T}_{power}) \equiv$ standard uncertainty due to power supply effects on the temperature transmitter.

$u(\hat{T}_{cable}) \equiv$ standard uncertainty of lead resistance effects on the temperature transmitter.

$u(\hat{T}_{misc}) \equiv$ standard uncertainty of other (miscellaneous) effects on the temperature transmitter.

$u_c(\hat{T})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{T}_{elem,transm})$, $u(\hat{T}_{stab,transm})$, $u(\hat{T}_{RFI})$, $u(\hat{T}_{temp})$, $u(\hat{T}_{stab,elem})$, $u(\hat{T}_{vibration})$, $u(\hat{T}_{power})$ and $u(\hat{T}_{cable})$, and document their traceability.

As an example, the uncertainty of the Rosemount 3144 temperature transmitter used with a Pt 100 element is evaluated in Section 3.2.2.

3.2.2 Example uncertainty evaluation

The combined standard uncertainty of the temperature measurement, $u_c(\hat{T})$, is given by Eqn. (3.7). This expression is evaluated in the following.

Performance specifications for the Rosemount Model 3144 Smart Temperature Transmitter and the Pt 100 4-wire RTD element are given in Table 3.4[24], as specified in the data sheet [Rosemount, 2001], etc.

The contributions to the combined standard uncertainty of the temperature measurement are described in the following.

24 Note that the expanded uncertainties given in the transmitter data sheet [Rosemount, 2001] are specified at a 99 % confidence level (k = 3).

Table 3.4 Performance specifications of the Rosemount Model 3144 Temperature Transmitter [Rosemount, 2001] and the Pt 100 4-wire RTD element, used as input to the uncertainty calculations given in Table 3.5.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, *k***	**Reference**
Calibration ambient temperature (air)	20 °C	-	Calibration certificate *(NA)*
Time between calibrations	12 months	-	Example
Transmitter/element uncertainty (not calibrated as a unit), $U(\hat{T}_{elem,transm})$	"Digital accuracy": 0.10 °C "D/A accuracy": ±0.02 % of span.	3 3	[Rosemount, 2001]
Transmitter/element uncertainty (calibrated as a unit), $U(\hat{T}_{elem,transm})$	*NA*	*NA*	Calibration certificate *(NA)*
Stability - temperature transmitter, $U(\hat{T}_{stab,transm})$	0.1 % of reading or 0.1 °C, whichever is greater, for 24 months.	3	[Rosemount, 2001]
RFI effects - transmitter, $U(\hat{T}_{RFI})$	Worst case, with unshielded cable: equivalent to the transmitter "accuracy".	3	[Rosemount, 2001]
Ambient temperature effects - transmitter, $U(\hat{T}_{temp})$	"Digital accuracy": 0.0015 °C per 1 °C. D/A effect: 0.001 % of span, per 1 °C.	3 3	[Rosemount, 2001]
Stability - temperature element, $U(\hat{T}_{stab,elem})$	0.050 °C	-	[BIPM, 1997]
Vibration effects, $U(\hat{T}_{vibration})$	*Negligible* (tested to given specifications with no effect on performance).	3	[Rosemount, 2001]
Power supply effects, $U(\hat{T}_{power})$	*Negligible* (less than ±0.005 % of span per volt).	3	[Rosemount, 2001]
Lead resistance effects, $U(\hat{T}_{cable})$	*Negligible* (no effect, independent on lead resistance).	3	[Rosemount, 1998]

1. ***Transmitter/element uncertainty (calibrated as a unit),*** $U(\hat{T}_{elem,transm})$***:*** The temperature element and the temperature transmitter are calibrated as a unit [NORSOK, 1998a].

   If the expanded uncertainty specified in the calibration certificate is used for the uncertainty evaluation, the transmitter/element uncertainty (calibrated as a unit) will include the uncertainty of the temperature calibration laboratory (to be traceable to international standards). The confidence level of the reported expanded uncertainty is to be specified. When first recording the characteristics of the temperature element and then loading this characteristic into the transmitter prior to the final calibration, the uncertainty due to the element can be minimised [Fimas, 1999].

Alternatively, if the calibration laboratory states that the transmitter/element uncertainty (calibrated as a unit, and including the calibration laboratory uncertainty) is within the "accuracy" given in the manufacturer data sheet [Rosemount, 2001], one may - as a conservative approach - use the latter uncertainty value in the calculations. This approach is used here.

The "accuracy" of the 3144 temperature transmitter used together with a Pt 100 4-wire RTD element is tabulated in the data sheet [Rosemount, 2001, Table 2]. The output signal is accessed using a HART protocol, i.e. only the "digital accuracy" is used here (cf. Table 3.4). The expanded uncertainty is then given as 0.10 °C at a 99 % confidence level (k = 3, cf. Section B.3). That is, $u(\hat{T}_{elem,transm}) = U(\hat{T}_{elem,transm})/3 = 0.10\ ^oC/3 = 0.033\ ^oC$ [25].

2. ***Stability - temperature transmitter,*** $u(\hat{T}_{stab,transm})$***:*** The stability of the temperature transmitter represents a drift in the readings with time. This contribution is zero at the time of calibration, and is specified as a maximum value at a given time.

   For use in combination with RTD elements, the stability of the 3144 temperature transmitter is given in the manufacturer data sheet [Rosemount, 2001] as 0.1 % of reading (measured value), or 0.1 °C, whichever is greater for 24 months, cf. Table 3.4. The time dependency is not necessarily linear. However, for simplicity, a linear time dependency is assumed here[26].

   The value "0.1 % of reading for 24 months" corresponds to $[(273+65)\cdot 0.001]\ ^oC \approx 0.338\ ^oC$. As this is greater than 0.1 °C, this uncertainty value is used. Consequently, if the transmitter is calibrated every 12 months, the uncertainty given in the data sheet due to stability effects is divided by 24 and multiplied with 12. That is, $u(\hat{T}_{stab,transm}) = U(\hat{T}_{stab,transm})/3$ $= [(273+65)\cdot 0.001\cdot(12/24)]\ ^oC/3 = 0.1690\ ^oC/3 \approx 0.056\ ^oC$.

---

25 The manufacturer's uncertainty specification is used here, for temperature element and transmitter combined. By calibration of the element and transmitter in an accredited calibration laboratory, the element/transmitter uncertainty may be significantly reduced. As an example, the calibration certificate specification for the element/transmitter's expanded uncertainty $U(\hat{T}_{elem,transm})$ may be 0.03 °C, at a 95 % confidence level (k = 2) [Eide, 2001a], corresponding to 0.015 °C for the standard uncertainty.

26 In a worst case scenario, the uncertainty due to stability may be used directly without using the time division specified.

3. ***RFI effects - temperature transmitter,*** $u(\hat{T}_{RFI})$***:*** Radio-frequency interference, effects (RFI) may cause a worst case uncertainty equivalent to the transmitter's nominal uncertainty, when used with an unshielded cable [Rosemount, 2001]. For fiscal metering stations all cables are shielded, i.e. the RFI effects should be less than the worst case specified in the data sheet. Nevertheless, RFI effects (and also effects due to bad instrument earth) may cause additional uncertainty to the temperature measurement that is hard to quantify.

   It is time consuming to predict or measure the actual RFI effects at the metering station, and difficult to evaluate correctly the influence on the temperature measurement.

   It is therefore recommended to use the worst case uncertainty specified in the data sheet for the uncertainty due to RFI effects. For the "digital acuracy" of the 3144 transmitter, the expanded uncertainty is specified to be 0.10 ^oC, cf. Table 3.4. That is, $u(\hat{T}_{RFI}) = U(\hat{T}_{RFI})/3 = 0.10\ ^oC/3 = 0.033\ ^oC$.

4. ***Ambient temperature effects - temperature transmitter,*** $u(\hat{T}_{temp})$***:*** The Rosemount 3144 temperature transmitters are individually characterised for the ambient temperature range -40 °C to 85 °C , and automatically compensate for change in ambient temperature [Rosemount, 2001].

   Some uncertainty still arises due to the change in ambient temperature. This uncertainty is tabulated in the data sheet as a function of changes in the ambient temperature (in operation) from the ambient temperature when the transmitter was calibrated, cf. Table 3.4

   The ambient temperature uncertainty for Rosemount 3144 temperature transmitters used together with Pt-100 4-wire RTDs is given in the data sheet as 0.0015 °C per 1 °C change in ambient temperature relative to the calibration ambient temperature (the "digital accuracy").

   Consequently, for a possible "worst case" ambient North Sea temperature taken as 0 ^oC, and a calibration temperature equal to 20 ^oC, i.e. a max. temperature change of 20 ^oC, one obtains $u(\hat{T}_{temp}) = U(\hat{T}_{temp})/3$
   $= 0.0015 \cdot 20\ ^oC/3 = 0.03\ ^oC/3 = 0.01\ ^oC$.

5. ***Stability - temperature element,*** $u(\hat{T}_{stab,elem})$***:*** The Pt-100 4-wire RTD element will cause uncertainty to the temperature measurement due to drift during

operation. Oxidation, moisture inside the encapsulation and mechanical stress during operation may cause instability and hysteresis effects [EN 60751, 1995], [BIPM, 1997].

BIPM [BIPM, 1997] has performed several tests of the stability of temperature elements which shows that this uncertainty is typically of the order of 0.050 °C, cf. Table 3.4. The confidence level of this expanded uncertainty is not given, however, and a 95 % confidence level and a normal probability distribution is assumed here (k = 2, cf. Section 2.3). That is, $u(\hat{T}_{stab,elem}) = U(\hat{T}_{stab,elem})/2$ = 0.050 ^{o}C / 2 = 0.025 ^{o}C.

6. ***Vibration effects - temperature transmitter,*** $u(\hat{T}_{vibration})$***:*** According to the manufacturer data sheet [Rosemount, 2001], "transmitters are tested to the following specifications with no effect on performance: 0.21 mm peak displacement for 10-60 Hz; 3*g* acceleration for 60-2000 Hz". Moreover, in communication with the manufacturer [Rosemount, 1999] and a calibration laboratory [Fimas, 1999], and considering that the vibration level at fiscal metering stations shall be very low (and according to recognised standards), the uncertainty due to vibration effects may be neglected.

   Hence, in the program *EMU - Turbine Fiscal Oil Metering Station*, the uncertainty due to vibration effects is neglected for the Rosemount 3144 temperature transmitter, $u(\hat{T}_{vibration}) = 0$.

7. ***Power supply effects - temperature transmitter,*** $u(\hat{T}_{power})$***:*** The power supply effect is quantified in the manufacturer data sheet [Rosemount, 2001] as being less than 0.005 % of span per volt. According to the supplier [Rosemount, 1999] this uncertainty is specified to indicate that the uncertainty due to power supply effects is negligible for the 3144 transmitter, which was not always the case for the older transmitters [Dahl *et al.*, 1999].

   Hence, in the program *EMU - Turbine Fiscal Oil Metering Station*, the uncertainty due to power supply effects is neglected for the Rosemount 3144 temperature transmitter, $u(\hat{T}_{power}) = 0$.

8. ***Sensor lead resistance effects - temperature transmitter,*** $u(\hat{T}_{cable})$***:*** According to the manufacturer data sheet for the 3144 transmitter [Rosemount, 1998], the error due to lead resistance effects is "none" (independent of lead resistance) for 4-wire RTDs. 4-wire RTDs are normally used in fiscal metering stations.

Hence, in the program *EMU - Turbine Fiscal Oil Metering Station*, the uncertainty due to lead resistance effects is neglected for the 3144 transmitter: $u(\hat{T}_{cable}) = 0$.

A sample uncertainty budget is given in Table 4.8 for evaluation of the expanded uncertainty of the temperature measurement according to Eqn. (3.12). The figures used for the input uncertainties are those given in the discussion above.

Table 3.5 Sample uncertainty budget for the temperature measurement using the Rosemount Model 3144 Temperature Transmitter [Rosemount, 2000] with a Pt 100 4-wire RTD element, calculated according to Eqn. (3.7).

Source	Input uncertainty				Combined uncertainty	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Transmitter/element uncertainty	0.10 ^{o}C	99 % (norm)	3	0.0333 ^{o}C	1	$1.11\cdot10^{-3}$ ^{o}C^2
Stability, transmitter	0.169 ^{o}C	99 % (norm)	3	0.0564 ^{o}C	1	$3.18\cdot10^{-3}$ ^{o}C^2
RFI effects	0.10 ^{o}C	99 % (norm)	3	0.0333 ^{o}C	1	$1.11\cdot10^{-3}$ ^{o}C^2
Ambient temperature effects, transmitter	0.030 ^{o}C	99 % (norm)	3	0.010 ^{o}C	1	$1.00\cdot10^{-4}$ ^{o}C^2
Stability, element	0.050 ^{o}C	95 % (norm)	2	0.025 ^{o}C	1	$6.25\cdot10^{-4}$ ^{o}C^2
Sum of variances				$u_c^2(\hat{T})$		$6.12\cdot10^{-3}$ ^{o}C^2
Combined standard uncertainty				$u_c(\hat{T})$		0.0783 ^{o}C
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{T})$		**0.1565 ^{o}C**
Operating temperature				$\hat{T}$		65 ^{o}C (≈338 K)
Relative expanded uncertainty (95 % confidence level)				$U(\hat{T})/\hat{T}$		**0.0463 %**

It is seen from Table 3.5 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with $k = 2$, cf. Section 2.3) are 0.16 ^{o}C and 0.05 %, respectively. Hence, the uncertainty of the temperature measurement is within the NPD requirement [NPD, 2001a] of an expanded uncertainty of 0.30 °C (see Table 3.1).

3.3 Line pressure measurement (static, gauge)

As described in Section 1.4, the uncertainty of the gauge pressure transmitter can in the program *EMU - Turbine Fiscal Oil Metering Station* be specified at two levels (cf. also Chapter 5):

(1) ***"Overall level":*** The user gives $u_c(\hat{P})$ directly as input to the program. It is left to the user to calculate and document $u_c(\hat{P})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the pressure measurement.

(2) ***"Detailed level":*** $u_c(\hat{P})$ is calculated in the program, from more basic input uncertainties for the pressure transmitter, provided by the instrument manufacturer and calibration laboratory.

The following discussion concerns the "Detailed level". It has been found convenient to base the user input to the program on the type of data which are typically specified for common pressure transmitters used in North Sea fiscal metering stations.

The example pressure transmitter chosen by NFOGM, NPD and CMR to be used in the present *Handbook* for the uncertainty evaluation example of Chapter 4 is the Rosemount 3051P Reference Class Pressure Transmitter [Rosemount, 2002a], cf. Table 2.4 and Figure 3.4. This transmitter is also chosen for the layout of the pressure transmitter user input to the program *EMU - Turbine Fiscal Oil Metering Station*. The Rosemount 3051P is a widely used pressure transmitter when upgrading existing North Sea fiscal gas metering stations and when designing new metering stations. The pressure transmitter output is normally the overpressure (gauge pressure), i.e. the pressure relative to the atmospheric pressure [barg].

Figure 3.4 The Rosemount 3051S Reference Class Pressure Transmitter (example). © 2000 Rosemount Inc. Used by permission [Rosemount, 2002b].

Measurement principles of gauge pressure sensors and transmitters are described e.g. in [ISO/CD 15970, 1999]. However, as the transmitter is calibrated and given a specific "accuracy" in the calibration data sheet, no functional relationship is actually used here for calculation of the uncertainty of the pressure measurements. The functional relationship is only internal to the pressure transmitter, and the uncertainty due to the functional relationship is included in the calibrated "accuracy" of the transmitter.

3.3.1 Functional relationship

As the "Overall level" is straightforward, only the "Detailed level" is discussed in the following. The uncertainty model for the pressure transmitter is quite general, and applies to e.g. the Rosemount 3051P Pressure Transmitter, and similar transmitters.

At the "Detailed level", $u_c(\hat{P})$ may be given as[27]

$$\begin{aligned} u_c^2(\hat{P}) = {} & u^2(\hat{P}_{transmitter}) + u^2(\hat{P}_{stability}) + u^2(\hat{P}_{RFI}) + u^2(\hat{P}_{temp}) \\ & + u^2(\hat{P}_{atm}) + u^2(\hat{P}_{vibration}) + u^2(\hat{P}_{power}) + u^2(\hat{P}_{misc}) \end{aligned} \tag{3.8}$$

---

27 Here, the sensitivity coefficients have been assumed to be equal to 1 throughout Eqn. (3.11), as a simplified approach, and in accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001]. An alternative and more correct approach would have been to start from the functional relationship of the pressure measurement, and derive the uncertainty model according to the recommendations of the *GUM* [ISO, 1995a].

where [Rosemount, 2002a]:

$u(\hat{P}_{transmitter}) \equiv$ standard uncertainty of the pressure transmitter, including hysteresis, terminal-based linearity, repeatability and the standard uncertainty of the pressure calibration laboratory.

$u(\hat{P}_{stability}) \equiv$ standard uncertainty of the stability of the pressure transmitter, with respect to drift in readings over time.

$u(\hat{P}_{RFI}) \equiv$ standard uncertainty due to radio-frequency interference (RFI) effects on the pressure transmitter.

$u(\hat{P}_{temp}) \equiv$ standard uncertainty of the effect of ambient gas temperature on the pressure transmitter, for change of ambient temperature relative to the temperature at calibration.

$u(\hat{P}_{atm}) \equiv$ standard uncertainty of the atmospheric pressure, relative to 1 atm. ≡ 1.01325 bar, due to local meteorological effects.

$u(\hat{P}_{vibration}) \equiv$ standard uncertainty due to vibration effects on the pressure measurement.

$u(\hat{P}_{power}) \equiv$ standard uncertainty due to power supply effects on the pressure transmitter.

$u(\hat{P}_{misc}) \equiv$ standard uncertainty due to other (miscellaneous) effects on the pressure transmitter, such as mounting effects, etc.

$u(\hat{P})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{P}_{transmitter})$, $u(\hat{P}_{stability})$, $u(\hat{P}_{temp})$, $u(\hat{P}_{RFI})$, $u(\hat{P}_{vibration})$ and $u(\hat{P}_{power})$, and document their traceability.

As an example, the uncertainty of the Rosemount 3051P pressure transmitter is evaluated in Section 3.3.2.

3.3.2 Example uncertainty evaluation

The combined standard uncertainty of the gauge pressure measurement, $u_c(\hat{P})$, is given by Eqn. (3.8). This expression is evaluated in the following.

Performance specifications for the Rosemount Model 3051P Reference Class Pressure Transmitter are given in Table 3.6[28], as specified in the data sheet [Rosemount, 2002a], etc.

The contributions to the combined standard uncertainty of the pressure measurement are described in the following.

Table 3.6 Performance specifications of the Rosemount Model 3051P Reference Class Pressure Transmitter [Rosemount, 2002a], used as input to the uncertainty calculations in Table 3.7.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, k**	**Reference**
Calibration ambient temperature (air)	20 °C	-	Calibration certificate, (NA)
Time between calibrations	12 months	-	Example
Span (calibrated)	20 bar	-	Calibration certificate, (NA)
URL (upper range limit)	20.6 barg	-	[Rosemount, 2002a]
Transmitter uncertainty, $U(\hat{P}_{transmitter})$	0.05 % of span	3	[Rosemount, 2002a]
Stability, $U(\hat{P}_{stability})$	0.125 % of URL for 5 years for 28 °C temperature changes	3	[Rosemount, 2002a]
RFI effects, $U(\hat{P}_{RFI})$	0.1 % of span from 20 to 1000 MHz and for field strength up to 30 V/m.	3	[Rosemount, 2002a]
Ambient temperature effects (air), $U(\hat{P}_{temp})$	(0.006% URL + 0.03% span) per 28°C	3	[Rosemount, 2002a]
Vibration effects, $U(\hat{P}_{vibration})$	Negligible (except at resonance frequencies, see text below).	3	[Rosemount, 2002a]
Power supply effects, $U(\hat{P}_{power})$	Negligible (less than ±0.005 % of calibrated span per volt).	3	[Rosemount, 2002a]
Mounting position effect	Negligible (influence only on differential pressure measurement, not static pressure measurement)	3	[Dahl et al., 1999]
Static pressure effect	Negligible (influence only on differential pressure measurement, not static pressure measurement)	3	[Dahl et al., 1999]

28 Note that the expanded uncertainties given in the transmitter data sheet [Rosemount, 2002a] are specified at a 99 % confidence level (k = 3).

1. ***Pressure transmitter uncertainty,*** $U(\hat{P}_{transmitter})$**:** If the expanded uncertainty specified in the calibration certificate is used for the uncertainty evaluation, the transmitter uncertainty is to include the uncertainty of the temperature calibration laboratory (which shall be traceable to international standards). The confidence level and the probability distribution of the reported expanded uncertainty shall be specified.

   Alternatively, if the calibration laboratory states that the transmitter uncertainty (including the calibration laboratory uncertainty) is within the "reference accuracy" given in the manufacturer data sheet [Rosemount, 2002a], one may - as a conservative approach - use the latter uncertainty value in the calculations. This approach is used here.

   The "reference accuracy" of the 3051P pressure transmitter accounts for hysteresis, terminal-based linearity and repeatability, and is given in the manufacturer data sheet as 0.05 % of span at a 99 % confidence level (cf. Table 3.6), i.e. with k = 3 (Section 2.3). It is assumed here that this figure refers to the calibrated span. As an example, the calibrated span is here taken to be 20.6 - 0.6 barg, i.e. 20 bar (Table 3.6), giving $u(\hat{P}_{transmitter})$ = $U(\hat{P}_{transmitter})/3$ = $[20\cdot 0.0005]bar/3$ = $[20\cdot 0.0005]bar/3 = 0.01bar/3 = 0.0033bar$ [29].

2. ***Stability - pressure transmitter,*** $u(\hat{P}_{stability})$**:** The stability of the pressure transmitter represents a drift (increasing/decreasing offset) in the readings with time. This contribution is zero at the time of calibration, and is specified as a maximum value at a given time.

   The stability of the 3051P pressure transmitter is given in the manufacturer data sheet [Rosemount, 2002a] as 0.125 % of URL for 5 years for maximum 28 °C temperature changes (Table 3.6).

   The time dependency of the stability uncertainty is not necessarily linear. However, for simplicity, a linear time dependency has been assumed here[30].

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29 The manufacturer's uncertainty specification is used here. By calibration of the pressure transmitter in an accredited calibration laboratory, the transmitter uncertainty may be further reduced. An example of a calibration certificate specification for the expanded uncertainty $U(\hat{P}_{transmitter})$ may be in the range 0.018-0.022 bar, at a 95 % confidence level (k = 2) [Eide, 2001a], i.e. 0.009-0.011 bar for the standard uncertainty. This includes linearity, hysteresis, repeatability, reading uncertainty, and reference instruments uncertainty.

30 In a worst case scenario, the uncertainty due to stability may be used directly without using the time division specified.

The confidence level is specified to be 99 % with a normal probability distribution (k = 2, cf. Section 2.3). Consequently, if the transmitter is calibrated every 12 months, the uncertainty due to stability effects becomes, $u(\hat{P}_{stability}) = U(\hat{P}_{stability})/3 = [20.6 \cdot 0.00125 \cdot (1/5)]bar/3$ ≈ 0.00515 bar / 3 ≈ 0.0017 bar.

3. ***RFI effects - pressure transmitter,*** $u(\hat{P}_{RFI})$***:*** Radio-frequency interference, effects (RFI) is given in the manufacturer data sheet [Rosemount, 2002a] as 0.1 % of span for frequencies from 20 to 1000 MHz, and for field strength up to 30 V/m, cf. Table 3.6.

It is noted that the specified RFI uncertainty is actually twice as large as the uncertainty of the transmitter itself. In practice, this uncertainty contribution may be difficult to evaluate, and the RFI electric field at the actual metering station should be measured in order to document the actual electric field at the pressure transmitter. I.e. the RFI electric field must be documented in order to evaluate if, and to what extent, the uncertainty due to RFI effects may be reduced.

However, as long as the RFI electric field at the pressure transmitter is not documented by measurement, the uncertainty due to RFI effects must be included in the uncertainty evaluation as given in the data sheet. Consequently, $u(\hat{P}_{RFI}) = U(\hat{P}_{RFI})/3 = [20 \cdot 0.001]bar/3 = 0.02\,bar/3 = 0.0067\,bar$.

4. ***Ambient temperature effects - pressure transmitter,*** $u(\hat{P}_{temp})$***:*** The ambient temperature effect on the Rosemount 3051P pressure transmitter is given in the manufacturer data sheet [Rosemount, 2002a] as (0.006 % URL + 0.03 % span) per 28 °C temperature change, cf. Table 3.6. The temperature change referred to is the change in ambient temperature relative to the ambient temperature at calibration (to be specified in the calibration certificate).

Consequently, for a possible "worst case" example of ambient North Sea temperature taken as 0 °C (Table 3.3), and a calibration temperature equal to 20 °C (Table 3.6), i.e. a max. temperature change of 20 °C, one obtains $u(\hat{P}_{temp}) = U(\hat{P}_{temp})/3 = [(20.6 \cdot 0.006 + 20 \cdot 0.03) \cdot 10^{-2} \cdot (20/28)]bar/3$
$\approx 0.0017\,bar$.

5. ***Atmospheric pressure,*** $u(\hat{P}_{atm})$***:*** The Rosemount 3051P pressure transmitter is here used for gauge pressure measurements, where it measures the excess pressure relative to the atmospheric pressure. Uncertainty due to atmospheric pressure variations is therefore not of relevance here. I.e. $u(\hat{P}_{atm}) = 0$.

   For absolute pressure measurements, an additional uncertainty needs to be included due to day-by-day atmospheric pressure variations, see Section 5.3.2 for a discussion.

6. ***Vibration effects - pressure transmitter,*** $u(\hat{P}_{vibration})$***:*** According to the manufacturer data sheet [Rosemount, 2002a], "measurement effect due to vibrations is negligible except at resonance frequencies. When at resonance frequencies, vibration effect is less than 0.1 % of URL per *g* when tested from 15 to 2000 Hz in any axis relative to pipe-mounted process conditions" (Table 3.6). Based on communication with the manufacturer [Rosemount, 1999] and a calibration laboratory [Fimas, 1999], the vibration level at fiscal metering stations is considered to be very low (and according to recognised standards). Hence, the uncertainty due to vibration effects may be neglected.

   In the program *EMU - Turbine Fiscal Oil Metering Station*, the uncertainty due to vibration effects is neglected for the 3051P transmitter: $u(\hat{P}_{vibration}) = 0$.

7. ***Power supply effects - pressure transmitter,*** $u(\hat{P}_{power})$***:*** The power supply effect is quantified in the manufacturer data sheet [Rosemount, 2002a] as less than ±0.005 % of the calibrated span per volt (Table 3.6). According to the supplier [Rosemount, 1999] this uncertainty is specified to indicate that the uncertainty due to power supply effects is negligible for the 3051P transmitter, which was not always the case for the older transmitters [Dahl *et al.*, 1999].

   Hence, in the program, the uncertainty due to power supply effects is neglected for the 3051P transmitter: $u(\hat{P}_{power}) = 0$.

8. ***Static pressure effect - pressure transmitter:*** The static pressure effect [Rosemount, 2002a] will only influence on a differential pressure transmitter, and not on static pressure measurements while the static pressure transmitter actually measure this static pressure [Dahl *et al.*, 1999][31].

   a) *Zero effect*

      The zero effect is given in the data sheet as 0.05% of *URL* per 69 barg (1,000 psi). However, the zero pressure effect is easily removed by a zero calibration, and may therefore be neglected for both the static and the differential pressure transmitter.

   b) *Span effect*

      The *Span* effect is given in the data sheet as 0.10% of reading per 69 barg (1,000 psi) and applies only to the differential pressure transmitter. I.e., this uncertainty must be included in the uncertainty evaluation of the 3051P differential pressure transmitter.

9. ***Mounting position effects - pressure transmitter:*** The mounting position effect [Rosemount, 2002a] will only influence on a differential pressure transmitter, and not on static pressure measurements, as considered here [Dahl *et al.*, 1999][32].

A sample uncertainty budget is given in Table 3.7 for evaluation of the expanded uncertainty of the pressure measurement according to Eqn. (3.8). The figures used for the input uncertainties are those given in the discussion above.

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31 The static pressure effect influencing on 3051P differential pressure transmitters consists of (a) the *zero error*, and (b) the *span error* [Rosemount, 2002a]. The zero error is given in the data sheet [Rosemount, 2002a] as ±0.04 % of URL per 69 barg. The zero error can be calibrated out at line pressure. The span error is given in the data sheet [Rosemount, 2002a] as ±0.10 % of reading per 69 barg.

32 Mounting position effects are due to the construction of the 3051P differential pressure transmitter with oil filled chambers [Dahl *et al.*, 1999]. These may influence the measurement if the transmitter is not properly mounted. The mounting position error is specified in the data sheet [Rosemount, 2002a] as “zero shifts up to ±1.25 inH_2O (0.31 kPa = 0.0031 bar), which can be calibrated out. No span effect”.

Table 3.7 Sample uncertainty budget for the measurement of the static gauge pressure using the Rosemount Model 3051P Pressure Transmitter [Rosemount, 2002a], calculated according to Eqn. (3.8).

Source	**Input uncertainty**				**Combined uncertainty**	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Transmitter uncertainty	0.01 bar	99 % (norm)	3	0.0033 bar	1	$1.11 \cdot 10^{-5}$ bar^2
Stability, transmitter	0.00515 bar	99 % (norm)	3	0.0017 bar	1	$2.95 \cdot 10^{-6}$ bar^2
RFI effects	0.020 bar	99 % (norm)	3	0.0067 bar	1	$4.44 \cdot 10^{-5}$ bar^2
Ambient temperature effects, transmitter	0.052 bar	99 % (norm)	3	0.0017 bar	1	$2.97 \cdot 10^{-6}$ bar^2
Sum of variances				$u_c^2(\hat{P})$		$6.15 \cdot 10^{-5}$ bar^2
Combined standard uncertainty				$u_c(\hat{P})$		0.0078 bar
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{P})$		**0.0157 bar**
Operating pressure				$\hat{P}$		18 barg
Relative expanded uncertainty (95 % confidence level)				$U(\hat{P})/\hat{P}$		**0.1311 %**

It is seen from Table 3.7 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with k = 2, cf. Section 2.3) are 0.024 bar and 0.13%, respectively. Hence, the uncertainty of the gauge pressure measurement is within the NPD requirement [NPD, 2001a] of a relative expanded uncertainty of 0.30% of measured value (see Table 3.1).

3.4 Liquid density measurement

As described in Section 1.4, the uncertainty of the density transmitter can in the program *EMU - Turbine Fiscal Oil Metering Station* be specified at two levels (cf. also Chapter 5):

(1) ***"Overall level":*** The user gives $u_c(\hat{\rho})$ directly as input to the program. It is left to the user to calculate and document $u_c(\hat{\rho})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the density measurement.

(2) ***"Detailed level":*** $u_c(\hat{\rho})$ is calculated in the program, from more basic input uncertainties for the density transmitter, provided by the instrument manufacturer and calibration laboratory.

The following discussion concerns the "Detailed level". It has been found convenient to base the user input to the program on the type of data which are typically specified for common density transmitters used in North Sea fiscal metering stations.

The example density transmitter chosen by NFOGM, NPD and CMR to be used in the present *Handbook* for the uncertainty evaluation example of Chapter 4 is the Solartron 7835 liquid densitometer [Solartron, 2001b], cf. Table 3.8 and Figure 3.5. This densitometer is also chosen for the layout of the densitometer user input to the program *EMU - Turbine Fiscal Oil Metering Station*. The Solartron 7835 liquid densitometer is a widely used densitometer when upgrading existing North Sea fiscal oil metering stations and when designing new stations, and is in this case mounted on-line, downstream the turbine meter.

It should be noted that the internal temperature measurement in the Solartron 7835 liquid densitometer can not be used for fiscal measurements, as it is not possible to calibrate the temperature element and transmitter as a separate unit. Separate dedicated temperature and pressure transmitter must therefore be used for performing density corrections and calculation of the standard reference density, cf. Sections 3.4.1.2, 3.4.1.3 and 3.6, respectively. In the evaluation example in this *Handbook*, we consider a metering station equipped with dedicated temperature and pressure transmitters in the by-pass loop where the densitometer is located. The evaluation of these dedicated temperature and pressure transmitters are included in separate worksheets in the EMU programs ("*T-density*" and "*P-density*").

However, if the metering station is not equipped with a dedicated pressure and/or temperature transmitter in the by-pass where the densitometer is located, the line temperature and/or pressure measurements would have to be used as estimates for the temperature or pressure at the densitometer. In such a case, an additional uncertainty contribution to the temperature and pressure estimates needs to be included to account for the possible deviation in conditions between the by-pass and the line

In practise, these cases are handled in the EMU programs by setting equal temperatures and/or pressures for the line and densitometer conditions in the "*Oil parameters*" worksheet (see Section 4.2) and by making the temperature and/or pressure uncertainty evaluations equal for the line (the "*T*" and/or "*P*") and the density (the "*T-density*" and/or "*P-density*") worksheets. However, one must include an additional uncertainty contribution using the *miscellaneous* option in the "*T-density*" and "*P-density*" worksheets to account for the possible deviations in conditions between the line and by-pass.

For example, if one assumes a 4 bar maximum pressure deviation between line and by-pass, the additional miscellaneous uncertainty contribution could be estimated as (assuming a rectangular distribution, see Section 2.3, hence $k = \sqrt{3}$): $u(\hat{P}_{misc}) = 4/\sqrt{3} = 2.31$ bar. For a 2 °C maximum temperature deviation between line and by-pass, the additional miscellaneous uncertainty contribution could be estimated as (assuming a rectangular distribution, hence $k = \sqrt{3}$): $u(\hat{T}_{misc}) = 2/\sqrt{3} = 1.15$ °C.

Figure 3.5 The Solartron 7835 liquid densitometer (example). Published in the Solartron Mobrey Data Sheet No. B1016usa [Solartron, 2001b]. Used by permission [Solartron, 2002].

3.4.1 Functional relationship

3.4.1.1 General density equation (frequency relationship regression curve)

The Solatron 7835 liquid densitometer [Solartron, 2001a, 2001b] is based on the vibrating cylinder principle, where the output is the periodic time of the resonance frequency of the cylinders Hoop vibrational mode. The relation between the density and the periodic time is obtained through calibration of the densitometer at a given calibration temperature and pressure using known pure reference liquids.

One known regressions curve relating the periodic time to the density is given as:

$$\rho_u = K_0 + K_1 \cdot \tau + K_2 \cdot \tau^2 \tag{3.9}$$

where

D	- indicated (uncorrected) density [kg/m^3]
K_0, K_1, K_2	- regression curve constants (given in the calibration certificate)
τ	- periodic time (inverse of the resonance frequency, output from the densitometer) [μs]

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).

The form of the regression curve can vary from manufacturer to manufacturer, and Eqn. (3.9) is one example of such a curve. However, note that the form of the regression curve is not actually used in the densitometer uncertainty model, and that K_0, K_1, K_2 are not needed as input to the uncertainty model. The present uncertainty model is thus independent of the type of regression curve used.

3.4.1.2 *Temperature correction*

If the transducer operates at temperatures other than the calibration temperature, a correction of the calculated density should be made for optimal performance. The equation for temperature correction uses coefficient data given on the calibration certificate, and is given as:

$$\rho_T = \rho_u \cdot \left(1 + K_{18} \cdot \left(T - T_{cal}\right)\right) + K_{19} \cdot \left(T - T_{cal}\right) \tag{3.10}$$

where

ρ_T	- temperature corrected density [kg/m^3]
K_{18}, K_{19}	- constants from the calibration certificate
T	- operating temperature [K]
T_{cal}	- calibration temperature [K]

3.4.1.3 *Pressure correction*

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:

$$\rho_{PT} = \rho_T \cdot \left(1 + K_{20} \cdot \left(P - P_{cal}\right)\right) + K_{21} \cdot \left(P - P_{cal}\right) \tag{3.11}$$

where

ρ_{PT}	- pressure (and temperature) corrected density [kg/m^3]
K_{20}, K_{21}	- constants from the calibration certificate
P	- operating pressure [bar]
P_{cal}	- calibration pressure [bar]

The constants, K_{20} and K_{21}, are given as a function of the line pressure and the calibration pressure:

$$\begin{aligned} K_{20} &= K_{20A} + K_{20B} \cdot (P - P_{cal}) \\ K_{21} &= K_{21A} + K_{21B} \cdot (P - P_{cal}) \end{aligned} \tag{3.12}$$

where

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

3.4.1.4 *Corrected density*

By combining Eqs. (3.10) - (3.12), the functional relationship of the corrected density measurement becomes

$$\begin{aligned} \rho_{PT} &= \{\rho_u \cdot (1 + K_{18} \cdot (T - T_{cal})) + K_{19} \cdot (T - T_{cal})\} \\ &\cdot (1 + [K_{20A} + K_{20B} \cdot (P - P_{cal})] \cdot (P - P_{cal})) \\ &+ [K_{21A} + K_{21B} \cdot (P - P_{cal})] \cdot (P - P_{cal}) \end{aligned} \tag{3.13}$$

in which both corrections (temperature and pressure) are accounted for in one single expression.

Note that in Eqn. (3.13), the *indicated* (uncorrected) density ρ_u has been used as the input quantity related to the densitometer reading instead of the periodic time τ. That has been done since $u(\hat{\rho})$ is the uncertainty specified by the manufacturer, and not $u(\hat{\tau})$.

Eqn. (3.13) is a relatively general functional relationship for on-line installed vibrating element liquid densitometers, which apply to the Solartron 7835 liquid density transducer, as well as others of this type.

3.4.1.5 *Uncertainty model*

The relative combined standard uncertainty of the liquid density measurement, E_ρ, can be given as input to the program *"EMU - Turbine Fiscal Oil Metering Station"* at two levels: "

As the "Overall level" is straightforward, only the "Detailed level" is discussed in the following. The uncertainty model for the densitometer is quite general, and should apply to any on-line installed vibrating-element densitometer, such as e.g. the Solartron 7835 liquid densitometer.

$$u_c^2(\hat{\rho}) = s_{\rho_u}^2 u^2(\hat{\rho}_u) + u^2(\hat{\rho}_{stab}) + u^2(\hat{\rho}_{rept}) + s_{\rho,T_d}^2 u_c^2(\hat{T}_d) + s_{\rho,P_d}^2 u_c^2(\hat{P}_d) + u^2(\hat{\rho}_{temp}) + +u^2(\hat{\rho}_{pres}) + u_c^2(\hat{\rho}_{inst}) + u^2(\hat{\rho}_{misc}) \qquad (3.14)$$

where

$u(\hat{\rho}_u) \equiv$ standard uncertainty of the indicated (uncorrected) density estimate, $\hat{\rho}_u$, including the calibration laboratory uncertainty, the reading error during calibration, and hysteresis,

$u(\hat{\rho}_{stab}) \equiv$ standard uncertainty of the stability of the indicated (uncorrected) density estimate, $\hat{\rho}_u$,

$u(\hat{\rho}_{rept}) \equiv$ standard uncertainty of the repeatability of the indicated (uncorrected) density estimate, $\hat{\rho}_u$,

$u(\hat{T}_d) \equiv$ standard uncertainty of the temperature estimate in the densitometer, $\hat{T}_d$,

$u(\hat{P}_d) \equiv$ standard uncertainty of the pressure estimate in the densitometer, $\hat{P}_d$,

$u(\hat{\rho}_{temp}) \equiv$ standard uncertainty of the temperature correction factor for the density estimate, $\hat{\rho}$ (represents the *model uncertainty* of the temperature correction model used, Eqn. (3.11)). The model uncertainty also includes the uncertainty of the K_{ii} coefficients and the temperature measurement during the calibration, T_{cal}.

$u(\hat{\rho}_{pres}) \equiv$ standard uncertainty of the pressure correction factor for the density estimate, $\hat{\rho}$ (represents the *model uncertainty* of the pressure correction model used, Eqn. (3.12)). The model uncertainty also includes the uncertainty of the K_{ii} coefficients and the pressure measurement during the calibration, P_{cal}.

$u_c(\hat{\rho}_{inst}) \equiv$ combined standard uncertainty of the temperature and pressure effect of an on-line installation (by-pass) of the densitometer.

$u(\hat{\rho}_{misc}) \equiv$ standard uncertainty of the indicated (uncorrected) density estimate, $\hat{\rho}_u$, accounting for miscellaneous uncertainty contributions[33], such as due to:

- reading error during measurement (for digital display instruments)[34],
- possible deposits on the vibrating element,
- possible corrosion of the vibrating element,
- mechanical (structural) vibrations on the oil line,
- variations in power supply,
- self-induced heat,
- flow in the bypass density line,
- possible liquid viscosity effects,

The sensitivity coefficients appearing in Eqn. (3.14) are defined as:

$$s_{\rho_u} = \{(1 + K_{18} \cdot (T - T_{cal})) + K_{19} \cdot (T - T_{cal})\} \cdot (1 + [K_{20A} + K_{20B} \cdot (P - P_{cal})] \cdot (P - P_{cal})) \quad (3.15)$$

$$s_{\rho,T} = \{\rho_u \cdot K_{18} + K_{19}\} \cdot (1 + [K_{20A} + K_{20B} \cdot (P - P_{cal})] \cdot (P - P_{cal})) \quad (3.16)$$

$$s_{\rho,P} = \{\rho_u \cdot [(1 + K_{18} \cdot (T - T_{cal})) + K_{19} \cdot (T - T_{cal})]\} \cdot (2 \cdot K_{20B} \cdot (P - P_{cal}) + K_{20A}) + 2 \cdot K_{21B} \cdot (P - P_{cal}) + K_{21A} \quad (3.17)$$

$u_c(\hat{\rho})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{\rho}_{\rho_u})$, $u(\hat{\rho}_{stab})$, $u(\hat{\rho}_{rept})$, $u(\hat{\rho}_{temp})$, $u(\hat{\rho}_{pres})$, $u_c(\hat{\rho}_{inst})$, and document their traceability. It is left to the user of the program *EMU - Turbine Fiscal Oil Metering Station* to specify and $u(\hat{\rho}_{misc})$. $u_c(\hat{T})$ are given by Eqn. (3.7) and $u_c(\hat{P})$ is given by Eqn. (3.8).

[33] In accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001], various "miscellaneous uncertainty contributions" listed in the text have been accounted for in the uncertainty model (Eqn. (3.14) by a "lumped" term, $u(\hat{\rho}_{misc})$, with a weight (sensitivity coefficient) equal to one. Note that this is a simplified approach. An alternative and more correct approach would have been to start from the full functional relationship of the uncorrected density measurement ρ_u, Eqn. (2.23), and derive the influences of such miscellaneous uncertainty contributions on the total uncertainty according to the recommendations of the *GUM* [ISO, 1995a], i.e. with derived sensitivity coefficients.

[34] For guidelines with respect to uncertainty evaluation of reading error during measurement, cf. [Tambo and Søgaard, 1997, Annex 2].

As an example of liquid density uncertainty evaluation, the Solartron 7835 liquid densitometer is evaluated in Section 3.4.2

3.4.2 Example uncertainty evaluation

The combined standard uncertainty of the density measurement, $u_c(\hat{\rho})$, is given by Eqn. (3.14). This expression is evaluated in the following, for the example considered here.

Performance specifications for the Solartron 7835 liquid densitometer are given in Table 3.8 as specified in the data sheet [Solartron, 2001b], etc.

Table 3.8 Performance specifications of the Solartron 7835 liquid densitometer [Solartron, 2001b, 2002] used as input to the uncertainty calculations given in Table 3.10.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, *k***	**Reference**
Calibration temperature (air)	20 °C	-	[Solartron, 2001b]
Full scale density range	300 - 1100 kg/m^3	-	[Solartron, 2001b]
Densitometer "accuracy", $U(\hat{\rho}_u)$	0.15 kg/m^3	2	[Solartron, 2001b]
Repeatability, $U(\hat{\rho}_{rept})$	0.02 kg/m^3	2	[Solartron, 2001b]
Calibration pressure	1.01325 bara (1 atm)	-	[Solartron, 2001a]
Temperature effect, $U(\hat{\rho}_{temp})$	0.005 kg/m^3/^{o}C	2	[Solartron, 2002]
Pressure effect, $U(\hat{\rho}_{misc})$	0.003 kg/m^3/bar	2	[Solartron, 2001b]
Stability, $U(\hat{\rho}_{misc})$	0.15 kg/m^3/year		[Solartron, 1999, §1.3.3], [Solartron, 2002]

The contributions to the combined standard uncertainty of the density measurement are described in the following. As the confidence level of the expanded uncertainties is not specified in [Solartron, 2001a, 2001b], this is here assumed to be 95 %, with a normal probability distribution (k = 2, cf. Section 2.3).

The contributors to the uncertainty of the liquid density measurement are:

1. **Densitometer "accuracy",** $u(\hat{\rho}_u)$: The densitometer "accuracy"[35] is specified in the manufacturer instrument manual [Solartron, 2001b] as being 0.15 kg/m^3 for the range 300 – 1100 kg/m^3. The given uncertainty includes the uncertainty of the calibration reference with traceability to international standards [Eide, 1999]. Hence, the standard uncertainty becomes $u(\hat{\rho}_u) = U(\hat{\rho}_u)/2$ = 0.075 kg/m^3.

   The value reported in the calibration certificate may replace the expanded uncertainty given in the data sheet[36] if the calibration certificate reports a smaller expanded uncertainty for the transmitter than the data sheet.

2. **Stability,** $u(\hat{\rho}_{stab})$: The stability of the 7835 liquid density transducer represents a drift (increasing/ decreasing offset) in the readings with time. This contribution is zero at the time of calibration, and is specified as a maximum value at a given time.

   The uncertainty due to drift is given in the data sheet as 0.15 kg/m^3 per year. The uncertainty given for one year must be divided by twelve and multiplied by the time between the calibrations (in months) in order to calculate the drift between the calibrations[37]. With annual calibrations, the standard uncertainty due to drift becomes $u(\hat{\rho}_{stab}) = U(\hat{\rho}_{stab})/2$ = 0.075 kg/m^3.

3. **Repeatability,** $u(\hat{\rho}_{rept})$: The uncertainty due to repeatability of the density transducer is given in the manufacturer data sheet as 0.02 kg/m^3 [Solartron, 2001b]. Hence, the standard uncertainty becomes $u(\hat{\rho}_{rept}) = U(\hat{\rho}_{rept})/2$ = 0.01 kg/m^3.

4. **Temperature effects (temperature correction model),** $u(\hat{\rho}_{temp})$: Temperature changes will affect both the modulus of elasticity of the vibrating element, and its dimensions. Both of these affect the resonance frequency [Matthews, 1994]. For

[35] According to the manufacturer [Solartron, 2002] it is possible to reduce this uncertainty to 0.1kg/m^3 for liquids below 1000 kg/m^3 or 0.1% of reading when the density is over 1000 kg/m^3, with calibration in water.

[36] If the expanded uncertainty reported in the calibration certificate is used, the user must also assure that the confidence level reported in the calibration certificate is used. I.e. not simply assume that the confidence level given in the data sheet equals the one in the calibration certificate.

[37] In a worst case scenario, the uncertainty due to stability may be used directly without using the time division specified.

high accuracy densitometers like the Solartron 7835, this effect is largely eliminated using Ni-span-C stainless steel, and the temperature correction model given by Eqn. (3.10). However, even if the density measurement is temperature corrected, this correction *itself* is not perfect and will have an uncertainty.

This uncertainty is given in the manufacturer data sheet to be 0.05 kg/m^3/°C [Solartron, 2001a], but this is in fact a printing error in the data sheet. According to the manufacturer, the correct uncertainty is 0.005 kg/m^3/C [Solartron, 2002]. The temperature change referred to in the specification is the change in line temperature from the calibration temperature. Hence, the standard uncertainty becomes $u(\hat{\rho}_{temp}) = U(\hat{\rho}_{temp})/2$ = 0.0025 kg/m^3/°C. With a temperature variation of 43 °C between calibration and densitometer conditions, the standard uncertainty to be used in the sample calculation becomes

$$u(\hat{\rho}_{temp}) = 0.0025 kg/m^3/°C \cdot 43°C = 0.1075 kg/m^3$$

This uncertainty covers the uncertainty of the temperature correction model in the correction from calibration conditions to densitometer conditions.

5. **Pressure effects (pressure correction model),** $u(\hat{\rho}_{pres})$: Even if the density is pressure corrected, this correction *itself* is not perfect and will have an uncertainty. This is given in the manufacturer instrument manual as less than 0.003 kg/m^3/bar. The pressure change referred to in the specification is the change in line pressure from the calibration pressure. Hence, the standard uncertainty becomes $u(\hat{\rho}_{pres}) = U(\hat{\rho}_{pres})/2$ = 0.0015 kg/m^3/bar. With a pressure variation of 17.5 bar between calibration and densitometer conditions, the standard uncertainty to be used in the sample calculation becomes

$$u(\hat{\rho}_{pres}) = 0.0015 kg/m^3/bar \cdot 17.5 bar = 0.02625 kg/m^3$$

This uncertainty covers the uncertainty of the pressure correction model in the correction from calibration conditions to densitometer conditions.

(If the density measurement is not pressure corrected an uncertainty of maximum 2 kg/m^3 or 15 kg/m^3 may result for pressures at 50 or 100 bar, respectively, according to the manufacturer instrument manual [Solartron, 1999])

6. **Densitometer temperature,** $u(\hat{T}_d)$: The temperature at the densitometer is input to the temperature correction model, and this uncertainty must therefore be included in the combined uncertainty of the liquid densitometer. The expanded uncertainty of the line temperature is taken from Table 3.5.

7. **Densitometer pressure,** $u(\hat{P}_d)$: The pressure at the densitometer is input to the pressure correction model, and this uncertainty must therefore be included in the combined uncertainty of the liquid densitometer. The uncertainty of the pressure measurement at the densitometer is taken from Table 3.7.

A sample uncertainty budget has been established for evaluation of the expanded uncertainty of the liquid density measurement. The sample uncertainty budget is shown in Table 3.10, and has among others been based on the figures listed in Table 3.9.

Table 3.9. Figures used in the sample calculation in Table 3.10.

Parameter	Value	Reference / Source
Uncorrected density	776 kg/m^3	Table 3.3
Time between calibrations	12 months	Table 3.3
Temperature at densitometer	63 °C	Table 3.3
Pressure at densitometer	17.5 barg	Table 3.3
Calibration temperature	20 °C	
Calibration pressure	1.01325 bara	
Calibration constant, K_{18}	$-1.394 \cdot 10^{-5}$	[Solartron, 1999] pp. 9.11
Calibration constant, K_{19}	$9.234 \cdot 10^{-3}$	[Solartron, 1999] pp. 9.11
Calibration constant, K_{20A}	$4.466 \cdot 10^{-9}$	[Solartron, 1999] pp. 9.11
Calibration constant, K_{20B}	$-1.213 \cdot 10^{-6}$	[Solartron, 1999] pp. 9.11
Calibration constant, K_{21A}	$6.046 \cdot 10^{-2}$	[Solartron, 1999] pp. 9.11
Calibration constant, K_{21B}	$-1.641 \cdot 10^{-3}$	[Solartron, 1999] pp. 9.11

Table 3.10 Sample uncertainty budget for the uncertainty of the Solatron 7835 liquid density transducer in an on-line installation.

Source	Input uncertainty				Combined uncertainty	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact. *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Densitometer "accuracy", $U(\hat{\rho}_u)$	0.15 kg/m^3	95 % (norm)	2	0.075 kg/m^3	0.99887	$5.61 \cdot 10^{-3}$ $(kg/m^3)^2$
Stability, $U(\hat{\rho}_{stab})$	0.15 kg/m^3	95 % (norm)	2	0.075 kg/m^3	1	$5.63 \cdot 10^{-3}$ $(kg/m^3)^2$
Repeatability, $U(\hat{\rho}_{rept})$	0.02 kg/m^3	95 % (norm)	2	0.010 kg/m^3	1	$1.00 \cdot 10^{-4}$ $(kg/m^3)^2$
Temperature effect, $U(\hat{\rho}_{temp})$	0.005 $kg/m^3/°C$	95 % (norm)	2	0.1075 kg/m^3	1	$1.16 \cdot 10^{-2}$ $(kg/m^3)^2$
Pressure effect, $U(\hat{\rho}_{pres})$	0.003 $kg/m^3/bar$	95 % (norm)	2	0.026 kg/m^3	1	$6.89 \cdot 10^{-4}$ $(kg/m^3)^2$
T, $U(\hat{T}_d)$	0.15651 °C	95 % (norm)	2	0.078 °C	-0.00158 $kg/m^3/°C$	$1.53 \cdot 10^{-8}$ $(kg/m^3)^2$
P, $U(\hat{P}_d)$	0.01568 bar	95 % (norm)	2	0.078 bar	-0.0299 $kg/m^3/bar$	$5.5 \cdot 10^{-8}$ $(kg/m^3)^2$
Sum of variances				$u_c^2(\hat{\rho})$		$2.36 \cdot 10^{-2}$ $(kg/m^3)^2$
Combined standard uncertainty				$u_c(\hat{\rho})$		0.1536 kg/m^3
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{\rho})$		**0.3071 kg/m^3**
Oil density at densitometer				$\hat{\rho}$		776 kg/m^3
Relative expanded uncertainty (95 % confidence level)				$U(\hat{\rho})/\hat{\rho}$		**0.0396 %**

It is seen from Table 3.10 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with *k* = 2, cf. Section 2.3) are 0.33 kg/m^3 and 0.04%, respectively. Hence, the uncertainty of the density measurement is within the NPD requirement [NPD, 2001a] of a relative expanded uncertainty of 0.50 kg/m^3 of measured value (see Table 3.1).

From the uncertainty budget in Table 3.10 it is evident that the uncertainty due to the temperature and pressure used in the correction of the density, is negligibly small compared to the other uncertainties.

3.5 Liquid and Turbine meter and Prover steel correction factors

This chapter briefly describes the correction factors, which are used to correct the volume of liquid or steel due to changes in temperature or pressure. These correction factors are used in calculation of the density at standard reference conditions, the *K-Factor* and the standard volume flow rate. The functional relationships of the correction factors are given in the referenced standards, where their model uncertainties to some extent are specified.

The uncertainties of the input quantities of the correction factors will be evaluated when applied in the calculations of the standard density, the *K-Factor* and the standard volume flow rate. Then it will be evaluated to what extent the different input quantities contribute to the different combined uncertainties.

It must be noted that the calculation procedures regarding truncating and rounding of the numbers are not implemented in this uncertainty evaluation. The influences of these procedures are considered to be minor and the uncertainties they introduce are assumed to be included in the model uncertainties of the correction factors.

The volume correction factors may alternatively be obtained from laboratory experiments on oil with a given composition instead of using API standards and tables. The uncertainties of the correction factors are then determined from statistical analysis of the laboratory measurements. This method enables one to optimise the volume correction factors and minimising their model uncertainties.

The principal correction factors employed in the calculations are shown in Table 3.11.

Table 3.11 Description of the correction factors.

Factor	Description	Reference
C_{ts}	The volume correction factor for the effect of temperature on steel.	API MPMS 12.2.5.1
C_{ps}	The volume correction factor for the effect of pressure on steel.	API MPMS 12.2.5.2
C_{tl}	The volume correction factor for the effect of temperature on the liquid.	API MPMS 11.1.54.2.4
C_{pl}	The volume correction factor for the effect of pressure on the liquid.	API MPMS 12.2.5.4

Additional subscripts are added to the symbolic notations to indicate what part of the measuring apparatus it applies to, namely "*p*" for the Prover, "*d*" for the densitometer (see Section 3.6) and "*m*" for the turbine meter.

The volume correction factors are applied according to Eqn. (3.18) as

$$V_{ref} = V_{T,P} \cdot C_{tl} \cdot C_{pl} \tag{3.18}$$

where

V_{ref}	- volume at standard reference conditions (15 °C and 101.325 kPa) [kg/m^3]
$V_{T,P}$	- volume at line temperature and pressure [kg/m^3]
C_{tl}	- correction from line temperature to standard temperature
C_{pl}	- correction from line pressure to standard pressure

3.5.1 Functional relationship - Correction for the effect of temperature on the liquid, C_{tl}

The effect of temperature on the liquid shall according to [NORSOK, 1998b] be calculated in conformance with API MPMS 11.1.54.2.4 [API, 1980]. The volume correction factor must then be calculated as:

$$C_{tl} = e^{\left(-\alpha \cdot \Delta T - 0.8 \cdot \alpha^2 \cdot \Delta T^2\right)} \tag{3.19}$$

where

$$\alpha = \frac{K_0}{\rho_{ref}{}^2} + \frac{K_1}{\rho_{ref}} \tag{3.20}$$

and

$$\Delta T = T - 15 \tag{3.21}$$

where

C_{tl}	- volume correction from line temperature to standard temperature
K_0	- constant (API MPMS 11.1.54.7.1)
K_1	- constant (API MPMS 11.1.54.7.1)
ρ_{ref}	- density at standard reference conditions (15 °C and 101.325 kPa) [kg/m^3]
ΔT	- difference in line temperature from standard temperature [°C]
T	- operating temperature [°C]

The coefficient α in (3.20) is different for each major group of hydrocarbons, where the K_0 and K_1 constants are given in API MPMS 11.1.54.7.1 and shown in Table 3.12.

Table 3.12 The constants K_0 *and* K_1 *reprinted from the Petroleum Measurement Manual, Part VII, Appendix F, used in the correction factors in the Tables 53A and 53B of the revised API-ASTM-IP Petroleum Measurement Tables (API 2540, ASTM D 1250, IP200)*

Hydrocarbon group	K_0	K_1	**Density range (kg/m^3**
Crude Oil	613.97226	0.0000	771 – 981
Gasolines	346.42278	0.43884	654 – 779
Jet Fuels	594.54180	0.0000	779 – 839
Fuel Oils	186.96960	0.48618	839 – 1075

The values of the constants K_0 and K_1 for crude oil are used in the EMU programs. It should be noted that there is an unknown uncertainty attached to the classification of crude oil, gasolines, jet fuels and fuel oils presented in Table 3.12. The values for K_0 and K_1 may be optimised based on laboratory testing, where the correction factor for temperature of a liquid sample is determined experimentally and the model uncertainty is determined using statistical analysis.

The model uncertainty of the temperature liquid correction factor is given in API MPMS 11.1.54.2 and is reprinted in Table 3.13:

Table 3.13 The model uncertainty of the temperature correction factors according to API MPMS 11.1.54.2 (95% confidence level).

Temperature	**40 °C**	**65 °C**	**90 °C**	**120 °C**
Crudes & Products	0.05 %	0.15 %	0.25 %	0.35 %

The uncertainties according to Table 3.13 will be used for the model uncertainty of the correction factor, C_{tl}. In addition to this model uncertainty there will be uncertainty due to the input quantities used in the calculation of the compressibility factor. However, the uncertainties due to the input quantities will be covered in later chapters where the correction factors are applied.

The uncertainties in Table 3.13 are here interpreted as 0.05% for temperatures below 40°C, 0.15% for temperatures in the range 40 °C to 65°C, 0.25% for temperatures in the range 65 °C to 90 °C, and so on[38]. If these uncertainties are considered too large to be accepted, a laboratory can measure the actual thermal expansion properties of the liquid in question. The volume correction factor of the sample of the liquid may

[38] As the interpretation of Table 3.13 is not specified, interpolation of the uncertainties vs. temperature is not used, but rather the “worst case” interpretation as described in this paragraph.

then be determined from the measured data and maybe reduce the uncertainty of the correction factor.

3.5.2 Functional relationship - Correction for the effect of pressure on the liquid, C_{pl}

The effect of pressure on a liquid shall according to [NORSOK, 1998b] be calculated in conformance with API MPMS 12.2.5.4 [API, 1995] (API MPMS 12.1.11.1.2). The volume correction factor must then be calculated as:

$$C_{pl} = \frac{1}{1 - \left[P - \left(Pe_a - Pb_a\right)\right] \cdot F} \quad \text{and} \quad (Pe_a - Pb_a) \geq 0 \qquad (3.22)$$

where

- C_{pl} - volume correction from line pressure to standard pressure
- P - operating pressure [kPa], in **gauge** pressure units.
- Pb_a - base (reference or standard) pressure [kPa], in **absolute** pressure units.
- Pe_a - equilibrium vapour pressure at the temperature of the liquid being measured [kPa], in **absolute** pressure units.
- F - the compressibility factor for the liquid [1/kPa]

The liquid equilibrium vapour pressure (Pe_a) is considered to be equal to base (reference or standard) pressure (Pb_a) for liquids that have an equilibrium vapour pressure less than atmospheric pressure at the flowing temperature (API MPMS 12.2.1.11.1.2). The base conditions for the measurement of liquids, such as crude petroleum and its liquid products, having a vapour pressure equal to or less than atmospheric at base temperature are (in SI units):

Pressure: 101.325 kPa_a
Temperature: 15.00 °C

For liquids, such as liquid hydrocarbons, having a vapour pressure greater than the atmospheric pressure at base temperature, the base pressure shall be the equilibrium vapour pressure at base temperature (API MPMS 12.2.2.2.6.2).

According to [NORSOK, 1998b][39] the compressibility factor shall be calculated according to API MPMS 11.2.1 (metric units must be used in order to comply with the reference conditions required by the NPD, i.e. API MPMS 11.2.1M must be used).

The compressibility factor defined in API MPMS 11.2.1M is given as

$$F = \frac{e^{\left(A + B \cdot T + \frac{C}{\rho_{ref}^{\;2}} + \frac{D \cdot T}{\rho_{ref}^{\;2}}\right)}}{10^6} \tag{3.23}$$

where

F	- compressibility factor [1/kPa]	
T	- operating temperature [°C]	
ρ_{ref}	- density at the reference temperature, 15°C [g/cm^3]	
A	- constant = -1.62080	(Cf. API MPMS 11.2.1M)
B	- constant = 0.00021592	(Cf. API MPMS 11.2.1M)
C	- constant = 0.87096	(Cf. API MPMS 11.2.1M)
D	- constant = 0.0042092	(Cf. API MPMS 11.2.1M)

The combined uncertainty in C_{pl} in Eqn. (3.22) depends on the measurement of the operating, base and vapour pressures and the uncertainty of the compressibility factor.

In API MPMS 11.2.1.5.1M the model uncertainty of the compressibility factor, *F*, is evaluated. The functional relationship in Eqn. (3.23) is determined using experimental data stored in a database (API MPMS 11.2.1.4M, Table 1). The expression is therefore only true within the limits of the database from which the expression is derived. Hence, the uncertainties specified may not be true for extrapolated values.

The analysis in API MPMS 11.2.1.5.1M states that the compressibility factor can be assumed independent of pressure at low pressures. At higher pressures, however, mean compressibility will decrease with increasing pressure, and at what pressure this effect becomes significant is not definitely known. Incorporating both the compressibility correlation uncertainty and the potential pressure uncertainty yields

[39] It should be noted that the expression for the compressibility factor used in the Petroleum Measurement Paper No 2 [IP, 1984], Section 4.3, is not equal to the expression used in the API MPMS 11.2.1M.

volumetric uncertainties in the range 0.03% to 0.13% of the compressibility factor for crude oils (API MPMS 11.2.1M, Table 2).

Table 3.14 The uncertainty in volume (API MPMS 11.2.1.5.1M, Table 2) for a typical compressibility value for 850 kg/m^3 crude oil at 38°C and at various pressures. The uncertainties include both compressibility correlation uncertainty and uncertainty due to the effect of pressure.

Pressure	34.47 bar	68.95 bar	103.42 bar
Relative Expanded Uncertainty (in volume) (95% confidence level)	0.03 %	0.08 %	0.13 %

It should be pointed out that the values in Table 3.14 are given for a crude oil with density 850 kg/m^3 at 38°C, and that variations in temperature and density may also influence the uncertainty.

The pressure in the example is less than 34.47 bar. Therefore, the uncertainty used as the model uncertainty of the C_{pl} correction factor is 0.03% (95% confidence level). In addition, uncertainties due to the reference density, temperature and pressures in Eqn. (3.22) and (3.23) must be included in the combined uncertainty of C_{pl}.

3.5.3 Functional relationship - Correction for the effect of temperature on Prover steel, C_{tsp}

The effect of temperature on the Prover steel shall according to [NORSOK, 1998b] be calculated in conformance with API MPMS 12.2.5.1. The volume correction factor must then be calculated as:

$$C_{tsp} = 1 + EM \cdot \left(T_{pa} - 15\right) \tag{3.24}$$

where

C_{tsp} - Prover temperature steel correction factor

EM - Coefficient of cubical expansion per degree Celsius of the material of which the Prover is made [mm/mm/°C].

T_{pa} - average temperature of Prover inlet and outlet [°C]

The expansion of the steel described by the functional relationship in Eqn. (3.24) is well known, where the coefficient of cubical expansion is empirically determined. The coefficient of cubical expansion, *EM*, is determined from empirical measurements using the same functional relationship as for the correction factor.

If the steel is of high quality and may be regarded as an isotropic[40] material, and the pipe Prover is not exposed to stress from other pipe-work or mounting arrangements, it may be assumed that the model uncertainty is confined within the uncertainty of *EM* [Vik, 1999][Eide, 1999] (or at least negligible small compared to the uncertainty of *EM*). No model uncertainty is therefore included for the C_{tsp} correction factor, and the uncertainty of the correction factor is calculated from the uncertainties of the input quantities.

3.5.4 Functional relationship - Correction for the effect of pressure on Prover steel, C_{psp}

The effect of pressure on the Prover steel shall according to [NORSOK, 1998b] be calculated in conformance with API MPMS 12.2.5.2. The volume correction factor must then be calculated as:

$$C_{psp} = 1 + \frac{P_{pa} \cdot DP}{EMP \cdot TP} \tag{3.25}$$

where

- C_{psp} - Prover pressure steel correction factor
- P_{pa} - average internal pressure of Prover inlet and outlet [barg]
- DP - internal diameter of Prover pipe [m]
- EMP - modulus of elasticity for the Prover material [barg]
- TP - wall thickness of Prover pipe [m]

As was the case for the temperature steel correction, the expansion of the steel described by the functional relationship in Eqn. (3.25) is well known, where the modulus of elasticity is empirically determined. The modulus of elasticity, *EMP*, is determined from empirical measurements using the same functional relationship as for the correction factor.

If the steel is of high quality and may be regarded as an isotropic[40] material, and the Prover pipe is not exposed to stress from other pipe-work or mounting arrangements, it may be assumed that the model uncertainty is confined within the uncertainty of *EMP* [Vik, 1999][Eide, 1999a] (or at least negligible small compared to the uncertainty of *EMP*).

[40] The properties of the material are the same in any direction within the material. Liquids are actually more correctly described as isotropic than are solids, whose crystal structure implies preferred directions [Fishbane, 1993].

No model uncertainty is therefore included for the C_{psp} correction factor, and the uncertainty of the correction factor is calculated from the uncertainties of the input quantities.

3.5.5 Functional relationship - Correction for the effect of temperature and pressure on the turbine meter steel, C_{tsm} and C_{psm}.

The effect of temperature on the turbine meter steel shall according to the NORSOK I-105 standard [NORSOK, 1998b] be calculated according to:

$$C_{tsm} = \left(1 + EH \cdot (T - 15)\right)^2 \cdot \left(1 + ER \cdot (T - 15)\right) \tag{3.26}$$

where

C_{tsm}	- turbine meter temperature steel correction factor
EH	- linear expansion coefficient in meter housing [1/°C]
T	- operating temperature [°C]
ER	- linear expansion coefficient in rotor [1/°C]

The effect of pressure on the turbine meter steel shall according to the NORSOK I-105 [NORSOK 1998b] standard be calculated according to:

$$C_{psm} = 1 + \frac{P \cdot (2 - e) \cdot R}{EMM \cdot \left(1 - \frac{AT}{\pi \cdot R^2}\right) \cdot t} \tag{3.27}$$

where

C_{psm}	- turbine meter pressure steel correction factor
P	- operating pressure [barg]
e	- Poisson ratio
EMM	- Elasticity module
AT	- Area of rotor [m^2]
R	- Radius of meter housing [m]
t	- Wall thickness of meter housing [m]

There is no traceability, model uncertainty or criteria for evaluation of these formulas specified in the NORSOK I-105 standard. Hence, C_{tsm} and C_{psm} cannot be easily evaluated with respect to their uncertainties. Since the standard further states that the *accuracy* of the formulas must be evaluated before implementation, it may be interpreted as optional to exclude these corrections from the calculations.

If there is only a small temperature and pressure difference between the Prover and the turbine meter during proving, and only a small temperature and pressure

difference between the operating and calibrating conditions of the turbine meter, the volume correction due to these changes may be negligible. Using the C_{tsm} and C_{psm} correction factors may in fact introduce uncertainties that are larger than the one resulting from not correcting for these small volume changes.
In order to evaluate the above-mentioned effect one must know the model uncertainties of the correction factors and the uncertainties of the input quantities. It is expected that the model uncertainties are larger than the uncertainties due the input quantities in Eqn. (3.26) and (3.27).

For large differences in temperature or pressure values during proving and metering, the correction factors C_{tsm} and C_{psm} may be applied. However, the criteria for evaluating when to apply these correction factors are not defined. In the case of application, their uncertainties must be documented including the model uncertainties and the uncertainties of the input quantities. In addition, an evaluation of the combined uncertainty achieved with and without using the correction factors must be included in order to document the application of the correction factors.

According to normal practise, the correction factors C_{psm} and C_{tsm} are not applied if stable calibration and operating conditions are observed. If the temperature difference is more than say 5 °C, the proving is aborted, and if the temperature difference between proving and metering conditions increase above say 5 °C, a re-calibration of the turbine meter is initiated.

In the example evaluated in this *Handbook*, stable calibration and operating conditions are assumed, with small deviations between the calibration and operating conditions. The volume correction factors are therefore expected to be small, and despite the fact that the model uncertainties of these correction factors are unknown they are expected to be small. It is therefore decided to not include C_{psm} and C_{tsm} in the calculations in this handbook[41].

In this chapter the application of the different volume correction factors have been briefly described and the model uncertainties of the correction factors that are included in the uncertainty calculations have been evaluated. This forms the basis for the next Sections where the volume correction factors are applied in example

[41] NOTE: If a known systematic deviation is not corrected for, this will introduce additional uncertainty to the measurement. It should therefore be emphasised that these correction factors might have significant influence in the case of large deviations between operating and calibration conditions. More effort should therefore be made to reveal the model uncertainties of these correction factors and the criteria for their application in such cases.

calculations of the standard reference density, the *K-Factor* and the standard volume flow rate.

3.6 Conversion of density to standard reference conditions

The online measured density (at densitometer conditions) must be converted to standard reference conditions, 15 °C and 101.325 kPa, using a standardised calculation procedure and the volume correction factors, C_{tld} and C_{pld}.

Table 3.15. Values used in the sample calculation in Table 3.18.

Parameter	**Value**
Densitometer pressure	17.5 barg
Densitometer temperature	63.0 °C
Base pressure, Pb_a	101.325 kPa
Equilibrium vapour pressure[42], Pe_a	101.325 kPa
Density at densitometer conditions, $\rho_{T,P}$	776.0 kg/m^3

3.6.1 Functional relationship

The standard reference density must be calculated according to recognised standards. In API MPMS 12.2.1, Appendix B, a short guide to reference (base-) density calculations for most of the liquids associated with the petroleum and petrochemical industry is given. The standard reference density is determined according to Eqn. (3.28).

$$\rho_{ref} = \frac{\rho_{T,P}}{C_{tld} \cdot C_{pld}} \tag{3.28}$$

where

ρ_{ref} - standard reference density (at 15 °C and 101.325 kPa) [kg/m^3]
$\rho_{T,P}$ - density at line temperature and pressure [kg/m^3]
C_{tld} - correction from line temperature to reference temperature (Cf. Chapter 3.5.1)
C_{pld} - correction from line pressure to reference pressure (Cf. Chapter 3.5.2)

42 The equilibrium vapour pressure is set equal to base pressure in this sample calculation but is likely to be different from the base pressure for closed systems.

The volume correction factors C_{tld} and C_{pld} are both functions of the standard reference density, which means that an iterative procedure is required. In API MPMS 12.2, Part 1, Appendix B.4, the procedure for calculation of the reference density is specified. The procedure is summarised in Table 3.16 and Table 3.17.

Table 3.16 API MPMS 12.2, Part 1, Appendix B.4, defines how to calculate the factors used in the reference density calculation.

Quantity	**Calculate according to:**	**Description**
Reference density, ρ_{ref}	API MPMS 11.1, Vol. X, Table 54A	The document specifies the determination of the reference density from the line density at reference pressure and temperature
Liquid temperature correction, C_{tld}	API MPMS 11.1, Vol. X, Table 54A	The document specifies the determination of C_{tl} from the reference density and line temperature.
Liquid pressure correction, C_{pld}, and the compressibility factor, F	API MPMS 11.2.1M	The document specifies the determination of C_{pl} and the compressibility factor from reference density and line temperature and pressure.

Table 3.17 Procedure for calculation of the reference density according to API MPMS 12.2, Part 1, Appendix B.4.

Step	**Calculate**	**Description**
1	$\rho_{15,0}$	Use the measured density at densitometer conditions (temperature and pressure), $\rho_{T,P}$, as an initial guess of the reference density.
2	C_{pld}	Calculate the volume correction factor that corrects the volume at densitometer conditions (temperature and pressure) to the volume at reference pressure.
3	$\rho_{T,0} = \dfrac{\rho_{T,P}}{C_{pld}}$	Calculate the density at reference pressure and densitometer temperature using C_{pl} from step 1.
4	C_{tld}	Calculate the volume correction factor that corrects the volume at densitometer temperature and reference density to the volume at reference temperature and pressure according to API MPMS 11.1.54.2.4.
5	$\rho_{15,0}$	Calculate the density at reference conditions from the density at reference pressure and densitometer temperature by iterative procedures according to API MPMS 11.1.53.2.4.
6	Go to step 1.	Repeat the steps 2 to 5 until the change in reference density in two successive passes is less than 0.05 kg/m^3 (API MPMS 11.1.53.2.4)
7	C_{pld}	Calculate the final value of the volume-correcting factor based on the final reference density value.
8	C_{tld}	Calculate the final value of the volume-correcting factor based on the final reference density value.

3.6.2 Example uncertainty evaluation

It is expected that the uncertainty due to the iteration is small and thus negligible compared to the other uncertainties involved in the calculation of density at standard reference conditions. Since the standard reference density has to be calculated by iteration (implicit function) this will influence the sensitivity coefficients according to the common rule for implicit differentiation. An example of this is the sensitivity of the standard reference density with respect to the measured temperature, which is shown in general terms in Eqn.(3.29). The expressions for the sensitivity coefficients become quite large, and should therefore be solved using mathematical tools to avoid typing errors and errors in the calculations.

$$S_T = \frac{\partial \rho_{ref}(T, P, P_{e_a}, P_{b_a}, \rho_{T,P}, \rho_{ref}) \big/ \partial T}{1 - \partial \rho_{ref}(T, P, P_{e_a}, P_{b_a}, \rho_{T,P}, \rho_{ref}) \big/ \partial \rho_{ref}} \tag{3.29}$$

For the evaluation of the uncertainties of the standard reference density a sample uncertainty budget is established in Table 3.18.

Table 3.18 Sample uncertainty budget for the conversion of line density to standard reference density.

Source	**Input uncertainty**				**Combined uncertainty**	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact. *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
T	0.1565 DegC	95 % (norm)	2	0.0783 °C	0.744 kg/m^3 / °C	3.39·10^{-3} (kg/m^3)^2
P	0.01568 bar	95 % (norm)	2	0.00784 bar	-0.0841 kg/m^3 / bar	4.35·10^{-7} (kg/m^3)^2
Pe_a [43]	0.0 bar	Standard	1	0.0 bar	0.0841 kg/m^3 / bar	0 (kg/m^3)^2
Pb_a [43]	0.0 bar	Standard	1	0.0 bar	-0.0841 kg/m^3 / bar	0 (kg/m^3)^2
$\rho_{T,P}$	0.3071 kg/m^3	95 % (norm)	2	0.154 kg/m^3	0.960	2.17·10^{-2} (kg/m^3)^2
C_{pld} (model)	3.0·10^{-4}	95 % (norm)	2	1.5·10^{-4}	-743 kg/m^3	1.24·10^{-2} (kg/m^3)^2
C_{tld} (model)	7.15·10^{-4}	Standard	1	7.15·10^{-4}	-780 kg/m^3	3.11·10^{-1} (kg/m^3)^2
Sum of variances					$u_c^2(\hat{\rho}_{ref})$	0.3487 (kg/m^3)^2
Combined standard uncertainty					$u_c(\hat{\rho}_{ref})$	0.5905 kg/m^3
Expanded uncertainty (95 % confidence level, *k* = 2)					$U(\hat{\rho}_{ref})$	1.181 kg/m^3
Reference density					$\hat{\rho}_{ref}$	811.24 kg/m^3
Relative expanded uncertainty (95 % confidence level)					$U(\hat{\rho}_{ref}) / \hat{\rho}_{ref}$	**0.1456 %**

43 See Table 3.19

For the standard uncertainty of the equilibrium vapour pressure, Pe_a, and base pressure, Pb_a, little information is available for the project group. However, it is seen that due to the value of the sensitivity coefficients, the contribution from these uncertainties most likely will be negligible. Therefore, these two uncertainties have been set to zero.

Compared to the uncertainties due to the measured line density, $\rho_{P,T}$, and line temperature, T, the uncertainty due to the measured line pressure may be neglected. It is evident that the sensitivity with respect to the equilibrium vapour pressure, Pe_a, and base pressure, Pb_a, is equal in magnitude to the measured line pressure, and the uncertainties due to the equilibrium vapour and base pressures may thus also be neglected.

The correction factors, C_{pld} and C_{tld}, are calculated from different models, and the model uncertainties of C_{pld} and C_{tld} are described in Chapter 3.5.2 and 3.5.1, respectively. This means that no covariance terms exist other than the term due to the measured temperature, which is common to the two correction factors. However, the covariance term due to the temperature is avoided in the uncertainty calculation by expressing the standard reference density directly in terms of the input quantities (T, P, $\rho_{T,P}$, Pb_a and Pe_a).

Table 3.18 shows that the uncertainties due to the measured pressure at the densitometer, the equilibrium vapour pressure, the base pressure and the model uncertainty of C_{pld} are negligible in the calculation of the combined uncertainty of the standard reference density. The uncertainties of the other input quantities must be included.

The model uncertainty of the volume correction factor C_{tld} is the most dominating uncertainty, causing the combined uncertainty of the calculated standard reference density to become about an order of magnitude larger than the combined uncertainty of the measured density. As mentioned in Chapter 6.3.1 it is possible to reduce this uncertainty by performing laboratory experiments on a sample of the liquid to determine the correction factor instead of using the API tables, especially concerning high temperature corrections and the uncertainties specified in Table 3.13.

3.7 Signal communication and flow computer uncertainty

Uncertainty contributions from signal communication and flow computer are not addressed in this *Handbook*, but in the program *EMU - Turbine Fiscal Oil Metering Station* the user has the possibility to specify such uncertainty contributions, in case that is found to be necessary. Normally these contributions are very small and probably negligible.

3.8 Flow calibration uncertainty

The *K-Factor*[44] is determined by proving, i.e. by sending a predefined liquid volume through the turbine meter and counting the number of pulses representative of that volume. This predefined volume is called the base volume of the Prover, and is calibrated prior to the calibration of the turbine meter by an accredited calibration laboratory. The functional relationship for the *K-Factor* has previously been given in Eqn. (3.4) on page 31, but is re-printed here for convenience:

$$\text{K} - \text{Factor} = \frac{MRp \cdot \left(C_{tlm} \cdot C_{plm}\right)}{BV \cdot \left(C_{tsp} \cdot C_{psp}\right) \cdot \left(C_{tlp} \cdot C_{plp}\right)} \qquad (3.30)$$

where

K-Factor	factor relating the number of pulses to a given volume [pulses/m^3]
MRp	number of pulses counted during the proving period [pulses]
BV	base volume of Prover [m^3]
C_{tsp}	volume correction factor for the effect of temperature on Prover steel
C_{psp}	volume correction factor for the effect of pressure on Prover steel
C_{tlp}	volume correction factor for the effect of temperature on the liquid in the Prover
C_{plp}	volume correction factor for the effect of pressure on the liquid in the Prover
C_{tlp}	volume correction factor for the effect of temperature on the liquid in the Turbine meter
C_{plp}	volume correction factor for the effect of pressure on the liquid in the Turbine meter

Please refer to Sections 3.1.3.2 and 3.5 for discussion regarding the *K-factor* expression and the volume correction factors.

[44] Cf. guidelines to the NPD regulations [NPD, 1997], paragraph 3.

Provided all the volume correction factors that are part of the *K-Factor* in Eqn. (3.4) is written directly in terms of their input quantities, most covariance terms due to correlation of input quantities are avoided. Hence, the only covariance terms remaining are due to the temperature and pressure correction factors for the liquid during proving and metering. This covariance has previously been given in Eqn. (3.6) on page 33, but is re-printed here for convenience.

$$\text{Covariance} = 2 \cdot \left\{ \begin{array}{l} \dfrac{\partial \text{K}-\text{Factor}}{\partial C_{tlm}} \cdot \dfrac{\partial \text{K}-\text{Factor}}{\partial C_{tlp}} \cdot u(C_{tlm}) \cdot u(C_{tlp}) \cdot r(C_{tlm}, C_{tlp}) \\ + \dfrac{\partial \text{K}-\text{Factor}}{\partial C_{plm}} \cdot \dfrac{\partial \text{K}-\text{Factor}}{\partial C_{plp}} \cdot u(C_{plm}) \cdot u(C_{plp}) \cdot r(C_{plm}, C_{plp}) \end{array} \right\} \qquad (3.31)$$

The correlation coefficient $r(C_{tlm},C_{tlp})$ in Eqn. (3.31) indicates the covariance between the two volume correction factors and takes values between -1 and 1. It is a parameter that must be evaluated by means of engineering judgement, and since the models are equal and the values of the input quantities are almost equal in magnitude and uncertainty, $r(C_{tlm},C_{tlp})$ and $r(C_{plm},C_{plp})$ may be considered to unity.

Please refer to Section 3.1.3.2 for further discussions regarding the covariance term of the *K-factor*.

An uncertainty model for the *K-Factor* may then be established as:

$$\begin{aligned} u_c^2(\hat{K}) = {} & s_{K,Ppa}^2 u^2(\hat{P}_{Pa}) + s_{K,Tpa}^2 u^2(\hat{T}_{Pa}) + s_{K,P}^2 u_c^2(\hat{P}) + s_{K,Pe_a}^2 u^2(\hat{P}_{e_a}) + s_{K,Pb_a}^2 u^2(\hat{P}_{b_a}) + s_{K,T}^2 u_c^2(\hat{T}) + s_{K,DP}^2 u^2(\hat{D}P) \\ & + s_{K,EMP}^2 u^2(\hat{E}MP) + s_{K,TP}^2 u^2(\hat{T}P) + s_{K,EM}^2 u^2(\hat{E}M) + s_{K,\rho_{ref}}^2 u^2(\hat{\rho}_{ref}) + s_{K,MRP}^2 u^2(\hat{M}RP) + s_{K,BV}^2 u^2(\hat{B}V) \\ & + s_{K,Cplm}^2 u^2(\hat{C}_{psm}) + s_{K,Ctlm}^2 u^2(\hat{C}_{tsm}) + s_{K,Cplp}^2 u^2(\hat{C}_{plp}) + s_{K,Ctlp}^2 u^2(\hat{C}_{tlp}) + s_{K,Ctsp}^2 u^2(\hat{C}_{tsp}) + s_{K,Cpsp}^2 u^2(\hat{C}_{psp}) \\ & + u^2(\hat{K}_{lin}) + u^2(\hat{K}_{rept}) + u^2(\hat{K}_{flocom}) + Covariance \end{aligned} \qquad (3.32)$$

where all input quantities and models have been described in previous Sections. However, a brief comment with reference to the relevant Sections is given for reference:

$u^2(\hat{P}_{Pa}) \equiv$ standard uncertainty of average Prover inlet and outlet pressure [barg], see Section 3.5.4.

$u^2(\hat{T}_{Pa}) \equiv$ standard uncertainty of average Prover inlet and outlet temperature [°C], see Section 3.5.3.

$u_c^2(\hat{P}) \equiv$ combined standard uncertainty of line pressure measurement [bar], see Section 3.3.

$u^2(\hat{P}_{e_a}) \equiv$ standard uncertainty of equilibrium vapour pressure at the temperature of the liquid being measured [kPa], in absolute pressure units, see Section 3.5.2.

$u^2(\hat{P}_{b_a}) \equiv$ standard uncertainty of the base (reference or standard) pressure [kPa], in absolute pressure units, see Section 3.5.2.

$u_c^2(\hat{T}) \equiv$ combined standard uncertainty of line temperature measurement [°C], see Section 3.2.

$u^2(\hat{D}P) \equiv$ standard uncertainty of internal diameter of Prover pipe [m], see Section 3.5.4.

$u^2(\hat{E}MP) \equiv$ standard uncertainty of modulus of elasticity of the Prover material [barg], see Section 3.5.4.

$u^2(\hat{T}P) \equiv$ standard uncertainty of wall thickness of Prover pipe [m], see Section 3.5.4.

$u^2(\hat{E}M) \equiv$ standard uncertainty of the coefficient of cubical expansion per °C of the material of which the prover is made, see Section 3.5.3.

$u_c^2(\hat{\rho}_{ref}) \equiv$ combined standard uncertainty in standard reference density [kg/m^3], see Section 3.6.

$u^2(\hat{M}RP) \equiv$ standard uncertainty if the number of pulses counted during the proving period [pulses], see Section 3.1.3.2.

$u^2(\hat{B}V) \equiv$ standard uncertainty of the Prover volume [m^3], see Section 3.1.3.2.

$u^2(\hat{C}_{psm}) \equiv$ standard uncertainty of the C_{psm} volume correction model itself, see Section 3.5.5.

$u^2(\hat{C}_{tsm}) \equiv$ standard uncertainty of the C_{tsm} volume correction model itself, see Section 3.5.5.

$u^2(\hat{C}_{plp}) \equiv$ standard uncertainty of the C_{plp} volume correction model itself, see Section 3.5.2.

$u^2(\hat{C}_{tlp}) \equiv$ standard uncertainty of the C_{tlp} volume correction model itself, see Section 3.5.1.

$u^2(\hat{C}_{tsp}) \equiv$ standard uncertainty of the C_{tsp} volume correction model itself, see Section 3.5.3.

$u^2(\hat{C}_{psp}) \equiv$ standard uncertainty of the C_{psp} volume correction model itself, see Section 3.5.4.

$u^2(\hat{K}_{lin}) \equiv$ standard uncertainty of the linearity of the *K-factor* estimate, see Section 3.1.3.2.

$u^2(\hat{K}_{rept}) \equiv$ standard uncertainty of the repeatability of the *K-factor* estimate, see Section 3.1.3.2.

$u^2(\hat{K}_{flocom}) \equiv$ standard uncertainty of the signal communication and flow computer (calculations), see Section 3.7.

Covariance $\equiv$ covariance term due to the correlation of volume correction factor model uncertainties, see Eqn. (3.31).

The functional relationships for the sensitivity coefficients have not been given in this document, as the expressions become too large to print. If required, computational aids should be used to derive and present these expressions on basis of the functional relationships described in Sections 3.1 to 3.8.

A computational aid has also been used to derive these expressions for implementation in the *EMU - Turbine Fiscal Oil Metering Station* program.

3.8.1 Example uncertainty evaluation

A sample uncertainty budget has been established for the *K-Factor* for evaluation of the influence of the individual input quantities, and this uncertainty budget is shown in Table 3.20. The uncertainty budget is based on the input data described in Table 3.19.

Depending on the MR_p/BV value, the uncertainties of the volume correction factors will be subjected to rather large sensitivity coefficients when calculating the combined uncertainty of the *K-Factor*. However, a covariance term must be included since the C_{psp} and C_{psm}, and C_{tsp} and C_{tsm}, volume correction factors are calculated using the same models and hence become correlated.

Table 3.19 Figures used in the sample uncertainty budget in Table 3.20.

Input quantity	**Comment / Description**	**Value**	**Expanded Uncertainty (95% confidence level)**
Ppa	Avg. internal pressure of prover inlet and outlet [barg]	18.0 barg	0.16 bar (Cf. Section 3.3)
Tpa	Average temperature of prover inlet and outlet [°C]	65 °C	0.16 °C (Cf. Section 3.2)
P	Line pressure [barg]	18.0 barg	0.16 bar (Cf. Section 3.3)
Pb_a	Base (reference or standard) pressure, in absolute pressure units [bar].	1.01325 bar	0.0 bar (Cf. Section 3.6.2)
Pe_a	Equilibrium vapour pressure at the temperature of the liquid being measured, in absolute pressure units [bar].	1.01325 bar	0.0 bar (Cf. Section 3.6.2)
T	Line temperature [°C]	65 °C	0.16 °C (Cf. Section 3.2)
DP	Internal diameter of prover pipe [m]	444.5·10-3 m	0.75% of DP [Sample values, 1999]
EMP	Modulus of elasticity for the prover material [barg]	2034000 barg	0.5% of EMP [Sample values, 1999]
TP	Wall thickness of prover pipe [m]	0.014275 m	0.07% of TP [Sample values, 1999]
EM	Coefficient of cubical expansion per degree Celsius of the material of which the prover is made [1/°C]	0.0000335 1/°C	0.5% of EM [Sample values, 1999]
ρ_{ref}	Density at standard temperature (15 °C) and pressure (1.01325 bara) [kg/m3]	812.48 kg/m^3	1.25 kg/m3 (Cf. Section 3.4)
MRp	Measured turbine meter pulses using pulse interpolation.	90092	0.0001% of MRp
BV	Base volume of the prover [m3]	28.646 m^3	0.011 m^3 [Con-Tech, 1999]]
Flocom	Flow computer calculation uncertainty.	-	0.0001% of average K-factor
Linearity	Linearity of the turbine meter.	-	0.15% of average K-factor [NPD, 2001a]
Repeatabi lity	Repeatability of the turbine meter	-	0.020% of average K-factor [NPD, 2001a]

The uncertainties of the volume correction factor models are given in Chapter 3.5.

Table 3.20 Sample uncertainty budget for the uncertainty of the K-Factor.

Source	Input uncertainty				Combined uncertainty	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact. *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
P_{pa}	0.01568 bar	95% (norm)	2	0.0078 bar	$-4.07 \cdot 10^{-1}$ P/(m^3 bar)	$1.02 \cdot 10^{-5}$ (P/m^3)^2
T_{pa}	0.1565 °C	95% (norm)	2	0.0783 °C	3.00 P/(m^3 °C)	$5.51 \cdot 10^{-2}$ (P/m^3)^2
P	0.01568 bar	95% (norm)	2	0.0078 bar	$3.59 \cdot 10^{-1}$P/(m^3 bar)	$7.93 \cdot 10^{-6}$ (P/m^3)^2
Pe_a	0.0 bar	Standard	1	0.0 bar	0 P/(m^3 bar)	0 (P/m^3)^2
Pb_a	0.0 bar	Standard	1	0.0 bar	0 P/(m^3 bar)	0 (P/m^3)^2
T	0.1565 °C	95% (norm)	2	0.0783 °C	-3.10 P/(m^3 °C)	$5.90 \cdot 10^{-2}$ (P/m^3)^2
DP	0.001607 mm	Standard	1	$1.61 \cdot 10^{-6}$ mm	-1.95 P/(m^3 m)	$9.77 \cdot 10^{-12}$ (P/m^3)^2
EMP	5085 bar	Standard	1	5085 bar	$4.25 \cdot 10^{-7}$ P/(m^3 bar)	$4.67 \cdot 10^{-6}$ (P/m^3)^2
TP	0.004996 mm	Standard	1	$5.0 \cdot 10^{-6}$ mm	$6.06 \cdot 10^{-1}$ P/(m^3 m)	$9.16 \cdot 10^{-8}$ (P/m^3)^2
EM	$8.38 \cdot 10^{-8}$ 1/K	Standard	1	$8.38 \cdot 10^{-8}$ 1/K	$-1.57 \cdot 10^{-5}$ P K	$1.72 \cdot 10^{-4}$ (P/m^3)^2
ρ_{ref}	1.181 kg/m^3	95% (norm)	2	0.591 kg/m^3	0 P/kg	0 (P/m^3)^2
MRp	0.045046 P	Standard	1	0.045046 P	$3.48 \cdot 10^{-2}$ 1/m^3	$2.46 \cdot 10^{-6}$ (P/m^3)^2
BV	0.0055 m^3	Standard	1	0.0055 m^3	$-1.10 \cdot 10^{2}$ P/(m^{3}m^3)	$3.63 \cdot 10^{-1}$ (P/m^3)^2
C_{plm}	$3.0 \cdot 10^{-4}$	95% (norm)	2	$1.5 \cdot 10^{-4}$	$3.13 \cdot 10^{3}$ P/m^3	$2.21 \cdot 10^{-1}$ (P/m^3)^2
C_{tlm}	$7.15 \cdot 10^{-4}$	Standard	1	$7.15 \cdot 10^{-4}$	$3.29 \cdot 10^{3}$ P/m^3	5.55 (P/m^3)^2
C_{plp}	$3.0 \cdot 10^{-4}$	95% (norm)	2	$1.5 \cdot 10^{-4}$	$-3.13 \cdot 10^{3}$ P/m^3	$2.21 \cdot 10^{-1}$ (P/m^3)^2
C_{tlp}	$7.15 \cdot 10^{-4}$	Standard	1	$7.15 \cdot 10^{-4}$	$-3.29 \cdot 10^{3}$ P/m^3	5.55 (P/m^3)^2
C_{tsp}	0	Standard	1	0	$-3.13 \cdot 10^{3}$ P/m^3	0 (P/m^3)^2
C_{psp}	0	Standard	1	0	$-3.14 \cdot 10^{3}$ P/m^3	0 (P/m^3)^2
Linearity	2.35411 P/m^3	Standard	1	2.35411	1	5.54 (P/m^3)^2
Repeatability	0.31388 P/m^3	Standard	1	0.31388	1	$9.85 \cdot 10^{-2}$ (P/m^3)^2
Calculation	0.001569 P/m^3	Standard	1	0.001569	1	$2.46 \cdot 10^{-6}$ (P/m^3)^2
Covariance						$-1.15 \cdot 10^{1}$ (P/m^3)^2
Sum of variances					$u_c^2(\hat{K}-factor)$	6.12 (P/m^3)^2
Combined standard uncertainty					$u_c(\hat{K}-factor)$	2.473 P/m^3
Expanded uncertainty (95 % confidence level, *k* = 2)					$U(\hat{K}-factor)$	**4.947 P/m^3**
Reference density					$\hat{K}-factor$	3138.89 P/m^3
Relative expanded uncertainty (95 % confidence level)					$\frac{U(\hat{K}-factor)}{\hat{K}-factor}$	**0.1576 %**

From Table 3.20 it is evident that the uncertainty due to the linearity is the most dominating uncertainty of the *K-factor*, and that many of the uncertainties of the input quantities are negligible. Furthermore, the model uncertainty of the liquid temperature volume correction factors is quite large (Cf. Chapter 3.5.1) compared to the other uncertainties. However, the covariance term is also large and cancels much of the volume correction factor model uncertainties.

3.8.1.1 Simplified calculation of the combined standard uncertainty of the K-factor

Since many of the uncertainty contributions to the *K-factor* are very small, Table 3.21 shows a reduced sample uncertainty budget where the input quantities that are considered to have negligible influence on the combined uncertainty are left out. The uncertainty due to the pulse interpolation is still included while an increase in the uncertainty of the pulse interpolation leads to a rapid increase in the influence on the combined uncertainty of the *K-Factor* due to the large numbers involved.

The model uncertainty due to the pressure correction factors might also be neglected, but as they are implemented in the uncertainty calculation program (both as model uncertainty and in the covariance term) they are still included in the evaluation.

Table 3.21 Reduced uncertainty budget for the uncertainty of the K-Factor.

Source	**Given uncertainty**	**Conf. level & Distribut.**	**Cov. fact. *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
T_{pa}	0.1565 °C	95% (norm)	2	0.0783 °C	3.00 P/(m^3 °C)	5.51·10^{-2} (P/m^3)^2
T	0.1565 °C	95% (norm)	2	0.0783 °C	-3.10 P/(m^3 °C)	5.90·10^{-2} (P/m^3)^2
MRp	0.045046 P	Standard	1	0.045046 P	3.48·10^{-2} 1/m^3	2.46·10^{-6} (P/m^3)^2
BV	0.0055 m^3	Standard	1	0.0055 m^3	-1.10·10^2 P/(m^{3}m^3)	3.63·10^{-1} (P/m^3)^2
C_{plm}	3.0·10^{-4}	95% (norm)	2	1.5·10^{-4}	3.13·10^3 P/m^3	2.21·10^{-1} (P/m^3)^2
C_{tlm}	7.15·10^{-4}	Standard	1	7.15·10^{-4}	3.29·10^3 P/m^3	5.55 (P/m^3)^2
C_{plp}	3.0·10^{-4}	95% (norm)	2	1.5·10^{-4}	-3.13·10^3 P/m^3	2.21·10^{-1} (P/m^3)^2
C_{tlp}	7.15·10^{-4}	Standard	1	7.15·10^{-4}	-3.29·10^3 P/m^3	5.55 (P/m^3)^2
Linearity	2.35411 P/m^3	Standard	1	2.35411	1	5.54 (P/m^3)^2
Repeatability	0.31388 P/m^3	Standard	1	0.31388	1	9.85·10^{-2} (P/m^3)^2
Covariance						-1.15·10^1 (P/m^3)^2
Sum of variances					$u_c^2(\hat{K}-factor)$	6.12 (P/m^3)^2
Combined standard uncertainty					$u_c(\hat{K}-factor)$	2.473 P/m^3
Expanded uncertainty (95 % confidence level, *k* = 2)					$U(\hat{K}-factor)$	**4.947 P/m^3**
Reference density					$\hat{K}-factor$	3138.89 P/m^3
Relative expanded uncertainty (95 % confidence level)					$\frac{U(\hat{K}-factor)}{\hat{K}-factor}$	**0.1576 %**

There is no deviation between the uncertainty calculated in Table 3.21 and the uncertainty calculated in Table 3.20; hence the uncertainty introduced by this simplification is negligible.

From the sample uncertainty budgets in Table 3.20 and Table 3.21 it is evident that the simplified uncertainty evaluation shown in Table 3.21 can be applied. This significantly reduces the number of input quantity uncertainties that need to be specified and documented as part of the uncertainty evaluation, although the figures of all input quantities are still required. Furthermore, the model uncertainties of the volume correction factors and the covariance term should be included, since these uncertainties depend strongly on the operating conditions. The reduced uncertainty calculation shown in Table 3.21 is also implemented an as option to use in the *EMU - Turbine Fiscal Oil Metering Station* program.

3.9 Combined expanded uncertainty of the Turbine fiscal oil metering station

The combined expanded uncertainty of the Turbine fiscal oil metering station is calculated in terms of standard volume flow rate. The functional relationship for the standard volume flow rate has previously been given in Eqn. (3.1) on page 29, but is re-printed here for convenience:

$$Q = \frac{MR_m}{K} \cdot C_{tlm} \cdot C_{plm} \cdot 3600 \quad [\mathrm{m^3/h}] \tag{3.2}$$

where

Q - standard volume flow rate [m^3/h]

MR_m - pulses counted per minute during metering [pulses/minute]

K - *K-Factor* [pulses/m^3]

C_{tlm} - volume correction factor for the effect of temperature on the liquid during metering (line conditions)

C_{plm} - volume correction factor for the effect of pressure on the liquid during metering (line conditions)

Please refer to Sections 3.1.3.1 and 3.5 for discussion regarding the functional relationship for the standard volume flow rate and the volume correction factors.

By writing the volume correction factors in Eqn. (3.2) directly in terms of their input quantities, correlation between these input quantities are avoided[45]. The model uncertainties of the volume correction factors must be included separately. However, there will be correlations due to the common input quantities *T, P,* MR_m and the volume correction factors and standard density that are applied both in the calculation of the *K-factor* and *Q*.

The functional relationship for the covariance term for the standard volume flow rate given in Eqn. (3.3) has also been re-printed here for convenience:

$$\text{Covariance} = 2 \cdot \left\{ \begin{array}{l} \dfrac{\partial Q}{\partial T_{m\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial T_{m\_proving}} \right) \cdot u(T_{m\_metering}) \cdot u(T_{m\_proving}) \cdot 1 \\ + \dfrac{\partial Q}{\partial P_{m\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial P_{m\_proving}} \right) \cdot u(P_{m\_metering}) \cdot u(P_{m\_proving}) \cdot 1 \\ + \dfrac{\partial Q}{\partial MR_m} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial MR_p} \right) \cdot u(MR_m) \cdot u(MR_p) \cdot 1 \\ + \dfrac{\partial Q}{\partial C_{tlm\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial C_{tlm\_proving}} \right) \cdot u(C_{tlm\_metering}) \cdot u(C_{tlm\_proving}) \cdot 1 \\ + \dfrac{\partial Q}{\partial C_{tlm\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial C_{tlp}} \right) \cdot u(C_{tlm\_metering}) \cdot u(C_{tlp}) \cdot 1 \\ + \dfrac{\partial Q}{\partial C_{plm\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial C_{plm\_proving}} \right) \cdot u(C_{plm\_metering}) \cdot u(C_{plm\_proving}) \cdot 1 \\ + \dfrac{\partial Q}{\partial C_{plm\_metering}} \cdot \left(\dfrac{\partial Q}{\partial K-factor} \cdot \dfrac{\partial K-Factor}{\partial C_{plp}} \right) \cdot u(C_{plm\_metering}) \cdot u(C_{plp}) \cdot 1 \end{array} \right\} \qquad (3.33)$$

An uncertainty model for the standard volume flow rate, *Q*, may then be established as:

$$\begin{aligned} u_c^2(\hat{Q}) &= s_{\hat{Q},MRm}^2 u^2(\hat{M}Rm) + s_{\hat{Q},K}^2 u^2(\hat{K}) + s_{\hat{Q},C_{tlm}}^2 u^2(\hat{C}_{tlm}) + s_{\hat{Q},C_{plm}}^2 u^2(\hat{C}_{plm}) \\ &+ s_{\hat{Q},C_P}^2 u^2(\hat{P}) + s_{\hat{Q},C_T}^2 u^2(\hat{T}) + s_{\hat{Q},C_{\rho_{ref}}}^2 u^2(\hat{\rho}_{ref}) + Covariance \end{aligned} \qquad (3.34)$$

where all input quantities and models have been described in previous Sections. However, a brief comment with reference to the relevant Sections are given for reference:

$u^2(\hat{M}Rm) \equiv$ standard uncertainty of the number of pulses counted per second during metering [pulses/sec], see Section 3.1.3.1.

[45] Eqn. (3.2) has not been written with all volume correction factors given in terms of input quantities, as this would become a rather large and complex expression. Computational aids should be used in order to avoid typing errors.

$u^2(\hat{K}) \equiv$ standard uncertainty of the K-factor, see Sections 3.1.3.2 and 3.8.

$u^2(\hat{C}_{plm}) \equiv$ standard uncertainty of the C_{plm} volume correction model itself, see Section 3.5.2.

$u^2(\hat{C}_{tlm}) \equiv$ standard uncertainty of the C_{tlm} volume correction model itself, see Section 3.5.1.

$u_c^2(\hat{P}) \equiv$ combined standard uncertainty of the line pressure measurement, see Section 3.2.

$u_c^2(\hat{T}) \equiv$ combined standard uncertainty of the line temperature measurement, see Section 3.3.

$u_c^2(\hat{\rho}_{ref}) \equiv$ combined standard uncertainty of the density at standard reference conditions, see Section 3.6.

Covariance $\equiv$ covariance term due to the correlation of volume correction factor model uncertainties, Eqn. (3.33).

The sensitivity coefficients appearing in Eqn. (3.34) are defined as:

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{M}Rm} \qquad (3.35)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{P}} \qquad (3.36)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{K}} \qquad (3.37)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{T}} \qquad (3.38)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{C}_{plm}} \qquad (3.39)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{\rho}_{ref}} \qquad (3.40)$$

$$s_{Q,MRm} = \frac{\delta\hat{Q}}{\delta\hat{C}_{tlm}} \qquad (3.41)$$

3.9.1 Example uncertainty evaluation

The evaluation of the uncertainty of the standard volume flow rate is based on the previous chapters (Table 3.22).

Table 3.22. Values used in the sample calculations in Table 3.23.

Input quantity	Comment / Description	Value	Expanded Uncertainty (95% confidence level)
Mrm	Number of meter pulses during metering	53465 pulses / second	0.0001% of *Mrm*

Table 3.23 Sample uncertainty budget for the uncertainty of the standard volume flow rate.

Source	Input uncertainty				Combined uncertainty	
	Given uncertainty	**Conf. level & Distribut.**	**Cov. fact. *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
T, $U(\hat{T})$	0.1565 °C	95 % (norm)	2	0.0783 °C	-0.989 Sm³/h/°C	$6.00 \cdot 10^{-3}$ (Sm³/h)²
P, $U(\hat{P})$	0.01568 bar	95 % (norm)	2	0.00784 bar	0.113 Sm³/h/bar	$7.83 \cdot 10^{-7}$ (Sm³/h)²
ρ_{ref}, $U(\hat{\rho}_{ref})$	1.181 kg/m^3	95 % (norm)	2	0.591 kg/m^3	0.115 Sm³/h/(kg/m^3)	$4.62 \cdot 10^{-3}$ (Sm³/h)²
MRm, $U(\hat{M}Rm)$	0.009 P/s	95 % (norm)	2	0.0045 P/s	1.10 Sm³/h/(P/s)	$2.44 \cdot 10^{-5}$ (Sm³/h)²
K-Factor, $U(\hat{K} - factor)$	4.947 P/m³	95 % (norm)	2	2.473 P/m^3	-0.319 Sm³/h/(P/m^3)	$6.21 \cdot 10^{-1}$ (Sm³/h)²
C_{plm}, $U(\hat{C}_{plm})$	0.0003	95 % (norm)	2	$1.5 \cdot 10^{-4}$	$9.98 \cdot 10^{2}$ Sm³/h	$2.24 \cdot 10^{-2}$ (Sm³/h)²
C_{tlm}, $U(\hat{C}_{tlm})$	0.00143	95 % (norm)	2	$7.15 \cdot 10^{-4}$	$1.05 \cdot 10^{3}$ Sm³/h	$5.61 \cdot 10^{-1}$ (Sm³/h)²
Covariance						$-1.2 \cdot 10^{-2}$ (Sm³/h)²
Sum of variances				$u_c^2(\hat{Q})$		1.20 (Sm³/h)²
Combined standard uncertainty				$u_c(\hat{Q})$		1.097 Sm³/h
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{Q})$		**2.194** Sm³/h
Operating density				$\hat{Q}$		1000 Sm³/h
Relative expanded uncertainty (95 % confidence level)				$U(\hat{Q})/\hat{Q}$		**0.2194 %**

From the uncertainty budget in Table 3.23 it is seen that the resulting relative expanded uncertainty becomes 0.22% which is well within the NPD requirement [NPD, 2001a] of 0.30% relative expanded uncertainty of measured standard volume flow rate.

The covariance term is large and has a reducing influence on the uncertainty. This is consistent with the fact that the turbine meter measurements are relative measurements (relative to a calibrated volume), and by calibration during proving the systematic uncertainties are minimised. It is also evident that the uncertainty due to the flow computer calculation and the pulse interpolation may be neglected from the calculation.

The uncertainty calculation shown in Table 3.23, without the uncertainty due to the flow computer calculation, is therefore implemented in the uncertainty calculation program.

3.9.2 Parallel metering runs

Uncertainty evaluation of parallel metering runs is not part of this handbook. This matter should be handled with care, because instruments common to several metering runs introduce correlations that may be hard to evaluate. An ideal situation, with no common instrumentation (and a pipe Prover for each run), would give no correlation between the metering runs.

The total standard volume flow rate of a two-run oil metering station would then become:

$$Q_{TOTAL} = Q_A + Q_B \tag{3.42}$$

where

$Q_{\_TOTAL}$ - is the total standard volume flow rate [Sm^3/h]
$Q_{\_A}$ - is the standard volume flow rate [Sm^3/h] of run A
$Q_{\_B}$ - is the standard volume flow rate [Sm^3/h] of run B

With two metering stations for fiscal oil measurement like the one evaluated in this handbook, with no common instrumentation, the combined standard uncertainty of the metering station parallel runs can simply be calculated as:

$$u_c(Q_{TOTAL}) = \sqrt{[u(Q_A)]^2 + [u(Q_B)]^2} \;=\; 3.10 \text{ Sm}^3/\text{h} \tag{3.43}$$

With two metering stations for fiscal oil measurement like the one evaluated in this handbook, with no common instrumentation, the relative expanded uncertainty becomes:

$$\delta Q_{TOTAL} = \frac{k_{95} \cdot u_c(Q_{TOTAL})}{Q_{TOTAL}} = \frac{2 \cdot 3.10}{2000} = 0.31\% \qquad (3.44)$$

It is seen that for this ideal case the combined uncertainty of the metering station becomes smaller than the combined uncertainty of each metering run. It is important to note, however, that in practise at least a pipe prover is common to the metering runs and often a common densitometer is used. This introduces correlation between the metering runs, and this correlation becomes even harder to evaluate if also other instruments are common to the metering runs as well.

4. PROGRAM "EMU - TURBINE FISCAL OIL METERING STATION"

The present chapter describes the Excel program *EMU - Turbine Fiscal Oil Metering Station* which has been implemented for performing uncertainty analysis of turbine meter based fiscal oil metering stations. The program applies to metering stations equipped as described in Section 3.1.1, and is based on the uncertainty model for such metering stations as described in Chapter 3. Using this program, uncertainty evaluation can be made for the expanded uncertainty (at a 95% confidence level, using $k = 2$) for the standard volume flow rate, Q.

The program simplifies the calculation of the combined uncertainty of the fiscal oil metering station significantly, and it may be used for evaluation of the individual and combined uncertainties. The program enables one to simulate different operating conditions, and calculate the corresponding uncertainties to study the influence of changes in the operating conditions.

The uncertainties calculated by the program may be used in the documentation with reference to the handbook. However, it must be emphasised that the inputs to the program must be documented (Cf. Section 2.4), and that the user must document that the calculation procedures and functional relationships implemented in the program (Cf. Chapter 3) are equal to the ones actually applied in the fiscal oil metering station.

4.1 General

The program is implemented in Microsoft Excel 2000 and is based on worksheets where the user enters input data to the calculations. These "input worksheets" are mainly formed as uncertainty budgets, which are continuously updated as the user enters new input data. Other worksheets provide display of the uncertainty calculation results, and are continuously updated in the same way.

With respect to specification of inpu parameters, colour codes are used in the program *EMU - Turbine Fiscal Oil Metering Stations*, according to the following scheme:

- Black font: Value that <u>must</u> be entered by the user,
- Blue font: Outputs from the program, or number read from another worksheet (editing prohibited)

In the following subsections the worksheets of the program are shown and briefly explained, and the necessary input parameters are addressed with an indication of where in Chapter 3 the input values are discussed.

Output data are presented in separate worksheets, graphically (curves and bar-charts), and by listing. An output report worksheet is available, summarizing the main uncertainty calculation results.

The expanded uncertainties calculated by the program may be used in the documentation of the metering station uncertainty, with reference to the present *Handbook*. The worksheets are designed so that printouts of these can be used directly as part of the uncertainty evaluation documentation. They may also conveniently be copied into a text document[46], for documentation and reporting purposes. However, it must be emphasised that the inputs to the program (quantities, uncertainties, confidence levels and probability distributions) must be documented by the user of the program. The user must also document that the calculation procedures and functional relationships implemented in the program are in conformity with the ones actually applied in the fiscal oil metering station.

In a practical work situation in the evaluation of a metering station, a convenient way to use the program may be the following. After the desired input parameters and uncertainties have been entered, the Excel file document may be saved e.g. using a modified file name, e.g. "*EMU - Turbine Fiscal Oil Metering Station - MetStat1.xls*", "*EMU - Turbine Fiscal Oil Metering Station - MetStat2.xls*", etc. Old evaluations may then conveniently be revisited, used as basis for new evaluations, etc.

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46 For instance, by using Microsoft Word 2000, a "cut and paste special" with "picture" functionality may be sufficient for most worksheets. However, for some of the worksheets the full worksheet is (for some reason) not being pasted using the "paste special" with "picture" feature. Only parts of the worksheet are copied. In this case use of the "paste special" with "bitmap" feature may solve the problem.
However, if the Word (doc) file is to be converted to a pdf-file, use of the "bitmap" feature results in poor-quality pictures. In this case it is recommended to first convert the Excel worksheet in question into an 8-bit gif-file (e.g. using Corel Photo Paint 7), and then import the gif-file as a picture into the Word document. The resulting quality is not excellent, but still useful.

4.2 Oil parameters

In the worksheet denoted “Oil parameters” shown in Figure 4.1, the user enters data for

- o The operating and proving oil conditions for the fiscal oil metering station and prover
- o The oil conditions in the densitometer
- o The oil conditions at flow calibration
- o The ambient temperature and pressure

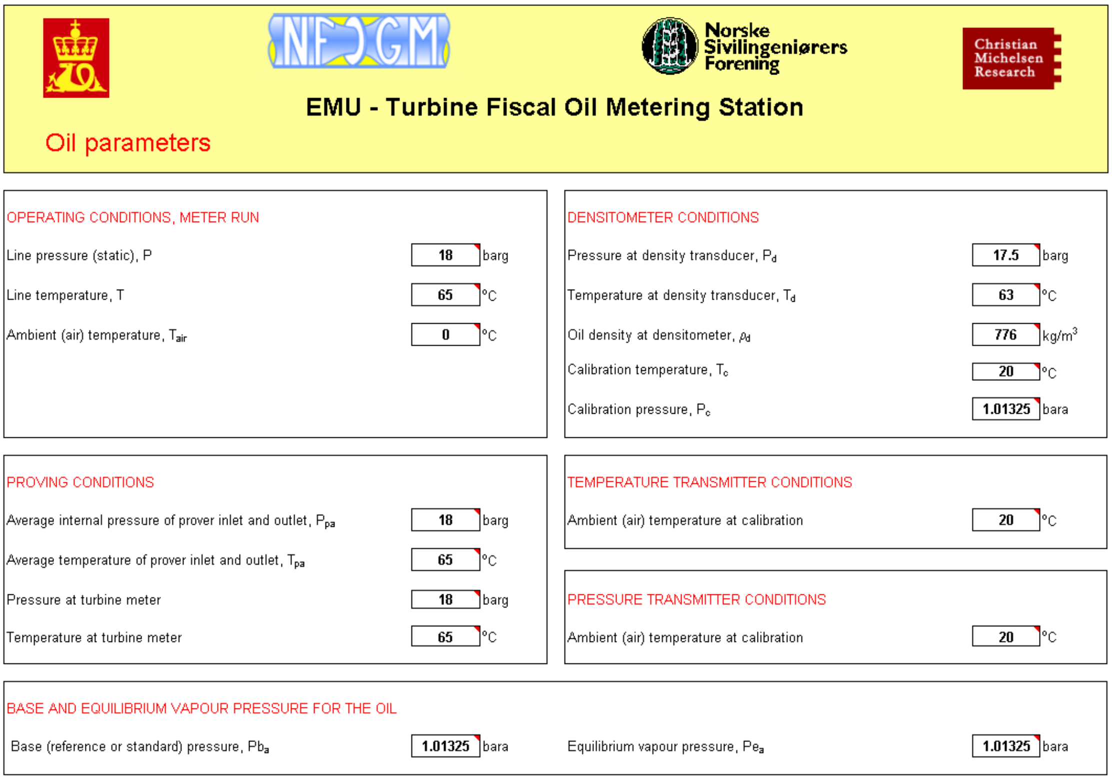


Figure 4.1 Operation condition display from the program EMU - Turbine Fiscal Oil Metering Station. (Corresponds to Table 3.2).

The program uses these data in the calculation of the individual uncertainties of the primary measurements, and in calculation of the combined oil metering station uncertainty. The data used in the input worksheet shown in Figure 4.1 are the same data as specified in Table 3.2 for the calculation example given in Chapter 3.

4.3 Turbine meter and Prover setup parameters

The worksheet for setup of the Turbine meter and Prover is shown in Figure 4.2. The input parameters are the inner diameter of the Turbine meter and Prover material data.

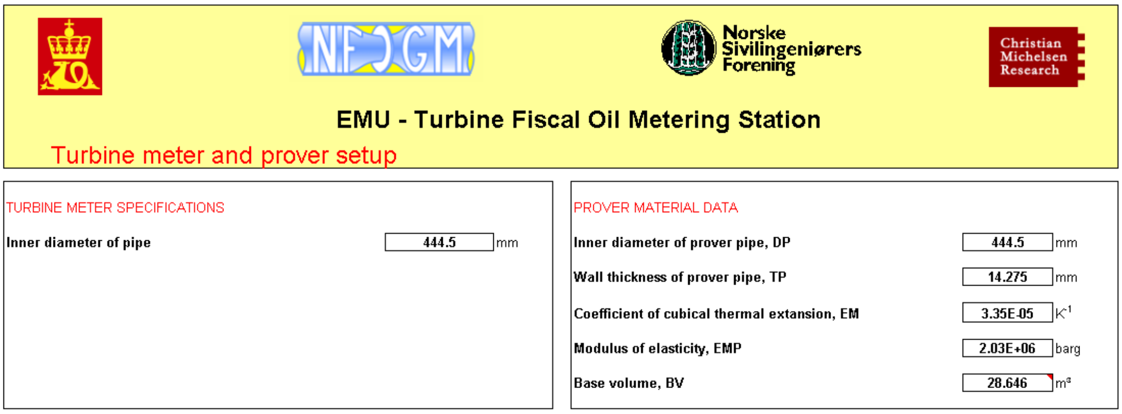


Figure 4.2 The "Turbine meter and Prover setup" worksheet in the program EMU - Turbine Fiscal Oil Metering Station.

4.4 Temperature measurement uncertainty

The worksheet "*T*" for evaluation of the expanded uncertainty of the temperature measurement in the meter run is shown in Figure 4.3 and Figure 4.4, for the "overall level" and the "detailed level", respectively. These are described separately below.

4.4.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the temperature measurement uncertainty, the user specifies only the relative expanded uncertainty of the temperature measurement, and the accompanying confidence level / probability distribution, see Figure 4.3.

This option is used e.g. when the user does not want to go into the "detailed" level of the temperature measurement, or if the "detailed level" setup does not fit sufficiently well to the temperature element and transmitter at hand. The user must then document the input value used for the relative expanded uncertainty of the temperature measurement (the "given uncertainty"), and its confidence level and probability distribution.

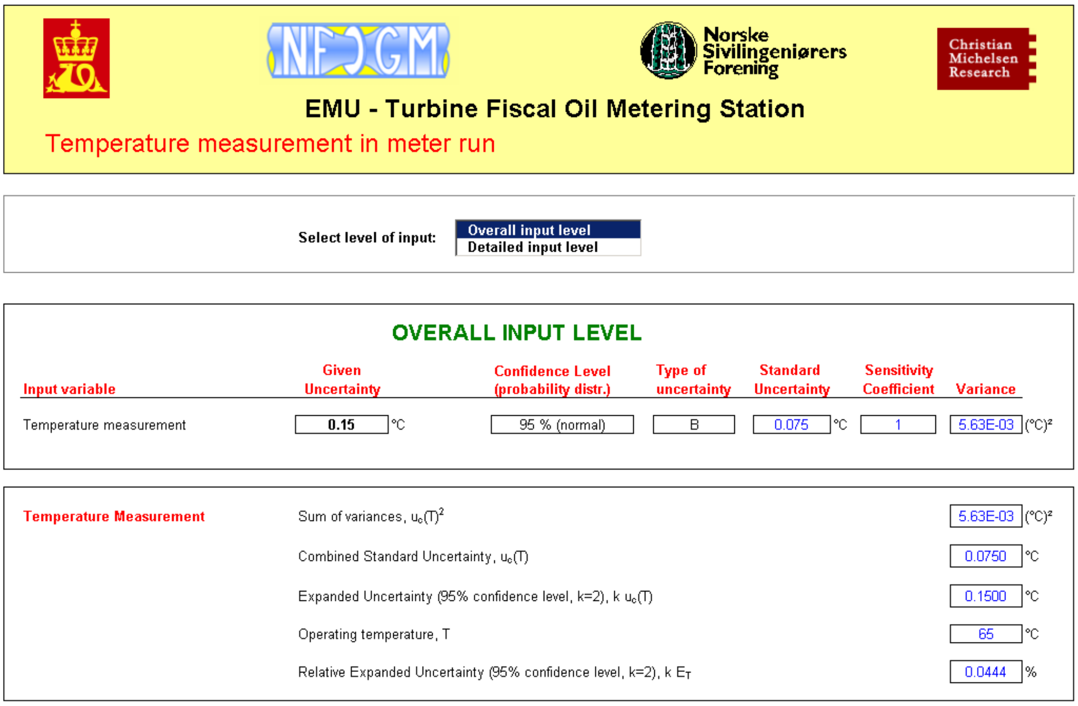


Figure 4.3 The "T" worksheet in the program EMU - Turbine Fiscal Oil Metering Station, shown for the "overall level" option.

4.4.2 Detailed level

When the "detailed level" is chosen for specification of input uncertainties to calculation of the temperature measurement uncertainty, the user specifies the uncertainty data of the temperature element and transmitter in question, together with the accompanying confidence levels / probability distributions. Cf. Table 3.5. The user must himself document the input uncertainty values for the temperature measurement, e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.

In Table 3.4 the uncertainty figures given for the Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2001] used in combination with a Pt 100 temperature element, have been specified. These are the same as used in Table 3.5, see Section 3.2 for details. A blank field denoted "type of instrument" can be filled in to document the instrument evaluated, for reporting purposes.

In addition to the input uncertainty data, the user must specify the "time between calibrations". The "ambient temperature deviation" is calculated by the program from data given in the "Oil parameters" worksheet.

In addition to the "usual" temperature transmitter input uncertainties given in the worksheet, a "blank cell" has been defined, where the user can specify miscellaneous uncertainty contributions to the temperature measurement not covered by the other input cells in the worksheet. The user must then document the input value used for the "miscellaneous uncertainty" of the temperature measurement, and its confidence level and probability distribution.

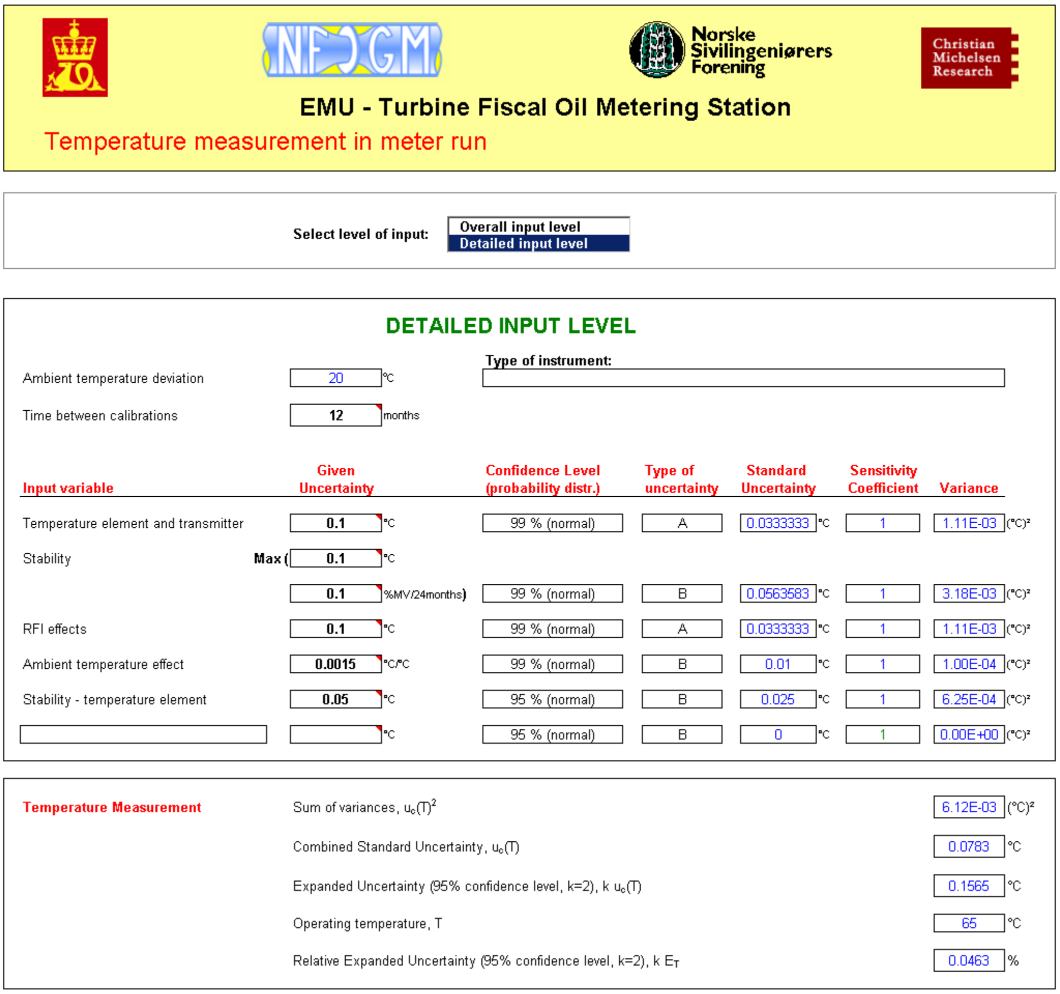


Figure 4.4 The "T" worksheet in the program EMU - Turbine Fiscal Oil Metering Station, shown for the "detailed level" option. (Corresponds to Table 3.5).

4.5 Pressure measurement uncertainty

The worksheet "*P*" for evaluation of the expanded uncertainty of the pressure measurement in the meter run is shown in Figure 4.5 and Figure 4.6, for the "overall level" and the "detailed level", respectively. These are described separately below.

4.5.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters only the relative expanded uncertainty of the pressure measurement, and the accompanying confidence level / probability distribution, see Figure 4.5.

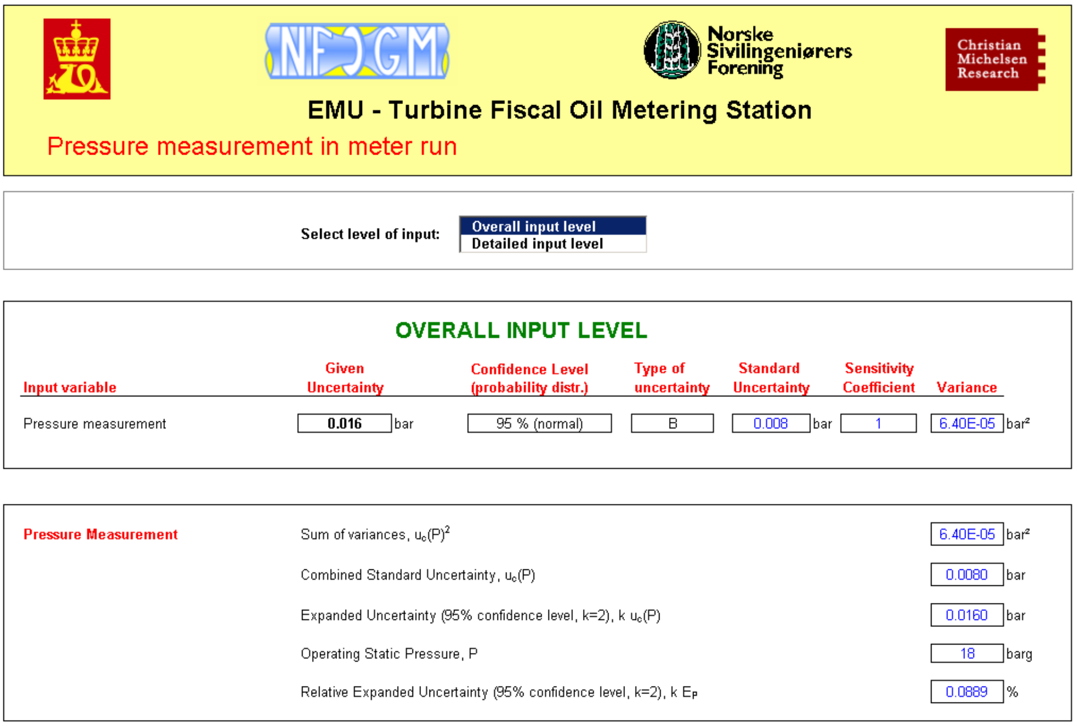
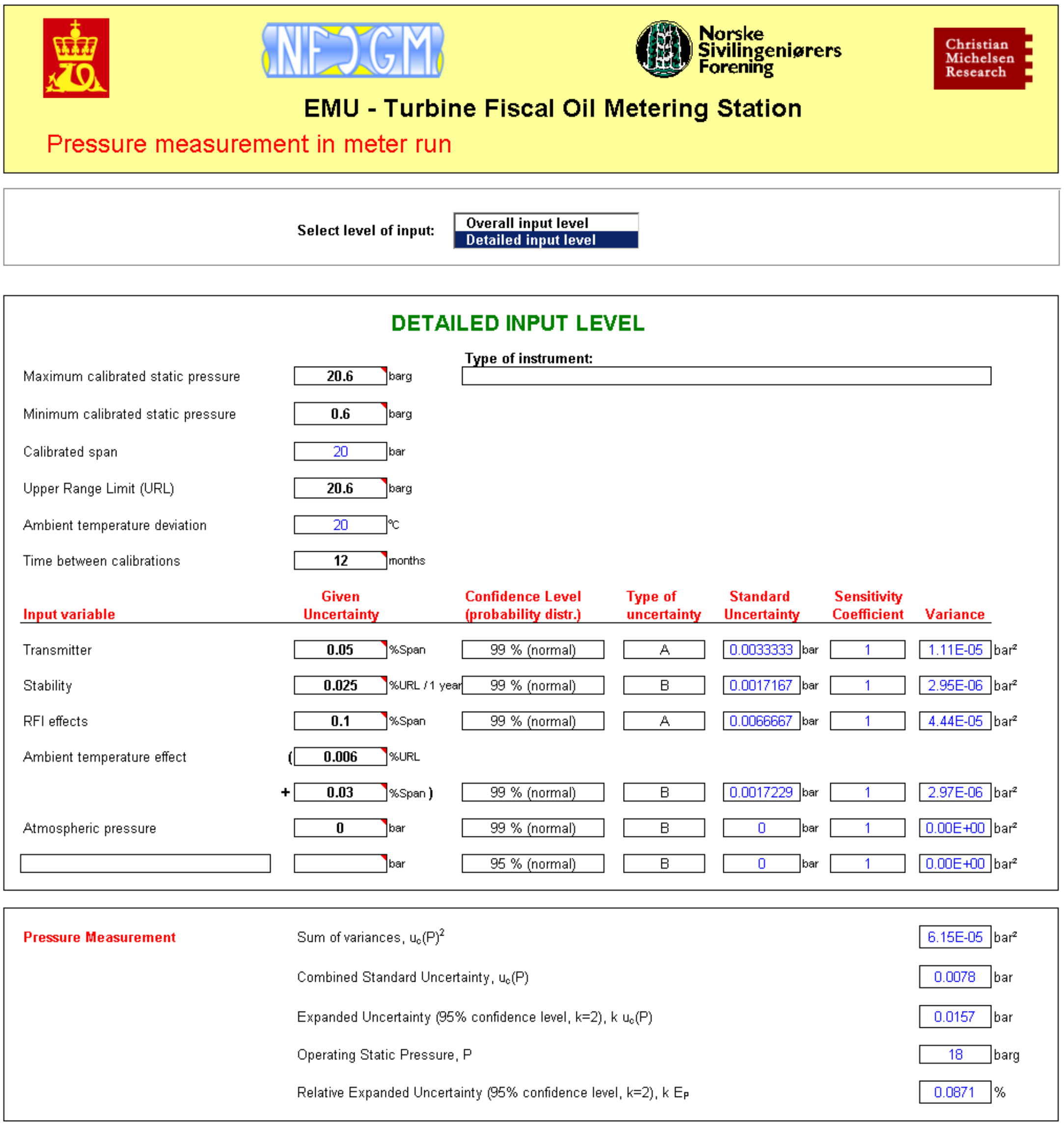


Figure 4.5 The "P" worksheet in the program EMU - Turbine Fiscal Oil Metering Station, *shown for the "overall level" option.*

This option is used e.g. when the user does not want to go into the "detailed level" of the pressure measurement, or if the "detailed level" setup does not fit sufficiently well to the pressure transmitter at hand. The user must then document the input value used for the relative expanded uncertainty of the pressure measurement (the "given uncertainty"), and its confidence level and probability distribution.

4.5.2 Detailed level

When the "detailed level" is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters the uncertainty figures of the pressure transmitter in question, in addition to the accompanying confidence levels / probability distributions. Cf. Table 3.6 and Section 3.3.



NFOGM
Norske Sivilingeniørers Forening
Christian Michelsen Research

EMU - Turbine Fiscal Oil Metering Station

Pressure measurement in meter run

Select level of input: Overall input level / **Detailed input level**

DETAILED INPUT LEVEL

Type of instrument:

Maximum calibrated static pressure	20.6	barg
Minimum calibrated static pressure	0.6	barg
Calibrated span	20	bar
Upper Range Limit (URL)	20.6	barg
Ambient temperature deviation	20	°C
Time between calibrations	12	months

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient	Variance	
Transmitter	0.05	%Span	99 % (normal)	A	0.0033333	bar	1	1.11E-05	bar²
Stability	0.025	%URL / 1 year	99 % (normal)	B	0.0017167	bar	1	2.95E-06	bar²
RFI effects	0.1	%Span	99 % (normal)	A	0.0066667	bar	1	4.44E-05	bar²
Ambient temperature effect	(0.006	%URL							
	+ 0.03	%Span)	99 % (normal)	B	0.0017229	bar	1	2.97E-06	bar²
Atmospheric pressure	0	bar	99 % (normal)	B	0	bar	1	0.00E+00	bar²
		bar	95 % (normal)	B	0	bar	1	0.00E+00	bar²

Pressure Measurement		
Sum of variances, $u_c(P)^2$	6.15E-05	bar²
Combined Standard Uncertainty, $u_c(P)$	0.0078	bar
Expanded Uncertainty (95% confidence level, k=2), k $u_c(P)$	0.0157	bar
Operating Static Pressure, P	18	barg
Relative Expanded Uncertainty (95% confidence level, k=2), k E_P	0.0871	%

Figure 4.6 The "P" worksheet in the program EMU - Turbine Fiscal Oil Metering Station, shown for the "detailed level" option. (Corresponds to Table 3.7).

In Figure 4.6 the uncertainty data specified for the Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a] have been used, cf. Table 3.6. A blank field denoted "type of instrument" can be filled in to document the actual instrument being evaluated for reporting purposes.

In addition to the input uncertainty values, the user must specify a few other data, found in instrument data sheets. By selecting the “maximum” and “minimum calibrated static pressure”, the program automatically calculates the “calibrated span”. The “URL” is entered by the user. The “ambient temperature deviation” is calculated by the program from data given in the “Oil parameters” worksheet. Also the “time between calibrations” has to be specified.

In addition to the “usual” pressure transmitter input uncertainties given in the worksheet, a “blank cell” has been defined, where the user can specify miscellaneous uncertainty contributions to the pressure measurement not covered by the other input cells in the worksheet.

The user must himself document the input uncertainty values used for the pressure measurement (the “given uncertainty”), e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.

4.6 Density measurement uncertainty

The worksheet “*Density*” for evaluation of the expanded uncertainty of the density measurement in the meter run is shown in Figure 4.7 and Figure 4.8, for the “overall level” and the “detailed level”, respectively. These are described separately below.

4.6.1 Overall level

When the “overall level” is chosen for specification of input uncertainties to calculation of the density measurement uncertainty, the user specifies only the relative expanded uncertainty of the density measurement, and the accompanying confidence level and probability distribution, see Figure 4.7.

This option is used e.g. when the user does not want to go into the “detailed” level of the density measurement, in case a different method for density measurement is used, or if the “detailed level” setup does not fit sufficiently well to the densitometer at hand. The user must then document the input value used for the relative expanded uncertainty of the density measurement (the “given uncertainty”), and its confidence level and probability distribution.

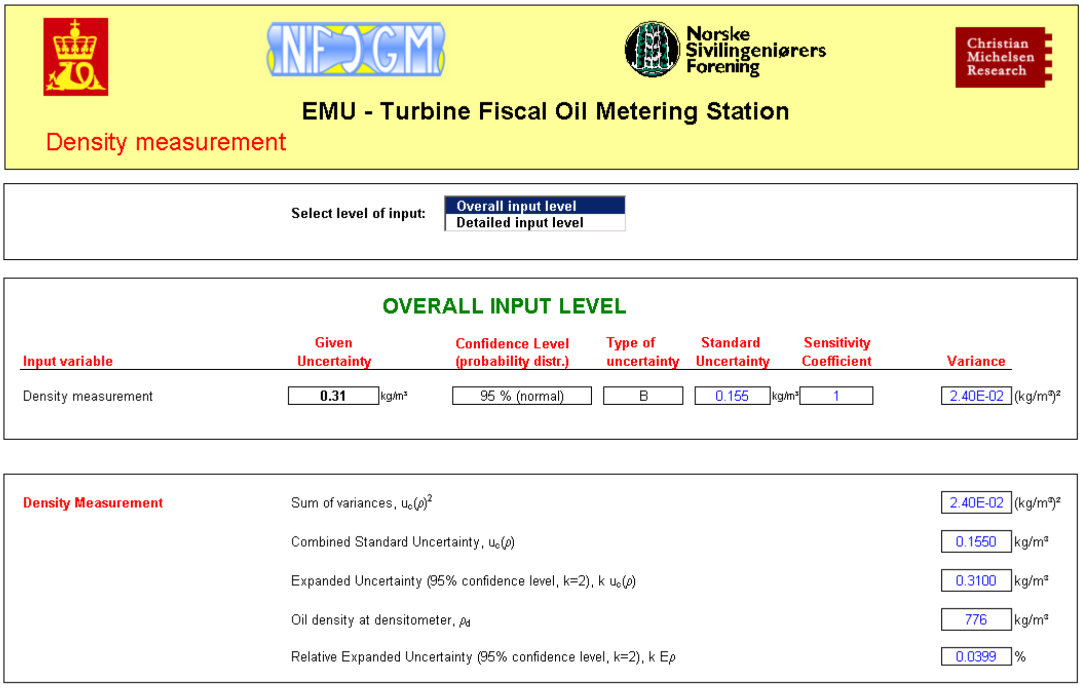
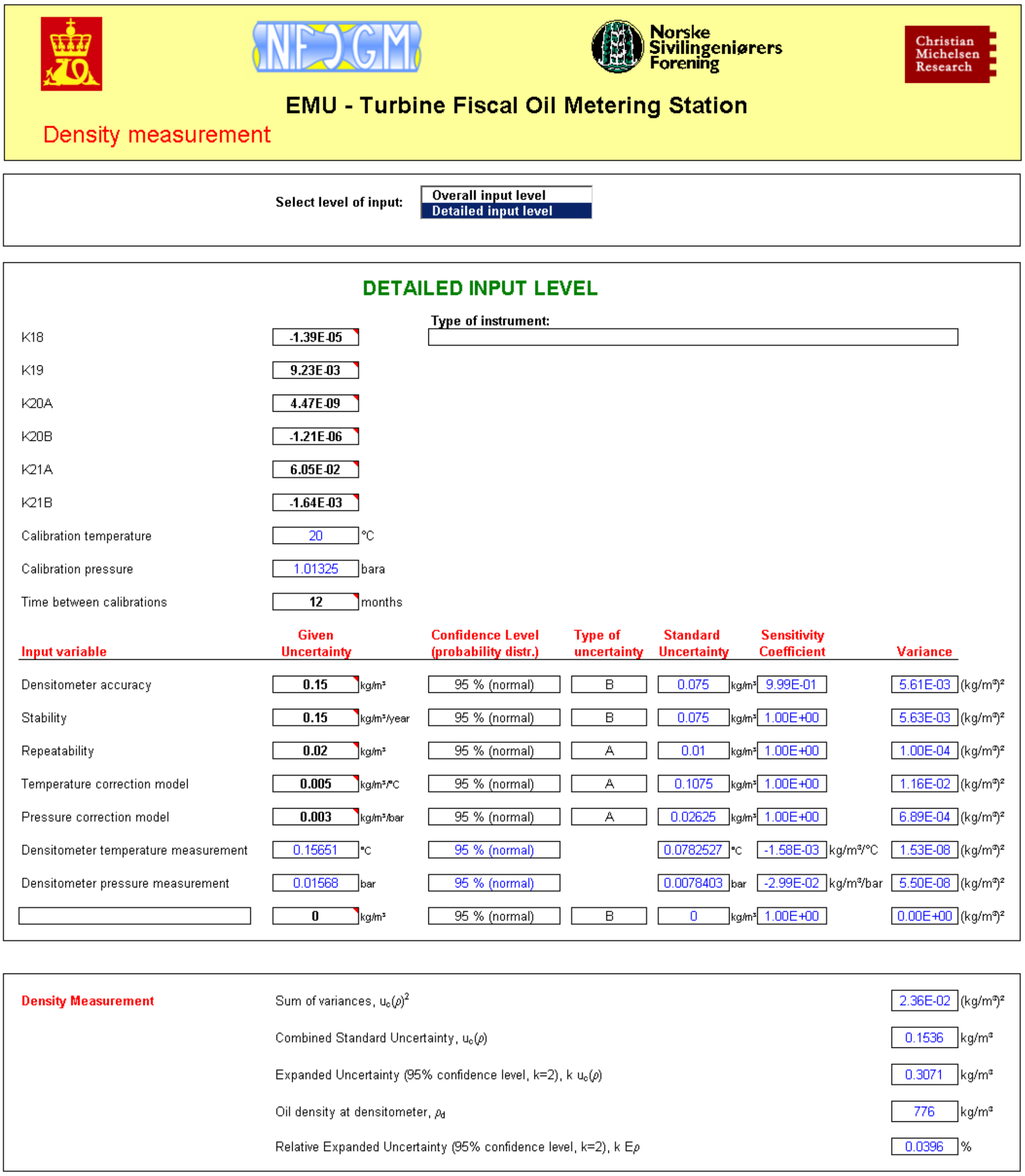


Figure 4.7 *The* "Density" *worksheet in the program EMU - Turbine Fiscal Oil Metering Station, shown for the "overall level" option.*

4.6.2 Detailed level

When the "detailed level" is chosen for specification of input uncertainties to calculation of the density measurement uncertainty, the user specifies the uncertainty figures of the online installed vibrating element densitometer in question, in addition to the accompanying confidence levels / probability distributions. Cf. Table 3.10. The user must himself document the input uncertainty values for the density measurement, e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.



EMU - Turbine Fiscal Oil Metering Station

Density measurement

Select level of input: Overall input level / Detailed input level

DETAILED INPUT LEVEL

Type of instrument:

K18	-1.39E-05	
K19	9.23E-03	
K20A	4.47E-09	
K20B	-1.21E-06	
K21A	6.05E-02	
K21B	-1.64E-03	
Calibration temperature	20	°C
Calibration pressure	1.01325	bara
Time between calibrations	12	months

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance	
Densitometer accuracy	0.15	kg/m³	95 % (normal)	B	0.075	kg/m³	9.99E-01		5.61E-03	(kg/m³)²
Stability	0.15	kg/m³/year	95 % (normal)	B	0.075	kg/m³	1.00E+00		5.63E-03	(kg/m³)²
Repeatability	0.02	kg/m³	95 % (normal)	A	0.01	kg/m³	1.00E+00		1.00E-04	(kg/m³)²
Temperature correction model	0.005	kg/m³/°C	95 % (normal)	A	0.1075	kg/m³	1.00E+00		1.16E-02	(kg/m³)²
Pressure correction model	0.003	kg/m³/bar	95 % (normal)	A	0.02625	kg/m³	1.00E+00		6.89E-04	(kg/m³)²
Densitometer temperature measurement	0.15651	°C	95 % (normal)		0.0782527	°C	-1.58E-03	kg/m³/°C	1.53E-08	(kg/m³)²
Densitometer pressure measurement	0.01568	bar	95 % (normal)		0.0078403	bar	-2.99E-02	kg/m³/bar	5.50E-08	(kg/m³)²
	0	kg/m³	95 % (normal)	B	0	kg/m³	1.00E+00		0.00E+00	(kg/m³)²

Density Measurement

Sum of variances, $u_c(\rho)^2$	2.36E-02	(kg/m³)²
Combined Standard Uncertainty, $u_c(\rho)$	0.1536	kg/m³
Expanded Uncertainty (95% confidence level, k=2), k $u_c(\rho)$	0.3071	kg/m³
Oil density at densitometer, ρ_d	776	kg/m³
Relative Expanded Uncertainty (95% confidence level, k=2), k E_ρ	0.0396	%

Figure 4.8 *The* "Density" *worksheet in the program EMU - Turbine Fiscal Oil Metering Station, shown for the* "*detailed level*" *option. (Corresponds to Table 3.10).*

In Figure 4.8 the uncertainty figures specified for the Solartron Model 7835 Liquid densitometer [Solartron, 2001b] have been used, cf. Table 3.8. These are the same as used in Table 3.10, see Section 3.4 for details. A blank field denoted "type of instrument" can be filled in to document the actual instrument being evaluated, for reporting purposes.

The input uncertainty of the densitometer temperature (T_d) and the densitometer pressure (P_d) are taken from the "*T-density*" and "*P-density*" worksheets. The densitometer calibration pressure and calibration temperature are taken from the "*Oil parameters*" worksheet. See discussions in section 3.4 for more details.

In addition to the input uncertainty values, the user must specify six liquid densitometer constants, K_{18}, K_{19}, K_{20A}, K_{20B}, K_{21A}, K_{21B}, defined in Section 3.4.1.

In addition to the "usual" densitometer input uncertainties given in the worksheet, a "blank cell" has been defined, where the user can specify miscellaneous uncertainty contributions to the density measurement not covered by the other input cells in the worksheet. The user must then document the input value used for the "miscellaneous uncertainty" of the densitometer measurement, together with its confidence level and probability distribution.

4.7 Reference density

In the worksheet denoted "Ref. density" shown in Figure 4.9 the user must enter data for the API constants K_1, K_0, A, B, C and D used in calculation of the compressibility factors (cf. Table 3.12 and Section 3.5.2 for details).

EMU - Turbine Fiscal Oil Metering Station

Reference density calculation

Pressure (densitometer conditions)	17.5	barg
Temperature (densitometer conditions)	63	°C
Oil density (densitometer conditions)	776	kg/m³
Oil parameters		
API Constant, K_0	**613.97226**	
API Constant, K_1	**0**	
API Constant, A	**-1.6208**	
API Constant, B	**0.00021592**	
API Constant, C	**0.87096**	
API Constant, D	**0.0042092**	
Base pressure, Pb_a	1.01325	bara
Equilibrium vapour pressure, Pe_a	1.01325	bara
Reference density, calculated, ρ_{ref}	811.240318	kg/m³
Reference density, used, ρ_{ref}	811.240318	kg/m³
Ctld	0.95467438	
Cpld	1.00197537	

◉ Use automatically calculated value for the reference density

○ Use manually given value for the reference density

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance	
Temperature at densitometer	0.15650539	°C	95 % (normal)		7.83E-02	°C	7.44E-01	kg/m³/°C	3.39E-03	(kg/m³)²
Pressure at densitometer	0.01568066	bar	95 % (normal)		7.84E-03	bar	-8.41E-02	kg/m³/bar	4.35E-07	(kg/m³)²
Equilibrium vapour pressure, Pe_a	**0**	bar	Standard	B	0.00E+00	bar	8.41E-02	kg/m³/bar	0.00E+00	(kg/m³)²
Base pressure, Pb_a	**0**	bar	Standard	B	0.00E+00	bar	-8.41E-02	kg/m³/bar	0.00E+00	(kg/m³)²
Density measurement	0.30714471	kg/m³	95 % (normal)		1.54E-01	kg/m³	9.60E-01		2.17E-02	(kg/m³)²
C_{pld} (model)	**3.00E-04**		95 % (normal)	B	1.50E-04		-7.43E+02	kg/m³	1.24E-02	(kg/m³)²
C_{tld} (model)	**7.15E-04**		Standard	B	7.15E-04		-7.80E+02	kg/m³	3.11E-01	(kg/m³)²

Reference density calculation			
	Sum of variances, $u_c(\rho_{ref})^2$	0.348739413	(kg/m³)²
	Combined Standard Uncertainty, $u_c(\rho_{ref})$	0.590542	kg/m³
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(\rho_{ref})$	1.181083254	kg/m³
	Reference Density, ρ_{ref}	811.2403183	kg/m³
	Relative Expanded Uncertainty (95% confidence level, k=2), k $E_{\rho_{ref}}$	0.1456	%

Figure 4.9 The "Ref. density" worksheet in the program EMU - Turbine Fiscal Oil Metering Station. (Corresponds to Table 3.18).

4.8 K-factor uncertainty

In the worksheet denoted "K-factor" shown in Figure 4.10 and Figure 4.11 the user must enter the measured turbine meter pulses during proving in addition to the uncertainty figures of the input quantities in use. The user may select a *full* or *simplified* uncertainty model. Cf. Section 3.8 for details.

K-factor

EMU - Turbine Fiscal Oil Metering Station

Select level of input: Simplified uncertainty model / **Full uncertainty model**

FULL UNCERTAINTY MODEL

Measured turbine meter pulses, MRp	**90092**	Cubic expansion, EM	3.35E-05 1/K
Internal pressure of prover inlet and outlet, P_{pa}	18 barg	Reference density, ρ_{ref}	811.240318 kg/m³
Temperature of prover inlet and outlet, T_{pa}	65 °C	Base volume of prover	28.646 m³
Line pressure (at turbine meter while proving), P	18 barg	Ctlm	0.95276472
Line temperature (at turbine meter while proving), T	65 °C	Cplm	1.00205903
Base pressure, Pb_a	1.01325 bara	Ctsp	1.001675
Equilibrium vapour pressure, Pe_a	1.01325 bara	Cpsp	1.00027556
Internal diameter of prover pipe, DP	444.5 mm	Ctlp	0.95276472
Modul of elasticity, prover, EMP	2.03E+06 barg	Cplp	1.00205903
Wall thickness of prover, TP	14.275 mm	K-factor	3138.88748 P/m³

Input variable	Given Uncertainty	Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty	Sensitivity Coefficient	Variance
Prover pressure	0.01568066 bar	95 % (normal)		0.007840328 bar	-4.07E-01 P/(m³ bar)	1.02E-05 (P/m³)²
Prover temperature	0.15650539 °C	95 % (normal)		0.078252693 °C	3.00E+00 P/(m³ °C)	5.51E-02 (P/m³)²
Line pressure (at turbine while proving)	0.01568066 bar	95 % (normal)		0.007840328 bar	3.59E-01 P/(m³ bar)	7.93E-06 (P/m³)²
Equilibrium vapour pressure	**0** bar	Standard	B	0 bar	0.00E+00 P/(m³ bar)	0.00E+00 (P/m³)²
Base pressure	**0** bar	Standard	B	0 bar	0.00E+00 P/(m³ bar)	0.00E+00 (P/m³)²
Line temperature (at turbine while proving)	0.15650539 °C	95 % (normal)		0.078252693 °C	-3.10E+00 P/(m³ °C)	5.90E-02 (P/m³)²
Inner diameter of prover	**0.001607** mm	Standard	B	0.000001607 m	-1.95E+00 P/(m³ m)	9.77E-12 (P/m³)²
Prover modulus of elasticity	**5085** bar	Standard	B	5085 bar	4.25E-07 P/(m³ bar)	4.67E-06 (P/m³)²
Wall thickness (prover pipe)	**0.00499625** mm	Standard	B	4.99625E-06 m	6.06E+01 P/(m³ m)	9.16E-08 (P/m³)²
Thermal expansion coefficient (prover)	**8.38E-08** 1/K	Standard	B	8.375E-08 1/K	-1.57E+05 P K	1.72E-04 (P/m³)²
Standard reference density	1.18108325 kg/m³	95 % (normal)		0.590541627 kg/m³	0.00E+00 P/kg	0.00E+00 (P/m³)²
Number of pulses counted	**0.045046** P	Standard	B	0.045046 P	3.48E-02 1/m³	2.46E-06 (P/m³)²
Prover volume	**0.0055** m³	Standard	B	0.0055 m³	-1.10E+02 P/(m³m³)	3.63E-01 (P/m³)²
C_{plm} volume correction model	**3.00E-04**	95 % (normal)	B	0.00015	3.13E+03 P/m³	2.21E-01 (P/m³)²
C_{tlm} volume correction model	**7.15E-04**	Standard	B	0.000715046	3.29E+03 P/m³	5.55E+00 (P/m³)²
C_{plp} volume correction model	**3.00E-04**	95 % (normal)	B	0.00015	-3.13E+03 P/m³	2.21E-01 (P/m³)²
C_{tlp} volume correction model	**7.15E-04**	Standard	B	0.000715046	-3.29E+03 P/m³	5.55E+00 (P/m³)²
C_{tsp} volume correction model	**0**	Standard	B	0	-3.13E+03 P/m³	0.00E+00 (P/m³)²
C_{psp} volume correction model	**0**	Standard	B	0	-3.14E+03 P/m³	0.00E+00 (P/m³)²
Linearity, K-factor estimate	**2.35411** P/m³	Standard	B	2.35411 P/m³	1.00E+00	5.54E+00 (P/m³)²
Repeatability, K-factor estimate	**0.31388** P/m³	Standard	B	0.31388 P/m³	1.00E+00	9.85E-02 (P/m³)²
Signal communication and flow computer (calculations)	**0.00156941** P/m³	Standard	B	0.00156941 P/m³	1.00E+00	2.46E-06 (P/m³)²
Covariance						-1.15E+01 (P/m³)²

K-factor measurement		
	Sum of variances, $u_c(\text{K-factor})^2$	6.12E+00 (P/m³)²
	Combined Standard Uncertainty, $u_c(\text{K-factor})$	2.473428 P/m³
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(\text{K-factor})$	4.946855772 P/m³
	K-factor	3138.887481 P/m³
	Relative Expanded Uncertainty (95% confidence level, k=2), k $E_{K\text{-factor}}$	0.1576 %

Figure 4.10 The "K-factor" worksheet (full uncertainty model) in the program EMU - Turbine Fiscal Oil Metering Station. (Corresponds to Table 3.20).

EMU - Turbine Fiscal Oil Metering Station

K-factor

Select level of input: **Simplified uncertainty model** / Full uncertainty model

SIMPLIFIED UNCERTAINTY MODEL

Measured turbine meter pulses, MRp	90092		Cubic expansion, EM	3.35E-05	1/K
Internal pressure of prover inlet and outlet, P_{pa}	18	barg	Reference density, ρ_{ref}	811.240318	kg/m³
Temperature of prover inlet and outlet, T_{pa}	65	°C	Base volume of prover	28.646	m³
Line pressure (at turbine meter while proving), P	18	barg	Ctlm	0.95276472	
Line temperature (at turbine meter while proving), T	65	°C	Cplm	1.00205903	
Base pressure, Pb_a	1.01325	bara	Ctsp	1.001675	
Equilibrium vapour pressure, Pe_a	1.01325	bara	Cpsp	1.00027556	
Internal diameter of prover pipe, DP	444.5	mm	Ctlp	0.95276472	
Modul of elasticity, prover, EMP	2.03E+06	barg	Cplp	1.00205903	
Wall thickness of prover, TP	14.275	mm	K-factor	3138.88748	P/m³

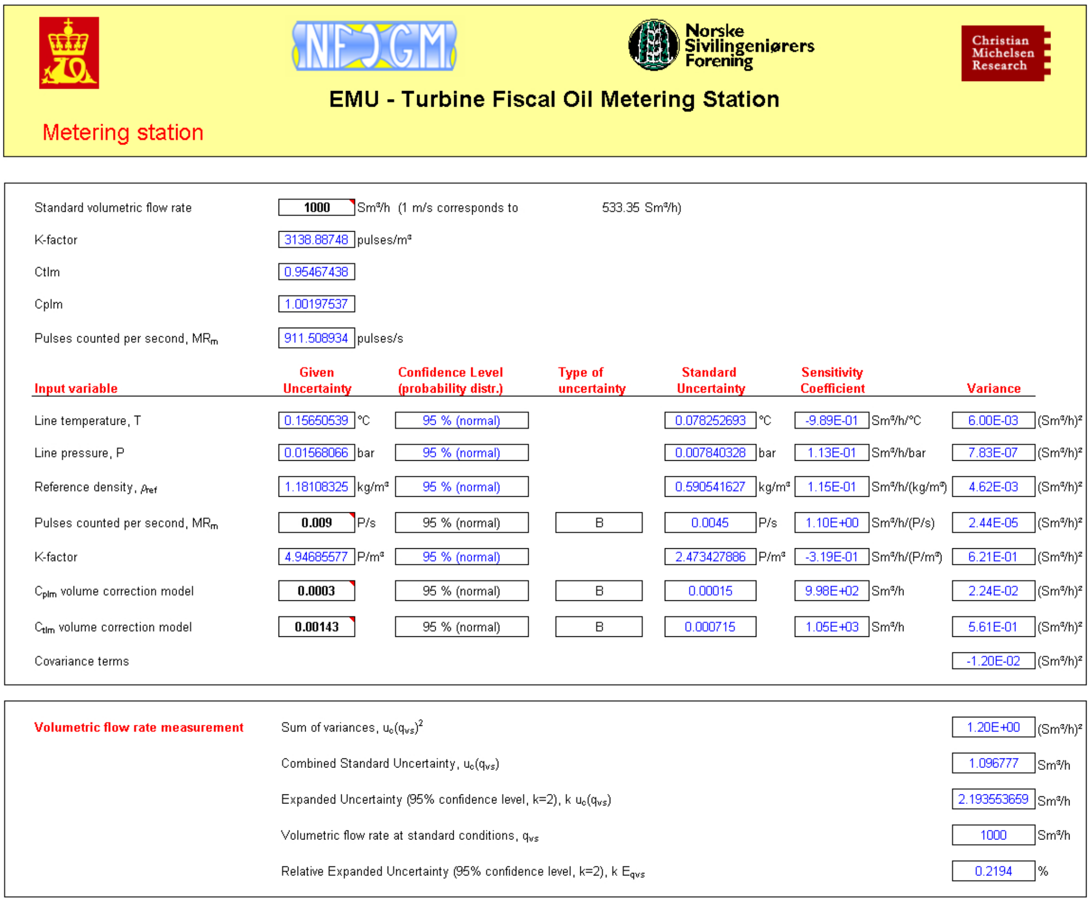
Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance	
Prover temperature	0.15650539	°C	95 % (normal)		0.078252693	°C	3.00E+00	P/(m³ °C)	5.51E-02	(P/m³)²
Line temperature (at turbine while proving)	0.15650539	°C	95 % (normal)		0.078252693	°C	-3.10E+00	P/(m³ °C)	5.90E-02	(P/m³)²
Number of pulses counted	0.045046	P	Standard	B	0.045046	P	3.48E-02	1/m³	2.46E-06	(P/m³)²
Prover volume	0.0055	m³	Standard	B	0.0055	m³	-1.10E+02	P/(m³m³)	3.63E-01	(P/m³)²
C_{plm} volume correction model	3.00E-04		95 % (normal)	B	0.00015		3.13E+03	P/m³	2.21E-01	(P/m³)²
C_{tlm} volume correction model	7.15E-04		Standard	B	0.000715046		3.29E+03	P/m³	5.55E+00	(P/m³)²
C_{plp} volume correction model	3.00E-04		95 % (normal)	B	0.00015		-3.13E+03	P/m³	2.21E-01	(P/m³)²
C_{tlp} volume correction model	7.15E-04		Standard	B	0.000715046		-3.29E+03	P/m³	5.55E+00	(P/m³)²
Linearity, K-factor estimate	2.35411	P/m³	Standard	B	2.35411	P/m³	1.00E+00		5.54E+00	(P/m³)²
Repeatability, K-factor estimate	0.31388	P/m³	Standard	B	0.31388	P/m³	1.00E+00		9.85E-02	(P/m³)²
Covariance									-1.15E+01	(P/m³)²

K-factor measurement			
	Sum of variances, u_c(K-factor)²	6.12E+00	(P/m³)²
	Combined Standard Uncertainty, u_c(K-factor)	2.473388	P/m³
	Expanded Uncertainty (95% confidence level, k=2), k u_c(K-factor)	4.94677591	P/m³
	K-factor	3138.887481	P/m³
	Relative Expanded Uncertainty (95% confidence level, k=2), k $E_{K\text{-}factor}$	0.1576	%

Figure 4.11 The "K-factor" worksheet (simplified uncertainty model) in the program EMU - Turbine Fiscal Oil Metering Station. (Corresponds to Table 3.23).

4.9 Metering station uncertainty

In the worksheet denoted "Metering station" shown Figure 4.12 the user must enter the standard volumetric flow rate for which the uncertainty shall be calculated. All other values besides from the specification of uncertainties for C_{tlm}, C_{plm} and Pulses counted per second are taken automatically from the previously described worksheets.



Norske Sivilingeniørers Forening

Christian Michelsen Research

EMU - Turbine Fiscal Oil Metering Station

Metering station

Standard volumetric flow rate	1000	Sm³/h (1 m/s corresponds to 533.35 Sm³/h)
K-factor	3138.88748	pulses/m³
Ctlm	0.95467438	
Cplm	1.00197537	
Pulses counted per second, MR_m	911.508934	pulses/s

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance	
Line temperature, T	0.15650539	°C	95 % (normal)		0.078252693	°C	-9.89E-01	Sm³/h/°C	6.00E-03	(Sm³/h)²
Line pressure, P	0.01568066	bar	95 % (normal)		0.007840328	bar	1.13E-01	Sm³/h/bar	7.83E-07	(Sm³/h)²
Reference density, ρ_{ref}	1.18108325	kg/m³	95 % (normal)		0.590541627	kg/m³	1.15E-01	Sm³/h/(kg/m³)	4.62E-03	(Sm³/h)²
Pulses counted per second, MR_m	0.009	P/s	95 % (normal)	B	0.0045	P/s	1.10E+00	Sm³/h/(P/s)	2.44E-05	(Sm³/h)²
K-factor	4.94685577	P/m³	95 % (normal)		2.473427886	P/m³	-3.19E-01	Sm³/h/(P/m³)	6.21E-01	(Sm³/h)²
C_{plm} volume correction model	0.0003		95 % (normal)	B	0.00015		9.98E+02	Sm³/h	2.24E-02	(Sm³/h)²
C_{tlm} volume correction model	0.00143		95 % (normal)	B	0.000715		1.05E+03	Sm³/h	5.61E-01	(Sm³/h)²
Covariance terms									-1.20E-02	(Sm³/h)²

Volumetric flow rate measurement			
	Sum of variances, $u_c(q_{vs})^2$	1.20E+00	(Sm³/h)²
	Combined Standard Uncertainty, $u_c(q_{vs})$	1.096777	Sm³/h
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(q_{vs})$	2.193553659	Sm³/h
	Volumetric flow rate at standard conditions, q_{vs}	1000	Sm³/h
	Relative Expanded Uncertainty (95% confidence level, k=2), k E_{qvs}	0.2194	%

Figure 4.12 The "Metering station" worksheet in the program EMU - Turbine Fiscal Oil Metering Station.

4.10 Graphical presentation of uncertainty calculations

Various worksheets are available in the program *EMU - Turbine Fiscal Oil Metering Station* to plot and display the calculation results, such as curve plots and bar-charts. These worksheets are described in the following.

4.10.1 Uncertainty curve plots

Plotting of uncertainty curves is made using the "*Graph*" worksheet. Editing of plot options is made using the "*Graph menu*" worksheet ("curve plot set-up").

Plotting of the relative expanded uncertainty can be made for the standard volume flow rate (i.e., the volumetric flow rate at standard ref. conditions), *Q*,

The relative expanded uncertainty can be plotted as a function of

- Axial flow velocity,
- Standard volume flow rate, *Q*,

Axes may be scaled according to user needs (automatic or manual), and various options for curve display (points only, line between points and smooth curve[47]) are available.

47 For the "smooth curve" display option, the default method implemented in Microsoft Excel 2000 is used.

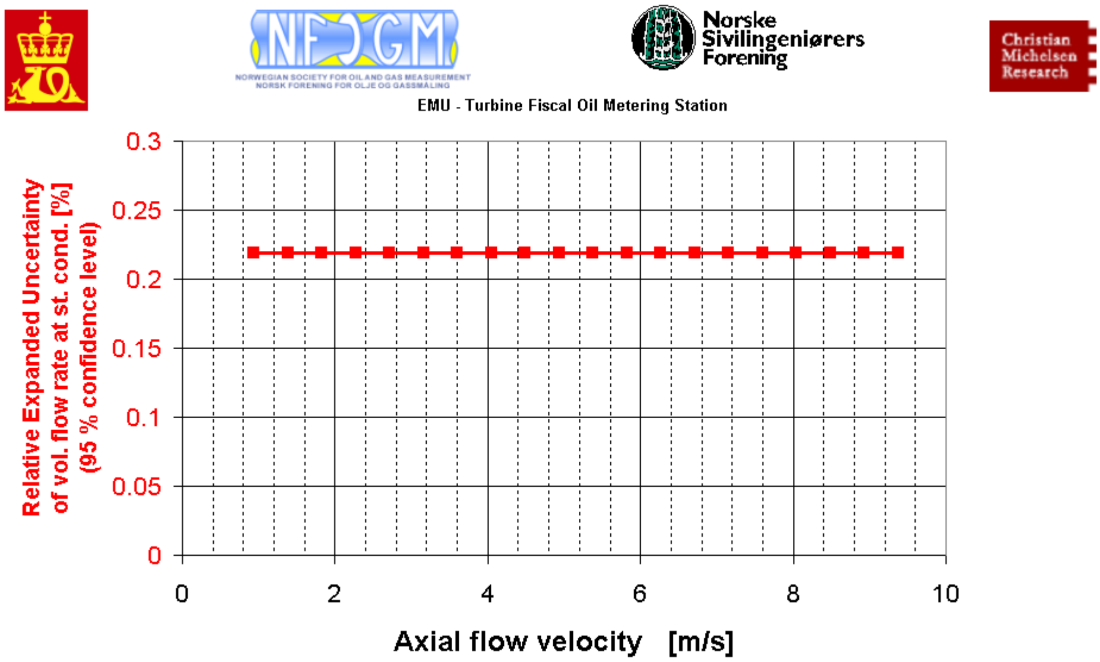


Figure 4.13 *The* "Graph" *worksheet in the program EMU - Turbine Fiscal Oil Metering Station (example).*

Figure 4.13 shows an example where the relative expanded uncertainty of the standard volume flow rate (at a 95 % confidence level and a normal probability distribution, with k = 2) is plotted as a function of the flow velocity.

4.10.2 Uncertainty bar-charts

Plotting of bar charts is made using the "*NN-chart*" worksheets. Editing of bar chart options is made using the "*Graph menu*" worksheet ("bar-chart set-up" section). Bar charts are typically used to evaluate the relative contributions of various input uncertainties to the expanded uncertainty of the "measurand" in question.

Such bar-charts are available for the following seven "measurands":

- Pressure measurement ("*P-chart*" worksheet),
- Pressure measurement ("*P-density-chart*" worksheet),
- Pressure measurement ("*P-prover-chart*" worksheet),
- Temperature measurement ("*T-chart*" worksheet),
- Temperature measurement ("*T-density-chart*" worksheet),
- Temperature measurement ("*T-prover-chart*" worksheet),
- Density measurement ("*D-chart*" worksheet),
- Reference density calculation ("*D-ref-chart*" worksheet),
- K-factor calculation ("*K-factor-chart*" worksheet), and
- Oil metering station ("*MetStat-chart*" worksheet).

As for the "Graph" worksheet, axes may be scaled according to user needs (automatic or manual). These bar charts are described separately in the following.

Since the three pressure and temperatures charts are generally equal in layout and content, only the *"P-chart"* and *"T-chart"* worksheets are shown here.

4.10.2.1 Pressure

The pressure-measurement bar chart is given in the "*P-chart*" worksheet. Figure 4.14 shows an example where the contributions to the expanded uncertainty of the pressure measurement are plotted (blue), together with the expanded uncertainty of the pressure measurement (green).

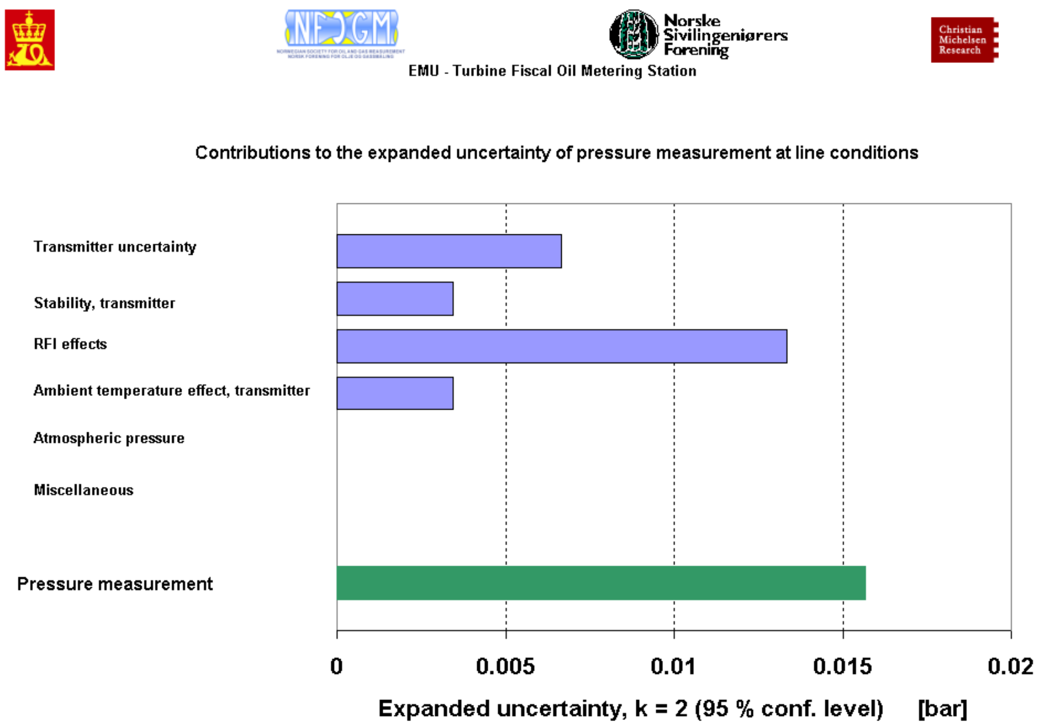


Figure 4.14 The "P-chart" *worksheet in the program* EMU - Turbine Fiscal Oil Metering Station.

4.10.2.2 Temperature

The temperature-measurement bar chart is given in the "*T-chart*" worksheet. Figure 4.15 shows an example where the contributions to the expanded uncertainty of the temperature measurement are plotted (blue), together with the expanded uncertainty of the temperature measurement (green).

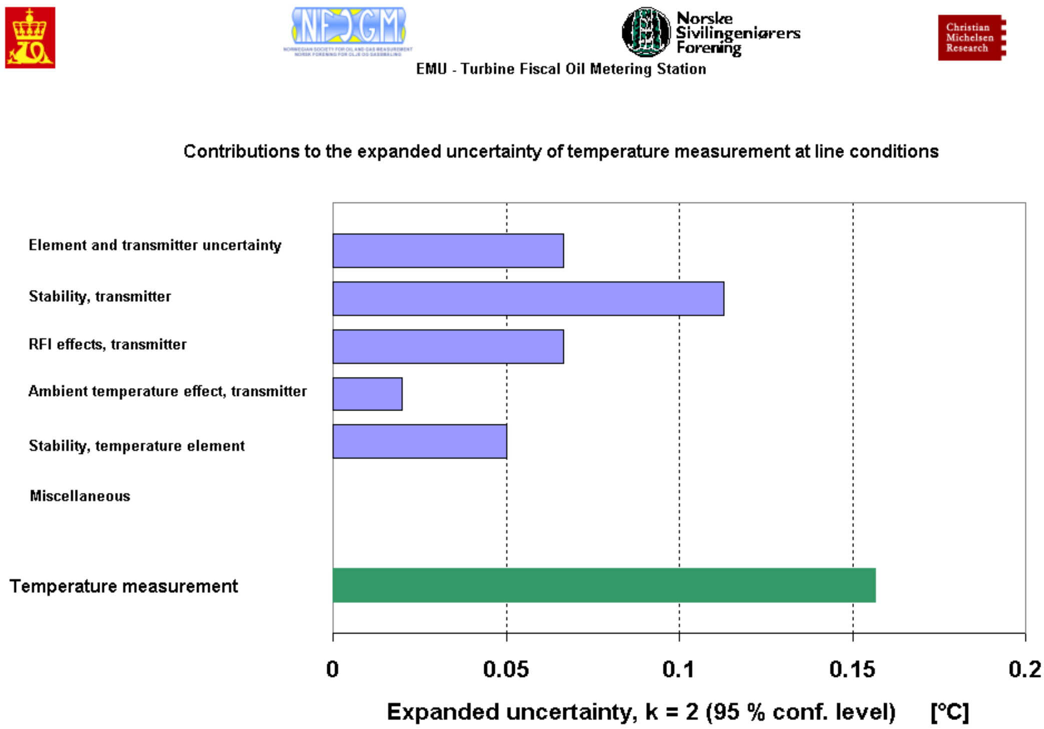


Figure 4.15 *The* "T-chart" *worksheet in the program* EMU - Turbine Fiscal Oil Metering Station.

4.10.2.3 Density

The density-measurement bar chart is given in the "*D-chart*" worksheet. Figure 4.16 shows an example where the contributions to the expanded uncertainty of the density measurement are plotted (blue), together with the expanded uncertainty of the density measurement (green).

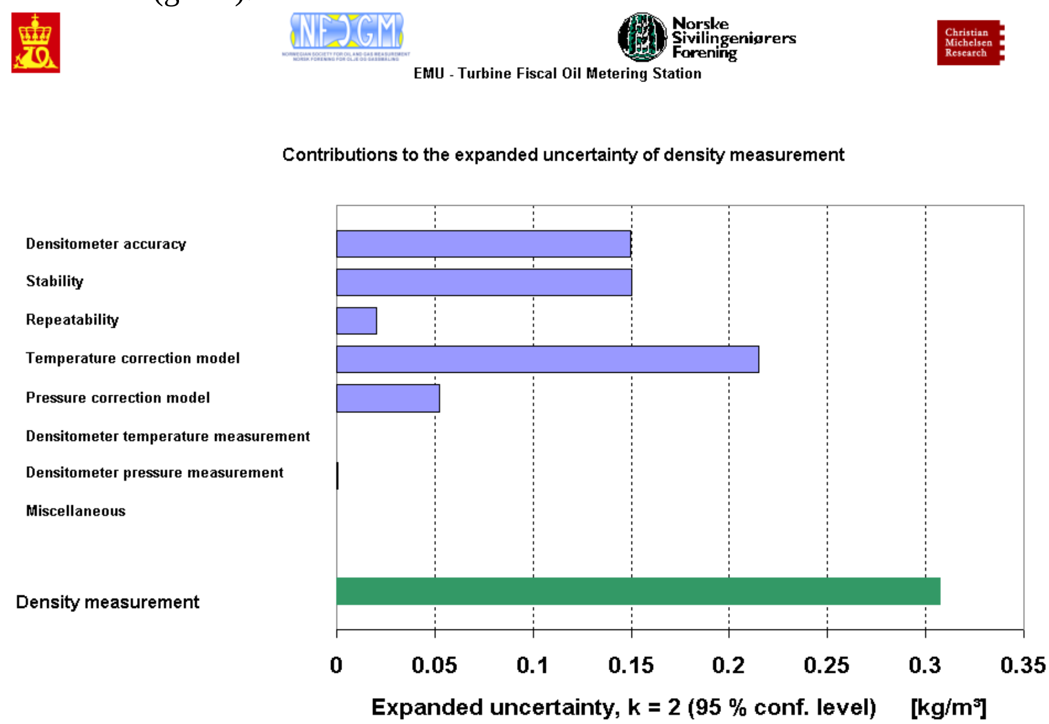


Figure 4.16 *The* "D-chart" *worksheet in the program EMU - Turbine Fiscal Oil Metering Station.*

4.10.2.4 Reference density

The reference density calculation bar chart is given in the "*D-ref-chart*" worksheet. Figure 4.17 shows an example where the contributions to the expanded uncertainty of the reference density calculation are plotted (blue), together with the expanded uncertainty of the calculated reference density (green).

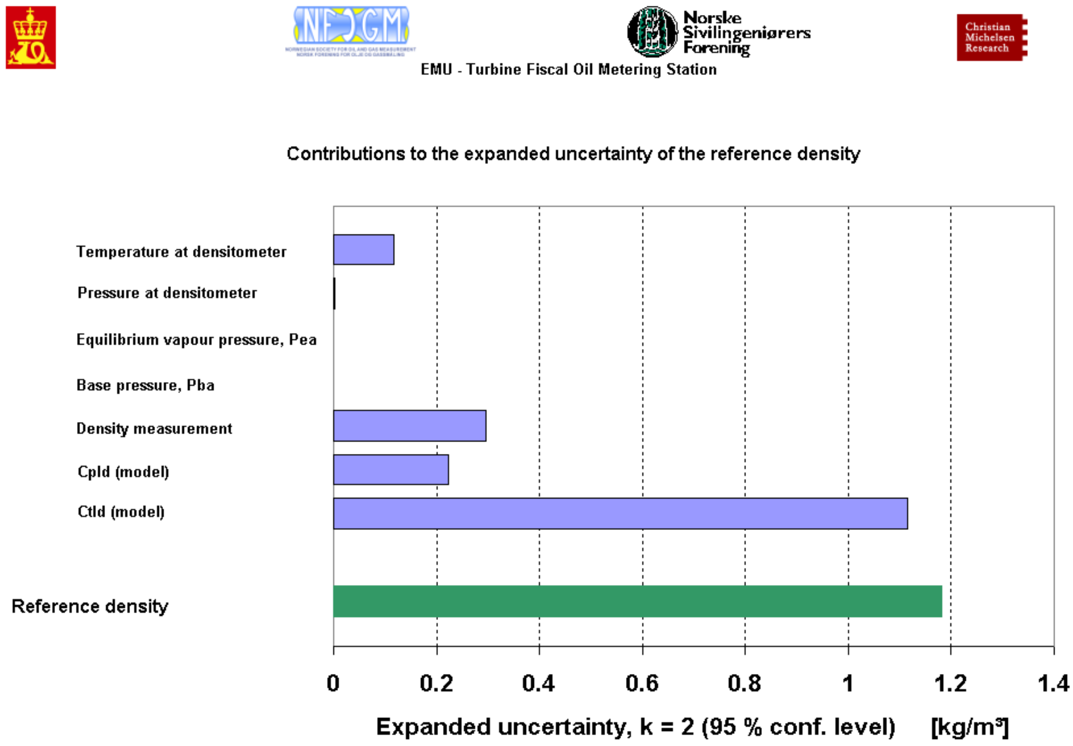


Figure 4.17 *The "D-ref-chart" worksheet in the program EMU - Turbine Fiscal Oil Metering Station*

4.10.2.5 K-factor

The *K-factor* calculation bar chart is given in the "*K-factor-chart*" worksheet. Figure 4.18 shows an example where the contributions to the expanded uncertainty of the K-factor calculation are plotted (blue), together with the expanded uncertainty of the K-factor (green).

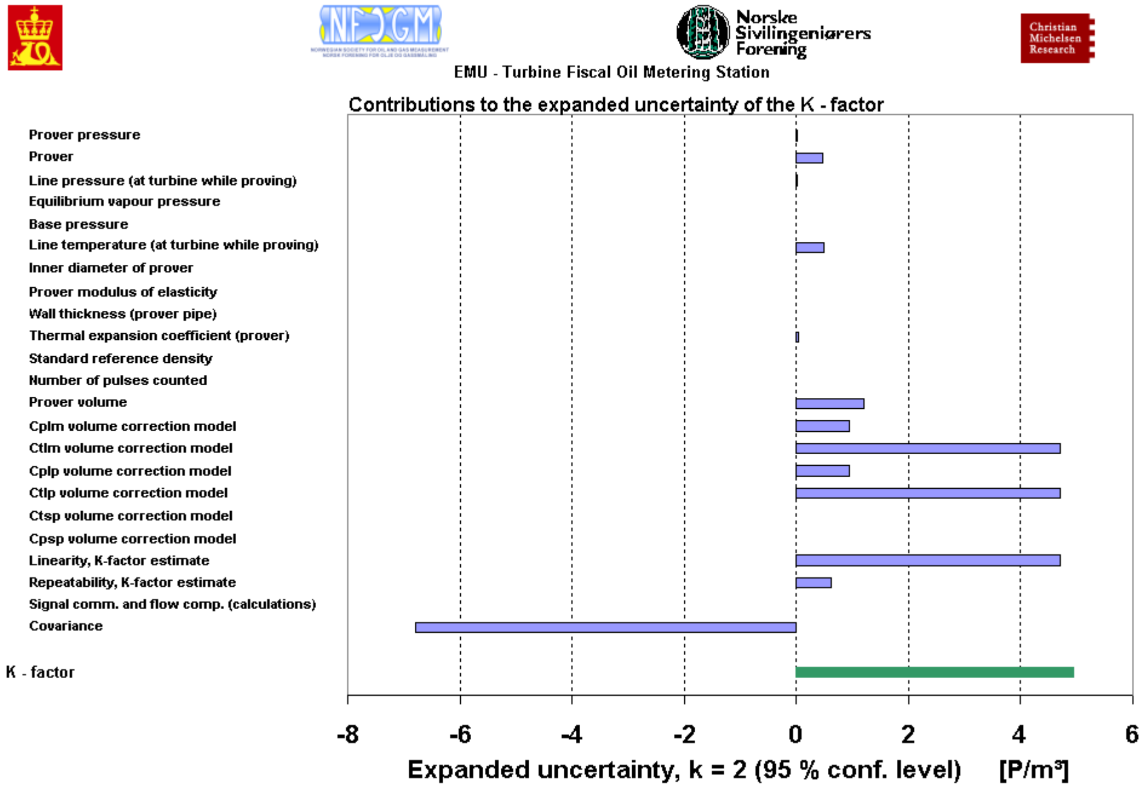


Figure 4.18 *The "K-factor-chart" worksheet in the program EMU - Turbine Fiscal Oil Metering Station.*

4.10.2.6 Oil metering station

The oil metering station bar chart is given in the "*MetStat-chart*" worksheet. Figure 4.19 shows an example where the contributions to the expanded uncertainty of the standard volume flow rate are plotted (blue), together with the expanded uncertainty of the standard volume flow rate (green).

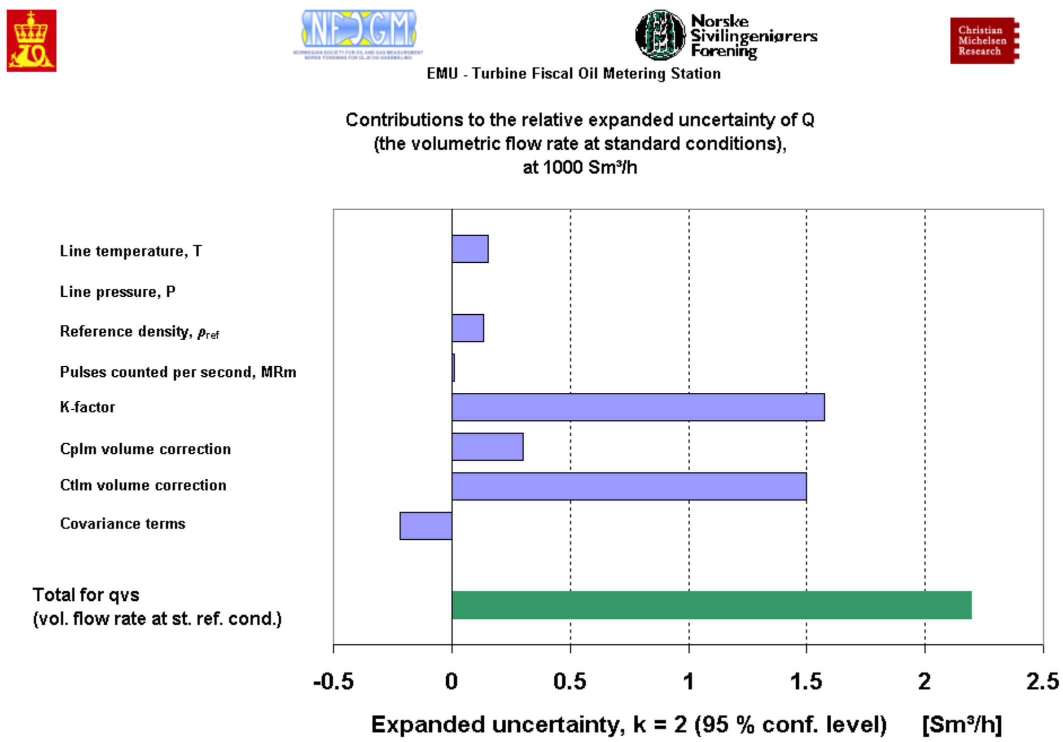


Figure 4.19 The "MetStat" worksheet in the program EMU - Turbine Fiscal Oil Metering Station.

4.11 Summary report - Expanded uncertainty of the Turbine fiscal oil metering station

A "*Report*" worksheet is available in the program *EMU - Turbine Fiscal Oil Metering Station* to provide a condensed report of the calculated expanded uncertainty of the Turbine fiscal oil metering station. For documentation purposes, this one-page report can be used alone, or together with printout of other worksheets in the program.

Blank fields are available for filling in program user information and other comments. Also some of the settings of the "*Oil parameter*" and "*Turbine meter and Prover setup*" worksheets are included for documentation purposes.

EMU - Turbine Fiscal Oil Metering Station

Uncertainty evaluation report

Calculation performed by: ______________________

Date: 14-mar-2003

OPERATING CONDITIONS, METER RUN

Line pressure (static), P	18 barg
Line temperature, T	65 °C
Ambient (air) temperature, T_{air}	0 °C

PROVING CONDITIONS

Ave. internal pressure of prover inlet and outlet, P_{pa}	18 barg
Average temperature of prover inlet and outlet, T_{pa}	65 °C
Pressure at turbine meter	18 barg
Temperature at turbine meter	65 °C
Inner diameter of prover pipe, DP	444.5 mm

DENSITOMETER CONDITIONS

Pressure at density transducer, P_d	17.5 barg
Temperature at density transducer, T_d	63 °C
Oil density at densitometer, ρ_d	776 kg/m³
Calibration temperature, T_c	20 °C
Calibration pressure, P_c	1.0133 bara

BASE AND EQUILIBRIUM VAPOUR PRESSURE FOR THE OIL

Base (reference or standard) pressure, Pb_a	1.0133 bara
Equilibrium vapour pressure, Pe_a	1.0133 bara

User comments:

Flow rate at standard reference conditions, Q: 1000 Sm³/h

Flow velocity, v_A: 1.875 m/s

	Unit	Value	Standard Uncertainty	Rel. Expanded Uncertainty (95 % c. l., k=2)	Contribution to k E_Q
Line temperature, T	°C	65	0.1565	0.0926 %	**0.0155 %**
Line pressure, P	barg	18	0.0157	0.1742 %	**0.0002 %**
Reference density, ρ_{ref}	kg/m³	811.2403	1.1811	0.2912 %	**0.0136 %**
Pulses counted per second, MRm	P/s	911.5089	0.0090	0.0020 %	**0.0010 %**
K-factor	P/m³	3138.8875	4.9469	0.3152 %	**0.1576 %**
C_{plm} volume correction model	-	1.0020	0.0003	0.0599 %	**0.0299 %**
C_{tlm} volume correction model	-	0.9547	0.0014	0.2996 %	**0.1498 %**
Covariance terms	-	-	-	-	**-0.0219 %**
Volumetric flow rate at standard reference conditions, Q	**Sm³/h**	**1000**	**1.0968**	**0.2194 %**	**0.2194 %**

Figure 4.20 The "Report" *worksheet in the program EMU - Turbine Fiscal Oil Metering Station.*

4.12 Listing of plot data

A worksheet is available in the program *EMU - Turbine Fiscal Oil Metering Station* to provide listing of data involved in the uncertainty evaluation.

EMU - Turbine Fiscal Oil Metering Station

Plot data

Plot data for the "Graph" - sheet

First column: Flow velocity, [m/s]
Second column: Rel. exp. uncertainty of vol. flow rate at st. ref. cond. [%] (95 % confidence level)

0.937465	0.219362
1.381528	0.219357
1.82559	0.219355
2.269652	0.219355
2.713715	0.219354
3.157777	0.219354
3.60184	0.219354
4.045902	0.219354
4.489965	0.219354
4.934027	0.219353
5.378089	0.219353
5.822152	0.219353
6.266214	0.219353
6.710277	0.219353
7.154339	0.219353
7.598402	0.219353
8.042464	0.219353
8.486526	0.219353
8.930589	0.219353
9.374651	0.219353

Plot data for the "P-chart" - sheet

All data: expanded uncertainty (k=2) (bar)

Transmitter uncertainty	0.006667
Stability, transmitter	0.003433
RFI effects	0.013333
Ambient temperature effect, transmitter	0.003446
Atmospheric pressure	0
Miscellaneous	0
Total	0.015681

Plot data for the "P-density-chart" - sheet

All data: expanded uncertainty (k=2) (bar)

Transmitter uncertainty	0.006667
Stability, transmitter	0.003433
RFI effects	0.013333
Ambient temperature effect, transmitter	0.003446
Atmospheric pressure	0
Miscellaneous	0
Total	0.015681

Plot data for the "P-prover-chart" - sheet

All data: expanded uncertainty (k=2) (bar)

Transmitter uncertainty	0.006667
Stability, transmitter	0.003433
RFI effects	0.013333
Ambient temperature effect, transmitter	0.003446
Atmospheric pressure	0
Miscellaneous	0
Total	0.015681

Plot data for the "Met-stat-chart" - sheet

All data: expanded uncertainty (k=2) (Sm³/h)

Line temperature, T	0.154861996
Line pressure, P	0.001770008
Reference density, ρ_{ref}	0.135959194
Pulses counted per second, MRm	0.009873738
K-factor	1.575990157
Cplm volume correction model	0.299408556
Ctlm volume correction model	1.497892918
Covariance terms	-0.219006303
Total	2.193553659

Plot data for the "T-chart" - sheet

All data: expanded uncertainty (k=2) (°C)

Element and transmitter uncertainty	0.066666667
Stability, transmitter	0.112716667
RFI effects, transmitter	0.066666667
Ambient temperature effect, transmitter	0.02
Stability, temperature element	0.05
Miscellaneous	0
Total	0.156505386

Plot data for the "T-density-chart" - sheet

All data: expanded uncertainty (k=2) (°C)

Element and transmitter uncertainty	0.066666667
Stability, transmitter	0.112716667
RFI effects, transmitter	0.066666667
Ambient temperature effect, transmitter	0.02
Stability, temperature element	0.05
Miscellaneous	0
Total	0.156505386

Plot data for the "T-prover-chart" - sheet

All data: expanded uncertainty (k=2) (°C)

Element and transmitter uncertainty	0.066666667
Stability, transmitter	0.112716667
RFI effects, transmitter	0.066666667
Ambient temperature effect, transmitter	0.02
Stability, temperature element	0.05
Miscellaneous	0
Total	0.156505386

Plot data for the "D-chart" - sheet

All data: expanded uncertainty (k=2) (kg/m³)

Densitometer accuracy	0.14985441
Stability	0.15
Repeatability	0.02
Temperature correction model	0.215
Pressure correction model	0.0525
Densitometer temperature measurement	0.000247725
Densitometer pressure measurement	0.000469067
Miscellaneous	0
Total	0.307144714

Plot data for the "D-ref-chart" - sheet

All data: expanded uncertainty (k=2) (kg/m³)

Temperature at densitometer	0.116494337
Pressure at densitometer	0.001318359
Equilibrium vapour pressure, Pea	0
Base pressure, Pba	0
Density measurement	0.294808405
Cpld (model)	0.223009182
Ctld (model)	1.115679117
Total	1.181083254

Plot data for the "K-factor-chart" - sheet

All data: expanded uncertainty (k=2) (P/m³)

Prover pressure	0.006383578
Prover temperature	0.469393206
Line pressure (at turbine while proving)	0.005630283
Equilibrium vapour pressure	0
Base pressure	0
Line temperature (at turbine while proving)	0.485822655
Inner diameter of prover	6.25241E-06
Prover modulus of elasticity	0.004323578
Wall thickness (prover pipe)	0.000605301
Thermal expansion coefficient (prover)	0.026244224
Standard reference density	0
Number of pulses counted	0.003138887
Prover volume	1.20532578
Cplm volume correction model	0.939731309
Ctlm volume correction model	4.711444269
Cplp volume correction model	0.939731309
Ctlp volume correction model	4.711444269
Ctsp volume correction model	0
Cpsp volume correction model	0
Linearity, K-factor estimate	4.70822
Repeatability, K-factor estimate	0.62776
Signal comm. and flow comp. (calculations)	0.00313882
Covariance	-6.794233147
Total	4.946855772

Figure 4.21 The "Plot Data" worksheet in the program EMU - Turbine Fiscal Oil Metering Station.

The "*Plot data*" worksheet gives a listing of all data used and plotted in the "*Graph*" and "*NN-chart*" worksheets, cf. Figure 4.21. Such a listing may be useful for reporting purposes, and in case the user needs to present the data in a form not directly available in the program *EMU - Turbine Fiscal Oil Metering Station*. Note that the contents of the "plot data" sheet will change with the settings used in the "Graph menu" sheet.

4.13 Program information

Two worksheets are available to provide information on the program. These are the "About" and the "Readme" worksheets.

The "About" worksheet, which is displayed at startup of the program *EMU - Turbine Fiscal Oil Metering Station*, can be activated at any time and gives general information about the program. The "Readme" worksheet gives regulations and conditions for the distribution of the *Handbook* and the program, etc.

5. FISCAL ORIFICE GAS METERING STATION

The present chapter gives a description of a typical Orifice fiscal gas metering station, serving as a basis for the uncertainty model of such metering stations. This includes a brief description of metering station methods and equipment as well as the functional relationships of the metering station (Section 5.1), the temperature, absolute and differential pressure and density instruments (Sections 5.2, 5.3 and 5.4, respectively) and models for the expansibility factor (Section 5.7) and discharge coefficient (Section 5.8).

In this chapter the combined uncertainty of the actual mass flow rate, q_m, measured by an Orifice fiscal gas metering station is calculated, and the method of calculation provides a practical way of approach to uncertainty calculations on Orifice fiscal gas metering stations according to the principles of the *GUM* [ISO, 1995a].

An Excel program, *EMU - Orifice Fiscal Gas Metering Station*, has also been developed for calculation of the combined expanded uncertainty of the actual mass flow rate of Orifice fiscal gas metering stations. This program is described in Chapter 6, which serves as a user manual to the program. It is recommended to read Chapter 5 and 6 in parallel for better overview.

5.1 Description of an Orifice fiscal gas metering station

An Orifice meter consists of a constriction placed in the pipe where the differential pressure across the constriction is measured. The differential pressure measured across the constriction is related to the mass flow rate through the device.

In addition to measurement of differential pressure, the static line pressure, line temperature and line density of the gas is measured. The temperature and pressure is measured in order to correct for the influence of temperature and pressure on the measurement (e.g. the temperature and pressure influence quantities like the orifice and pipe diameters). The density is measured in order to relate the measured differential pressure to mass flow rate.

The metering station shown in Figure 5.1 is a typical fiscal gas metering station, where the gas density transducer (in this case the Solartron 7812) is mounted in a by-pass, downstream of the orifice. According to ISO 5167-1:2003 [ISO, 2003a] the temperature shall preferably be measured downstream of the primary device, and the density of the fluid shall be referred to the upstream pressure tapping; it can either be measured directly or calculated from an appropriate equation of state from knowledge of the absolute static pressure, absolute temperature and composition of the fluid at that location.

The gas densitometer is normally located in a by-pass loop, where a dedicated temperature[48] measurement is performed for temperature correction of the density measurement. In the example being evaluated in this *Handbook*, we consider a metering station equipped with a dedicated temperature transmitter in the by-pass loop. Pressure measurements are normally not available at the densitometer of gas metering stations, and the flow through the densitometer must be kept low enough to ensure the pressure change from the main line is negligible (see Section 5.4.1.4).

Figure 5.1 shows a typical fiscal gas metering station.

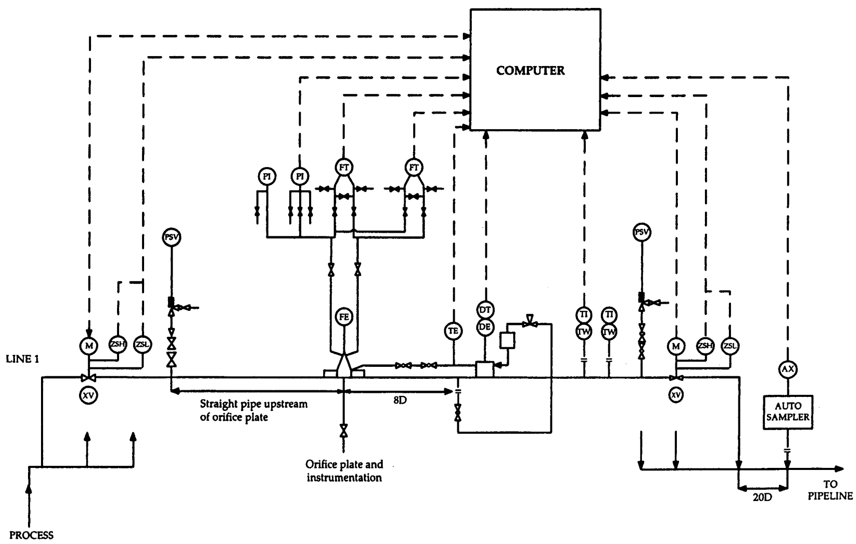


Figure 5.1 A typical gas metering station [NPD, 1997]

According to NPD [NPD, 2001a] the temperature and pressure shall be measured in each of the metering tubes. The density shall be measured in each of the metering pipes, or by two densitometers mounted at the inlet or outlet of the metering station in such a manner that they provide representative density values.

[48] The Solartron 7812 gas densitometer being evaluated in this *Handbook*, actually contains an internal temperature measurement where the Pt-100 temperature element that may be calibrated separately. It is therefore possible to use the Solartron 7812 internal temperature measurement as a fiscal temperature measurement.

5.1.1 Measurement uncertainty requirements according to NPD regulations

According to NPD regulations [NPD, 2001a], the total measurement uncertainty of the metering station shall be within 1.0% of mass flow rate using 95% confidence level.

The NPD regulations further impose additional requirements set for an Orifice fiscal gas metering station in terms of measurement uncertainties, listed in Table 5.1. Please refer to [NPD, 2001a] for the complete set of requirements also including linearity and repeatability limitations. One should also confer the Guidelines to the NPD regulations [NPD, 2001b] for details.

Table 5.1 Measurement uncertainty requirements of loop and components according to NPD regulations [NPD, 2001a]. All uncertainties specified with 95% confidence level.

Component	***Loop uncertainty limits***	***Component uncertainty limits***
Difference pressure measurement	0.30% of measured value within the working range	0.10% of measured value within the working range
Pressure measurement	0.30% of measured value	0.10% of measured value
Temperature measurement	0.30 °C	0.20 °C
Density measurement	0.30% of measured value	0.20% of measured value

5.1.2 Instrumentation and operating conditions

The Orifice fiscal gas metering station evaluated in the present *Handbook* consists of the equipment listed in Table 5.2, as specified by NFOGM, NPD and CMR to be the most widely used instrumentation on Orifice fiscal gas metering stations. With respect to the Orifice and flow computer no specific equipments are considered.

Operating conditions, etc., used for the present uncertainty evaluation example[49] are given in Table 5.3.

[49] As for the *USM Handbook* [Lunde & Frøysa, 2002], the ambient temperature has been set to 0 °C to achieve a worst-case calculation of ambient temperature effects on the temperature and pressure transmitters.

Table 5.2 The evaluated Orifice fiscal gas metering station instrumentation (cf. Table 2.4).

Measurement	**Instrument**
Orifice meter	Not specified.
Flow computer	Not specified.
Differential Pressure, ΔP	Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a].
Line Pressure (static), P	Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a].
Line Temperature, T	Pt 100 element: according to EN 60751 tolerance A [NORSOK, 1998a]. Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2001].
Line Density, ρ	Solartron Model 7812 Gas Density Transducer [Solartron, 2000].

Table 5.3 Operating conditions for the Orifice fiscal gas metering station being evaluated (example).

Conditions	**Quantity**	**Value**
Operating	Line pressure, P (static)	100 bar
	Line temperature, T	50 ^oC (= 323.15 K)
	Line density, ρ	81.62 kg/m^3
	Viscosity, μ	$1.05 \cdot 10^{-5}$ Ns/m^2
	Isentropic exponent, κ	1.18
	Ambient (air) temperature, T_{air}	0 ^oC
Densitometer	Temperature, T_d	48 ^oC [50]
	Indicated (uncorrected) density, ρ_u	82.443 kg/m^3
	Calibration temperature, T_c	15 ^oC
	Velocity of sound, c_d	415.24 m/s
	Calibration velocity of sound (VOS), P_c	350 m/s
	Calibration constant, K_{18}	$-1.36 \cdot 10^{-5}$
	Calibration constant, K_{19}	$8.44 \cdot 10^{-4}$
	VOS correction constant, K_d	21000 µm
	Periodic time, τ	650 µs
Pressure transmitter	Ambient (air) temperature at calibration	20 ^oC
Temperature transm.	Ambient (air) temperature at calibration	20 ^oC

From Table 5.3 it is seen that the user must enter the density at line conditions and the uncorrected density indicated by the densitometer. The reason for this is to reduce the number of user input parameters required by the program. If the EMU program

50 Temperature deviation between line and densitometer conditions may be as large as 7-8 ^oC [Sakariassen, 2001]. A representative value may be about 10 % of the temperature difference between densitometer and ambient (air) conditions. Here, 2 ^oC deviation is used as a moderate example.

shall perform the density correction from by-pass to line conditions, it would require more user input parameters (Z and Z_d). This is covered in more detail in Section 5.4, where it is also shown that these additional parameters have negligible influence on the uncertainty calculations and thus may be neglected. In the calculations in this *Handbook* and the EMU programs, the indicated (uncorrected) density from the densitometer is therefore only used in the calculations of the combined uncertainty of the corrected density, Eqn. (5.9), while the line density is the one used in the calculations of mass flow rate, Eqn. (5.1).

It is important to note that it is required that the fiscal gas metering station is manufactured and operated according to NPD regulations [NPD, 2001a] and recognised standards. The user must verify and document that the functional relationships (referred to standards) used in the handbook and the uncertainty calculation programs are equal to the ones applied in the Orifice fiscal gas metering station in question.

Some uncertainty contributions is not part of the scope of this handbook, like the uncertainties due to orifice plate buckling and base density for conversion to standard volume flow rate. The user must therefore self evaluate these uncertainties.

5.1.3 Functional relationship

The actual mass flow rate, q_m, is the mass of fluid passing through the orifice per unit time. The functional relationship for calculation of mass flow rate is given according to ISO-5167-1:2003, Chapter 5.1 [ISO, 2003a].

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon \ \frac{\pi}{4} d^2 \sqrt{2 \cdot \Delta P \cdot \rho_1} \tag{5.1}$$

where

q_m	- mass flow rate [kg/s]
C	- discharge coefficient
β	- diameter ratio
ε	- expansibility factor
ρ_1	- density at upstream conditions [kg/m^3]
d	- diameter of orifice [m]
ΔP	- differential pressure over orifice [Pa]

The discharge coefficient depends on the Reynolds number, which again depends on the mass flow rate. The mass flow rate must therefore be calculated by iteration, and it is assumed that the uncertainty due to the iteration is negligible.

5.2 Line temperature measurement

As described in Section 1.4, the uncertainty of the temperature transmitter can in the program *EMU - Orifice Fiscal Gas Metering Station* be specified at two levels (cf. also Chapter 6):

(1) ***"Overall level":*** The user gives $u_c(\hat{T})$ directly as input to the program. It is left to the user to calculate and document $u_c(\hat{T})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the gas temperature measurement.

(2) ***"Detailed level":*** $u_c(\hat{T})$ is calculated in the program from more basic input uncertainties for the temperature element / transmitter provided by the instrument manufacturer and calibration laboratory

The following discussion concerns the "Detailed level". As for the pressure measurement, it has been found convenient to base the user input to the program on the type of data that are typically specified for common temperature transmitters used in North Sea fiscal metering stations.

The temperature loop considered here consists of a Pt 100 or 4-wire RTD element and a smart temperature transmitter, installed either as two separate devices, or as one unit [NORSOK, 1998a; §5.2.3.5]. The Pt 100 temperature element is required as a minimum to be in accordance with EN 60751 tolerance A. By [NORSOK, 1998a; §5.2.3.5], the temperature transmitter and the Pt 100 element shall be calibrated as one system. A 3-wire temperature element may be used if the temperature element and transmitter are installed as one unit, where the Pt 100 element is screwed directly into the transmitter. The signal is transferred from the temperature transmitter using a HART protocol, i.e. the "digital accuracy" is used.

The temperature transmitter chosen by NFOGM, NPD and CMR to be used in the present *Handbook* for the example uncertainty evaluation of Chapter 6 is the Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2001], cf. Table 5.4 and Figure 5.2. The Rosemount 3144 transmitter is widely used in the North Sea when upgrading existing fiscal gas metering stations and when designing new metering stations. This transmitter is also chosen for the layout of the temperature transmitter user input to the program *EMU - Orifice Fiscal Gas Metering Station*.

Figure 5.2 The Rosemount 3244 Temperature Transmitter (example). © 2002 Rosemount Inc. Used by permission [Rosemount, 2002b].

Figure 5.2 shows a typical temperature transmitter with an integrated Pt-100 temperature element. However, the temperature transmitter is often installed remote from the Pt-100 temperature element with a 4-wire cable between the transmitter and the element.

The measurement principle and functional relationship of RTDs is described e.g. in [ISO/CD 15970, 1999]. However, as the element/transmitter is calibrated and given a specific “accuracy” in the calibration data sheet, no functional relationship is actually used here for calculation of the uncertainty of the temperature measurements. The functional relationship is only internal to the temperature element/transmitter, and the uncertainty due to the functional relationship is included in the calibrated “accuracy” of the element/transmitter.

As mentioned in Section 5.1, the temperature shall preferably be measured downstream of the primary device, and according to ISO-5167-1:2003 [ISO, 2003a] it may generally be assumed that the downstream and upstream temperatures of the fluid are the same at the differential pressure tappings. However, if the fluid is a non-ideal gas and a minimum uncertainty is required and there is a large pressure loss between the upstream pressure tapping and the temperature location downstream of the primary device, then it is necessary to calculate the upstream temperature from the downstream temperature assuming an isenthalpic expansion between the two points. To perform this calculation the permanent pressure loss $\Delta\varpi$ should be calculated depending on the primary device. Then the corresponding temperature drop from the upstream tapping to the downstream temperature location, ΔT, can be evaluated using the Joule Thomson coefficient, μ_{JT}, as $\Delta T = \mu_{JT} \cdot \Delta\varpi$.

Please refer to ISO 5167-2:2003 and therein referenced literature for details regarding this calculation. The ISO 5167-2:2003 does not however include a specification of the uncertainty for the Joule Thomson coefficient, μ_{JT}. Furthermore, it only gives approximate functional relationships for the permanent pressure drop across an orifice, and does not specify the uncertainty associated with these models. Hence, it is currently left to the user to evaluate whether to use this correction, and in case document its uncertainty.

It should be noted that the user is required to evaluate and document the potential uncertainty contribution caused by the temperature difference between the upstream pressure tapping and the temperature location, or the model used to correct for this difference. If the uncertainty contribution is not negligible, the uncertainty due to this difference or its correction should be included as a miscellaneous uncertainty contribution under the temperature measurement.

5.2.1 Functional relationship

The combined standard uncertainty of the temperature measurement, $u_c(\hat{T})$, can be given as input to the program *EMU - Orifice Fiscal Gas Metering Station* at two levels: "Overall level" and "Detailed level", cf. Section 1.4.

As the "Overall level" is straightforward, only the "Detailed level" is discussed in the following. The uncertainty model for the temperature element/transmitter is quite general, and applies to e.g. the Rosemount 3144 Temperature Transmitter used with a Pt 100 element, and similar transmitters.

At the "Detailed level", $u_c(\hat{T})$ may be given as[51]

[51] In accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001], the sensitivity coefficients have been assumed to be equal to 1 throughout Eqn. (3.12). Note that this is a simplified approach. An alternative and more correct approach would have been to start from the full functional relationship of the temperature measurement, and derive the uncertainty model according to the recommendations of the *GUM* [ISO, 1995a].

$$u_c^2(\hat{T}) = u^2(\hat{T}_{elem,transm}) + u^2(\hat{T}_{stab,transm}) + u^2(\hat{T}_{RFI}) + u^2(\hat{T}_{temp}) + u^2(\hat{T}_{stab,elem}) \\ + u^2(\hat{T}_{vinbration}) + u^2(\hat{T}_{power}) + u^2(\hat{T}_{cable}) + u^2(\hat{T}_{misc}) \tag{5.2}$$

where [Rosemount, 2001]:

$u(\hat{T}_{elem,transm}) \equiv$ standard uncertainty of the temperature element and temperature transmitter, calibrated as a unit.

$u(\hat{T}_{stab,transm}) \equiv$ standard uncertainty of the stability of the temperature transmitter, with respect to drift in the readings over time.

$u(\hat{T}_{RFI}) \equiv$ standard uncertainty due to radio-frequency interference (RFI) effects on the temperature transmitter.

$u(\hat{T}_{temp}) \equiv$ standard uncertainty of the effect of temperature on the temperature transmitter, for change of gas temperature relative to the temperature at calibration.

$u(\hat{T}_{stab,elem}) \equiv$ standard uncertainty of the stability of the Pt 100 4-wire RTD temperature element. Instability may relate e.g. to drift during operation, as well as instability and hysteresis effects due to oxidation and moisture inside the encapsulation, and mechanical stress during operation.

$u(\hat{T}_{vibration}) \equiv$ standard uncertainty due to vibration effects on the temperature transmitter.

$u(\hat{T}_{power}) \equiv$ standard uncertainty due to power supply effects on the temperature transmitter.

$u(\hat{T}_{cable}) \equiv$ standard uncertainty of lead resistance effects on the temperature transmitter.

$u(\hat{T}_{misc}) \equiv$ standard uncertainty of other (miscellaneous) effects on the temperature transmitter.

$u_c(\hat{T})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{T}_{elem,transm})$, $u(\hat{T}_{stab,transm})$, $u(\hat{T}_{RFI})$, $u(\hat{T}_{temp})$, $u(\hat{T}_{stab,elem})$, $u(\hat{T}_{vibration})$, $u(\hat{T}_{power})$ and $u(\hat{T}_{cable})$, and document their traceability.

As an example, the uncertainty of the Rosemount 3144 temperature transmitter used with a Pt 100 element is evaluated in Section 3.2.2.

5.2.2 Example uncertainty evaluation

The combined standard uncertainty of the temperature measurement, $u_c(\hat{T})$, is given by Eqn. (3.7). This expression is evaluated in the following.

Performance specifications for the Rosemount Model 3144 Smart Temperature Transmitter and the Pt 100 4-wire RTD element are given in Table 3.4[52], as specified in the data sheet [Rosemount, 2001], etc. The contributions to the combined standard uncertainty of the temperature measurement are described in the following.

Table 5.4 Performance specifications of the Rosemount Model 3144 Temperature Transmitter [Rosemount, 2001] and the Pt 100 4-wire RTD element, used as input to the uncertainty calculations given in Table 3.6.

Quantity or Source	Value or Expanded uncertainty	Coverage factor, *k*	Reference
Calibration ambient temperature (air)	20 °C	-	Calibration certificate *(NA)*
Time between calibrations	12 months	-	Example
Transmitter/element uncertainty (not calibrated as a unit), $U(\hat{T}_{elem,transm})$	"Digital accuracy": 0.10 °C "D/A accuracy": ±0.02 % of span.	3 3	[Rosemount, 2001]
Transmitter/element uncertainty (calibrated as a unit), $U(\hat{T}_{elem,transm})$	*NA*	*NA*	Calibration certificate *(NA)*
Stability - temperature transmitter, $U(\hat{T}_{stab,transm})$	0.1 % of reading or 0.1 °C, whichever is greater, for 24 months.	3	[Rosemount, 2001]
RFI effects - transmitter, $U(\hat{T}_{RFI})$	Worst case, with unshielded cable: equivalent to the transmitter "accuracy".	3	[Rosemount, 2001]
Ambient temperature effects - transmitter, $U(\hat{T}_{temp})$	"Digital accuracy": 0.0015 °C per 1 °C. D/A effect: 0.001 % of span, per 1 °C.	3 3	[Rosemount, 2001]
Stability - temperature element, $U(\hat{T}_{stab,elem})$	0.050 °C	-	[BIPM, 1997]
Vibration effects, $U(\hat{T}_{vibration})$	*Negligible* (tested to given specifications with no effect on performance).	3	[Rosemount, 2001]

52 Note that the expanded uncertainties given in the transmitter data sheet [Rosemount, 2001] are specified at a 99 % confidence level (k = 3).

Power supply effects, $U(\hat{T}_{power})$	*Negligible* (less than ±0.005 % of span per volt).	3	[Rosemount, 2001]
Lead resistance effects, $U(\hat{T}_{cable})$	*Negligible* (no effect, independent on lead resistance).	3	[Rosemount, 1998]

1. ***Transmitter/element uncertainty (calibrated as a unit),*** $U(\hat{T}_{elem,transm})$**:** The temperature element and the temperature transmitter are calibrated as a unit [NORSOK, 1998a].

   If the expanded uncertainty specified in the calibration certificate is used for the uncertainty evaluation, the transmitter/element uncertainty (calibrated as a unit) will include the uncertainty of the temperature calibration laboratory (to be traceable to international standards). The confidence level of the reported expanded uncertainty is to be specified. When first recording the characteristics of the temperature element and then loading this characteristic into the transmitter prior to the final calibration, the uncertainty due to the element can be minimised [Fimas, 1999].

   Alternatively, if the calibration laboratory states that the transmitter/element uncertainty (calibrated as a unit, and including the calibration laboratory uncertainty) is within the "accuracy" given in the manufacturer data sheet [Rosemount, 2001], one may - as a conservative approach - use the latter uncertainty value in the calculations. This approach is used here.

   The "accuracy" of the 3144 temperature transmitter used together with a Pt 100 4-wire RTD element is tabulated in the data sheet [Rosemount, 2001]. The output signal is accessed using a HART protocol, i.e. only the "digital accuracy" is used here (cf. Table 3.4). The expanded uncertainty is then given as 0.10 °C at a 99 % confidence level (k = 3). That is, $u(\hat{T}_{elem,transm}) = U(\hat{T}_{elem,transm})/3 = 0.10\ ^oC/3 = 0.033\ ^oC$ [53].

2. ***Stability - temperature transmitter,*** $u(\hat{T}_{stab,transm})$**:** The stability of the temperature transmitter represents a drift in the readings with time. This

53 The manufacturer's uncertainty specification is used here, for temperature element and transmitter combined. By calibration of the element and transmitter in an accredited calibration laboratory, the element/transmitter uncertainty may be significantly reduced. As an example, the calibration certificate specification for the element/transmitter's expanded uncertainty $U(\hat{T}_{elem,transm})$ may be 0.03 ^{o}C, at a 95 % confidence level (k = 2) [Eide, 2001a], corresponding to 0.015 ^{o}C for the standard uncertainty.

contribution is zero at the time of calibration, and is specified as a maximum value at a given time.

For use in combination with RTD elements, the stability of the 3144 temperature transmitter is given in the manufacturer data sheet [Rosemount, 2001] as 0.1 % of reading (measured value), or 0.1 °C, whichever is greater for 24 months, cf. Table 5.4. The time dependency is not necessarily linear. However, for simplicity, a linear time dependency is assumed here[54].

The value "0.1 % of reading for 24 months" corresponds to $[(273+50)\cdot 0.001]^oC \approx 0.323\,^oC$. As this is greater than 0.1 °C, this uncertainty value is used. Consequently, if the transmitter is calibrated every 12 months, the uncertainty given in the data sheet due to stability effects is divided by 24 and multiplied with 12. That is, $u(\hat{T}_{stab,transm}) = U(\hat{T}_{stab,transm})/3$ $= [(273+50)\cdot 0.001\cdot(12/24)]^oC/3 = 0.1615\,^oC/3 \approx 0.054\,^oC$.

3. ***RFI effects - temperature transmitter,*** $u(\hat{T}_{RFI})$***:*** Radio-frequency interference, effects (RFI) may cause a worst case uncertainty equivalent to the transmitter's nominal uncertainty, when used with an unshielded cable [Rosemount, 2001]. For fiscal metering stations all cables are shielded, i.e. the RFI effects should be less than the worst case specified in the data sheet. Nevertheless, RFI effects (and also effects due to bad instrument earth) may cause additional uncertainty to the temperature measurement that is hard to quantify.

   It is time consuming to predict or measure the actual RFI effects at the metering station, and difficult to evaluate correctly the influence on the temperature measurement.

   It is therefore recommended to use the worst case uncertainty specified in the data sheet for the uncertainty due to RFI effects. For the "digital acuracy" of the 3144 transmitter, the expanded uncertainty is specified to be 0.10 ^{o}C, cf. Table 5.4. That is, $u(\hat{T}_{RFI}) = U(\hat{T}_{RFI})/3 = 0.10\,^oC/3 = 0.033\,^oC$.

4. ***Ambient temperature effects - temperature transmitter,*** $u(\hat{T}_{temp})$***:*** The Rosemount 3144 temperature transmitters are individually characterised for the

[54] In a worst case scenario, the uncertainty due to stability may be used directly without using the time division specified.

ambient temperature range -40 °C to 85 °C , and automatically compensate for change in ambient temperature [Rosemount, 2001].

Some uncertainty still arises due to the change in ambient temperature. This uncertainty is tabulated in the data sheet as a function of changes in the ambient temperature (in operation) from the ambient temperature when the transmitter was calibrated, cf. Table 5.4.
The ambient temperature uncertainty for Rosemount 3144 temperature transmitters used together with Pt-100 4-wire RTDs is given in the data sheet as 0.0015 °C per 1 °C change in ambient temperature relative to the calibration ambient temperature (the “digital accuracy”).

Consequently, for a possible “worst case” ambient North Sea temperature taken as 0 ^oC, and a calibration temperature equal to 20 ^oC, i.e. a max. temperature change of 20 ^oC, one obtains $u(\hat{T}_{temp}) = U(\hat{T}_{temp})/3$ $= 0.0015 \cdot 20\,^oC/3 = 0.03\,^oC/3 = 0.01\,^oC$.

5. ***Stability - temperature element,*** $u(\hat{T}_{stab,elem})$***:*** The Pt-100 4-wire RTD element will cause uncertainty to the temperature measurement due to drift during operation. Oxidation, moisture inside the encapsulation and mechanical stress during operation may cause instability and hysteresis effects [EN 60751, 1995], [BIPM, 1997].

   BIPM [BIPM, 1997] has performed several tests of the stability of temperature elements which shows that this uncertainty is typically of the order of 0.050 °C, cf. Table 3.4. The confidence level of this expanded uncertainty is not given, however, and a 95 % confidence level and a normal probability distribution is assumed here (k = 2, cf. Section 2.3). That is, $u(\hat{T}_{stab,elem}) = U(\hat{T}_{stab,elem})/2$ = 0.050 ^oC / 2 = 0.025 ^oC.

6. ***Vibration effects - temperature transmitter,*** $u(\hat{T}_{vibration})$***:*** According to the manufacturer data sheet [Rosemount, 2001], "transmitters are tested to the following specifications with no effect on performance: 0.21 mm peak displacement for 10-60 Hz; 3*g* acceleration for 60-2000 Hz". Moreover, in communication with the manufacturer [Rosemount, 1999] and a calibration laboratory [Fimas, 1999], and considering that the vibration level at fiscal metering stations shall be very low (and according to recognised standards), the uncertainty due to vibration effects may be neglected.

Hence, in the program *EMU - Orifice Fiscal Gas Metering Station*, the uncertainty due to vibration effects is neglected for the Rosemount 3144 temperature transmitter, $u(\hat{T}_{vibration}) = 0$.

7. ***Power supply effects - temperature transmitter,*** $u(\hat{T}_{power})$**:** The power supply effect is quantified in the manufacturer data sheet [Rosemount, 2001] as being less than ±0.005 % of span per volt. According to the supplier [Rosemount, 1999] this uncertainty is specified to indicate that the uncertainty due to power supply effects is negligible for the 3144 transmitter, which was not always the case for the older transmitters [Dahl *et al.*, 1999].

   Hence, in the program *EMU - Orifice Fiscal Gas Metering Station*, the uncertainty due to power supply effects is neglected for the Rosemount 3144 temperature transmitter, $u(\hat{T}_{power}) = 0$.

8. ***Sensor lead resistance effects - temperature transmitter,*** $u(\hat{T}_{cable})$**:** According to the manufacturer data sheet for the 3144 transmitter [Rosemount, 1999], the error due to lead resistance effects is "none" (independent of lead resistance) for 4-wire RTDs. 4-wire RTDs are normally used in fiscal metering stations.

   Hence, in the program *EMU - Orifice Fiscal Gas Metering Station*, the uncertainty due to lead resistance effects is neglected for the 3144 transmitter: $u(\hat{T}_{cable}) = 0$.

A sample uncertainty budget is given in Table 4.8 for evaluation of the expanded uncertainty of the temperature measurement according to Eqn. (5.2). The figures used for the input uncertainties are those given in the discussion above.

Table 5.5 Sample uncertainty budget for the temperature measurement using the Rosemount Model 3144 Temperature Transmitter [Rosemount, 2001] with a Pt 100 4-wire RTD element, calculated according to Eqn. (3.7).

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Transmitter/element uncertainty	0.10 °C	99 % (norm)	3	0.033 °C	1	$1.11 \cdot 10^{-3}$ °C^2
Stability, transmitter	0.1615 °C	99 % (norm)	3	0.054 °C	1	$2.90 \cdot 10^{-3}$ °C^2
RFI effects	0.10 °C	99 % (norm)	3	0.033 °C	1	$1.11 \cdot 10^{-3}$ °C^2
Ambient temperature effects, transmitter	0.03 °C	99 % (norm)	3	0.010 °C	1	$1.00 \cdot 10^{-4}$ °C^2
Stability, element	0.050 °C	95 % (norm)	2	0.025 °C	1	$6.25 \cdot 10^{-4}$ °C^2
Sum of variances				$u_c^2(\hat{T})$		$5.848 \cdot 10^{-3}$ °C^2
Combined standard uncertainty				$u_c(\hat{T})$		0.0765 °C
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{T})$		**0.1529 °C**
Operating temperature				$\hat{T}$		50 °C (≈323 K)
Relative expanded uncertainty (95 % confidence level)				$U(\hat{T})/\hat{T}$		**0.0473 %**

It is seen from Table 5.5 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with *k* = 2, cf. Section 2.3) are 0.15 °C and 0.047 %, respectively. Hence, the uncertainty of the temperature measurement is within the NPD requirement [NPD, 2001a] of an expanded uncertainty of 0.30 °C (see Table 5.1).

5.3 Line (static, absolute) and differential pressure measurements

The descriptions in this Section apply to most extent to both the static absolute pressure and differential pressure transmitter, and only a few of the uncertainty contributions must be considered differently when using a pressure transmitter for either static absolute or differential pressure measurements.

As described in Section 1.4, the uncertainty of the pressure transmitter can in the program *EMU - Orifice Fiscal Gas Metering Station* be specified at two levels (cf. also Chapter 5):

(1) ***"Overall level":*** The user gives $u_c(\hat{P})$ and $u_c(\Delta\hat{P})$ directly as input to the program. It is left to the user to calculate and document $u_c(\hat{P})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the pressure measurement.

(2) ***"Detailed level":*** $u_c(\hat{P})$ and $u_c(\Delta\hat{P})$ is calculated in the program, from more basic input uncertainties for the pressure transmitter, provided by the instrument manufacturer and calibration laboratory.

The following discussion concerns the "Detailed level". It has been found convenient to base the user input to the program on the type of data which are typically specified for common pressure transmitters used in North Sea fiscal metering stations.

The example pressure transmitter chosen by NFOGM, NPD and CMR to be used in the present *Handbook* for the uncertainty evaluation example of Chapter 4 is the Rosemount 3051P Reference Class Pressure Transmitter [Rosemount, 2002a], cf. Table 2.4 and Figure 3.4. This transmitter is also chosen for the layout of the pressure transmitter user input to the program *EMU - Orifice Fiscal Gas Metering Station*. The Rosemount 3051P is a widely used pressure transmitter when upgrading existing North Sea fiscal gas metering stations and when designing new metering stations. The pressure transmitter output is normally the overpressure (gauge pressure), i.e. the pressure relative to the atmospheric pressure [barg], when used for static pressure measurements. Absolute pressure measurements are achieved by adding the atmospheric pressure to the gauge pressure measurement. Other vice, when used for differential pressure measurements the output is in mbar.

Figure 5.3 The Rosemount 3051P Reference Class Pressure Transmitter (example). © 2000 Rosemount Inc. Used by permission [Rosemount, 2002b].

Measurement principles of gauge pressure sensors and transmitters are described e.g. in [ISO/CD 15970, 1999]. However, as the transmitter is calibrated and given a specific "accuracy" in the calibration data sheet, no functional relationship is actually used here for calculation of the uncertainty of the pressure measurements. The functional relationship is only internal to the pressure transmitter, and the uncertainty due to the functional relationship is included in the calibrated "accuracy" of the transmitter.

5.3.1 Functional relationship

As the "Overall level" is straightforward, only the "Detailed level" is discussed in the following. The uncertainty model for the pressure transmitter is quite general, and applies to e.g. the Rosemount 3051P Pressure Transmitter, and similar transmitters.

For simplicity, as the functional relationship with only a few exceptions are the same for the pressure transmitter used for either static absolute and differential pressure measurements, only the static absolute pressure notation ($\hat{P}$) have been used in the following text. However, the discussions also apply to the differential pressure measurement ($\Delta\hat{P}$).

At the "Detailed level", $u_c(\hat{P})$ may be given as:[55]

$$u_c^2(\hat{P}) = u^2(\hat{P}_{transmitter}) + u^2(\hat{P}_{stability}) + u^2(\hat{P}_{RFI}) + u^2(\hat{P}_{temp}) + u^2(\hat{P}_{atm}) + u^2(\hat{P}_{vibration}) + u^2(\hat{P}_{power}) + u^2(\hat{P}_{misc}) \quad (5.3)$$

where [Rosemount, 2002a]:

$u(\hat{P}_{transmitter}) \equiv$	standard uncertainty of the pressure transmitter, including hysteresis, terminal-based linearity, repeatability and the standard uncertainty of the pressure calibration laboratory.
$u(\hat{P}_{stability}) \equiv$	standard uncertainty of the stability of the pressure transmitter, with respect to drift in readings over time.
$u(\hat{P}_{RFI}) \equiv$	standard uncertainty due to radio-frequency interference (RFI) effects on the pressure transmitter.
$u(\hat{P}_{temp}) \equiv$	standard uncertainty of the effect of ambient gas temperature on the pressure transmitter, for change of ambient temperature relative to the temperature at calibration.
$u(\hat{P}_{atm}) \equiv$	standard uncertainty of the atmospheric pressure, relative to 1 atm. ≡ 1.01325 bar, due to local meteorological effects.
$u(\hat{P}_{vibration}) \equiv$	standard uncertainty due to vibration effects on the pressure measurement.

[55] Here, the sensitivity coefficients have been assumed to be equal to 1 throughout Eqn. (3.11), as a simplified approach, and in accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001]. An alternative and more correct approach would have been to start from the functional relationship of the pressure measurement, and derive the uncertainty model according to the recommendations of the *GUM* [ISO, 1995a].

$u(\hat{P}_{power}) \equiv$ standard uncertainty due to power supply effects on the pressure transmitter.

$u(\hat{P}_{misc}) \equiv$ standard uncertainty due to other (miscellaneous) effects on the pressure transmitter, such as mounting effects, etc.

$u(\hat{P})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{P}_{transmitter})$, $u(\hat{P}_{stability})$, $u(\hat{P}_{temp})$, $u(\hat{P}_{RFI})$, $u(\hat{P}_{vibration})$ and $u(\hat{P}_{power})$, and document their traceability.

As an example, the uncertainty of the Rosemount 3051P pressure transmitter is evaluated in Section 3.3.2.

5.3.2 Example uncertainty evaluation

The combined standard uncertainty of the static absolute and differential pressure measurements, $u_c(\hat{P})$ and $u_c(\Delta\hat{P})$, is given by Eqn. (5.3). This expression is evaluated in the following.

Performance specifications for the Rosemount Model 3051P Reference Class Pressure Transmitter are given in Table 5.6[56], as specified in the data sheet [Rosemount, 2002a]. The contributions to the combined standard uncertainty of the pressure measurements are described in the following.

Table 5.6 Performance specifications of the Rosemount Model 3051P Reference Class Pressure Transmitter [Rosemount, 2002a], used as input to the uncertainty calculations given in Table 5.8.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, k**	**Reference**
Calibration ambient temperature (air)	20 °C	-	Calibration certificate
Time between calibrations	12 months	-	Example
Maxium calibrated static pressure	120 bara	-	Example
Minimum calibrated static pressure	50 bara	-	Example
Span (calibrated)	70 bar	-	Calibration certificate
URL (upper range limit)	138 barg	-	[Rosemount, 2002a]
Transmitter uncertainty, $U(\hat{P}_{transmitter})$	0.05 % of span	3	[Rosemount, 2002a]

56 Note that the expanded uncertainties given in the transmitter data sheet [Rosemount, 2002a] are specified at a 99 % confidence level (k = 3).

Stability, $U(\hat{P}_{stability})$	Static pressure meas.: 0.125 % of URL for 5 years for 28 °C temperature changes. Differential pressure meas.: 0.125 % of URL for 5 years for 28 °C temperature changes, and up to 69 bar line pressure.	3	[Rosemount, 2002a]
RFI effects, $U(\hat{P}_{RFI})$	0.1 % of span from 20 to 1000 MHz and for field strength up to 30 V/m.	3	[Rosemount, 2000]
Ambient temperature effects (air), $U(\hat{P}_{temp})$	(0.006% URL + 0.03% span) per 28°C	3	[Ro2emount, 2002]
Vibration effects, $U(\hat{P}_{vibration})$	Negligible (except at resonance frequencies, see text below).	3	[Rosemount, 2002a]
Power supply effects, $U(\hat{P}_{power})$	Negligible (less than ±0.005 % of calibrated span per volt).	3	[Rosemount, 2002a]
Mounting position effect	Negligible (in case this will influence only on differential pressure measurements, not static pressure measurements)	3	[Dahl et al., 1999]
Static pressure effect	Negligible (influence only on differential pressure measurement, not static pressure measurement)	3	[Dahl et al., 1999]

Table 5.7 Performance specifications of the Rosemount Model 3051P Reference Class Pressure Transmitter [Rosemount, 2002a], used as input to the uncertainty calculations given in Table 5.9.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, k**	**Reference**
Calibration ambient temperature (air)	20 °C	-	Calibration certificate
Time between calibrations	6 months	-	Example
Span (calibrated)	550 mbar	-	Calibration certificate
URL (upper range limit)	622 mbar	-	[Rosemount, 2002a]
Transmitter uncertainty, $U(\hat{P}_{transmitter})$	0.05 % of span	3	[Rosemount, 2002a]
Stability, $U(\hat{P}_{stability})$	0.125 % of URL for 5 years for 28 °C temperature changes, and up to 69 bar line pressure.	3	[Rosemount, 2002a]
	For fiscal gas metering: 0.1 % of URL for 1 year (used here).	3	[Rosemount, 1999, 2003]
RFI effects, $U(\hat{P}_{RFI})$	0.1 % of span from 20 to 1000 MHz and for field strength up	3	[Rosemount,

	to 30 V/m.		2000]
Ambient temperature effects (air), $U(\hat{P}_{temp})$	(0.006% URL + 0.03% span) per 28°C	3	[Ro2emount, 2002]
Vibration effects, $U(\hat{P}_{vibration})$	Negligible (except at resonance frequencies, see text below).	3	[Rosemount, 2002a]
Power supply effects, $U(\hat{P}_{power})$	Negligible (less than ±0.005 % of calibrated span per volt).	3	[Rosemount, 2002a]
Mounting position effect	Negligible (in case this will influence only on differential pressure measurements, not static pressure measurements)	3	[Dahl et al., 1999]
Static pressure effect	Negligible (influence only on differential pressure measurement, not static pressure measurement)	3	[Dahl et al., 1999]

1. ***Pressure transmitter uncertainty,*** $U(\hat{P}_{transmitter})$***:*** If the expanded uncertainty specified in the calibration certificate is used for the uncertainty evaluation, the transmitter uncertainty is to include the uncertainty of the temperature calibration laboratory (which shall be traceable to international standards). The confidence level and the probability distribution of the reported expanded uncertainty shall be specified.

   Alternatively, if the calibration laboratory states that the transmitter uncertainty (including the calibration laboratory uncertainty) is within the "reference accuracy" given in the manufacturer data sheet [Rosemount, 2002a], one may - as a conservative approach - use the latter uncertainty value in the calculations. This approach is used here.

   The "reference accuracy" of the 3051P pressure transmitter accounts for hysteresis, terminal-based linearity and repeatability, and is given in the manufacturer data sheet as 0.05 % of span at a 99 % confidence level (cf. Table 5.6), i.e. with k = 3 (Section 2.3). It is assumed here that this figure refers to the calibrated span. As an example, the calibrated span is here taken to be 50 - 120 bar, i.e. 70 bar, giving $u(\hat{P}_{transmitter}) = U(\hat{P}_{transmitter})/3 = [70 \cdot 0.0005] bar/3 = 0.035\, bar/3 = 0.012\, bar$ [57].

[57] The manufacturer's uncertainty specification is used here. By calibration of the pressure transmitter in an accredited calibration laboratory, the transmitter uncertainty may be further reduced. An example of a calibration certificate specification for the expanded uncertainty $U(\hat{P}_{transmitter})$ may be in the range 0.018-0.022 bar, at a 95 % confidence level (k = 2) [Eide, 2001a], i.e. 0.009-0.011 bar for the standard uncertainty. This includes linearity, hysteresis, repeatability, reading uncertainty, and reference instruments uncertainty.

2. ***Stability - pressure transmitter,*** $u(\hat{P}_{stability})$***:*** The stability of the pressure transmitter represents a drift (increasing/decreasing offset) in the readings with time. This contribution is zero at the time of calibration, and is specified as a maximum value at a given time.

   The stability of the 3051P pressure transmitter for static (3051PG) and differential (3051PD) pressure measurements is given in the manufacturer data sheet [Rosemount, 2002a] as 0.125 % of URL for 5 years for a maximum 28 °C changes in temperature and up to 69 barg static line pressures (Table 5.6). For the static pressure transmitter the limitation with respect to static pressure does not apply.

   The time dependency of the stability uncertainty is not necessarily linear. However, for simplicity, a linear time dependency has been assumed here[58].

   The confidence level is specified to be 99 % with a normal probability distribution (k = 2, cf. Section 2.3) [Rosemount, 2003]. Consequently, if the static pressure transmitter is calibrated every 12 months, the uncertainty due to stability effects becomes, $u(\hat{P}_{stability}) = U(\hat{P}_{stability})/3 = [138 \cdot 0.00125 \cdot (1/5)] bar/3$ ≈ 0.0345 bar / 3 ≈ 0.0115 bar. For the differential pressure transmitter the uncertainty due to stability becomes, $u(\hat{P}_{stability}) = U(\hat{P}_{stability})/3$ $= [622 \cdot 0.00125 \cdot (1/5)] mbar/3$ ≈ 0.1555 mbar / 3 ≈ 0.052 mbar.

3. ***RFI effects - pressure transmitter,*** $u(\hat{P}_{RFI})$***:*** Radio-frequency interference, effects (RFI) is given in the manufacturer data sheet [Rosemount, 2002a] as ±0.1 % of span for frequencies from 20 to 1000 MHz, and for field strength up to 30 V/m, cf. Table 5.6.

   It is noted that the specified RFI uncertainty is actually twice as large as the uncertainty of the transmitter itself. In practice, this uncertainty contribution may be difficult to evaluate, and the RFI electric field at the actual metering station should be measured in order to document the actual electric field at the pressure transmitter. I.e. the RFI electric field must be documented in order to evaluate if, and to what extent, the uncertainty due to RFI effects may be reduced.

58 In a worst case scenario, the uncertainty due to stability may be used directly without using the time division specified.

However, as long as the RFI electric field at the pressure transmitter is not documented by measurement, the uncertainty due to RFI effects must be included in the uncertainty evaluation as given in the data sheet. Consequently, $u(\hat{P}_{RFI}) = U(\hat{P}_{RFI})/3 = [70 \cdot 0.001] bar/3 = 0.07\, bar/3 = 0.023\, bar$.

4. ***Ambient temperature effects - pressure transmitter,*** $u(\hat{P}_{temp})$***:*** The ambient temperature effect on the Rosemount 3051P pressure transmitter is given in the manufacturer data sheet [Rosemount, 2002a] as (0.006 % URL + 0.03 % span) per 28 °C temperature change, cf. Table 5.6. The temperature change referred to is the change in ambient temperature relative to the ambient temperature at calibration (to be specified in the calibration certificate).

   Consequently, for a possible "worst case" example of ambient North Sea temperature taken as 0 ^{o}C, and a calibration temperature equal to 20 ^{o}C, i.e. a max. temperature change of 20 ^{o}C, one obtains $u(\hat{P}_{temp}) = U(\hat{P}_{temp})/3$ $= [(138 \cdot 0.006 + 70 \cdot 0.03) \cdot 10^{-2} \cdot (20/28)] bar/3 = [0.0059 + 0.0150] bar/3$ $\approx 0.0209\, bar/3 \approx 0.007\, bar$.

5. ***Atmospheric pressure,*** $u(\hat{P}_{atm})$***:*** The Rosemount 3051P pressure transmitter is here used for static absolute pressure measurements, where it measures the excess pressure relative to the atmospheric pressure. The atmospheric pressure is then added to the gauge pressure measurement to achieve an absolute pressure measurement. The uncertainty of the absolute static pressure $u_c(\hat{P})$ must therefore also include the uncertainty of the atmospheric pressure, due to day-by-day atmospheric pressure variations.

   The atmospheric pressure does not influence on the differential pressure measurement.

   In the North Sea, the average atmospheric pressure is about 1008 and 1012 mbar for the winter and summer seasons, respectively (averaged over the years 1955-1991) [Lothe, 1994]. For convenience, 1 atm. ≡ 1013.25 mbar is taken as the average value. On a worldwide basis, the observed atmospheric pressure range includes the range 920 - 1060 mbar, - however, the upper and lower parts of this range (beyond about 940 and 1040 mbar) are very rare (not observed every year) [Lothe, 2001].

   The variation of the atmospheric pressure around the value 1 atm. ≡ 1013.25 mbar is here taken to be 90 mbar, as a conservative approach. Assuming a 99 %

confidence level, and a normal probability distribution for the variation range of the atmospheric pressure (k = 3, cf. Section 2.3), one obtains $u(\hat{P}_{atm}) = U(\hat{P}_{atm})/3 = 90\,mbar/3 = 0.09\,bar/3 = 0.03\,bar$.

6. ***Vibration effects - pressure transmitter,*** $u(\hat{P}_{vibration})$**:** According to the manufacturer data sheet [Rosemount, 2002a], "measurement effect due to vibrations is negligible except at resonance frequencies. When at resonance frequencies, vibration effect is less than 0.1 % of URL per *g* when tested from 15 to 2000 Hz in any axis relative to pipe-mounted process conditions" (Table 5.6).

   Based on communication with the manufacturer [Rosemount, 1999] and a calibration laboratory [Fimas, 1999], the vibration level at fiscal metering stations is considered to be very low (and according to recognised standards). Hence, the uncertainty due to vibration effects may be neglected.

   In the program *EMU - Orifice Fiscal Gas Metering Station*, the uncertainty due to vibration effects is neglected for the 3051P transmitter: $u(\hat{P}_{vibration}) = 0$.

7. ***Power supply effects - pressure transmitter,*** $u(\hat{P}_{power})$**:** The power supply effect is quantified in the manufacturer data sheet [Rosemount, 2002a] as less than ±0.005 % of the calibrated span per volt (Table 5.6). According to the supplier [Rosemount, 1999] this uncertainty is specified to indicate that the uncertainty due to power supply effects is negligible for the 3051P transmitter, which was not always the case for the older transmitters [Dahl *et al.*, 1999].

   Hence, in the program, the uncertainty due to power supply effects is neglected for the 3051P transmitter: $u(\hat{P}_{power}) = 0$.

8. ***Static pressure effect - pressure transmitter:*** The static pressure effect [Rosemount, 2002a] will only influence on a differential pressure transmitter, and not on static pressure measurements while the static pressure transmitter actually measure this static pressure [Dahl *et al.*, 1999][59].

[59] The static pressure effect influencing on 3051P differential pressure transmitters consists of (a) the *zero error*, and (b) the *span error* [Rosemount, 2002a]. The zero error is given in the data sheet [Rosemount, 2002a] as ±0.04 % of URL per 69 barg. The zero error can be calibrated out at line pressure. The span error is given in the data sheet [Rosemount, 2002a] as ±0.10 % of reading per 69 barG.

a) Zero effect

The zero effect is given in the data sheet as 0.05% of *URL* per 69 barg (1,000 psi). However, the zero pressure effect is easily removed by a zero calibration, and may therefore be neglected for both the static and the differential pressure transmitter.

b) Span effect

The *Span* effect is given in the data sheet as 0.10% of reading per 69 barg (1,000 psi) and applies only to the differential pressure transmitter. I.e., this uncertainty must be included in the uncertainty evaluation of the 3051P differential pressure transmitter.

9. ***Mounting position effects - pressure transmitter:*** The mounting position effect [Rosemount, 2002a] will only influence on a differential pressure transmitter, and not on static pressure measurements [Dahl *et al.*, 1999][60]. The mounting position effects are due to the construction of the differential pressure transmitter with oil filled chambers. These may influence the measurement if the transmitter is not properly mounted. However, as was the case for the zero effect, uncertainty due to the mounting position effects may be calibrated out with a simple zero calibration. The uncertainty due to mounting position effects may therefore be neglected in the uncertainty evaluation.

Example uncertainty budgets are given in Table 5.8 and Table 5.9 for evaluation of the expanded uncertainty of the static and differential pressure measurements, respectively, according to Eqn. (5.3). The figures used for the input uncertainties are those given in the discussion above.

60 Mounting position effects are due to the construction of the 3051P differential pressure transmitter with oil filled chambers [Dahl *et al.*, 1999]. These may influence the measurement if the transmitter is not properly mounted. The mounting position error is specified in the data sheet [Rosemount, 2002a] as “zero shifts up to ±1.25 inH_2O (0.31 kPa = 0.0031 bar), which can be calibrated out. No span effect”.

Table 5.8 Sample uncertainty budget for the measurement of the static absolute gas pressure using the Rosemount Model 3051P Pressure Transmitter [Rosemount, 2002a], calculated according to Eqn. (5.3).

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Transmitter uncertainty	0.035 bar	99 % (norm)	3	0.012 bar	1	$1.36 \cdot 10^{-4}$ bar^2
Stability, transmitter	0.0345 bar	99 % (norm)	3	0.0115 bar	1	$1.32 \cdot 10^{-4}$ bar^2
RFI effects	0.070 bar	99 % (norm)	3	0.023 bar	1	$5.44 \cdot 10^{-4}$ bar^2
Ambient temperature effects, transmitter	0.021 bar	99 % (norm)	3	0.007 bar	1	$4.86 \cdot 10^{-5}$ bar^2
Atmospheric pressure	0.090 bar	99 % (norm)	3	0.030 bar	1	$9.00 \cdot 10^{-4}$ bar^2
Sum of variances				$u_c^2(\hat{P})$		$1.76 \cdot 10^{-3}$ bar^2
Combined standard uncertainty				$u_c(\hat{P})$		0.0420 bar
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{P})$		**0.0839 bar**
Operating pressure				$\hat{P}$		100 bara
Relative expanded uncertainty (95 % confidence level)				$U(\hat{P})/\hat{P}$		**0.0839 %**

It is seen from Table 5.8 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with *k* = 2, cf. Section 2.3) are 0.84 bar and 0.084%, respectively. Hence, the uncertainty of the pressure measurement is within the NPD requirement [NPD, 2001a] of a relative expanded uncertainty of 0.30% of measured value (see Table 5.1).

Table 5.9 Sample uncertainty budget for the measurement of the differential pressure across the Orifice using the Rosemount Model 3051P Pressure Transmitter [Rosemount, 2002a], calculated according to Eqn. (5.3).

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Transmitter uncertainty	0.275 mbar	99 % (norm)	3	0.092 mbar	1	$8.40 \cdot 10^{-3}$ mbar^2
Stability, transmitter	0.156 mbar	99 % (norm)	3	0.026 mbar	1	$6.72 \cdot 10^{-4}$ mbar^2
RFI effects	0.55 mbar	99 % (norm)	3	0.183 mbar	1	$3.36 \cdot 10^{-2}$ mbar^2
Ambient temperature effects, transmitter	0.145 mbar	99 % (norm)	3	0.048 mbar	1	$2.32 \cdot 10^{-3}$ mbar^2
Sum of variances				$u_c^2(\Delta\hat{P})$		$4.50 \cdot 10^{-2}$ mbar^2
Combined standard uncertainty				$u_c(\Delta\hat{P})$		0.2121 mbar
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\Delta\hat{P})$		**0.4243 mbar**
Operating pressure				$\Delta\hat{P}$		329.50 mbar
Relative expanded uncertainty (95 % confidence level)				$U(\Delta\hat{P})/\Delta\hat{P}$		**0.1288 %**

It is seen from Table 5.9 that the calculated expanded and relative expanded uncertainties (specified at 95 % confidence level and a normal probability distribution, with $k = 2$, cf. Section 2.3) are 0.42 mbar and 0.13%, respectively. Hence, the uncertainty of the differential pressure measurement is within the NPD requirement [NPD, 2001a] of a relative expanded uncertainty of 0.30% of measured value (see Table 5.1).

5.4 Gas density measurement

The gas density transducer evaluated is the Solartron 7812 gas density transducer [Solartron, 2000]. This is a widely used transducer when upgrading existing fiscal gas metering stations and when designing new stations. The Solartron 7812 gas density transducer is installed in a by-pass (on-line measurement), causing the need for an additional density correction from densitometer conditions to line conditions. The density is normally only corrected in terms of temperature, e.g. a dedicated temperature measurement is performed in the by-pass at the densitometer location, whereas a pressure correction is normally omitted (see discussion in Section 5.4.1.4).

In the example metering station being evaluated in this *Handbook*, a dedicated temperature measurement is performed in the by-pass at the densitometer location. The evaluation of the dedicated temperature transmitter is included in a separate worksheet in the EMU program (“*T-density”).*

However, if the metering station were not equipped with a dedicated temperature transmitter in the by-pass where the densitometer is located, the line temperature measurement would have to be used as an estimate for the temperature or pressure at the densitometer. In such a case, an additional uncertainty contribution to the temperature estimate needs to be included to account for the possible deviation in conditions between the by-pass and the line

In practise, these cases are handled in the EMU programs by setting equal temperatures for the line and densitometer conditions in the “*Gas parameters*” worksheet (see Section 6.2) and by making the temperature uncertainty evaluations equal for the line (the “*T*”) and the density (the “*T-density”*) worksheets. However, one must include an additional uncertainty contribution using the *miscellaneous* option in the “*T-density”* worksheet to account for the possible deviations in conditions between the line and by-pass.

For example, if one assumes a 2 °C maximum temperature deviation between line and by-pass, the additional miscellaneous uncertainty contribution could be estimated as (assuming a rectangular distribution, hence $k = \sqrt{3}$): $u(\hat{T}_{misc}) = 2/\sqrt{3} = 1.15$ °C.

As described in Section 1.3, the uncertainty of the gas densitometer can in the program *EMU - Orifice Fiscal Gas Metering Station* be specified at two levels (cf. also Chapter 6):

(1) ***"Overall level":*** The user specifies the combined standard uncertainty of the density measurement, $u_c(\hat{\rho})$, directly as input to the program. It is left to the user to calculate and document $u_c(\hat{\rho})$ first. This option is completely general, and covers any method of obtaining the uncertainty of the gas density estimate (measurement or calculation)[61].

(2) ***"Detailed level":*** $u_c(\hat{\rho})$ is calculated in the program, from more basic input uncertainties for the vibrating element gas densitometer, provided by the instrument manufacturer and calibration laboratory.

The following discussion concerns the "Detailed level". In this case a functional relationship of the gas densitometer is needed.

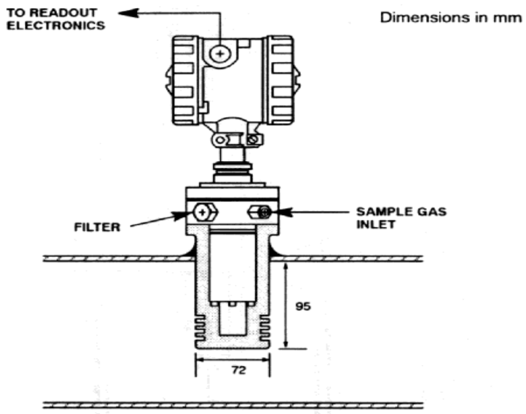
Gas densitometers considered in the "Detailed level" are based on the vibrating cylinder principle, vibrating in the cylinder's Hoop vibrational mode, cf. Fig. 2.5[62]. They consist of a measuring unit and an amplifier unit. The vibrating cylinder is situated in the measuring unit and is activated at its natural frequency by the amplifier unit. The output signal is a frequency or a periodic time (τ), which is primarily dependent upon density, and secondarily upon other parameters, such as pressure, temperature and gas composition [Tambo and Søgaard, 1997]. Any change in the natural frequency will represent a density change in the gas that surrounds the vibrating cylinder.

61 The "overall level" option may be of interest in several cases, such as e.g.:
- If the user wants a "simple" and quick evaluation of the influence of $u_c(\hat{\rho})$ on the expanded uncertainty of the gas metering station,
- In case of a different installation of the gas densitometer (e.g. in-line),
- In case of a different gas densitometer functional relationship than Eqn. ,
- In case of density measurement using GC analysis and calculation instead of densitometer measurement(s).

62 The NORSOK regulations for fiscal measurement of gas [NORSOK, 1998a, §5.2.3.7] state that "the density shall be measured by the vibrating element technique".

Here, only on-line installation of the densitometer is considered, using a by-pass gas sample line, cf. e.g. [ISO/CD 15970, 1999]. By this method, gas is extracted (sampled) from the pipe and introduced into the densitometer. From the densitometer the sample flow can either be returned to the pipe (to the sample probe or another low-pressure point) or sent to the atmosphere (by the flare system). To reduce the temperature differences between the densitometer and the line, the density transducer is installed in a pocket in the main line, and the whole density transducer installation including the sampling line is thermally insulated from the ambient.

(a)



(b)

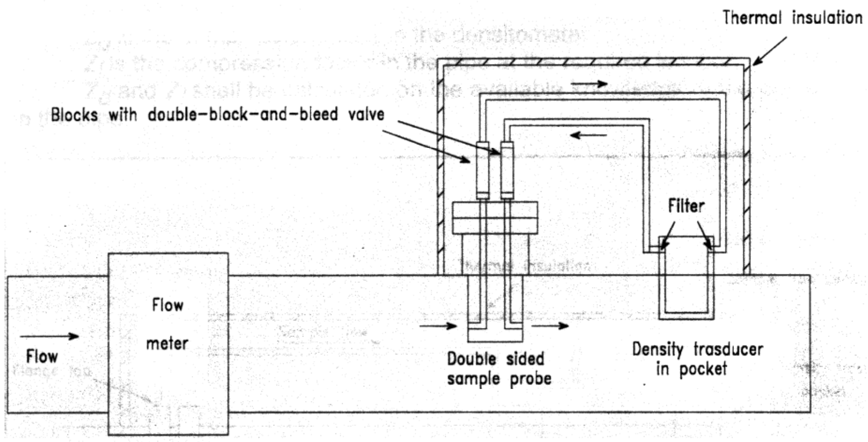


Figure 5.4 (a) The Solartron 7812 gas density transducer [Solartron, 1999] (example). (b) Principle sketch of possible on-line installation of a gas densitometer on a gas line (figure taken from [ISO/CD 15970, 1999]).

Figure 5.5 The Solartron 7812 gas densitometer (example). Used by permission [Solartron, 2002].

For metering stations where the flow meter causes no natural pressure drop in the pipe, the sampling device (probe) may be designed to form a pressure drop, so that the pressure difference between the sample inlet hole and the sample return hole can create sufficient flow through the sample line / densitometer to be continuously representative with respect to gas, pressure and temperature [ISO/CD 15970, 1999].

5.4.1 Functional relationship

The functional relationship involves a set of calibration constants, as well as temperature correction, velocity of sound (VOS) correction, and installation correction (see below).

In the following, reference will be made to the Solartron 7812 Gas Density Transducer [Solartron, 2000], a commonly used densitometer in North Sea fiscal gas metering stations. This is also the densitometer used for example calculations in Chapter 6. However, it should be emphasized that the functional relationship described in the following is relatively general, and should apply to any on-line installed vibrating element gas density transducer.

5.4.1.1 General density equation (frequency relationship regression curve)

For gas density transducers based on the vibrating cylinder principle, the output is the periodic time of the resonance frequency of the cylinder's Hoop vibrational mode. The relation between the density and the periodic time is obtained through calibration of the densitometer at a given calibration temperature (normally 20 °C), on a known pure reference gas (normally nitrogen, argon or methane, due to their acknowledged properties), and at several points along the densitometer's measuring range. The calibration results are then fitted with a regression curve, $\rho_u = f(\tau, c, T, P)$ [Tambo and Søgaard, 1997]. One common regression curve is [ISO/CD 15970, 1999], [Solartron, 1999; §6.4]

$$\rho_u = K_0 + K_1\tau + K_2\tau^2 \qquad (5.4)$$

where

ρ_u	- indicated (uncorrected) density, in density transducer [kg/m^3],
K_0, K_1, K_2	- regression curve constants (given in the calibration certificate),
τ	- periodic time (inverse of the resonance frequency, output from the densitometer) [μs].
c	- sound velocity of the gas surrounding the vibrating element [m/s].

The periodic time, τ, is a function of density and varies typically in the range 200 - 900 μs [Tambo and Søgaard, 1997].

The form of the regression curve can vary from manufacturer to manufacturer, and Eqn. (5.4) is one example of such a curve. However, note that the form of the regression curve is actually not used in the densitometer uncertainty model, and that K_0, K_1 and K_2 are not needed as input to the uncertainty model. The present uncertainty model is thus independent of the type of regression curve used.

5.4.1.2 Temperature correction

When the densitometer operates at temperatures other than the calibration temperature, a correction to the density calculated using Eqn. (5.5) should be made for best accuracy. In the Solartron 7812 gas density transducer, a 4-wire Pt 100 temperature element is incorporated, for installation and check purposes [Solartron, 1999]. The equation for temperature correction uses coefficient data given on the calibration certificate, and is given as [ISO/CD 15970, 1999], [Solartron, 1999; §6.5]

$$\rho_T = \rho_u\left[1 + K_{18}\left(T_d - T_c\right)\right] + K_{19}\left(T_d - T_c\right) \qquad (5.5)$$

where

ρ_T	- temperature corrected density, in density transducer [kg/m^3],
K_{18}, K_{19}	- constants from the calibration certificate[63],
T_d	- gas temperature in density transducer [K],
T_c	- calibration temperature [K].

63 Here, the notation of [Solartron, 1999] for the calibration constants K_{18} and K_{19} is used.

5.4.1.3 VOS correction

The periodic time, τ, of the vibrating cylinder is influenced by the gas compressibility (or, in other words, the gas composition), and thus on the VOS in the gas. Eqs. (5.4)-(5.5) do not account for such effects. Consequently, when the vibrating element gas densitometer is used on gases other than the calibration gases (normally nitrogen or argon), a small calibration offset may be experienced. This offset is predictable, and it may be desirable to introduce VOS corrections to maintain the accuracy of the transducer [Solartron, 1999; §6.6 and Appendix E][64].

The basic relationship for VOS correction is [ISO/CD 15970, 1999], [Solartron, 1999; §6.6, Appendix E]

$$\rho_d = \rho_T \cdot \left[\frac{1 + \left(\dfrac{K_d}{\tau c_c} \right)^2}{1 + \left(\dfrac{K_d}{\tau c_d} \right)^2} \right] \tag{5.6}$$

where

- ρ_d - temperature and VOS corrected density, in density transducer [kg/m^3],
- K_d - transducer constant [μm] (characteristic length for the Hoop mode resonance pattern of the vibrating element [Eide, 2001a]), equal to $2.10 \cdot 10^4$ μm for 7812, $1.35 \cdot 10^4$ μm for 7810 and $2.62 \cdot 10^4$ μm for 7811 sensors [Solartron, 1999].
- c_c - VOS for the calibration gas, at calibration temperature and pressure conditions [m/s].
- c_d - VOS for the measured gas, in the density transducer [m/s].

There are several well-established methods of VOS correction, and four common methods are:

1. For metering stations involving a USM, the VOS measured by the USM (averaged over the paths) is often used for c_d. This method is here referred to as the "**USM method**", and may be useful for measurement of different gases at varying operating conditions.

64 It is stated in [Solartron, 1999; §E.1] that "the 7812 Gas Density Transducer is less sensitive to VOS influence than previous models of this instrument and, in consequence, the need to apply VOS correction is less likely. However, when it is necessary, one of the correction methods are suggested".

2. The "**Pressure/Density method"** [ISO/CD 15970, 1999], [Solartron, 1999; Appendix E] calculates the VOS (c_d) based on the line pressure and density and applies the required correction. This method has been recommended for measurement of different gases at varying operating conditions.

3. The **"User Gas Equation" method** [Solartron, 1999; Appendix E] calculates the VOS (c_d) based on the specific gravity and the line temperature, and applies a correction based on two coefficients that define the VOS characteristic. This equation is shown on nitrogen or argon calibration certificates. The User Gas Equation is an approximate correction for a typical mixture of the calibration gas (normally nitrogen or argon) and methane. This correction method is recommended by Solartron for applications where pressure data is not available, but where gas composition and temperature do change. For this method, a different (and approximate) expression for the VOS correction than Eqn. (5.6) is used.

4. For measurement of gas that has a reasonably well-defined composition, Solartron can supply a "**User Gas Calibration Certificate"** [Solartron, 1999; Appendix E]. This specifies modified values of K_0, K_1, K_2, K_{18} and K_{19}, in order to include the effects of VOS for the given gas composition.

In the following, VOS correction methods based *directly* on Eqn. (5.6) are considered. This includes the "USM method" and the "pressure/density method"[65].

5.4.1.4 *Installation correction*

The vibrating element density transducer is here assumed to be installed in a by-pass line (on-line installation), downstream of the Orifice. Despite thermal insulation of the by-pass density line, and precautions to avoid pressure loss, the gas conditions at the density transducer may be different from the line conditions (at the Orifice), especially with respect to temperature (due to ambient temperature influence), but also possibly with respect to pressure (cf. e.g. [Geach, 1994]). There may thus be need for an installation correction of the density[66]. Temperature is a critical

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65 The VOS correction algorithm given by Eqn. (5.6) was chosen by [Ref. Group, 2001] for use in the *USM Handbook*, and has therefore also been the preferred algorithm in the revision of this Handbook. Other VOS correction algorithms may be included in later possible revisions.

66 The NORSOK I-104 industry standard for fiscal measurement of gas [NORSOK, 1998a, §5.2.3.7] state that (1) "The density shall be corrected to the conditions at the fiscal measurement point", and (2) "if density is of by-pass type, temperature compensation shall be applied".

installation consideration as a 1 ^{o}C temperature error represents a 0.3 % density error [Matthews, 1994], [Tambo and Søgaard, 1997] or more [Sakariassen, 2001][67].

In this connection it is worth remembering that the densitometer will always give the density for the gas in the density transducer. Installation errors result from the sample gas in the density transducer not being at the same temperature or pressure as the gas in the line, and hence its density is different.

With respect to temperature deviation between the density transducer and the main flow due to ambient temperature effects, [Geach, 1994] state that "The pipework should be fully insulated between these two points to reduce temperature changes and, where possible, external loop pipework should be in direct contact with the main line. Unfortunately, this can be difficult to achieve. To aid density equalization, density transducers should be installed in a thermal pocket in the main line". Temperature measurement is available in the density transducer since a Pt 100 element is integrated in the 7812 densitometer [Solartron, 1999]. The temperature transmitter for this Pt 100 element may be located close to the densitometer[68] or further away, in the flow computer.

With respect to possible pressure deviation, it is emphasized by [Geach, 1994] that "careful consideration should be given to any flow control valves, filters (including transducer in-built filters), etc., installed in the external loop. These devices, if installed between the flow element measuring point and the density transducer, are liable to cause unacceptable pressure drops". The flow through the densitometer must be kept low enough to ensure that the pressure change from the main line is negligible, but fast enough to represent the changes in gas composition [Tambo and Søgaard, 1997]. Normally, pressure measurement is *not* available in the density transducer [Geach, 1994], [ISO/CD 15970, 1999]. [Geach, 1994] state "such instrumentation should only be used as a last resort where it is not possible to ensure good pressure equalization with the meter stream". Procedures for pressure shift tests are discussed by [ISO/CD 15970, 1999], and resorts to overcome the problem of satisfying pressure and temperature equilibrium are discussed by [Geach, 1994].

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67 A temperature change of 1 ^{o}C can correspond to much more than 0.3 % in density change, since the temperature also changes the compressibility, *Z*. In some cases the change can be as large as 0.9 % (e.g. in dry gas at 110-150 bar and 10 ^{o}C) [Sakariassen, 2001].

68 In practice, the densitometer's temperature transmitter is usually located in the densitometer, and the temperature element and transmitter in the densitometer are calibrated together (at the same time as the densitometer), to minimize the uncertainty of the densitometer's temperature reading.

From the real gas law, correction for deviation in gas conditions at the densitometer (in the by-pass line) and at the Orifice (line conditions) is made according to [ISO, 1999]

$$\rho = \rho_d \left(\frac{T_d}{T} \right) \left(\frac{P}{P_d} \right) \left(\frac{Z_d}{Z} \right) \qquad (5.7)$$

where

- T - gas temperature in the pipe, at the Orifice location (line conditions) [K],
- P - gas pressure in the pipe, at the Orifice location (line conditions) [bara],
- P_d - pressure in the density transducer [bara],
- Z_d - gas compressibility factor for the gas in the density transducer,
- Z - gas compressibility factor for the gas in the pipe, at Orifice location (line conditions)

For a densitometer of the by-pass type, only one pressure transmitter is here assumed to be installed: in the meter run (close to the Orifice, for measurement of the line pressure P). That is, pressure measurement is not available in the density transducer, i.e. P_d is not measured. In practice, then, the operator of the metering station typically assumes that the densitometer pressure is equal to the line pressure, $\hat{P} \approx \hat{P}_d$. However, there will be an uncertainty associated with that assumption. To account for this situation, let $P_d = P + \Delta P_d$, where ΔP_d is the relatively small and unknown pressure difference between the line and the densitometer pressures (usually negative). ΔP_d may be estimated empirically, from pressure shift tests, etc., or just taken as a "worst case" value. In this description, ΔP_d represents the uncertainty of assuming that $P_d = P$.

Two temperature transmitters are assumed to be installed: in the meter run (close to the Orifice, for measurement of the line temperature T), and in the density transducer (for measurement of the temperature at the densitometer, T_d).

In practice, the gas composition is the same at the Orifice as in the densitometer, and the pressure deviation is relatively small[69]. However, the temperatures in the densitometer and in the line can vary by several ^{o}C, so that the gas compressibility factors in the line and in the densitometer (Z and Z_d) can differ significantly. Correction for deviation in gas compressibility factors is thus normally made.

69 Tests with densitometers have indicated a pressure difference between the densitometer and the line of up to 0.02 % of the line pressure [Eide, 2001a], which for a pressure of 100 bar corresponds to 20 mbar. Differences in pressure will have more influence on low pressure systems than high-pressure systems.

Consequently, with negligible loss of accuracy, the expression Eqn. (5.7) for installation correction is here replaced by

$$\rho = \rho_d \left(\frac{T_d}{T} \right) \left(\frac{1}{1 + \Delta P_d / P} \right) \left(\frac{Z_d}{Z} \right) \tag{5.8}$$

5.4.1.5 Corrected density

By combining Eqs.(5.4)-(5.8), the functional relationship of the corrected density measurement becomes

$$\rho = \left\{ \rho_u \left[1 + K_{18} (T_d - T_c) \right] + K_{19} (T_d - T_c) \right\} \left[\frac{1 + \left(\frac{K_d}{\tau c_c} \right)^2}{1 + \left(\frac{K_d}{\tau c_d} \right)^2} \right] \left(\frac{T_d}{T} \right) \left(\frac{1}{1 + \Delta P_d / P} \right) \left(\frac{Z_d}{Z} \right) \tag{5.9}$$

in which all three corrections (the temperature correction, the VOS correction and the installation correction) are accounted for in a single expression.

Note that in Eqn. (5.9), the *indicated* (uncorrected) density ρ_u has been used as the input quantity related to the densitometer reading instead of the periodic time τ. That has been done since $u(\hat{\rho}_u)$ is the uncertainty specified by the manufacturer [Solartron, 1999], and not $u(\hat{\tau})$.

Eqn. (5.9) is a relatively general functional relationship for on-line installed vibrating element gas densitometers, cf. e.g. [ISO/CD 15970, 1999], which apply to the Solartron 7812 Gas Density Transducer [Solartron, 2000] (used in the example calculations in Chapter 6), as well as other densitometers of this type[70].

5.4.1.6 Uncertainty model

The relative combined standard uncertainty of the gas density measurement, E_ρ, can be given as input to the program *EMU - Orifice Fiscal Gas Metering Station* at two levels: “Overall level” and “Detailed level”, cf. Sections 1.3, 2.4 and 5.7.

70 Note that alternative (but practically equivalent) formulations of the VOS correction may possibly be used in different densitometers.

As the "Overall level" is straightforward, only the "Detailed level" is discussed in the following. The uncertainty model for the gas densitometer is quite general, and should apply to any on-line installed vibrating-element densitometer, such as e.g. the Solartron 7812 gas density transducer[71]. It represents an extension of the uncertainty model for gas densitometers presented by [Tambo and Søgaard, 1997].
At the "Detailed level", the relative combined standard uncertainty E_ρ is given[72] as

$$\begin{aligned} u_c^2(\hat{\rho}) = {} & s_{\rho_u}^2 u^2(\hat{\rho}_u) + u^2(\hat{\rho}_{rept}) + s_{\rho,T}^2 u_c^2(\hat{T}) + s_{\rho,T_d}^2 u^2(\hat{T}_d) + s_{\rho,T_c}^2 u^2(\hat{T}_c) \\ & + s_{\rho,K_d}^2 u^2(\hat{K}_d) + s_{\rho,\tau}^2 u^2(\hat{\tau}) + s_{\rho,c_c}^2 u^2(\hat{c}_c) + s_{\rho,c_d}^2 u^2(\hat{c}_d) \\ & + s_{\rho,\Delta P_d}^2 u^2(\Delta\hat{P}_d) + s_{\rho,P}^2 u_c^2(\hat{P}) + u^2(\hat{\rho}_{temp}) + u^2(\hat{\rho}_{misc}) \end{aligned} \qquad (5.10)$$

where

$u(\hat{\rho}_u) \equiv$	standard uncertainty of the indicated (uncorrected) density estimate, $\hat{\rho}_u$, including the calibration laboratory uncertainty, the reading error during calibration, and hysteresis,
$u(\hat{\rho}_{rept}) \equiv$	standard uncertainty of the repeatability of the indicated (uncorrected) density estimate, $\hat{\rho}_u$,
$u(\hat{T}_d) \equiv$	standard uncertainty of the gas temperature estimate in the densitometer, $\hat{T}_d$,
$u(\hat{T}) \equiv$	standard uncertainty of the line temperature estimate, *T*,
$u(\hat{P}) \equiv$	standard uncertainty of the line pressure estimate, *P*,
$u(\hat{T}_c) \equiv$	standard uncertainty of the densitometer calibration temperature estimate, $\hat{T}_c$,
$u(\hat{K}_d) \equiv$	standard uncertainty of the VOS correction densitometer constant estimate, $\hat{K}_d$,
$u(\hat{c}_c) \equiv$	standard uncertainty of the calibration gas VOS estimate, $\hat{c}_c$,
$u(\hat{c}_d) \equiv$	standard uncertainty of the densitometer gas VOS estimate, $\hat{c}_d$,

71 The extension of the present densitometer uncertainty model in relation to the model presented in [Tambo and Søgaard, 1997, Annex 2 and 3], relates mainly to the more detailed approach which has been used here with respect to the temperature, VOS and installation corrections. Here, the uncertainty model includes sensitivity coefficients derived from the function relationship, Eqn.(5.9), instead of taking them to be equal to 1.

72 Note that the uncertainty model for the Solartron 7812 gas Density Transducer have been derived in detail in Appendix G in [Lunde & Frøysa, 2002].

$u(\hat{\tau}) \equiv$ standard uncertainty of the periodic time estimate, $\hat{\tau}$,

$u(\Delta\hat{P}_d) \equiv$ standard uncertainty of assuming that $\hat{P}_d = \hat{P}$, due to possible deviation of gas pressure from densitometer to line conditions,

$u(\hat{\rho}_{temp}) \equiv$ standard uncertainty of the temperature correction factor for the density estimate, $\hat{\rho}$ (represents the *model uncertainty* of the temperature correction model used, Eqn. (2.24)).

$u(\hat{\rho}_{misc}) \equiv$ standard uncertainty of the indicated (uncorrected) density estimate, $\hat{\rho}_u$, accounting for miscellaneous uncertainty contributions[73], such as due to:

- stability (drift, shift between calibrations[74]),
- reading error during measurement (for digital display instruments)[75],
- possible deposits on the vibrating element,
- possible corrosion of the vibrating element,
- possible liquid condensation on the vibrating element,
- mechanical (structural) vibrations on the gas line,
- variations in power supply,
- self-induced heat,
- flow in the bypass density line,
- possible gas viscosity effects,
- neglecting possible pressure dependency in the regression curve, Eqn. (5.4),
- model uncertainty of the VOS correction model.

In this model, the estimates $\hat{T}$, $\hat{T}_d$ and $\hat{T}_c$ are assumed to be uncorrelated (since random effects contribute significantly to the uncertainty of the temperature measurement, and so are also the estimates $\hat{P}$ and $\Delta\hat{P}_d$.

73 In accordance with common company practice [Dahl *et al.*, 1999], [Ref Group, 2001], various "miscellaneous uncertainty contributions" listed in the text have been accounted for in the uncertainty model (Eqn. (5.10) by a "lumped" term, $u(\hat{\rho}_{misc})$, with a weight (sensitivity coefficient) equal to one. Note that this is a simplified approach. An alternative and more correct approach would have been to start from the full functional relationship of the uncorrected density measurement ρ_u, Eqn. (5.4), and derive the influences of such miscellaneous uncertainty contributions on the total uncertainty according to the recommendations of the *GUM* [ISO, 1995a], i.e. with derived sensitivity coefficients.

74 For guidelines with respect to uncertainty evaluation of shift between calibrations, cf. [Tambo and Søgaard, 1997, Annex 2].

75 For guidelines with respect to uncertainty evaluation of reading error during measurement, cf. [Tambo and Søgaard, 1997, Annex 2].

The sensitivity coefficients appearing in Eqn. (5.10) are defined as

$$s_{\rho_u} = \frac{\hat{\rho}\left[1+\hat{K}_{18}(\hat{T}_d-\hat{T}_c)\right]}{\hat{\rho}_u\left[1+\hat{K}_{18}(\hat{T}_d-\hat{T}_c)\right]+\hat{K}_{19}(\hat{T}_d-\hat{T}_c)} \tag{5.11}$$

$$s_{\rho,T} = -\frac{\hat{\rho}}{\hat{T}} \tag{5.12}$$

$$s_{\rho,T_d} = \left[1+\frac{\hat{T}_d\left[\hat{\rho}_u\hat{K}_{18}+\hat{K}_{19}\right]}{\hat{\rho}_u\left[1+\hat{K}_{18}(\hat{T}_d-\hat{T}_c)\right]+\hat{K}_{19}(\hat{T}_d-\hat{T}_c)}\right]\frac{\hat{\rho}}{\hat{T}_d} \tag{5.13}$$

$$s_{\rho,T_c} = -\left[\frac{\hat{T}_c\left[\hat{\rho}_u\hat{K}_{18}+\hat{K}_{19}\right]}{\hat{\rho}_u\left[1+\hat{K}_{18}(\hat{T}_d-\hat{T}_c)\right]+\hat{K}_{19}(\hat{T}_d-\hat{T}_c)}\right]\frac{\hat{\rho}}{\hat{T}_c} \tag{5.14}$$

$$s_{\rho,K_d} = \left[\frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_c)^2}-\frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_d)^2}\right]\frac{\hat{\rho}}{\hat{K}_d}, \tag{5.15}$$

$$s_{\rho,\tau} = -\left[\frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_c)^2}-\frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_d)^2}\right]\frac{\hat{\rho}}{\hat{\tau}} \tag{5.16}$$

$$s_{\rho,c_c} = -\frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_c)^2}\frac{\hat{\rho}}{\hat{c}_c}, \qquad s_{\rho,c_d} = \frac{2\hat{K}_d^2}{\hat{K}_d^2+(\hat{\tau}\hat{c}_d)^2}\frac{\hat{\rho}}{\hat{c}_d}, \tag{5.17}$$

$$s_{\rho,\Delta P_d} = -\frac{\hat{\rho}}{\hat{P}+\Delta\hat{P}_d}, \qquad s_{\rho,P} = \frac{\Delta\hat{P}_d}{\hat{P}+\Delta\hat{P}_d}\frac{\hat{\rho}}{\hat{P}}, \tag{5.18}$$

respectively.

$u_c(\hat{\rho})$ needs to be traceable to national and international standards. It is left to the calibration laboratory and the manufacturer to specify $u(\hat{\rho}_{\rho_u})$, $u(\hat{\rho}_{rept})$, $u(\hat{T}_c)$, $u(\hat{\rho}_{temp})$, $u(\hat{\tau})$ *and* $u(\hat{K}_d)$, and document their traceability. It is left to the user of the program *EMU - Orifice Fiscal Gas Metering Station* to specify $u(\hat{c}_c)$, $u(\hat{c}_d)$, $u(\Delta\hat{P}_d)$ and $u(\hat{\rho}_{misc})$. $u_c(\hat{T})$ and $u_c(\hat{T}_d)$ are in the program set to be equal and are given by Eqn. (5.2). $u_c(\hat{P})$ is given by Eqn. (5.3).

In [Tambo and Søgaard, 1997, Annex 2 and 3], $u(\hat{\rho}_{rept})$ is referred to as "the standard uncertainty of type A component", to be obtained by determining the density (at stable conditions) at least 10 times and deriving the standard deviation of the mean.

With respect to $u(\hat{c}_d)$, there are at least two methods in use today to obtain the VOS at the density transducer, c_d: the "USM method" and the "pressure/density method". For the "USM method", there are basically two contributions to the uncertainty of c_d: (1) the uncertainty of the USM measurement of the line VOS, and (2) the deviation of the line VOS from the VOS at the densitometer. For the "pressure/density method", the uncertainty of c_d is to be calculated from the expressions used to calculate c_d and the input uncertainties to these. Evaluation of $u(\hat{c}_d)$ according to these (or other) methods is not a part of the present *Handbook*, - $u(\hat{c}_d)$ is to be calculated and given by the user of the program. In this approach, the uncertainty model is independent of the particular method used to estimate c_d in the metering station.

The uncertainty of the *Z*-factor correction part of the installation correction (see Section 5.4.1.4), $u(\hat{Z}_d / \hat{Z})$, may be considered negligible according to [Lunde & Frøysa, 2002], Appendix G, and has therefore also been neglected in this evaluation.

As an example of density uncertainty evaluation, the Solartron 7812 Gas Density Transducer is evaluated in 5.4.2.

5.4.2 Example uncertainty evaluation

Table 5.10. Values used in the sample calculation in Table 3.10.

Parameter	**Value**	**Reference**
Indicated (uncorrected) density by densitometer.	82.443 kg/m^3	Example
Temperature in densitometer	48 °C	Example
Calibration temperature	20 °C	Example
Calibration velocity of sound (VOS), P_c	350 m/s	Example
Calibration constant, K_{18}	$-1.36 \cdot 10^{-5}$	Example
Calibration constant, K_{19}	$8.44 \cdot 10^{-4}$	Example
VOS correction constant, K_d	21000 μm	Example
Periodic time, τ	650 μs	Example

The combined standard uncertainty of the density measurement, $u_c(\hat{\rho})$, is given by Eqn. (3.14). This expression is evaluated in the following, for the example considered here.

Performance specifications for the Solartron 7812 gas density transducer are given in Table 5.11 as specified in the data sheet [Solartron, 1999], etc.

Table 5.11 Performance specifications of the Solartron 7812 Gas Density Transducer [Solartron, 2000], used as input to the uncertainty calculations given in Table 4.11.

Quantity or Source	**Value or Expanded uncertainty**	**Coverage factor, *k***	**Reference**
Calibration temperature (air)	20 °C	-	[Solartron, 2000]
Full scale density range	1 - 400 kg/m^3	-	[Solartron, 2000]
Densitometer "accuracy", $U(\hat{\rho}_u)$	< 0.1 % of m.v. (nitrogen) < 0.15 % of m.v. (nat. gas)		[Solartron, 2000]
Repeatability, $U(\hat{\rho}_{rept})$	Within 0.01 % of full scale density		[Solartron, 2000]
Calibration temperature, $U(\hat{T}_c)$	0.1 ^{o}C (at 20 ^{o}C)		[Solartron, 2000]
Temperature correction model, $U(\hat{\rho}_{temp})$	< 0.001 kg/m^3/^{o}C		[Solartron, 2000]
VOS correction model, $U(\hat{\rho}_{misc})$	Not specified (see text)		[Solartron, 1999]
Pressure effect, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Solartron, 1999, §A.1]
Stability - element, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Solartron, 1999, §1.3.3]
Deposits, $U(\hat{\rho}_{misc})$	Not specified (see text)		[Solartron, 1999, §1.3.3; §3.8]
Condensation, $U(\hat{\rho}_{misc})$	Not specified (see text)		[Solartron, 1999, §3.8]
Corrosion, $U(\hat{\rho}_{misc})$	Not specified (see text)		[Solartron, 1999, §1.3.3; §3.8]
Gas viscosity, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Matthews, 1994]
Vibration effects, $U(\hat{\rho}_{misc})$	Not specified (see text)		[Solartron, 1999, §1.3.1; §3.8]
Power supply effects, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Solartron, 1999, §1.3.1]
Self induced heat effects, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Solartron, 1999, §1.3.1]
Sample flow effects, $U(\hat{\rho}_{misc})$	Negligible (see text)		[Matthews, 1994]

The contributions to the combined standard uncertainty of the density measurement are described in the following. As the confidence level of the expanded uncertainties is not specified in [Solartron, 2000], this is here assumed to be 95 %, with a normal probability distribution (k = 2).

1. ***Densitometer "accuracy",*** $u(\hat{\rho}_u)$**:** The densitometer "accuracy" is specified in the manufacturer instrument manual [Solartron, 2000] as being less than ±0.1 % of reading in nitrogen, and less than 0.15 % of reading in natural gas. This includes uncertainties of Eqn. (5.4). That is, $u(\hat{\rho}_u) = U(\hat{\rho}_u)/2$ $= [0.15 \cdot 10^{-2} \cdot 82.443\ kg/m^3]/2$ = 0.0618 kg/m^3 [76]. The relative standard uncertainty is $u(\hat{\rho}_u)/\hat{\rho}_u$ = $0.15\%/2$ = 0.075 %.

2. **Repeatability**, $u(\hat{\rho}_{rept})$**:** In the manufacturer data sheet [Solartron, 2000], the repeatability is specified to be within 0.01 % of full scale density. The density range of the 7812 densitometer is given to be 1 to 400 kg/m^3. That is, $u(\hat{\rho}_{rept}) = U(\hat{\rho}_{rept})/2 = 0.01 \cdot 10^{-2} \cdot 400/2 = 0.02\ kg/m^3$.

3. **Calibration temperature**, $u(\hat{T}_c)$**:** The uncertainty of the calibration temperature is specified in the manufacturer data sheet [Solartron, 2000] as 0.1 ^{o}C at 20 ^{o}C. That is, $u(\hat{T}_c) = U(\hat{T}_c)/2 = 0.1\ {}^oC/2 = 0.05\ {}^oC$.

4. **Line temperature**, $u_c(\hat{T})$**:** The uncertainty of the line temperature is taken from Table 5.5.

5. **Densitometer temperature**, $u_c(\hat{T}_d)$**:** The uncertainty of the densitometer temperature is taken from Table 5.5.

6. **Line pressure**, $u_c(\hat{P})$**:** The uncertainty of the line pressure is taken from Table 5.8.

7. **Pressure difference, densitometer to line**, $u(\Delta\hat{P}_d)$**:** The densitometer pressure $\hat{P}_d$ is not measured, and assumed to be equal to the line pressure $\hat{P}$. In practice the density sampling system is designed so that the pressure deviation between the densitometer and line, $\Delta\hat{P}_d$, is relatively small. Tests with densitometers have indicated a pressure deviation $\Delta\hat{P}_d$ of up to 0.02 % of the line pressure, $\hat{P}$ [Eide, 2001a]. $\Delta\hat{P}_d$ can be positive or negative, depending on the actual installation [Sakariassen, 2001].

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76 The manufacturer's uncertainty specification is used here. By calibration of the the densitometer in an accredited calibration laboratory, the densitometer "accuracy" may be significantly reduced. Example of a calibration certificate specification for the densitometer "accuracy" $U(\hat{\rho}_u)$ may be e.g. 0.027-0.053 %, for the density range 25-250 kg/m^3, at a 95 % confidence level (k = 2) [Eide, 2001a]. Such values correspond to 0.014-0.027 % for the relative standard uncertainty of the densitometer "accuracy". This includes linearity, hysteresis, repeatability, reading uncertainty, and reference instruments uncertainty.

For the present case ($\hat{P}$ = 100 bara), $\Delta\hat{P}_d$ = 20 mbar is used as a representative example. Assuming a Type B uncertainty, at a 100 % confidence level and a rectangular probability distribution within the range ±20 mbar (k = $\sqrt{3}$), one obtains $u(\Delta\hat{P}_d) = U(\Delta\hat{P}_d)/\sqrt{3}$ = 0.02 $bar/\sqrt{3}$ = $0.0115\ bar$.

8. **VOS, calibration gas**, $u(\hat{c}_c)$**:** The uncertainty of the sound velocity estimate of the calibration gas is tentatively taken to be 1 m/s. Assuming a Type B uncertainty, at a 100 % confidence level and a rectangular probability distribution within the range ±1 m/s (k = $\sqrt{3}$), one obtains $u(\hat{c}_c) = U(\hat{c}_c)/\sqrt{3} = 1/\sqrt{3}$ ≈ 0.577 m/s.

9. **VOS, densitometer gas**, $u(\hat{c}_d)$**:** As described in Section 5.4.1.3, when using Eqn. (5.6) for VOS correction, there are at least two methods in use today to obtain the VOS at the density transducer, c_d: the "USM method" and the "pressure/density method". As explained in Section 5.4.1, evaluation of $u(\hat{c}_d)$ according to these (or other) methods is not a part of the present *Handbook*. Hence, one does not rely on the particular method used to estimate c_d in the metering station.

   The uncertainty of the VOS estimate in the density transducer is here taken to be 1 m/s, tentatively. Assuming a Type B uncertainty, at a 100 % confidence level and a rectangular probability distribution within the range ±1 m/s (k = $\sqrt{3}$), one obtains $u(\hat{c}_d) = U(\hat{c}_d)/\sqrt{3} = 1/\sqrt{3}$ ≈ 0.577 m/s.

10. **Periodic time**, $u(\hat{\tau})$**:** The uncertainty of the periodic time τ involved in the VOS correction depends on the time resolution of the flow computer, which is here set to 0.1 μs, tentatively (10 MHz oscillator) [Eide, 2001a]. Assuming a Type A uncertainty, at a 100 % confidence level and a rectangular probability distribution within the range ±0.1 μs (k = $\sqrt{3}$), one obtains $u(\hat{\tau}) = U(\hat{\tau})/\sqrt{3}$ = $0.1\ \mu s/\sqrt{3}$ = 0.0577 μs.

11. **VOS correction constant**, $u(\hat{K}_d)$**:** A figure for the uncertainty of the dimensional constant $\hat{K}_d$ used in the VOS correction has not been available for the present study. A tentative uncertainty figure of 10 % is used here, as a reasonable example [Eide, 2001a]. For $\hat{K}_d$ = 21000 μm (cf. Table 4.4), that gives $U(\hat{K}_d)$ = 2100 μm. Assuming a Type B uncertainty, at a 100 % confidence level and a rectangular probability distribution within the range

±2100 μm ($k = \sqrt{3}$), one obtains $u(\hat{K}_d) = U(\hat{K}_d)/\sqrt{3} = 2100\ \mu m/\sqrt{3}$ = 1212 μm.

12. **Temperature correction model**, $u(\hat{\rho}_{temp})$**:** Temperature changes affect both the modulus of elasticity of the vibrating element, and its dimensions. Both of these affect the resonance frequency [Matthews, 1994]. For high-accuracy densitometers like the Solartron 7812, this effect is largely eliminated using Ni-span C stainless steel[77], and the temperature correction model given by Eqn. (5.5). However, the temperature correction model *itself* is not perfect, and will have an uncertainty.

    The uncertainty of the temperature correction model itself, Eqn. (5.5), is specified in the manufacturer instrument manual [Solartron, 1999, §A.1] as being less than 0.001 kg/m^3/^{o}C. That is, $u(\hat{\rho}_{temp}) = U(\hat{\rho}_{temp})/2 = [0.001 \cdot 48]/2 = 0.024\,kg/m^3$.

13. **VOS correction model**, $u(\hat{\rho}_{misc})$**:** For gas densitometers the fluids are very compressible (low VOS), and VOS correction is important [Solartron, 1999], [Matthews, 1994]. For high-accuracy densitometers like the Solartron 7812, this effect is largely eliminated using the VOS correction model given by Eqn. (2.25). However, the VOS correction model *itself* is not perfect (among others due to use of a calibration gas, with another VOS than the line gas in question), and will have an uncertainty.

    The uncertainty of the VOS correction model itself, Eqn. (5.6), is not specified in the manufacturer instrument manual [Solartron, 1999]. In the present calculation example the uncertainty of the VOS correction model is neglected for the Solartron 7812 densitometer. That is, the VOS correction model contribution to $u(\hat{\rho}_{misc})$ is set to zero.

14. **Pressure effect**, $u(\hat{\rho}_{misc})$**:** The uncertainty of the pressure effect is not specified in the manufacturer instrument manual [Solartron, 1999]. According to [Matthews, 1994], "for vibrating cylinders there is no pressure effect on the resonance frequency because the fluid surrounds the vibrating element, so all forces are balanced". Consequently, in the present calculation example this

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[77] For densitometers with vibrating element made from other materials than Ni-span C, the temperature effect may be considerably larger [Matthews, 1994].

uncertainty contribution is assumed to be negligible for the Solartron 7812 densitometer. That is, the pressure effect contribution to $u(\hat{\rho}_{misc})$ is set to zero.

15. **Stability - element**, $u(\hat{\rho}_{misc})$**:** The instrument manual states that [Solartron, 1999; §1.3.3] "The long term stability of this density sensor is mainly governed by the stability of the vibrating cylinder sensing element. This cylinder is manufactured from one of the most stable metals, and being unstressed, will maintain its properties for many years". In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the long time stability effects contribution to $u(\hat{\rho}_{misc})$ is set to zero.

16. **Deposits**, $u(\hat{\rho}_{misc})$**:** The instrument manual states that [Solartron, 1999; §1.3.3] "Deposition on the cylinder will degrade the long term stability, and care should be taken to ensure that the process gas is suitable for use with materials of construction. The possibility of deposition is reduced by the use of filters, but, should deposition take place, the sensing element can be removed and cleaned"[78]. According to [Campbell and Pinto, 1994], "another problem with the gas transducers can be the presence of black dust like particles on the walls of the sensing element. These particles can often cause pitting on the sensing element which renders the cylinder as scrap". In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to deposits is set to zero.

17. **Condensation and liquid contamination**, $u(\hat{\rho}_{misc})$**:** In the instrument manual it is stated that [Solartron, 1999; §3.8] "Condensation of water or liquid vapours on the sensing element will cause effects similar to deposition of solids except that the effects will disappear if re-evaporation takes place." Cf. also [Geach, 1994].

According to [Campbell and Pinto, 1994], "transducers which are returned for calibration have been found on many occasions to contain large quantities of lubricating type oil, which has the effect of stopping the transducer vibrating. The presence of this liquid usually indicates a problem with the lub oil seals of the export compressors".

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78 The risk of damaging the element in case of dismantling and clening offshore by unexperienced personnel may be large [Campbell and Pinto, 1994]. Scratches or denting during the cleaning procedure reduces the element to scrap.

In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to condensation is set to zero.

18. **Corrosion**, $u(\hat{\rho}_{misc})$**:** In the instrument manual it is stated that [Solartron, 1999; §1.3.3] "Corrosion will degrade the long term stability, and care should be taken to ensure that the process gas is suitable for use with materials of construction." In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to corrosion is set to zero.

19. **Gas viscosity**, $u(\hat{\rho}_{misc})$**:** Viscosity has the effect of damping all vibrating-element transducers which causes a small over-reading in density. For gas densitometers the effect of viscosity is so small that it is virtually impossible to measure at anything but very low densities [Matthews, 1994]. In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to gas viscosity is set to zero.

20. **Vibration effects**, $u(\hat{\rho}_{misc})$**:** In the instrument manual it is stated that [Solartron, 1999; §3.8] "The 7812 can tolerate vibration up to 0.5*g*, but levels in excess of this may affect the accuracy of the readings. Use of anti-vibration gasket will reduce the effects of vibration by at least a factor of 3, at levels up to 10g and 2200 Hz". In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to vibration effects is set to zero.

21. **Power supply effects**, $u(\hat{\rho}_{misc})$**:** In the instrument manual it is stated that [Solartron, 1999; §3.8] the 7812 is insensitive to variations in power supply. In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to power supply effects is set to zero.

22. **Self induced heat effects**, $u(\hat{\rho}_{misc})$**:** In the instrument manual it is stated that [Solartron, 1999; §3.8] "since the power consumption is extremely small, the self induced heat may be neglected". In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to heating is set to zero.

23. **Sample line flow effects**, $u(\hat{\rho}_{misc})$**:** According to [Matthews, 1994], "All resonant element sensors will be affected by flow rate in some way. As flow rate increases, the output will generally give a positive over-reading of density and the readings will become more unstable. However this effect is very small and providing the manufacturers recommendations are followed then the effects can be ignored". In the present calculation example this uncertainty contribution is neglected for the Solartron 7812 densitometer. That is, the uncertainty contribution to $u(\hat{\rho}_{misc})$ which is related to flow in the density sample line is set to zero.

A sample uncertainty budget is given in Table 5.12 for evaluation of the expanded uncertainty of the pressure measurement according to Eqn. (5.10). The figures used for the input uncertainties are those given in the discussion above.

Table 5.12 Sample uncertainty budget for the measurement of the gas density using the Solartron 7812 Gas Density Transducer [Solartron, 1999],[Solartron, 2000], calculated according to Eqn. (5.10).

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Densitometer "accuracy", $U(\hat{\rho}_u)$	0.124 kg/m^3	95 % (norm)	2	0.0618 kg/m^3	0.989734	$3.74 \cdot 10^{-3}$ (kg/m^3)^2
Repeatability, $U(\hat{\rho}_{rept})$	0.04 kg/m^3	95 % (norm)	2	0.02 kg/m^3	1	$4.00 \cdot 10^{-4}$ (kg/m^3)^2
Calibration temperature, $U(\hat{T}_c)$	0.1 ^{o}C	95 % (norm)	2	0.05 ^{o}C	-0.000274	$1.88 \cdot 10^{-10}$ (kg/m^3)^2
Line temperature, $U(\hat{T})$	0.1529 ^{o}C	95 % (norm)	2	0.0765 ^{o}C	0.252576	$3.73 \cdot 10^{-4}$ (kg/m^3)^2
Densitometer temperature, $U(\hat{T}_d)$	0.1529 ^{o}C	95 % (norm)	2	0.0765 ^{o}C	0.253875	$3.77 \cdot 10^{-4}$ (kg/m^3)^2
Line pressure, $U(\hat{P})$	0.0839 bar	95 % (norm)	2	0.04197 bar	0.000163	$4.69 \cdot 10^{-11}$ (kg/m^3)^2
Pressure difference, densitometer-line, $U(\Delta\hat{P}_d)$	20 mbar	100 % (rect)	$\sqrt{3}$	0.0116 bar	-0.816037	$8.88 \cdot 10^{-5}$ (kg/m^3)^2
VOS, calibration gas, $U(\hat{c}_c)$	1 m/s	100 % (rect)	$\sqrt{3}$	0.577 m/s	-0.00394	$5.18 \cdot 10^{-6}$ (kg/m^3)^2
VOS, densitometer gas, $U(\hat{c}_d)$	1 m/s	100 % (rect)	$\sqrt{3}$	0.577 m/s	0.002365	$1.87 \cdot 10^{-6}$ (kg/m^3)^2
Periodic time, $U(\hat{\tau})$	0.1 μs	100 % (rect)	$\sqrt{3}$	0.0577 μs	-0.000611	$1.24 \cdot 10^{-9}$ (kg/m^3)^2
Model constant, $U(\hat{K}_d)$	2100 μm	100 % (rect)	$\sqrt{3}$	1212.43 μm	$1.89 \cdot 10^{-5}$	$5.25 \cdot 10^{-4}$ (kg/m^3)^2
Temperature correction model, $U(\hat{\rho}_{temp})$	0.048 kg/m^3	95 % (norm)	2	0.024 kg/m^3	1	$5.76 \cdot 10^{-4}$ (kg/m^3)^2
Sum of variances				$u_c^2(\hat{\rho})$		$6.092 \cdot 10^{-3}$ (kg/m^3)^2
Combined standard uncertainty				$u_c(\hat{\rho})$		0.07805 kg/m^3
Expanded uncertainty (95 % confidence level, *k* = 2)				$U(\hat{\rho})$		**0.1561 kg/m^3**
Density				ρ		81.62 kg/m^3
Relative expanded uncertainty (95 % confidence level)				$U(\hat{\rho})/\hat{\rho}$		**0.1913 %**

The calculated expanded and relative expanded uncertainty (specified at a 95 % confidence level and a normal probability distribution, with $k = 2$) is 0.16 kg/m^3 and 0.19 %, respectively. Note that this value is calculated under the assumption that the input uncertainties taken from the [Solartron, 1999] data sheet correspond to a 95 %

confidence level (k = 2). As Solartron has not specified k, this is an assumption, and another coverage factor k would alter the densitometer uncertainty.

5.5 Pipe and orifice diameters

The orifice and pipe evaluated are not specified while the uncertainty evaluation does not restrict to specific types of orifices or pipes other than that the orifice and pipe must be manufactured according to international standards [ISO, 1995b].

Table 5.13. Values of variables used in the sample calculation in Table 5.14 and Table 5.15.

Parameter	**Value**	**Reference**
$D(T_0)$	$444.5\cdot10^{-3}$ m	[Sample values, 1999]
$d(T_0)$	$266.184\cdot10^{-3}$ m	[Sample values, 1999]
Operating temperature, T	50 °C	
Inital measurement temperature, T_0	15 °C	
Thermal coefficient of pipe, γ_D	$3.5\cdot10^{-6}$ m/°C	[Sample values, 1999]
Thermal coefficient of orifice, γ_d	$1.6\cdot10^{-5}$ m/°C	[Sample values, 1999]

5.5.1 Functional relationships

The temperature corrected orifice and pipe diameters are given in Eqn.(5.19) and (5.20).

$$d(T) = d(T_0)\cdot\left(1+\gamma_d\cdot(T-T_0)\right) \tag{5.19}$$

$$D(T) = D(T_0)\cdot\left(1+\gamma_D\cdot(T-T_0)\right) \tag{5.20}$$

where

- $d(T_0)$ - initial orifice diameter measured at a temperature T_0 [m].
- $d(T)$ - temperature corrected orifice plate diameter
- $D(T_0)$ - initial pipe diameter measured at a temperature T_0 [m].
- $D(T)$ - temperature corrected pipe diameter
- γ_d - thermal coefficient of orifice plate material [mm/mm/°C]
- γ_D - thermal coefficient of pipe material [mm/mm/°C]
- T_0 - temperature at which the diameters were initially measured [°C]
- T - operating line temperature [°C]

5.5.2 Example uncertainty evaluation

The uncertainty of the corrected diameters, *d* and *D*, are due to uncertainty in the initial measurement of the diameters, in addition to the measured temperatures and the thermal coefficients. However, the temperature correction will only cause small adjustments of the diameters, and it is therefore further expected that the temperature correction would have only a small influence on the combined uncertainty. In the sample calculations, the relative expanded uncertainties of *d* and *D* has been set to 0.07% and 0.4%, respectively[79].

Sample uncertainty budgets have been created for the pipe and orifice diameters in Table 5.14 and Table 5.15. The sensitivity coefficients are calculated as partial derivatives (Cf. Chapter 2).

Table 5.14 Example uncertainty budget for pipe diameter uncertainty.

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Initial pipe diameter, $D(T_0)$	1.778 mm	95 % (norm)	2	0.889 mm	1.000123	$7.91 \cdot 10^{-1}$ mm^2
Line temperature, T	0.1529 °C	95 % (norm)	2	0.0765 °C	$1.5558 \cdot 10^{-3}$ mm/°C	$1.42 \cdot 10^{-8}$ mm^2
Temperature when pipe diameter were measured, T_0	1.02 °C	95 % (norm)	2	0.51 °C	$-1.556 \cdot 10^{-6}$ mm/°C	$6.30 \cdot 10^{-7}$ mm^2
Thermal coefficient of pipe material, γ_D	$3 \cdot 10^{-7}$ 1/°C	95 % (norm)	2	$1.5 \cdot 10^{-7}$ mm/°C	15557.5 mm°C	$5.45 \cdot 10^{-6}$ mm^2
Sum of variances				$u_c^2(\hat{D}(T))$		$7.905 \cdot 10^{-1}$ mm^2
Combined standard uncertainty				$u_c(\hat{D}(T))$		0.8891 mm
Expanded uncertainty (95 % confidence level, *k* = 2)				$U_c(\hat{D}(T))$		**1.778 mm**
Operating pipe diameter				$\hat{D}(T)$		444.5 mm
Relative expanded uncertainty (95 % confidence level)				$U(\hat{D}(T))/\hat{D}(T)$		**0.40 %**

79 According to [Eide, 2002] these uncertainties are probably one orders of magnitude larger than what is achieved in practise today.

Table 5.15 Example uncertainty budget for orifice diameter uncertainty.

Source	Input uncertainty				Combined uncertainty	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Initial pipe diameter, $d(T_0)$	0.1864 mm	95 % (norm)	2	1.00056	1.00056	$8.70 \cdot 10^{-3}$ mm^2
Line temperature, T	0.1529 °C	95 % (norm)	2	0.0042589 mm/°C	$4.2589 \cdot 10^{-6}$ m/°C	$1.06 \cdot 10^{-7}$ mm^2
Temperature when pipe diameter were measured, T_0	1.02 °C	95 % (norm)	2	-0.004259 mm/°C	$-4.2589 \cdot 10^{-6}$ m/°C	$4.72 \cdot 10^{-6}$ mm^2
Thermal coefficient of pipe material, γ_D	$4 \cdot 10^{-7}$ 1/°C	95 % (norm)	2	9316.44 mm/°C	9.3164 °C^{-1}	$3.47 \cdot 10^{-6}$ mm^2
Sum of variances				$u_c^2(\hat{d}(T))$		$8.704 \cdot 10^{-3}$ m^2
Combined standard uncertainty				$u_c(\hat{d}(T))$		0.0933 mm
Expanded uncertainty (95 % confidence level, *k* = 2)				$U_c(\hat{d}(T))$		**0.1866 mm**
Operating pipe diameter				$\hat{d}(T)$		266.33 mm
Relative expanded uncertainty (95 % confidence level)				$U(\hat{d}(T))/\hat{d}(T)$		**0.07 %**

From the uncertainty budgets shown in Table 5.14 and Table 5.15 it is evident that the uncertainty due to the thermal coefficients and the measured temperatures may be neglected. The combined uncertainty then equals the uncertainty of the initial measurement of the diameters. The temperature-corrected diameters are input to other functional relationships used in the calculation of the mass flow rate. The values of the thermal coefficients and the measured temperatures must therefore still be input to the program in order to include the temperature correction of the diameters in the calculation, although the uncertainty introduced by this correction may be neglected.

5.6 Diameter ratio

The diameter ratio, β, is the ratio of the diameter of the orifice (or throat) of the primary device to the internal diameter of the measuring pipe upstream the primary device [ISO, 2003a].

The figures of the variables used in the sample calculation in Table 5.16 are listed in Table 5.13.

5.6.1 Functional relationship

The diameter ratio is thus calculated from the temperature corrected orifice and pipe diameters as:

$$\beta = \frac{d(T)}{D(T)} = \frac{d(T_0) \cdot \left(1 + \gamma_d \cdot \left(T - T_0\right)\right)}{D(T_0) \cdot \left(1 + \gamma_D \cdot \left(T - T_0\right)\right)} \tag{5.21}$$

where

β	- diameter ratio
$d(T_0)$	- initial orifice diameter measured at a temperature T_0 [m]
$d(T)$	- temperature corrected orifice plate diameter
$D(T_0)$	- initial pipe diameter measured at a temperature T_0 [m]
$D(T)$	- temperature corrected pipe diameter
γ_d	- thermal coefficient of orifice plate material [m/°C]
γ_D	- thermal coefficient of pipe material [m/°C]
T_0	- temperature at which the diameters were initially measured [°C]
T	- operating temperature [°C]

5.6.2 Example uncertainty evaluation

The uncertainty of the diameter ratio depends on the uncertainty in the measured orifice and pipe diameters, the thermal coefficients and the measured temperatures. In addition, uncertainty due to covariance in the measurement of operating temperature (and eventually the measurement of the temperature when the diameters were initially measured) must be included.

The uncertainty of the diameter ratio, β, is mainly due to the initial measurement of the orifice and pipe diameters (Cf. Chapter 5.5). Since the uncertainty due to the temperature measurements and the thermal coefficients can be neglected in the diameter uncertainty calculations, they can also be neglected in the diameter ratio uncertainty calculation. Further, if the uncertainty of the temperature measurements is negligible, the uncertainty due to the correlated temperature measurements will be even smaller, and thus also negligible.

In Table 5.16 a sample uncertainty calculation is shown for the diameter ratio including the uncertainties of diameters and the covariance term. The covariance term is calculated as:

$$\text{covariance} = 2\left\{\left(\frac{\partial\beta(d,D)}{\partial d}\cdot\frac{\partial d(\cdots)}{\partial T}\right)\left(\frac{\partial\beta(d,D)}{\partial D}\cdot\frac{\partial D(\cdot\cdot)}{\partial T}\right)\cdot u(T)\cdot u(T)\cdot 1\right\} \tag{5.22}$$

Table 5.16 Example uncertainty budget for the diameter ratio uncertainty.

Source	Input uncertainty				Combined uncertainty	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
d(*T*)	1.778 mm	95 % (norm)	2	0.889 mm	-0.001348 1/mm	$1.44 \cdot 10^{-6}$
D(*T*)	0.1866 mm	95 % (norm)	2	0.0932 mm	0.002249 1/mm	$4.40 \cdot 10^{-8}$
Covariance						$-2.35 \cdot 10^{-13}$
Sum of variances				$u_c^2(\hat{\beta})$		$1.48 \cdot 10^{-6}$
Combined standard uncertainty				$u_c(\hat{\beta})$		0.0012
Expanded uncertainty (95 % confidence level, *k* = 2)				$U_c(\hat{\beta})$		**0.0024**
Operating pipe diameter				$\hat{\beta}$		0.5991
Relative expanded uncertainty (95 % confidence level)				$U(\hat{\beta})/\hat{\beta}$		**0.406 %**

A covariance term exists due to the measured temperature that is common to the two diameter correction expressions. However, the covariance term is negligible and may be neglected. This is expected while the uncertainty of the measured temperature is negligible in the calculation of the uncertainty of the temperature-corrected diameters.

Hence, the uncertainty of the diameter ratio may therefore simply be calculated from the uncertainty of the orifice and pipe diameter input quantities.

5.7 Expansibility factor

The expansibility factor, ε, is a coefficient which takes into account the compressibility of the fluid. ε is equal to unity if the fluid is incompressible and is less than unity when the fluid is compressible. Theoretically ε depends on the Reynolds number as well as on the values of the pressure ration and the isentropic exponent of the fluid. According to ISO 5167-1:2003 [ISO, 2003a], experiments show that in practise ε may be regarded as independent of the Reynolds number. Hence, for a given diameter ratio of a given primary device, ε only depends on the pressure ratio and the isentropic exponent. It must be noted that the absolute pressure is to be used in the expression for the expansibility factor, and the atmospheric pressures must then be added to the measured gauge pressures.

5.7.1 Functional relationship

The expansibility factor, ε, is given according to ISO 5167-1:2003 [ISO, 2003b] when the static pressure is measured upstream of the orifice.

$$\varepsilon = 1 - \left(0.351 + 0.256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(\frac{P_2}{P_1}\right)^{1/\kappa}\right] \quad (5.23)$$

where

ε	- expansibility factor
β	- diameter ratio
P_1	- static pressure measured at upstream tapping [bara]
P_2	- static pressure measured at downstream tapping [bara]
κ	- isentropic exponent

Since the calculation of ε is in practise based on one static pressure measurement and one differential pressure measurement, the static pressure that is not measured must be calculated from the measured static and differential pressures:

$$P_1 = P_2 + \Delta P \quad (5.24)$$

or:

$$P_2 = P_1 - \Delta P \quad (5.25)$$

where

ΔP - differential pressure [bar]

As the static pressure may be measured either upstream or downstream, the functional relationship for the expansibility factor may take two forms:

1. Expansibility factor with a static pressure measurement at the upstream tapping:

$$\varepsilon = 1 - \left(0.351 + 0.256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(\frac{P_1 - \Delta P}{P_1}\right)^{1/\kappa}\right] \qquad (5.26)$$

2. Expansibility factor with a static pressure measurement at the downstream tapping:

$$\varepsilon = 1 - \left(0.351 + 0.256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(\frac{P_2}{P_2 + \Delta P}\right)^{1/\kappa}\right] \qquad (5.27)$$

5.7.2 Example uncertainty evaluation

The combined uncertainty of the expansibility factor depends on the functional relationship used. The uncertainty contributors are the diameter ratio, the isentropic exponent, the discharge coefficient, and the differential and static pressure measurements. In addition uncertainty arise due to the fact that the expansibility factor is experimentally determined and its coefficients are found by curve fitting to experimental data.

The model uncertainty is given in ISO 5167-2:2003 [ISO, 2003b], as a relative uncertainty (assumed to be given at 95% confidence level), relative to the value of the expansibility factor. This model uncertainty is shown in Eqn. (5.28) and is based on the assumption that β, $\Delta P/P_1$ and κ is known with zero uncertainty.

$$\frac{u(\varepsilon_{model})}{\varepsilon_{model}} = \frac{3.5 \dfrac{\Delta P}{\kappa \cdot P_1}}{100} \qquad (5.28)$$

Table 5.17 Sample uncertainty budget for expansibility factor referred to upstream conditions with static (gauge) pressure measurement at the upstream tapping. The atmospheric pressure is added to the gauge pressure to obtain the absolute static pressure.

Source	**Input uncertainty**				**Combined uncertainty**	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Diameter ratio, β	0.0024	95 % (norm)	2	0.001216	-0.00119	$2.1\cdot10^{-12}$
Isentropic exponent, κ	0.01	95 % (norm)	2	0.005	0.000944	$2.23\cdot10^{-11}$
Differential pressure, ΔP	0.4243 mbar	95 % (norm)	2	0.000212 m bar	-0.00386 1/bar	$5.16\cdot10^{-13}$
Static abs. pressure, P_1	0.0839 bar	95 % (norm)	2	0.041969 bar	$1.271\cdot10^{-5}$ 1/bar	$2.19\cdot10^{-13}$
Model	$9.7624\cdot10^{-5}$	95 % (norm)	2	$4.88\cdot10^{-5}$	1	$2.38\cdot10^{-9}$
Sum of variances				$u_c^2(\hat{\varepsilon}_1)$		$2.41\cdot10^{-9}$
Combined standard uncertainty				$u_c(\hat{\varepsilon}_1)$		$4.91\cdot10^{-5}$
Expanded uncertainty (95 % confidence level, *k* = 2)				$U_c(\hat{\varepsilon}_1)$		**$9.81\cdot10^{-5}$**
Expansibility factor				$\hat{\varepsilon}_1$		0.998884
Relative expanded uncertainty (95 % confidence level)				$U_c(\hat{\varepsilon}_1)/\hat{\varepsilon}_1$		**0.0098 %**

From the calculation shown in Table 5.17 it is evident that the model uncertainty dominates the uncertainties of the other input quantities.

According to [Dahl et al., 1999], the uncertainty contributions from the input quantities may actually be neglected when compared to the large model uncertainty independent of which functional relationship for the Expansibility factor is used.

5.8 Discharge coefficient

The discharge coefficient, *C*, defined for an incompressible fluid flow, relates the actual flow rate to the theoretical flow rate through the device [ISO, 2003b]. Calibration of standard primary devices by means of incompressible fluids (liquids) shows that the discharge coefficient is dependent only on the Reynolds number for a given primary device in a given installation (given diameter ratio).

5.8.1 Functional relationship

The functional relationship for calculation of the discharge coefficient is given according to ISO 5167-2:2003 [ISO, 2003b], as

$$\begin{aligned} C &= 0.5961 + 0.0261 \cdot \beta^2 - 0.216 \cdot \beta^8 \\ &+ 0.000521 \cdot \left(\frac{\beta \cdot 10^6}{\mathrm{Re}_D} \right)^{0.7} + (0.0188 + 0.0063 \cdot A) \cdot \beta^{3.5} \cdot \left(\frac{10^6}{\mathrm{Re}_D} \right)^{0.3} \\ &+ (0.043 + 0.080 \cdot e^{-10 \cdot L_1} - 0.123 \cdot e^{-7 \cdot L_1}) \cdot (1 - 0.11 \cdot A) \cdot \left[\frac{\beta^4}{1 - \beta^4} \right] \\ &- 0.031 \cdot (M'_2 - 0.8 \cdot {M'_2}^{1.1}) \cdot \beta^{1.3} \end{aligned} \qquad (5.29)$$

In the case where the pipe diameter, *D*, is less than 71.12 mm (2.8 in), the following term should be added to the equation in (5.29):

$$+ 0.011 \cdot (0.75 - \beta) \cdot \left(2.8 - \frac{D}{25.4} \right) \qquad (5.30)$$

where

- *C* - discharge coefficient
- β - diameter ratio (Cf. Chapter 8.4)
- Re_D - Reynolds number related to *D*
- *D* - Pipe diameter [mm] (Cf. Chapter 8.3)
- L_1 - is the quotient of the distance of the upstream tapping from the **upstream** face of the plate, and the pipe diameter ($L_1 = I_1/D$). (Cf. ISO 5167-2:2003 [ISO, 2003b])
- L'_2 - is the quotient of the distance of the downstream tapping from the **downstream** face of the plate, and the pipe diameter ($L'_2 = I'_2/D$). (L'_2 denotes the reference of the downstream spacing from the **downstrean** face, while L_2 would denote the reference of the downstream spacing from the **upstream** face). (Cf. ISO 5167-2:2003 [ISO, 2003b])

$$A = \left(\frac{19000 \cdot \beta}{\mathrm{Re}_D}\right)^{0.8} \qquad (5.31)$$

$$M'_2 = \frac{2 \cdot L'_2}{1-\beta} \qquad (5.32)$$

L_1 and L'_2 is defined in ISO 5167-2:2003 [ISO, 2003b], and is depending on the tapping arrangement:

Flange tappings: $L_1 = L'_2 = 25.4 / D$ (where D is in millimetre)
Corner tappings: $L_1 = L'_2 = 0$
D and $D/2$ tappings: $L_1 = 1$, $L'_2 = 0.47$

The Reynolds number is a dimensionless quantity expressing the ratio between the inertia and viscous forces of the upstream condition of the fluid of the upstream diameter of the pipe, D. It is calculated according to ISO 5167-1:2003 [ISO, 2003] as:

$$\mathrm{Re}_D = \frac{4 \cdot q_m}{\pi \cdot \mu_1 \cdot D} \qquad (5.33)$$

where

Re_D is the Reynolds number
q_m is the mass flow rate [kg/s]
μ_1 is the viscosity [Pa·s]
D is the pipe diameter [m]

5.8.2 Example uncertainty evaluation

The uncertainty contributors are the diameter ratio, the pipe diameter, the mass flow rate, the viscosity and the model uncertainty.

The functional relationship used for calculation of the discharge coefficient will influence not only the calculation of the discharge coefficient, but also the calculation of the uncertainty of the discharge coefficient.

The relative model uncertainty is given in ISO 5167-2:2003 [ISO, 2003b] as:

For $0.1 \le \beta < 0.2$: $(0.7 - \beta)$% of discharge coefficient value
(95% confidence level is assumed)

For $0.2 \le \beta \le 0.6$: 0.5% of discharge coefficient value
(95% confidence level is assumed)

For $0.6 < \beta \le 0.75$: $(1.667 \cdot \beta - 0.5)$ % of discharge coefficient value
(95% confidence level is assumed)

If D < 71.12 mm (2.8 in), the following relative uncertainty should be added arithmetically to the above values:

$$+0.9 \cdot (0.75 - \beta) \cdot \left\{ 2.8 - \frac{D}{25.4} \right\} \% \qquad (5.34)$$

If $\beta > 0.5$ and Re_D < 10000, the following relative uncertainty should be added arithmetically to the above values:

$$+0.5\% \qquad (5.35)$$

It is further stated in ISO 5167-2:2003 [ISO, 2003] that additional uncertainty contributions shall be added arithmetically to the uncertainty of the Discharge coefficient to account for divergent installations. Examples of such diverging installations are described in Section 6.2.4, 6.2.8 and 6.4.4 in ISO 5167-2:2003 [ISO, 2003]. According to [Dahl *et al*, 1999] the model uncertainty totally dominates the uncertainty of the Discharge coefficient. Hence, uncertainty contributions due to the input quantities may be considered negligibly small compared to this model uncertainty, independent of tapping arrangement and functional relationship used in calculation of the Discharge coefficient.

The combined uncertainty of the Discharge coefficient then simply comprises the *arithmetic summation* of the model uncertainty and additional uncertainty contributions, which is also implemented in a special uncertainty budget for the Discharge coefficient in the EMU-program.

5.9 Signal communication and flow computer uncertainty

Uncertainty contributions from signal communication and flow computer are not addressed in this *Handbook*, but in the program *EMU - Orifice Fiscal Gas Metering Station* the user has the possibility to specify such uncertainty contributions, in case that is found to be necessary. Normally these contributions are very small and probably negligible.

5.10 Combined expanded uncertainty of the Orifice fiscal gas metering station

The combined expanded uncertainty of the Orifice fiscal gas metering station is calculated in terms of actual mass flow rate. The functional relationships for the actual mass flow rate has previously been given in Eqn. (5.1), but is re-printed here for convenience:

$$q_m = \frac{C}{\sqrt{1-\beta^4}} \varepsilon_1 \frac{\pi}{4} d^2 \sqrt{2 \cdot \Delta P \cdot \rho_1} \qquad (5.36)$$

where

q_m	- mass flow rate [kg/s]
C	- discharge coefficient
β	- diameter ratio
ε_1	- expansibility at upstream conditions
ε_2	- expansibility at downstream conditions
ρ_1	- density at upstream conditions [kg/m^3]
ρ_2	- density at downstream conditions [kg/m^3]
d	- diameter of orifice [m]
ΔP	- differential pressure over orifice [Pa]

Eqn. (5.36) is used for measurements referred to upstream conditions.

The evaluation of the uncertainty of the actual mass flow rate is based on previous chapters and the sample metering station calculation has been performed for the following configuration:

- Flange pressure tapping arrangement
- Static pressure is measured from the upstream differential pressure tapping
- The expansibility factor is referred to upstream conditions

Table 5.18. Figures used in the example calculations.

Parameter	**Covered in…**
Diameter ratio, β	Cf. Section 5.6
Orifice diameter, d	Cf. Section 5.5
Discharge Coefficient	Cf. Section 5.8
Expansibility factor, ε	Cf. Section 5.7
Density, ρ	Cf. Section 5.4
Differential pressure, ΔP	Cf. Section 5.3

Regarding the operating conditions, please refer to Section 5.1.2 and the respective references given in Table 5.18.

A covariance term must be included in the evaluation of the combined uncertainty of the mass flow rate. This covariance term reduces significantly by the fact that uncertainties other than the model uncertainties may be neglected from the combined uncertainties of C (Cf. Chapter 5.8) and ε (Cf. Chapter 5.7). When the uncertainty of an input quantity does not contribute to the combined uncertainties of ε or C, the correlation's introduced to the combined uncertainty in mass flow rate are expected to be even smaller and thus negligible.

The covariance term will therefore only be due to the orifice diameter, which is a part of the expression for the mass flow rate and also a part of the diameter ratio, β.

This covariance term can be expressed as:

$$\text{Covariance} = 2 \cdot \left\{ \left(\frac{\partial q_m}{\partial d} \right) \cdot \left(\frac{\partial q_m}{\partial \beta} \frac{\partial \beta}{\partial d} \right) \cdot u(d) \cdot u(d) \cdot 1 \right\} \tag{5.37}$$

where $u(d)$ is the standard uncertainty of the orifice diameter.
It must be further noted that since the mass flow rate is a function of itself, and calculated by iteration, the sensitivity coefficients must be calculated using implicit differentiation. Hence,

$$S_C = \frac{\partial q_m(d, C, \beta, \varepsilon, \Delta P, \rho, q_m) \big/ \partial C}{1 - \partial q_m(d, C, \beta, \varepsilon, \Delta P, \rho, q_m) \big/ \partial q_m} \tag{5.38}$$

where S_c is the sensitivity of the mass flow rate with respect to the discharge coefficient and $q_m(d,C,\beta,\varepsilon,\Delta P,\rho,q_m)$ is the implicit mass flow rate expression.

Uncertainty due to buckling of the orifice plate is not part of the scope of this handbook, and it is expected that the orifice plate is manufactured and operated according to NPD regulations and “recognized standards” [NPD, 2001a]. However, in the program an option is prepared for manual insertion of uncertainty due to buckling.

5.10.1 Example uncertainty evaluation

A sample uncertainty budget for evaluation of the uncertainty of the mass flow rate is shown in Table 5.19.

Table 5.19 Sample uncertainty budget for mass flow rate uncertainty.

Source	Input uncertainty				Combined uncertainty	
	Expand. uncert.	**Conf. level & Distribut.**	**Cov. fact., *k***	**Standard uncertainty**	**Sens. coeff.**	**Variance**
Diameter ratio, β	0.0024	95 % (norm)	2	0.00122	147999.4 kg/h	$3.24 \cdot 10^{-4}$ (kg/h)^2
Orifice diameter, d	0.1866 mm	95 % (norm)	2	0.0933 mm	2251.33 kg/h·mm	$4.41 \cdot 10^{-4}$ (kg/h)^2
Discharge coefficient, C	0.00301	95 % (norm)	2	0.001507	497464 kg/h	$5.62 \cdot 10^{-5}$ (kg/h)^2
Differential pressure, ΔP	0.4243 mbar	95 % (norm)	2	0.000212 bar	454933.3 kg/h·bar	$9.31 \cdot 10^{-3}$ (kg/h)^2
Density, ρ	0.1561 kg/m^3	95 % (norm)	2	0.07805 kg/m^3	1836.57 1/h·m^3	$2.05 \cdot 10^{-4}$ (kg/h)^2
Expansibility coefficient, ε	$9.8138 \cdot 10^{-5}$	95 % (norm)	2	$4.91 \cdot 10^{-5}$	300137.1 kg/h	$2.17 \cdot 10^{-2}$ (kg/h)^2
Covariance						- $1.31 \cdot 10^{-4}$ (kg/h)^2
Sum of variances				$u_c^2(\hat{q}_m)$		$6.81 \cdot 10^{5}$ (kg/h)^2
Combined standard uncertainty				$u_c(\hat{q}_m)$		828.49 (kg/h)^2
Expanded uncertainty (95 % confidence level, k = 2)				$U_c(\hat{q}_m)$		1650.98 (kg/h)^2
Operating mass flow rate				$\hat{q}_m$		300000 kg/h
Relative expanded uncertainty (95 % confidence level)				$U(\hat{q}_m)/\hat{q}_m$		0.5503 %

It is seen from Table 5.19 that the expanded and relative expanded uncertainty of the actual mass flow rate is 1651 kg/h and 0.55%, respectively. Hence, the metering station performs according to the NPD regulations [NPD, 2001a] which require the relative expanded uncertainty of the mass flow rate to be less than 1.0%.

The maximum operating differential pressure should be less than 1 bar [NPD, 2001a]. The relative expanded uncertainty depends on the operating differential pressure. The minimum operating differential pressure may therefore be limited by the maximum allowed relative expanded uncertainty of 1.0%, since this uncertainty increases with decreasing differential pressure. This minimum operating differential pressure can thus be easily found using the graph option program *EMU - Orifice Fiscal Gas Metering Station* and displaying the relative expanded uncertainty vs. differential pressure.

5.10.2 Parallel metering runs

Uncertainty evaluation of parallel metering runs is not part of this handbook. This matter should be handled with care, because instruments common to several metering runs introduce correlations that may be hard to evaluate. An ideal situation, with no common instrumentation, would give no correlation between the metering runs.

The total mass flow rate of a two-run gas metering station would then become:

$$q_{m\_TOTAL} = q_{m\_A} + q_{m\_B} \tag{5.39}$$

where

q_{m_TOTAL}	- is the total mass flow rate [kg/h]
q_{m_A}	- is the mass flow rate [kg/h] of run A
q_{m_B}	- is the mass flow rate [kg/h] of run B

With two metering stations for fiscal gas measurement like the one evaluated in this handbook, with no common instrumentation, the combined standard uncertainty of the metering station parallel runs can simply be calculated as:

$$u_c(q_{m\_TOTAL}) = \sqrt{[u(q_{m\_A})]^2 + [u(q_{m\_B})]^2} \ = \ 1171.66 \text{ kg/h} \tag{5.40}$$

With two metering stations for fiscal gas measurement like the one evaluated in this handbook, with no common instrumentation, the relative expanded uncertainty becomes:

$$\delta q_{vs\_TOTAL} = \frac{k_{95} \cdot u_c(q_{vs\_TOTAL})}{q_{vs\_TOTAL}} = 0.39 \ \% \tag{5.41}$$

From Eqn. (5.41) it is seen that for this ideal case the combined uncertainty of the metering station becomes smaller than the combined uncertainty of each metering run. It is important to note, however, that common instrumentation introduces correlation between metering runs.

6. PROGRAM – GAS METERING STATION

The present chapter describes the Excel program *EMU - Orifice Fiscal Gas Metering Station* that has been implemented for performing uncertainty analysis of orifice meter based fiscal gas metering stations. The program applies to metering stations equipped as described in Section 5.1.2, and is based on the uncertainty model for such metering stations as described in Chapter 5.1. Using this program, uncertainty evaluation can be made for the expanded uncertainty (at a 95% confidence level, using k = 2) for the mass flow rate, q_m.

The program simplifies the calculation of the combined uncertainty of the fiscal gas metering station significantly, and it may be used for evaluation of the individual and combined uncertainties. The program enables one to simulate different operating conditions, and calculate the corresponding uncertainties to study the influence of changes in the operating conditions.

The uncertainties calculated by the program may be used in the documentation with reference to the handbook. However, it must be emphasised that the inputs to the program must be documented (Cf. Section 2.4), and that the user must document that the calculation procedures and functional relationships implemented in the program (Cf. Chapter 5) are equal to the ones actually applied in the fiscal oil metering station.

6.1 General

The program is implemented in Microsoft Excel 2000 and is based on worksheets where the user enters input data to the calculations. These “input worksheets” are mainly formed as uncertainty budgets, which are continuously updated as the user enters new input data. Other worksheets provide display of the uncertainty calculation results, and are continuously updated in the same way.

With respect to specification of inpu parameters, colour codes are used in the program *EMU - Orifice Fiscal Gas Metering Stations*, according to the following scheme:

- Black font: Value that <u>must</u> be entered by the user,
- Blue font: Outputs from the program, or number read from another worksheet (editing prohibited)

In the following subsections the worksheets of the program are shown and explained, and the necessary input parameters are addressed with an indication of where in Chapter 5 the input values are discussed.

Output data are presented in separate worksheets, graphically (curves and bar-charts), and by listing. An output report worksheet is available, summarizing the main uncertainty calculation results.

The expanded uncertainties calculated by the program may be used in the documentation of the metering station uncertainty, with reference to the present *Handbook*. The worksheets are designed so that printouts of these can be used directly as part of the uncertainty evaluation documentation. They may also conveniently be copied into a text document[80], for documentation and reporting purposes. However, it must be emphasised that the inputs to the program (quantities, uncertainties, confidence levels and probability distributions) must be documented by the user of the program. The user must also document that the calculation procedures and functional relationships implemented in the program are in conformity with the ones actually applied in the fiscal gas metering station.

In a practical work situation in the evaluation of a metering station, a convenient way to use the program may be the following. After the desired input parameters and uncertainties have been entered, the Excel file document may be saved e.g. using a modified file name, e.g. "*EMU - Orifice Fiscal Gas Metering Station - MetStat1.xls*", "*EMU - Orifice Fiscal Gas Metering Station - MetStat2.xls*", etc. Old evaluations may then conveniently be revisited, used as basis for new evaluations, etc.

80 For instance, by using Microsoft Word 2000, a "cut and paste special" with "picture" functionality may be sufficient for most worksheets. However, for some of the worksheets the full worksheet is (for some reason) not being pasted using the "paste special" with "picture" feature. Only parts of the worksheet are copied. In this case use of the "paste special" with "bitmap" feature may solve the problem.
However, if the Word (doc) file is to be converted to a pdf-file, use of the "bitmap" feature results in poor-quality pictures. In this case it is recommended to first convert the Excel worksheet in question into an 8-bit gif-file (e.g. using Corel Photo Paint 7), and then import the gif-file as a picture into the Word document. The resulting quality is not excellent, but still useful.

6.2 Gas parameters

In the worksheet denoted "Gas parameters" shown in Figure 6.1, the user enters data for

- The operating gas conditions for the fiscal gas metering station
- The gas conditions in the densitometer
- The ambient temperature and pressure

Most of the input cells should be self-explaining, but we would still emphasize the reason why the user must enter the density at line conditions and the uncorrected density indicated by the densitometer. The reason for this is to reduce the number of user input parameters required by the program. If the EMU program shall perform the density correction from by-pass to line conditions, it would require more user input parameters (Z and Z_d). This is covered in more detail in Section 5.4, where it is also shown that these additional parameters have negligible influence on the uncertainty calculations and thus may be neglected. In the calculations in this *Handbook* and the EMU programs, the indicated (uncorrected) density from the densitometer is therefore only used in the calculations of the combined uncertainty of the corrected density, Eqn. (5.9), while the line density is the one used in the calculations of mass flow rate, Eqn. (5.1).

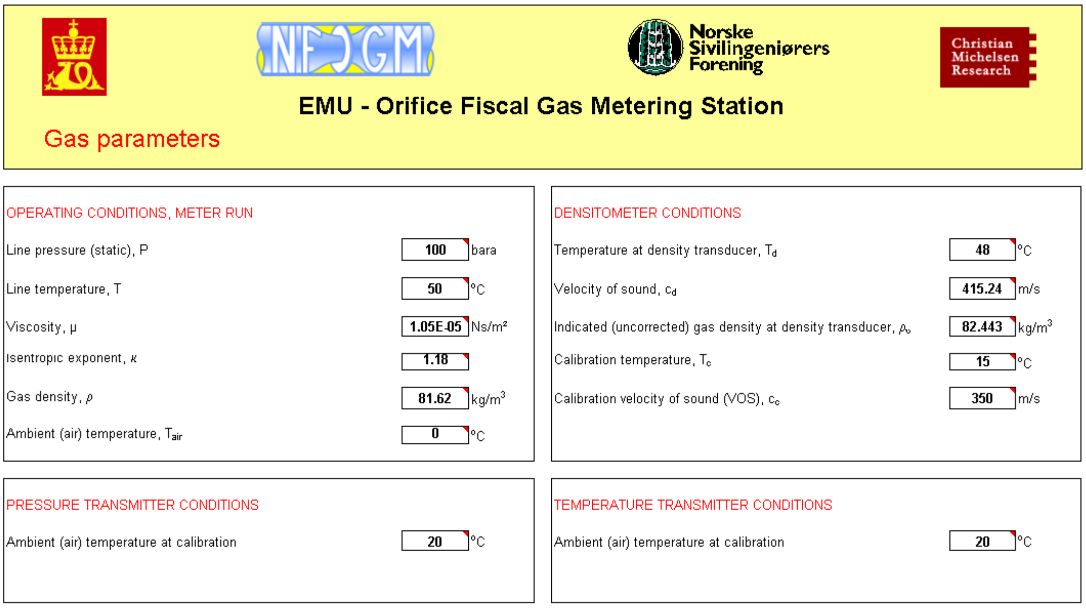


Figure 6.1 Operation condition display from the program EMU - Orifice Fiscal Gas Metering Station. (Corresponds to Table 5.3).

The program uses these data in the calculation of the individual uncertainties of the primary measurements, and in calculation of the combined gas metering station uncertainty. The data used in the input worksheet shown in Figure 6.1 are the same data as specified in Table 5.3 for the calculation example given in Chapter 5.

6.3 Temperature measurement uncertainty

The worksheet "*T*" for evaluation of the expanded uncertainty of the temperature measurement in the meter run is shown in Figure 6.2 and Figure 6.3, for the "overall level" and the "detailed level", respectively. These are described separately below.

6.3.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the temperature measurement uncertainty, the user specifies only the relative expanded uncertainty of the temperature measurement, and the accompanying confidence level / probability distribution, see Figure 6.2.

This option is used e.g. when the user does not want to go into the "detailed" level of the temperature measurement, or if the "detailed level" setup does not fit sufficiently well to the temperature element and transmitter at hand. The user must then document the input value used for the relative expanded uncertainty of the temperature measurement (the "given uncertainty"), and its confidence level and probability distribution.

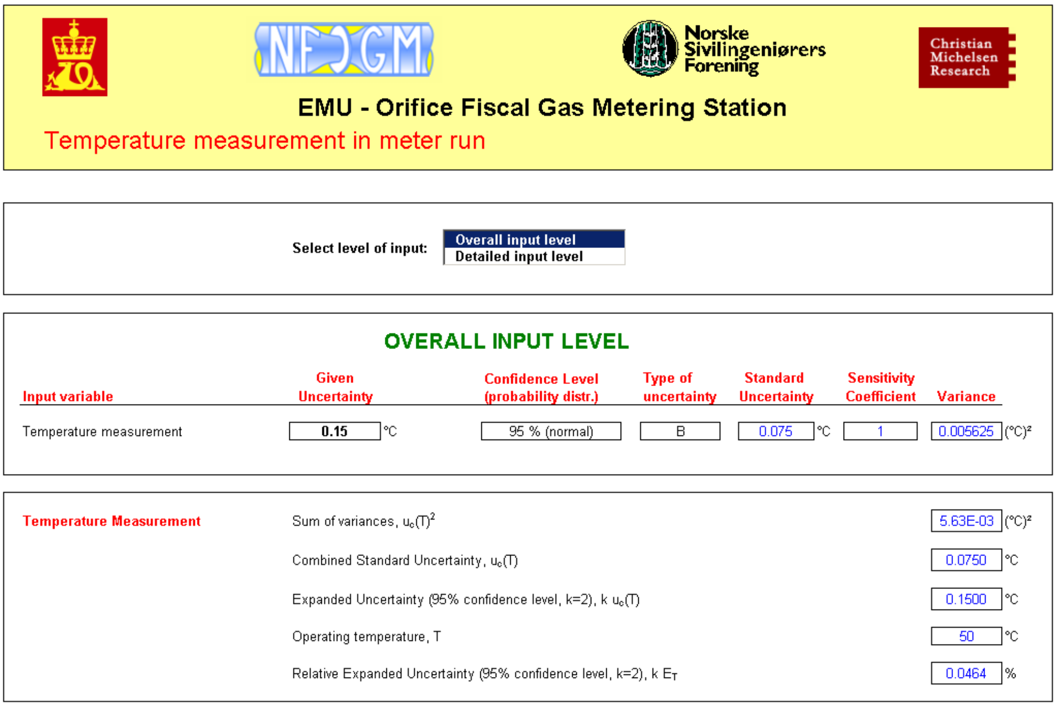


Figure 6.2 The "T" worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "overall level" option.

6.3.2 Detailed level

When the “detailed level” is chosen for specification of input uncertainties to calculation of the temperature measurement uncertainty, the user specifies the uncertainty data of the temperature element and transmitter in question, together with the accompanying confidence levels / probability distributions. Cf. Table 5.5. The user must himself document the input uncertainty values for the temperature measurement, e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.

In Table 5.4 the uncertainty figures given for the Rosemount 3144 Smart Temperature Transmitter [Rosemount, 2001] used in combination with a Pt 100 temperature element, have been specified. These are the same as used in Table 5.5, see Section 5.2 for details. A blank field denoted “type of instrument” can be filled in to document the instrument evaluated, for reporting purposes.

In addition to the input uncertainty data, the user must specify the “time between calibrations”. The “ambient temperature deviation” is calculated by the program from data given in the “Gas parameters” worksheet.

In addition to the “usual” temperature transmitter input uncertainties given in the worksheet, a “blank cell” has been defined, where the user can specify miscellaneous uncertainty contributions to the temperature measurement not covered by the other input cells in the worksheet. The user must then document the input value used for the “miscellaneous uncertainty” of the temperature measurement, and its confidence level and probability distribution.

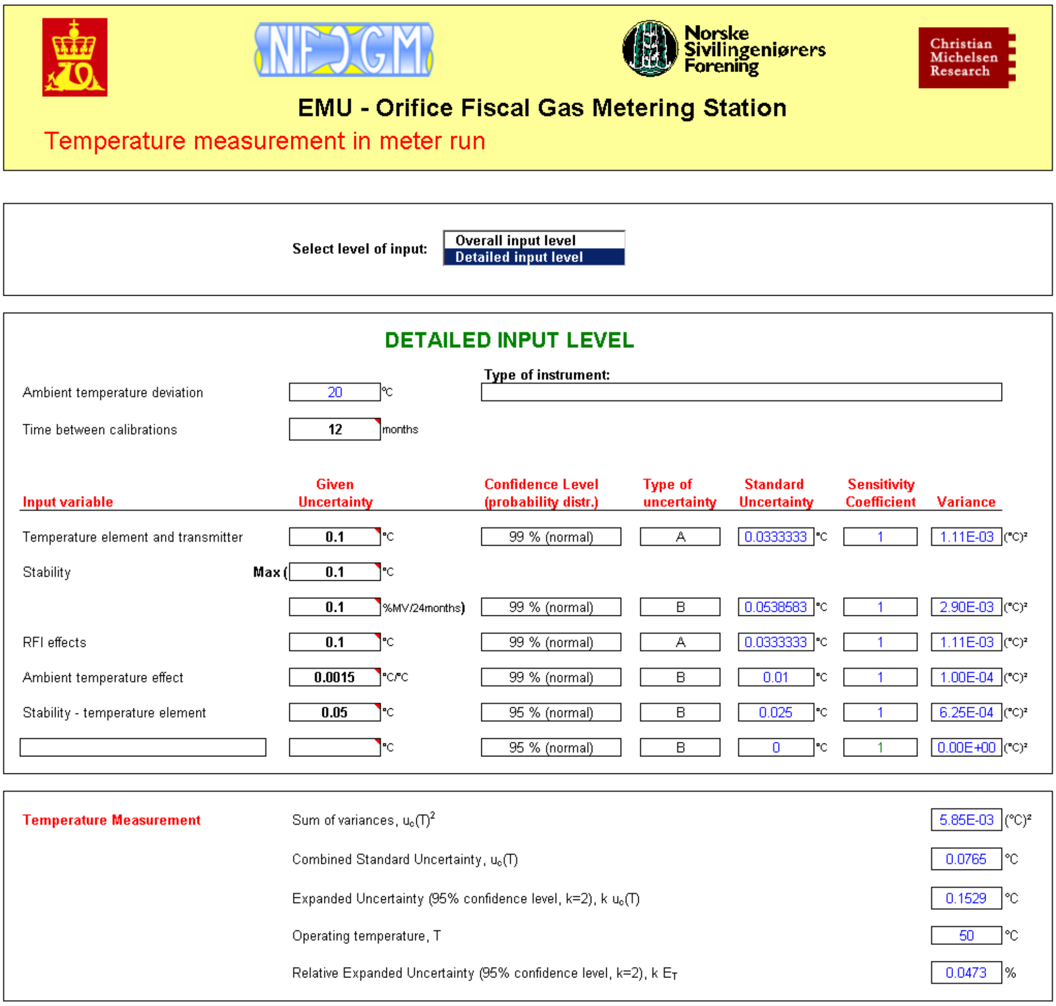


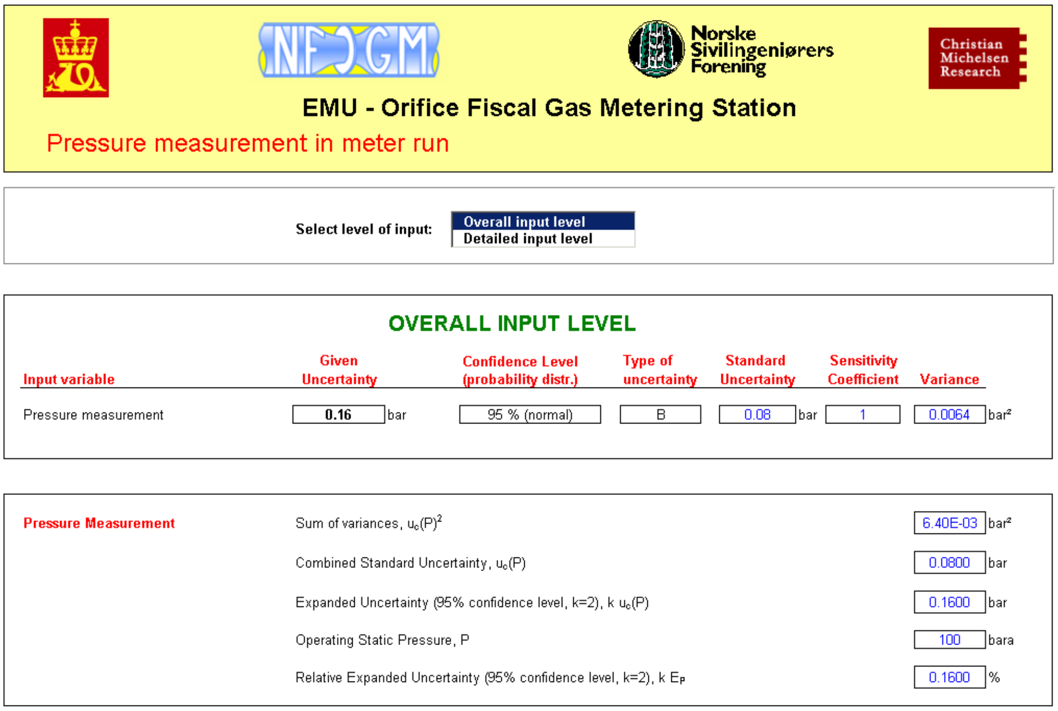
Figure 6.3 The "T" worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "detailed level" option. (Corresponds to Table 5.5).

6.4 Static pressure measurement uncertainty

The worksheet "*P*" for evaluation of the expanded uncertainty of the pressure measurement in the meter run is shown in Figure 6.4 and Figure 6.5, for the "overall level" and the "detailed level", respectively. These are described separately below.

6.4.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters only the relative expanded uncertainty of the pressure measurement, and the accompanying confidence level / probability distribution, see Figure 6.4.



Norske Sivilingeniørers Forening

Christian Michelsen Research

EMU - Orifice Fiscal Gas Metering Station

Pressure measurement in meter run

Select level of input: Overall input level / Detailed input level

OVERALL INPUT LEVEL

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient	Variance	
Pressure measurement	0.16	bar	95 % (normal)	B	0.08	bar	1	0.0064	bar²

Pressure Measurement			
	Sum of variances, $u_c(P)^2$	6.40E-03	bar²
	Combined Standard Uncertainty, $u_c(P)$	0.0800	bar
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(P)$	0.1600	bar
	Operating Static Pressure, P	100	bara
	Relative Expanded Uncertainty (95% confidence level, k=2), k E_P	0.1600	%

Figure 6.4 *The "P" worksheet in the program* EMU - Orifice Fiscal Gas Metering Station, *shown for the "overall level" option.*

This option is used e.g. when the user does not want to go into the "detailed level" of the pressure measurement, or if the "detailed level" setup does not fit sufficiently well to the pressure transmitter at hand. The user must then document the input value used for the relative expanded uncertainty of the pressure measurement (the "given uncertainty"), and its confidence level and probability distribution.

6.4.2 Detailed level

When the "detailed level" is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters the uncertainty figures of the pressure transmitter in question, in addition to the accompanying confidence levels / probability distributions. Cf. Table 5.8 and Section 5.3.

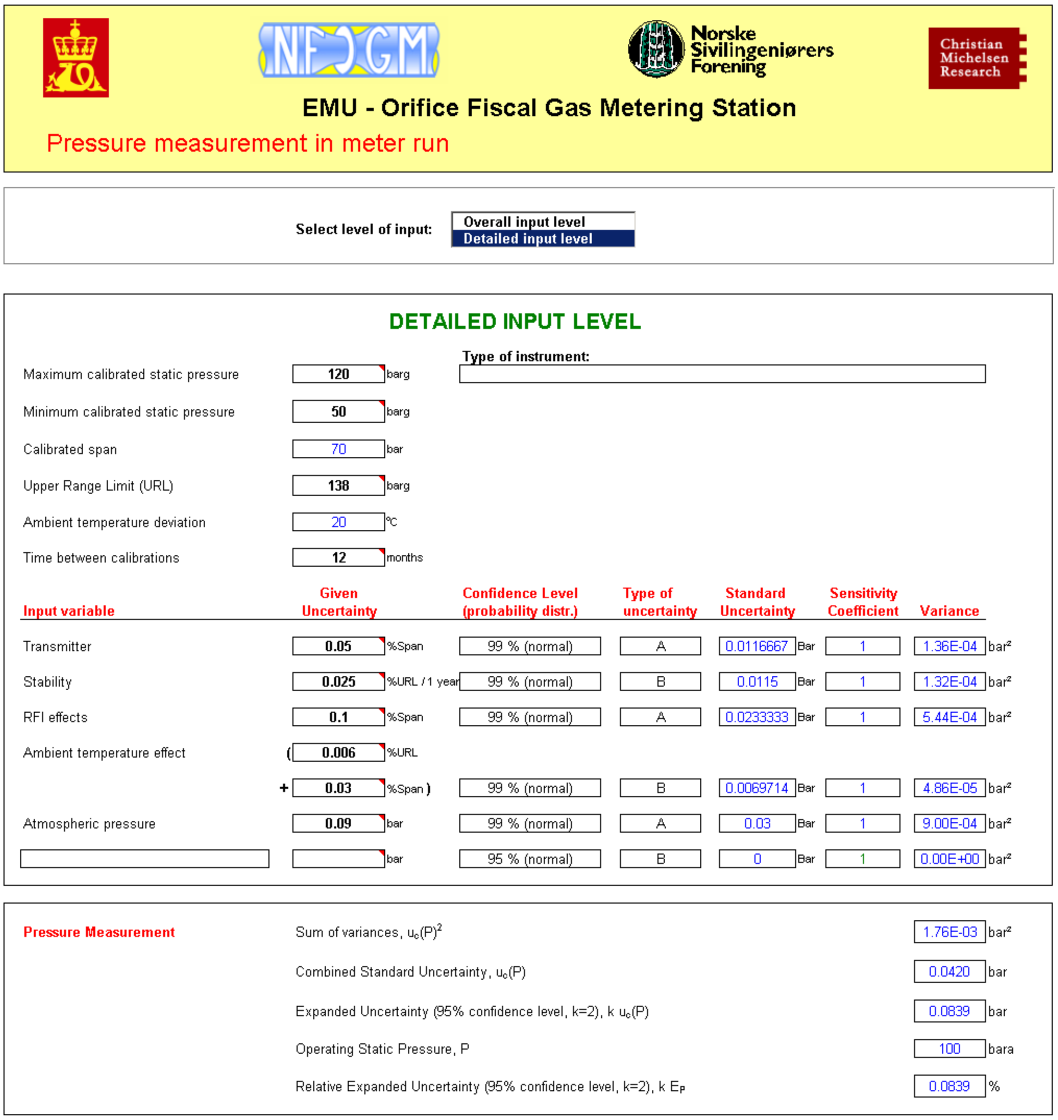


Figure 6.5 The "P" worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "detailed level" option. (Corresponds to Table 5.8).

In Figure 6.5 the uncertainty data specified for the Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a] have been used, cf. Table 5.6. A blank field denoted "type of instrument" can be filled in to document the actual instrument being evaluated, for reporting purposes.

In addition to the input uncertainty values, the user must specify a few other data, found in instrument data sheets. By selecting the "maximum" and "minimum calibrated static pressure", the program automatically calculates the "calibrated span". The "URL" is entered by the user. The "ambient temperature deviation" is calculated by the program from data given in the "Gas parameters" worksheet. Also the "time between calibrations" has to be specified.

In addition to the "usual" pressure transmitter input uncertainties given in the worksheet, a "blank cell" has been defined, where the user can specify miscellaneous uncertainty contributions to the pressure measurement not covered by the other input cells in the worksheet.

The user must himself document the input uncertainty values used for the pressure measurement (the "given uncertainty"), e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.

6.5 Differential pressure measurement uncertainty

The worksheet "*DP*" for evaluation of the expanded uncertainty of the pressure measurement in the meter run is shown in Figure 6.6 and Figure 6.7, for the "overall level" and the "detailed level", respectively. These are described separately below.

6.5.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters only the relative expanded uncertainty of the pressure measurement, and the accompanying confidence level / probability distribution, see Figure 6.6.

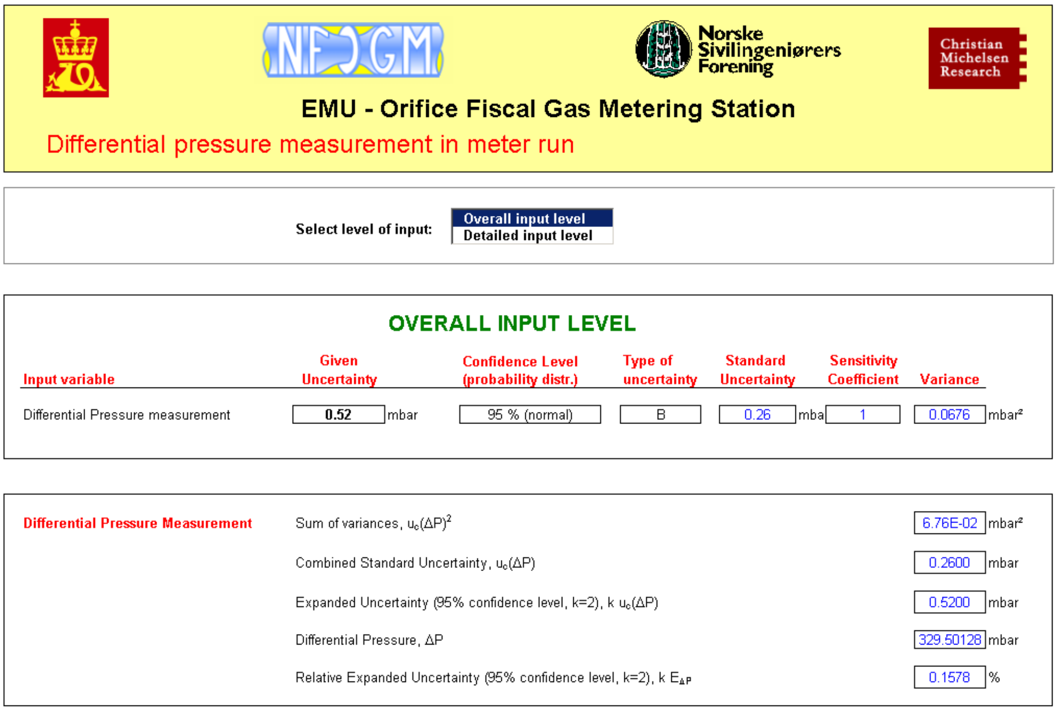


Figure 6.6 The "DP" worksheet in the program EMU - Orifice Fiscal Gas Metering Station, *shown for the "overall level" option.*

This option is used e.g. when the user does not want to go into the “detailed level” of the differential pressure measurement, or if the “detailed level” setup does not fit sufficiently well to the differential pressure transmitter at hand. The user must then document the input value used for the relative expanded uncertainty of the differential pressure measurement (the “given uncertainty”), and its confidence level and probability distribution.

6.5.2 Detailed level

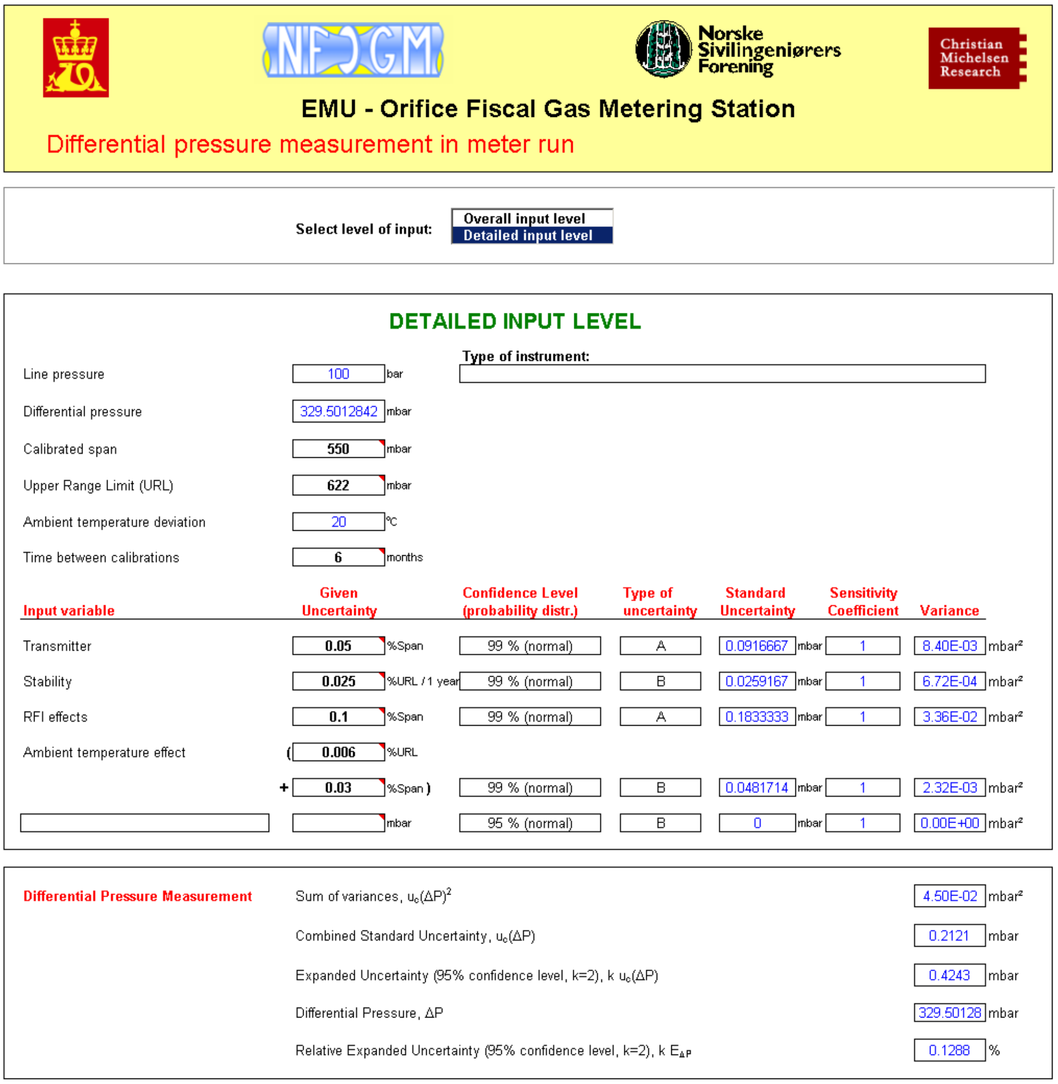
When the “detailed level” is chosen for specification of input uncertainties to calculation of the pressure measurement uncertainty, the user enters the uncertainty figures of the differential pressure transmitter in question, in addition to the accompanying confidence levels / probability distributions. Cf. Table 5.8 and Section 5.3.

In Figure 6.7 the uncertainty data specified for the Rosemount 3051P Reference Class Smart Pressure Transmitter [Rosemount, 2002a] have been used, cf. Table 5.6. A blank field denoted “type of instrument” can be filled in to document the actual instrument being evaluated, for reporting purposes.

In addition to the input uncertainty values, the user must specify a few other data, found in instrument data sheets. By selecting the “maximum” and “minimum calibrated static pressure”, the program automatically calculates the “calibrated span”. The “URL” is entered by the user. The “ambient temperature deviation” is calculated by the program from data given in the “Gas parameters” worksheet. Also the “time between calibrations” has to be specified.

In addition to the “usual” pressure transmitter input uncertainties given in the worksheet, a “blank cell” has been defined, where the user can specify miscellaneous uncertainty contributions to the pressure measurement not covered by the other input cells in the worksheet.

The user must himself document the input uncertainty values used for the pressure measurement (the “given uncertainty”), e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.



EMU - Orifice Fiscal Gas Metering Station

Differential pressure measurement in meter run

Select level of input: Overall input level / Detailed input level

DETAILED INPUT LEVEL

Line pressure	100	bar
Differential pressure	329.5012842	mbar
Calibrated span	550	mbar
Upper Range Limit (URL)	622	mbar
Ambient temperature deviation	20	°C
Time between calibrations	6	months

Type of instrument:

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient	Variance	
Transmitter	0.05	%Span	99 % (normal)	A	0.0916667	mbar	1	8.40E-03	mbar²
Stability	0.025	%URL / 1 year	99 % (normal)	B	0.0259167	mbar	1	6.72E-04	mbar²
RFI effects	0.1	%Span	99 % (normal)	A	0.1833333	mbar	1	3.36E-02	mbar²
Ambient temperature effect	(0.006	%URL							
	+ 0.03	%Span)	99 % (normal)	B	0.0481714	mbar	1	2.32E-03	mbar²
		mbar	95 % (normal)	B	0	mbar	1	0.00E+00	mbar²

Differential Pressure Measurement

Sum of variances, $u_c(\Delta P)^2$	4.50E-02	mbar²
Combined Standard Uncertainty, $u_c(\Delta P)$	0.2121	mbar
Expanded Uncertainty (95% confidence level, k=2), k $u_c(\Delta P)$	0.4243	mbar
Differential Pressure, ΔP	329.50128	mbar
Relative Expanded Uncertainty (95% confidence level, k=2), k $E_{\Delta P}$	0.1288	%

Figure 6.7 The "DP" worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "detailed level" option. (Corresponds to Table 5.9).

6.6 Density measurement uncertainty

The worksheet "*Density*" for evaluation of the expanded uncertainty of the density measurement in the meter run is shown in Figure 6.8 and Figure 6.9, for the "overall level" and the "detailed level", respectively. These are described separately below.

6.6.1 Overall level

When the "overall level" is chosen for specification of input uncertainties to calculation of the density measurement uncertainty, the user specifies only the relative expanded uncertainty of the density measurement, and the accompanying confidence level and probability distribution, see Figure 6.8.

This option is used e.g. when the user does not want to go into the "detailed" level of the density measurement, in case a different method for density measurement is used, in case of a different installation of the densitometer (e.g. in-line), or if the "detailed level" setup does not fit sufficiently well to the densitometer at hand. The user must then document the input value used for the relative expanded uncertainty of the density measurement (the "given uncertainty"), and its confidence level and probability distribution.

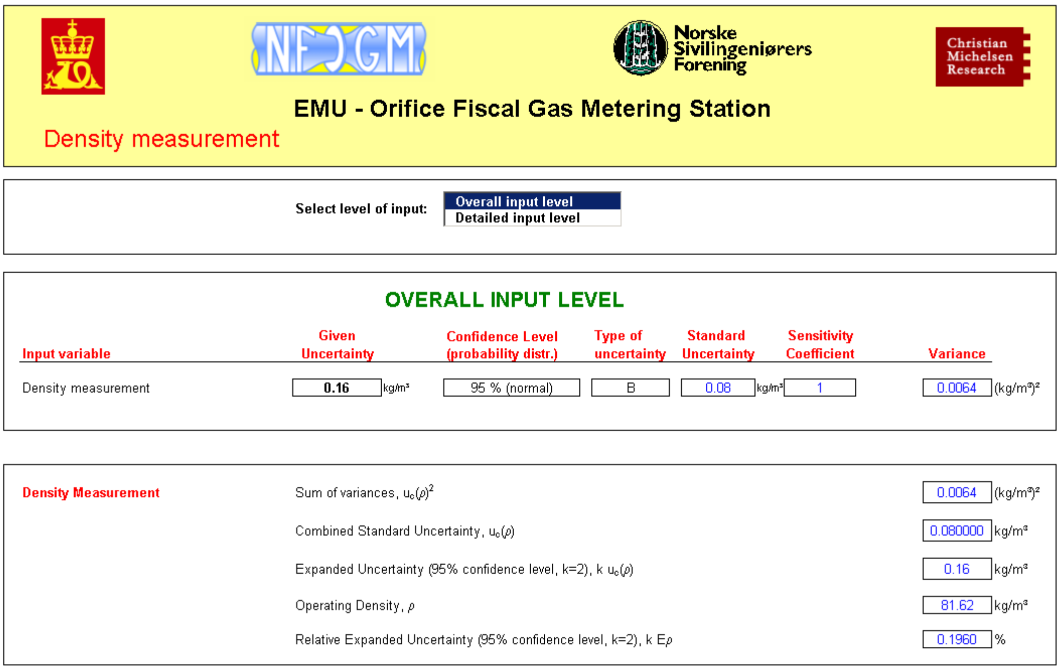
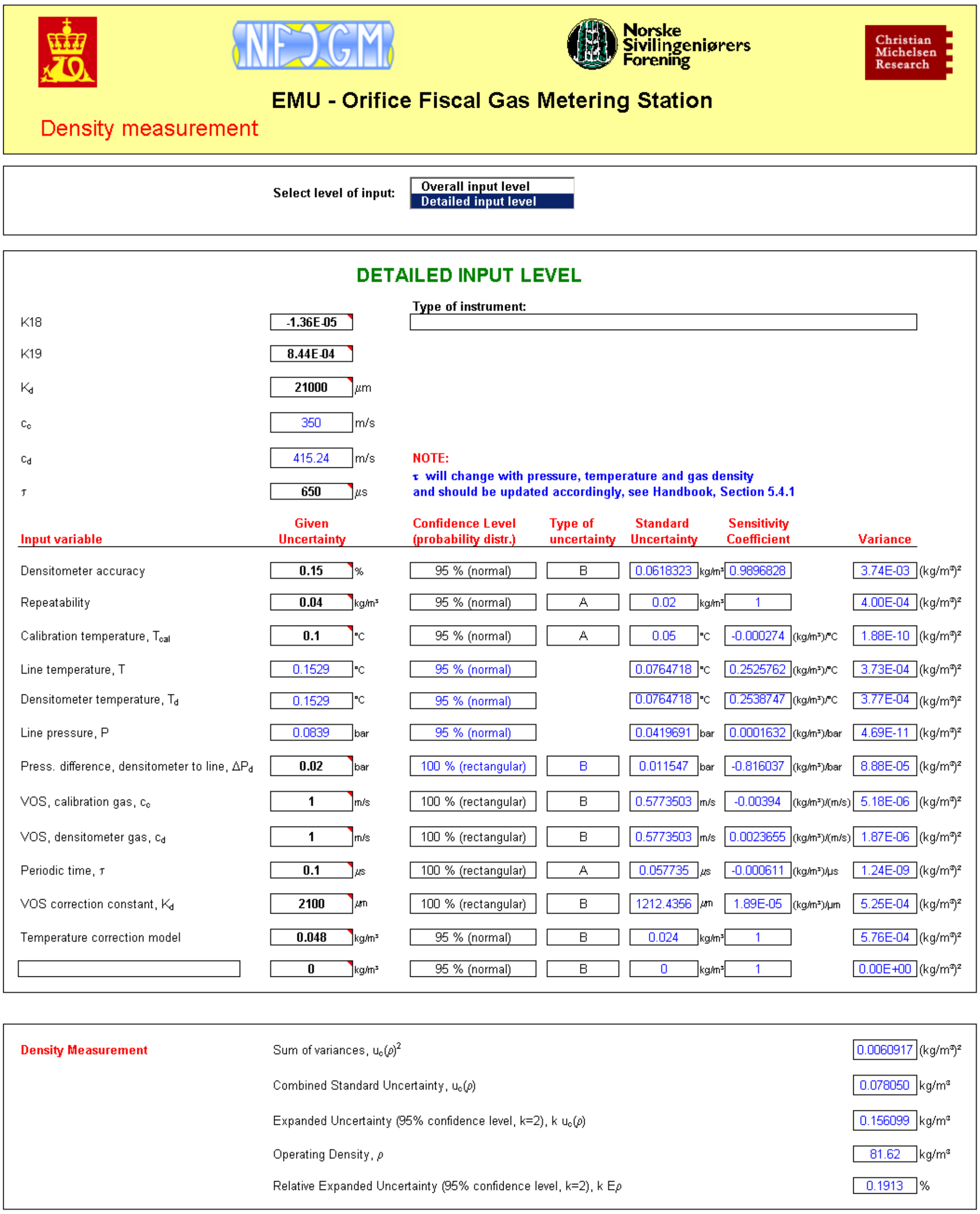


Figure 6.8 *The* "Density" *worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "overall level" option.*

6.6.2 Detailed level

When the "detailed level" is chosen for specification of input uncertainties to calculation of the density measurement uncertainty, the user specifies the uncertainty figures of the online installed vibrating element densitometer in question, in addition to the accompanying confidence levels / probability distributions. Cf. Table 5.12. The user must himself document the input uncertainty values for the density measurement, e.g. on basis of a manufacturer data sheet, a calibration certificate, or other manufacturer information.



EMU - Orifice Fiscal Gas Metering Station

Density measurement

Select level of input: Overall input level / Detailed input level

DETAILED INPUT LEVEL

K18	-1.36E-05	
K19	8.44E-04	
K_d	21000	μm
c_c	350	m/s
c_d	415.24	m/s
τ	650	μs

Type of instrument:

NOTE:
τ will change with pressure, temperature and gas density
and should be updated accordingly, see Handbook, Section 5.4.1

Input variable	Given Uncertainty	Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty	Sensitivity Coefficient	Variance
Densitometer accuracy	0.15 %	95 % (normal)	B	0.0618323 kg/m³	0.9896828	3.74E-03 (kg/m³)²
Repeatability	0.04 kg/m³	95 % (normal)	A	0.02 kg/m³	1	4.00E-04 (kg/m³)²
Calibration temperature, T_{cal}	0.1 °C	95 % (normal)	A	0.05 °C	-0.000274 (kg/m³)/°C	1.88E-10 (kg/m³)²
Line temperature, T	0.1529 °C	95 % (normal)		0.0764718 °C	0.2525762 (kg/m³)/°C	3.73E-04 (kg/m³)²
Densitometer temperature, T_d	0.1529 °C	95 % (normal)		0.0764718 °C	0.2538747 (kg/m³)/°C	3.77E-04 (kg/m³)²
Line pressure, P	0.0839 bar	95 % (normal)		0.0419691 bar	0.0001632 (kg/m³)/bar	4.69E-11 (kg/m³)²
Press. difference, densitometer to line, ΔP_d	0.02 bar	100 % (rectangular)	B	0.011547 bar	-0.816037 (kg/m³)/bar	8.88E-05 (kg/m³)²
VOS, calibration gas, c_c	1 m/s	100 % (rectangular)	B	0.5773503 m/s	-0.00394 (kg/m³)/(m/s)	5.18E-06 (kg/m³)²
VOS, densitometer gas, c_d	1 m/s	100 % (rectangular)	B	0.5773503 m/s	0.0023655 (kg/m³)/(m/s)	1.87E-06 (kg/m³)²
Periodic time, τ	0.1 μs	100 % (rectangular)	A	0.057735 μs	-0.000611 (kg/m³)/μs	1.24E-09 (kg/m³)²
VOS correction constant, K_d	2100 μm	100 % (rectangular)	B	1212.4356 μm	1.89E-05 (kg/m³)/μm	5.25E-04 (kg/m³)²
Temperature correction model	0.048 kg/m³	95 % (normal)	B	0.024 kg/m³	1	5.76E-04 (kg/m³)²
	0 kg/m³	95 % (normal)	B	0 kg/m³	1	0.00E+00 (kg/m³)²

Density Measurement		
Sum of variances, $u_c(\rho)^2$	0.0060917	(kg/m³)²
Combined Standard Uncertainty, $u_c(\rho)$	0.078050	kg/m³
Expanded Uncertainty (95% confidence level, k=2), k $u_c(\rho)$	0.156099	kg/m³
Operating Density, ρ	81.62	kg/m³
Relative Expanded Uncertainty (95% confidence level, k=2), k $E\rho$	0.1913	%

Figure 6.9 The "Density" *worksheet in the program EMU - Orifice Fiscal Gas Metering Station, shown for the "detailed level" option. (Corresponds to Table 5.12).*

In Figure 6.9 the uncertainty figures specified for the Solartron Model 7812 Gas densitometer [Solartron, 2000] have been used, cf. Table 5.11. These are the same as used in Table 5.12, see Section 5.4 for details. A blank field denoted "type of instrument" can be filled in to document the actual instrument being evaluated, for reporting purposes.

The input uncertainty of the densitometer temperature (T_d) is taken from the "*T-density*" worksheet. The densitometer calibration pressure and calibration temperature are taken from the "*Gas parameters*" worksheet.

In addition to the "usual" densitometer input uncertainties given in the worksheet, a "blank cell" has been defined, where the user can specify miscellaneous uncertainty contributions to the density measurement not covered by the other input cells in the worksheet. The user must then document the input value used for the "miscellaneous uncertainty" of the densitometer measurement, together with its confidence level and probability distribution.

6.7 Pipe diameter (D) uncertainty

In the worksheet denoted "Pipe" shown in Figure 6.10 the user must enter the initial measured pipe diameter, the temperature at which the diameter is measured and the thermal coefficient of the pipe.

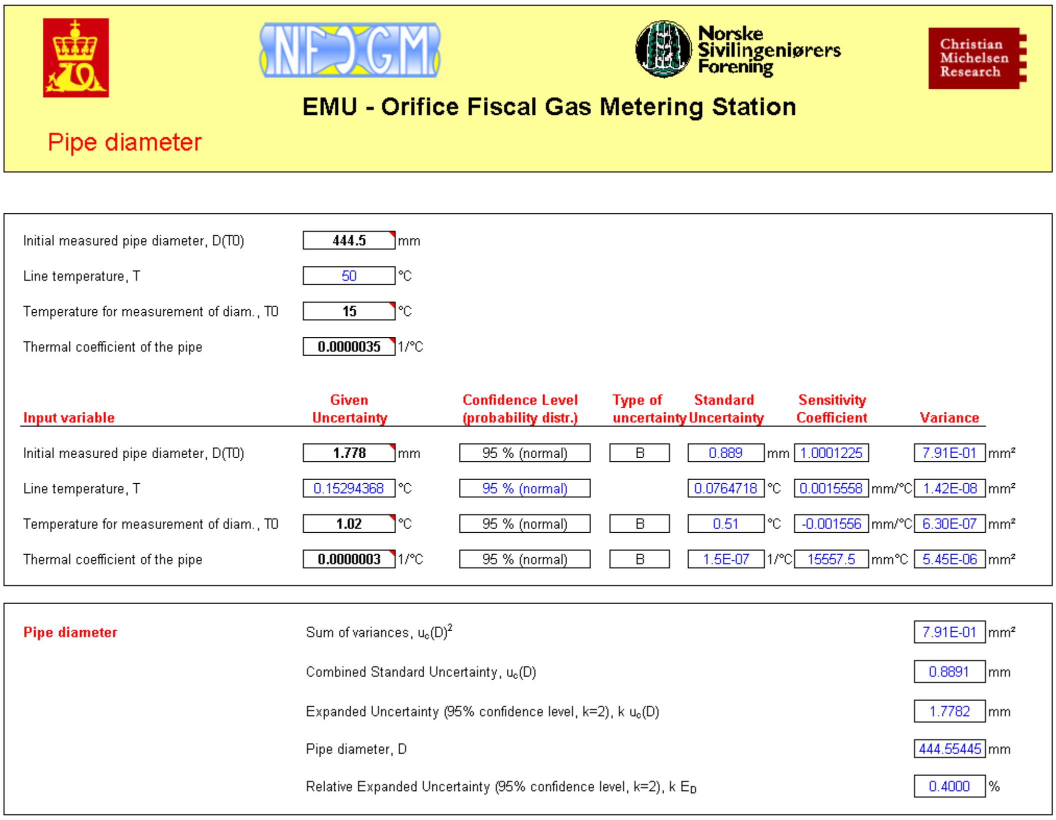


Figure 6.10 The "Pipe" worksheet in the program EMU - Orifice Fiscal Gas Metering Station. (Corresponds to Table 5.14).

6.8 Orifice diameter (d) uncertainty

In the worksheet denoted "Orifice" shown in Figure 6.11 the user must enter the initial measured orifice diameter, the temperature at which the diameter is measured and the thermal coefficient of the orifice.

EMU - Orifice Fiscal Gas Metering Station

Orifice plate

Initial measured orifice diameter, d(T0)	266.184	mm
Line temperature, T	50	°C
Temperature for measurement of diam., T0	15	°C
Thermal coefficient of orifice plate material	0.000016	1/°C

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance	
Initial measured orifice diameter, d(T0)	0.1864	mm	95 % (normal)	B	0.0932	mm	1.00056		8.70E-03	mm²
Line temperature	0.15294368	°C	95 % (normal)		0.0764718	°C	0.0042589	mm/°C	1.06E-07	mm²
Temperature for measurement of diam., T0	1.02	°C	95 % (normal)	B	0.51	°C	-0.004259	mm/°C	4.72E-06	mm²
Thermal coefficient of orifice plate material	0.0000004	1/°C	95 % (normal)	B	0.0000002	1/°C	9316.44	mm°C	3.47E-06	mm²

Orifice plate diameter			
	Sum of variances, $u_c(d)^2$	8.70E-03	mm²
	Combined Standard Uncertainty, $u_c(d)$	0.0933	mm
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(d)$	0.1866	mm
	Orifice plate diameter, d	266.33306	mm
	Relative Expanded Uncertainty (95% confidence level, k=2), k E_d	0.0701	%

Figure 6.11 The "Orifice" worksheet in the program EMU - Orifice Fiscal Gas Metering Station. (Corresponds to Table 5.19).

6.9 Diameter ratio (β) uncertainty

Figure 6.12 shows the worksheet denoted "Diameter ratio".

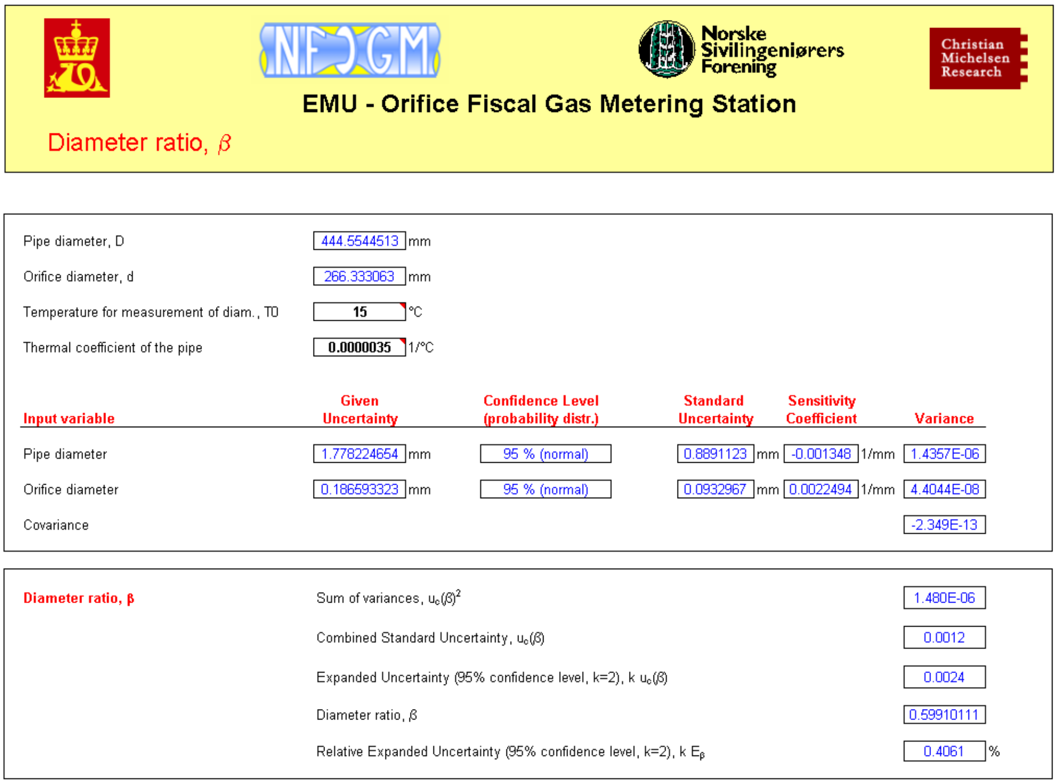
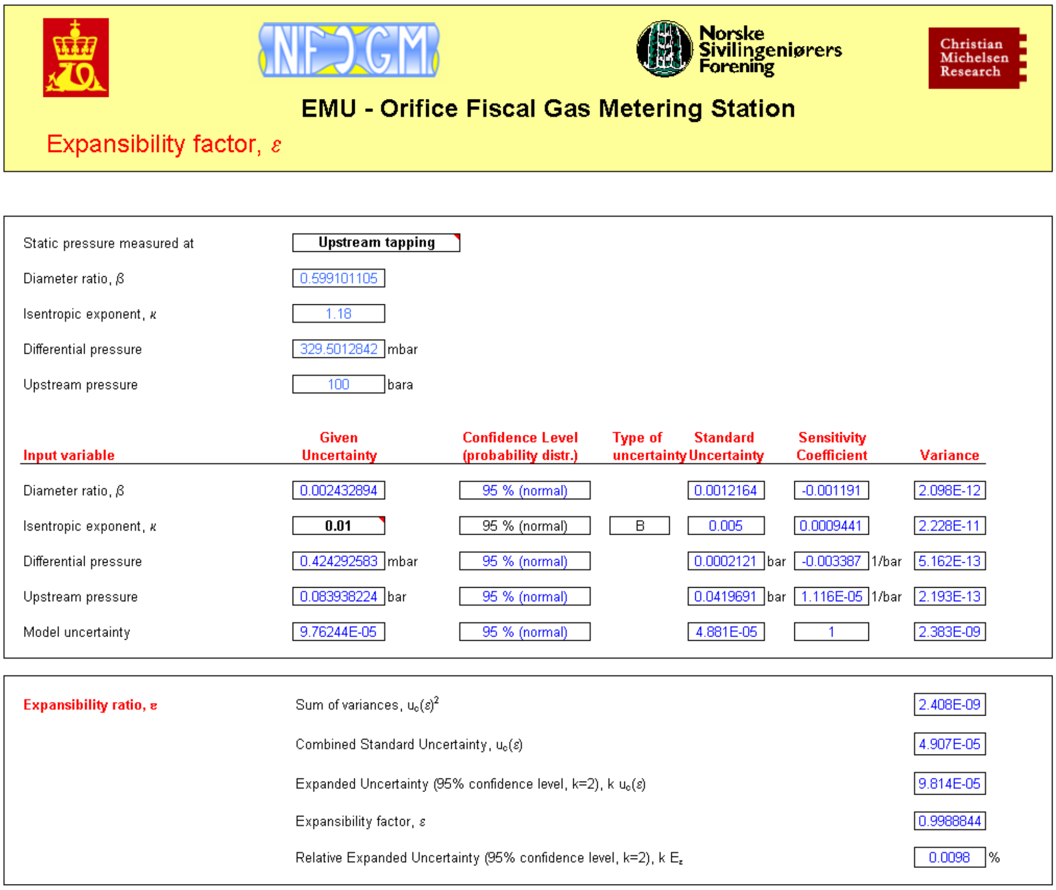


Figure 6.12 The "Diameter ratio" worksheet in the program EMU - Orifice Fiscal Gas Metering Station. (Corresponds to Table 5.16).

6.10 Expansibility factor (ε) uncertainty

In the worksheet denoted “Expansibility” shown in Figure 6.13 the user must select the location of the static pressure measurement and the physical location the expansibility factor shall be referred to.



EMU - Orifice Fiscal Gas Metering Station

Expansibility factor, ε

Static pressure measured at	Upstream tapping	
Diameter ratio, β	0.599101105	
Isentropic exponent, κ	1.18	
Differential pressure	329.5012842	mbar
Upstream pressure	100	bara

Input variable	Given Uncertainty		Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty		Sensitivity Coefficient		Variance
Diameter ratio, β	0.002432894		95 % (normal)		0.0012164		-0.001191		2.098E-12
Isentropic exponent, κ	0.01		95 % (normal)	B	0.005		0.0009441		2.228E-11
Differential pressure	0.424292583	mbar	95 % (normal)		0.0002121	bar	-0.003387	1/bar	5.162E-13
Upstream pressure	0.083938224	bar	95 % (normal)		0.0419691	bar	1.116E-05	1/bar	2.193E-13
Model uncertainty	9.76244E-05		95 % (normal)		4.881E-05		1		2.383E-09

Expansibility ratio, ε			
	Sum of variances, $u_c(\varepsilon)^2$	2.408E-09	
	Combined Standard Uncertainty, $u_c(\varepsilon)$	4.907E-05	
	Expanded Uncertainty (95% confidence level, k=2), k $u_c(\varepsilon)$	9.814E-05	
	Expansibility factor, ε	0.9988844	
	Relative Expanded Uncertainty (95% confidence level, k=2), k E_ε	0.0098	%

Figure 6.13 The “Expansibility” worksheet in the program EMU - Orifice Fiscal Gas Metering Station. (Corresponds to Table 5.17).

6.11 Discharge coefficient (C) uncertainty

In the worksheet denoted "Discharge" shown in Figure 6.14 the user must select the type of tapping arrangement of the metering station.

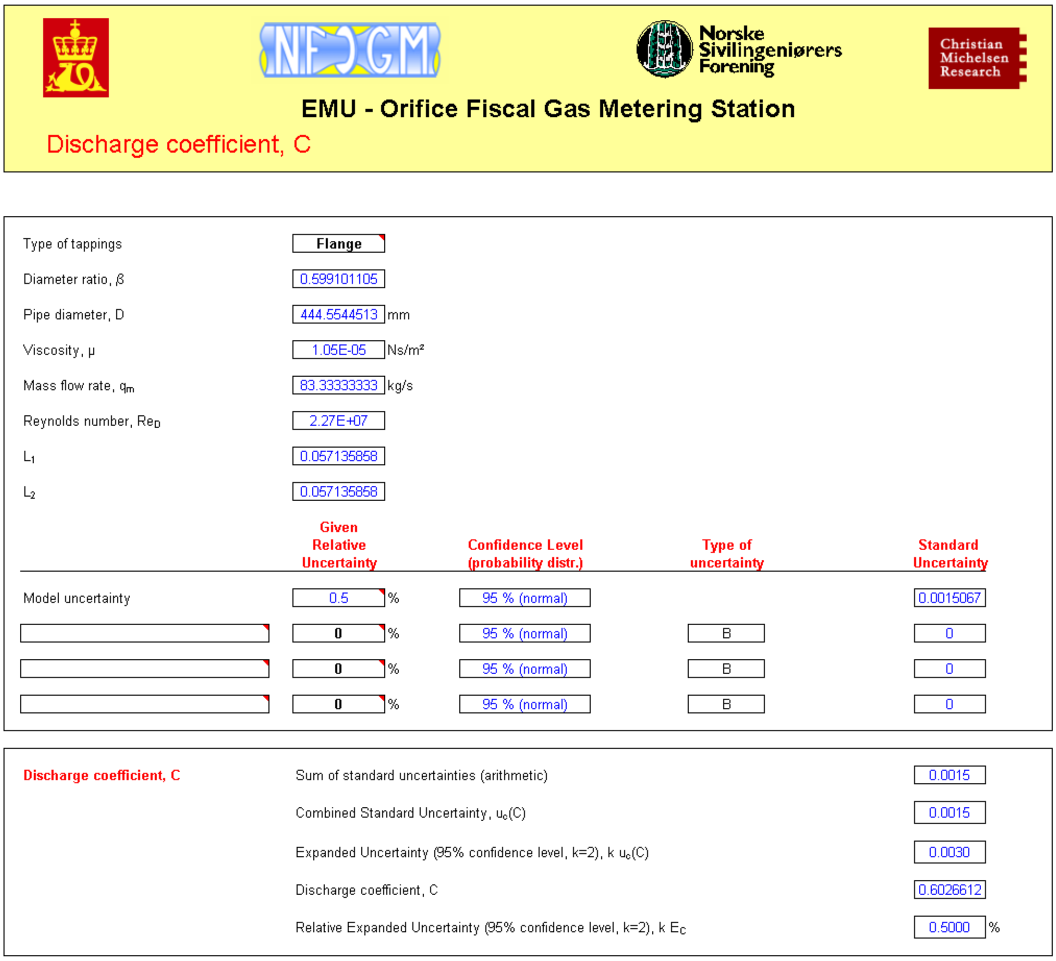


Figure 6.14 The "Discharge" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.12 Metering station uncertainty

In the worksheet denoted "Metering station" shown Figure 6.15 the user must enter the mass flow rate for which the uncertainty shall be calculated. All other values are taken automatically from the previously described worksheets.

EMU - Orifice Fiscal Gas Metering Station

Metering station

Mass flow rate 300000 kg/h (1 m/s corresponds to 45596.6 kg/h)

Input variable	Given Uncertainty	Confidence Level (probability distr.)	Type of uncertainty	Standard Uncertainty	Sensitivity Coefficient	Variance
Diameter ratio, β	0.002432894	95 % (normal)		0.0012164	147999.37 kg/h	3.24E+04 (kg/h)²
Orifice diameter, d	0.186593323 mm	95 % (normal)		0.0932967 mm	2251.3332 (kg/h)/mm	4.41E+04 (kg/h)²
Discharge coefficient, C	0.003013306	95 % (normal)		0.0015067	497463.97 kg/h	5.62E+05 (kg/h)²
Differential pressure, ΔP	0.424292583 mbar	95 % (normal)		0.0002121 bar	454933.32 (kg/h)/bar	9.31E+03 (kg/h)²
Density, ρ	0.156099008 kg/m³	95 % (normal)		0.0780495 kg/m³	1836.5733 (kg/h)/(kg/m³)	2.05E+04 (kg/h)²
Expansibility coefficient, ε	9.81376E-05	95 % (normal)		4.907E-05	300137.06 kg/h	2.17E+02 (kg/h)²
Buckling	0 (kg/h)²	95 % (normal)	B	0 kg/h	1	0.00E+00 (kg/h)²
Calculation	0 (kg/h)²	95 % (normal)	B	0 kg/h	1	0.00E+00 (kg/h)²
Covariance						1.31E+04 (kg/h)²

Mass flowrate measurement		
	Sum of variances, $u_c(q_m)^2$	6.81E+05 (kg/h³)²
	Combined Standard Uncertainty, $u_c(q_m)$	825.4890 kg/h³
	Expanded Uncertainty (95% confidence level, k=2), k u_c(qm)	1650.978 kg/h³
	Mass flow rate, q_m	300000 kg/h³
	Relative Expanded Uncertainty (95% confidence level, k=2), k Eqm	0.5503 %

Figure 6.15 The "Metering station" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.13 Graphical presentation of uncertainty calculations

Various worksheets are available in the program *EMU - Orifice Fiscal Gas Metering Station* to plot and display the calculation results, such as curve plots and bar-charts. These worksheets are described in the following.

6.13.1 Uncertainty curve plots

Plotting of uncertainty curves is made using the "*Graph*" worksheet. Editing of plot options is made using the "*Graph menu*" worksheet ("curve plot set-up").

Plotting of the relative expanded uncertainty can be made for the standard volume flow rate (i.e., the volumetric flow rate at standard ref. conditions), q_m,

The relative expanded uncertainty can be plotted as a function of

- Differential pressure,
- Mass flow rate, q_m,

Axes may be scaled according to user needs (automatic or manual), and various options for curve display (points only, line between points and smooth curve[81]) are available.

[81] For the "smooth curve" display option, the default method implemented in Microsoft Excel 2000 is used.

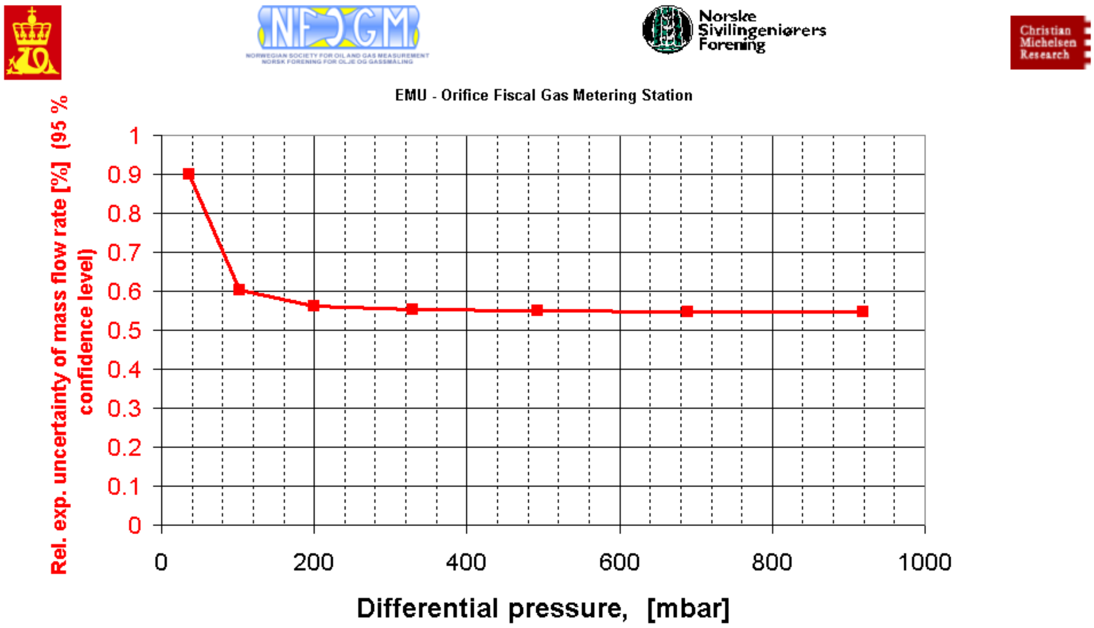


Figure 6.16 The "Graph" *worksheet in the program EMU - Orifice Fiscal Gas Metering Station (example).*

Figure 6.16 shows an example where the relative expanded uncertainty of the standard volume flow rate (at a 95 % confidence level and a normal probability distribution, with $k = 2$) is plotted as a function of the flow velocity.

6.13.2 Uncertainty bar-charts

Plotting of bar charts is made using the "*NN-chart*" worksheets. Editing of bar chart options is made using the "*Graph menu*" worksheet ("bar-chart set-up" section). Bar charts are typically used to evaluate the relative contributions of various input uncertainties to the expanded uncertainty of the "measurand" in question.

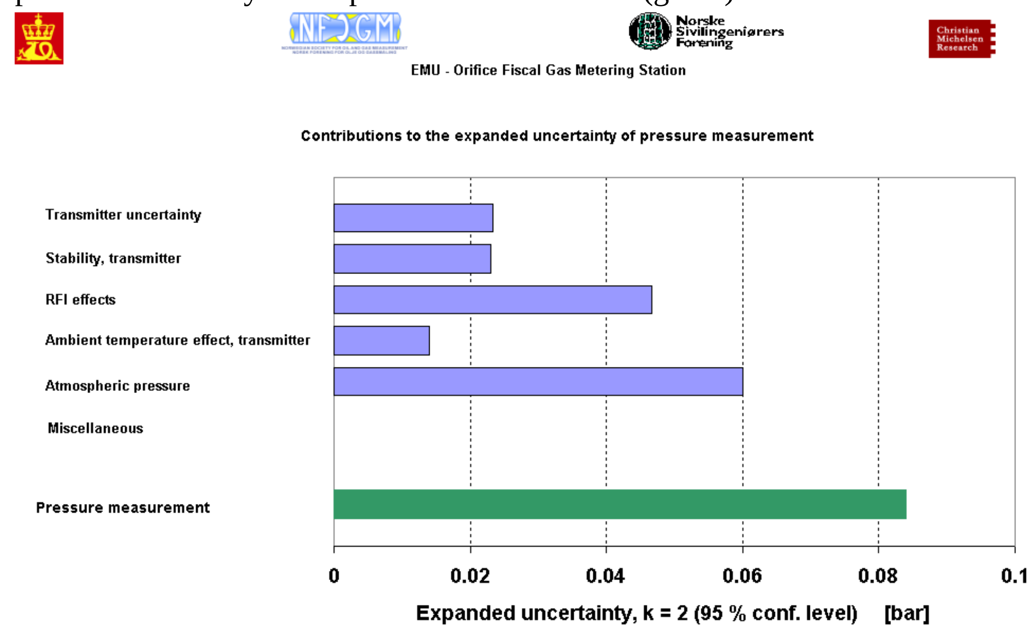
Such bar-charts are available for the following seven "measurands":

- Pressure measurement ("*P-chart*" worksheet),
- Differential Pressure measurement ("*DP -chart*" worksheet),
- Temperature measurement ("*T-chart*" worksheet),
- Temperature measurement ("*T-density-chart*" worksheet),
- Density measurement ("*D-chart*" worksheet),
- Pipe diameter ("*Pipe-chart*" worksheet),
- Orifice diameter ("*Orifice-chart*" worksheet),
- Diameter ratio ("*Diameter-ratio-chart*" worksheet),
- Expansibility factor ("*Expansibility-chart*" worksheet),
- Discharge coefficient ("*Discharge-chart*" worksheet),
- Gas metering station ("*MetStat-chart*" worksheet).

As for the "Graph" worksheet, axes may be scaled according to user needs (automatic or manual). These bar charts are described separately in the following.

6.13.2.1 Static and Differential Pressure

The pressure-measurement bar charts is given in the "*P-chart*" and "*DP-chart*" worksheets. Figure 6.17 shows an example where the contributions to the expanded uncertainty of the pressure measurement are plotted (blue), together with the expanded uncertainty of the pressure measurement (green).



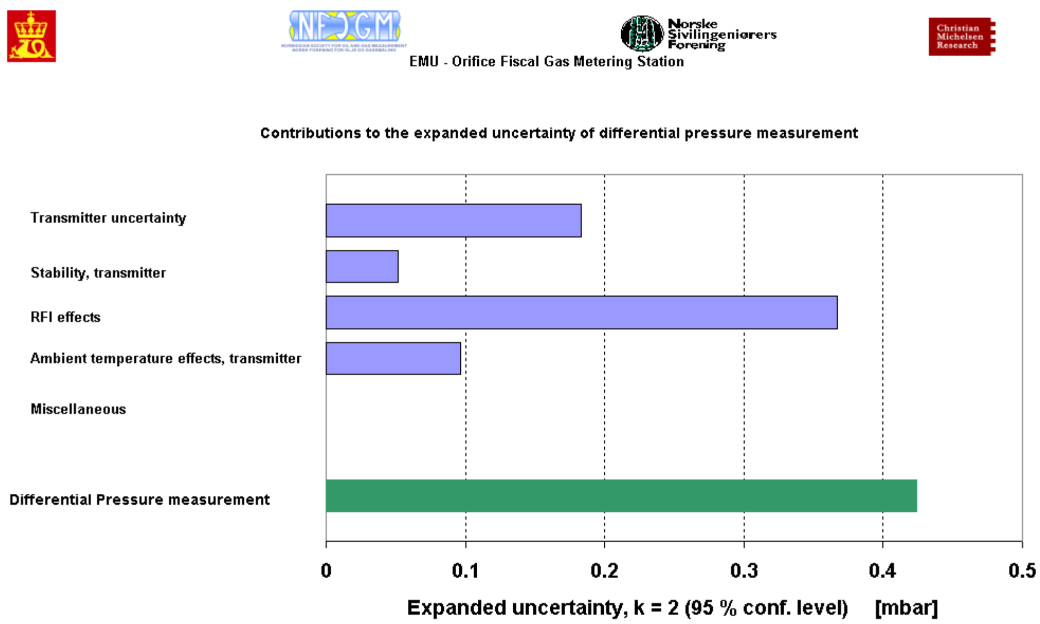


Figure 6.17 *The "P-chart" and "DP-chart" worksheet in the program* EMU - Turbine Fiscal Oil Metering Station.

6.13.2.2 Temperature

The temperature-measurement bar chart is given in the "*T-chart*" worksheet. Figure 6.18 shows an example where the contributions to the expanded uncertainty of the temperature measurement are plotted (blue), together with the expanded uncertainty of the temperature measurement (green).

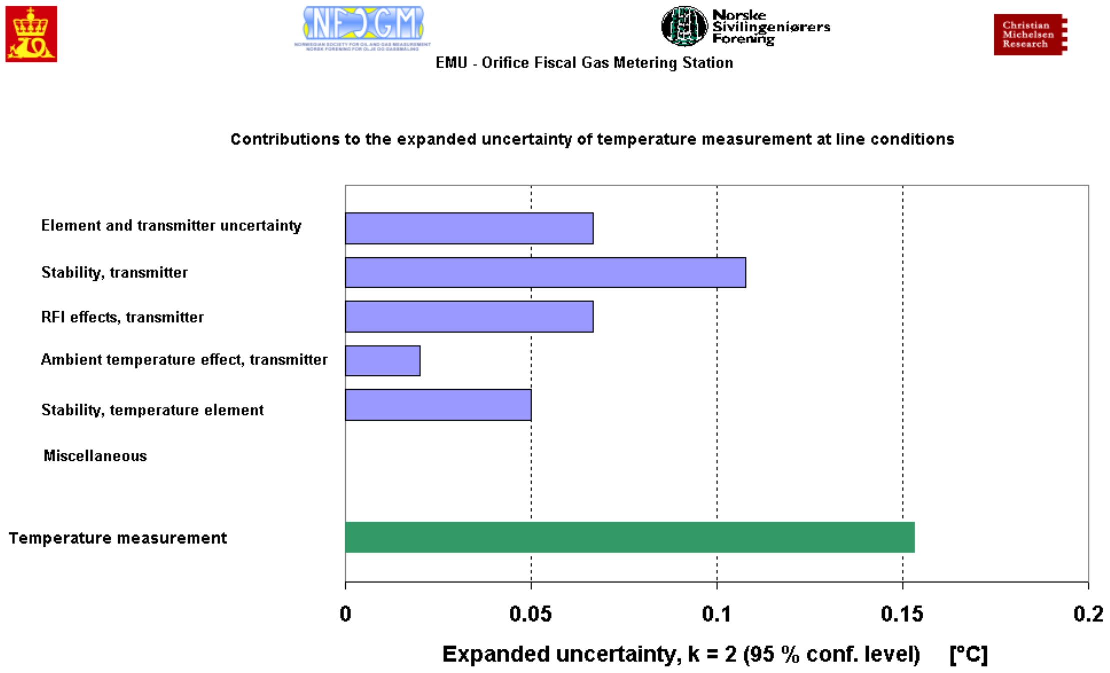


Figure 6.18 The "T-chart" *worksheet in the program* EMU - Orifice Fiscal Gas Metering Station.

6.13.2.3 Density

The density-measurement bar chart is given in the "*D-chart*" worksheet. Figure 6.19 shows an example where the contributions to the expanded uncertainty of the density measurement are plotted (blue), together with the expanded uncertainty of the density measurement (green).

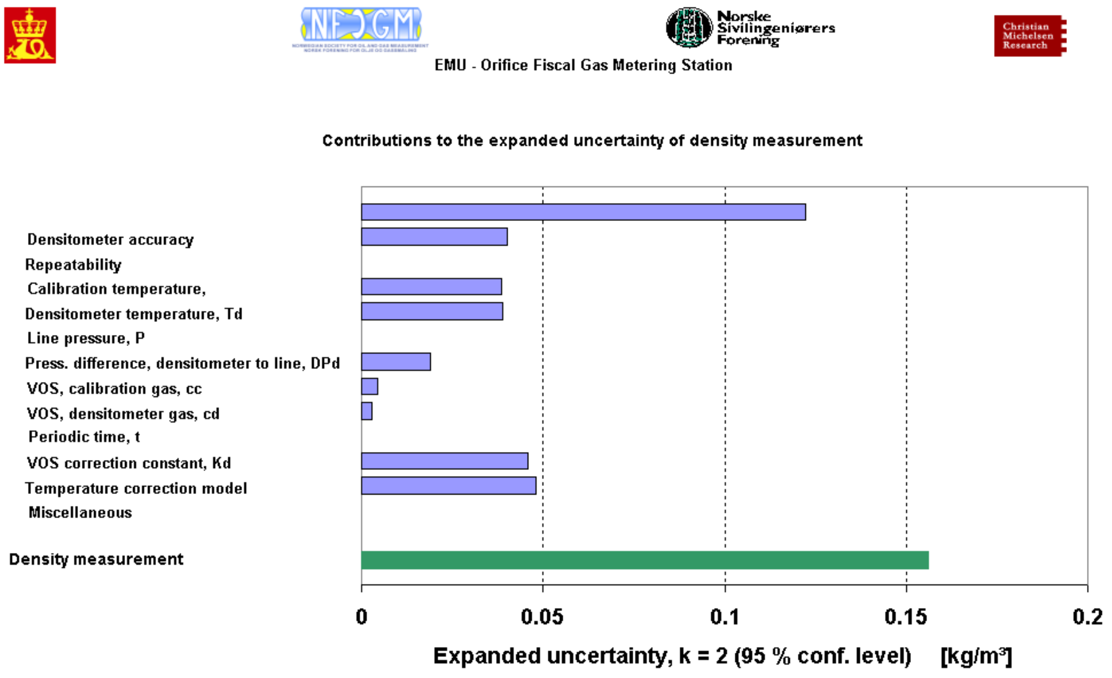


Figure 6.19 The "D-chart" *worksheet in the program EMU - Orifice Fiscal Gas Metering Station.*

6.13.2.4 Pipe diameter

The *Pipe diameter* calculation bar chart is given in the "*Pipe-chart*" worksheet. Figure 6.20 shows an example where the contributions to the expanded uncertainty of the Pipe diameter calculation are plotted (blue), together with the expanded uncertainty of the Pipe diameter (green).

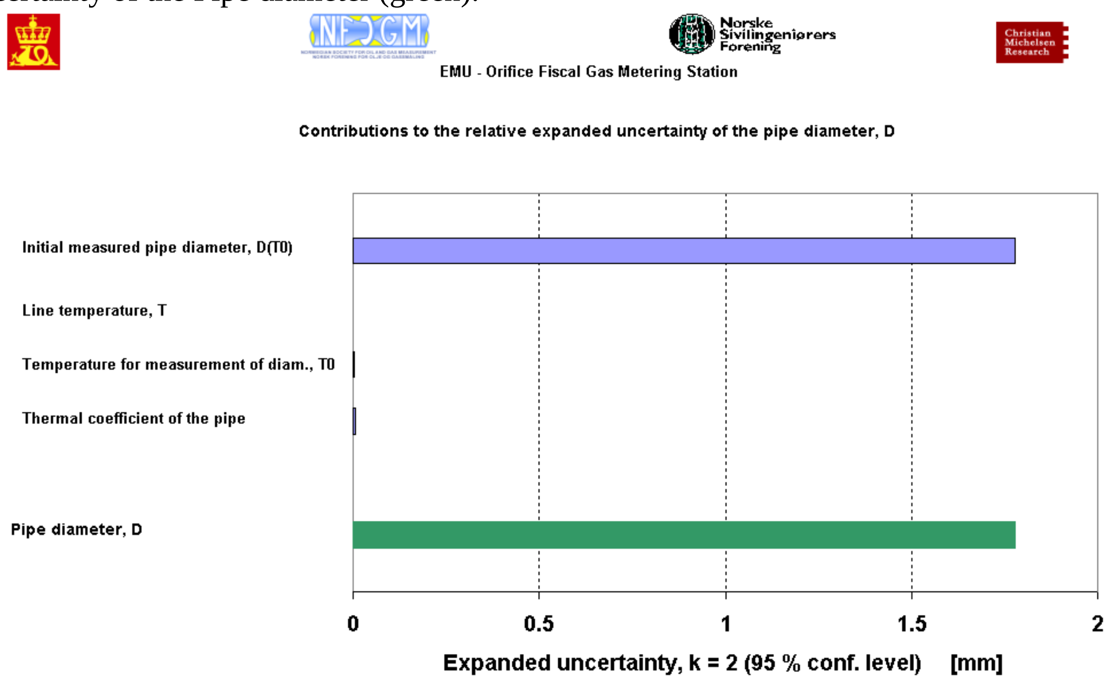


Figure 6.20 The "Pipe-chart" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.13.2.5 Orifice diameter

The *Orifice diameter* calculation bar chart is given in the "*Orifice-chart*" worksheet. Figure 6.21 shows an example where the contributions to the expanded uncertainty of the Orifice diameter calculation are plotted (blue), together with the expanded uncertainty of the Orifice diameter (green).

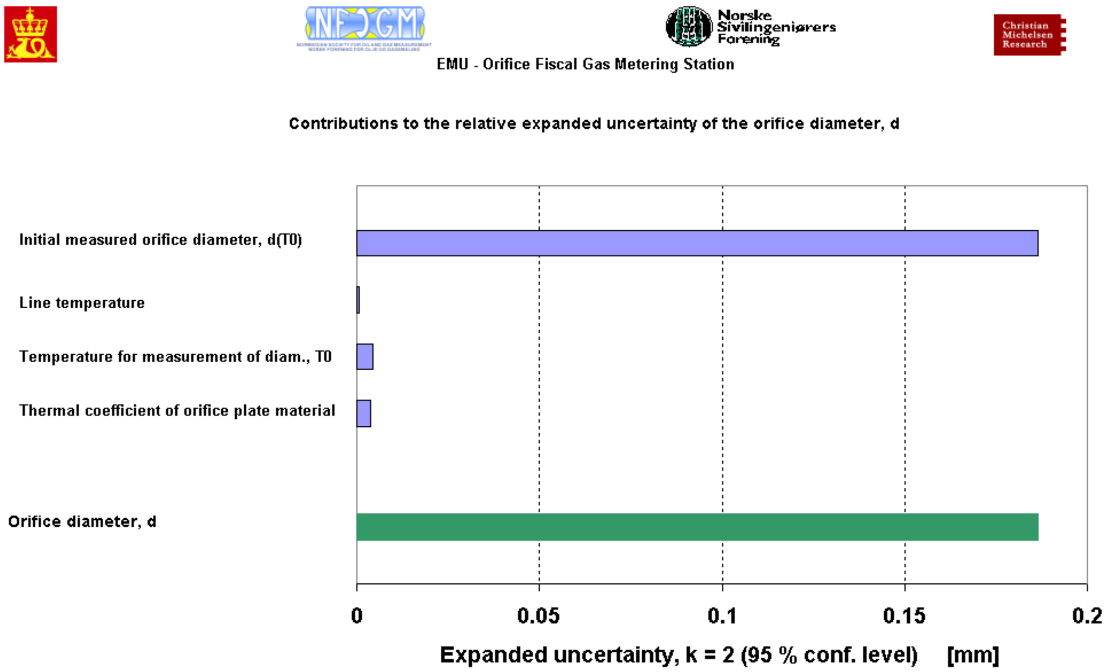


Figure 6.21 The "Orifice-chart" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.13.2.6 Beta ratio

The *Beta ratio* calculation bar chart is given in the "*Beta-chart*" worksheet. Figure 6.22 shows an example where the contributions to the expanded uncertainty of the Orifice diameter calculation are plotted (blue), together with the expanded uncertainty of the Beta ratio (green).

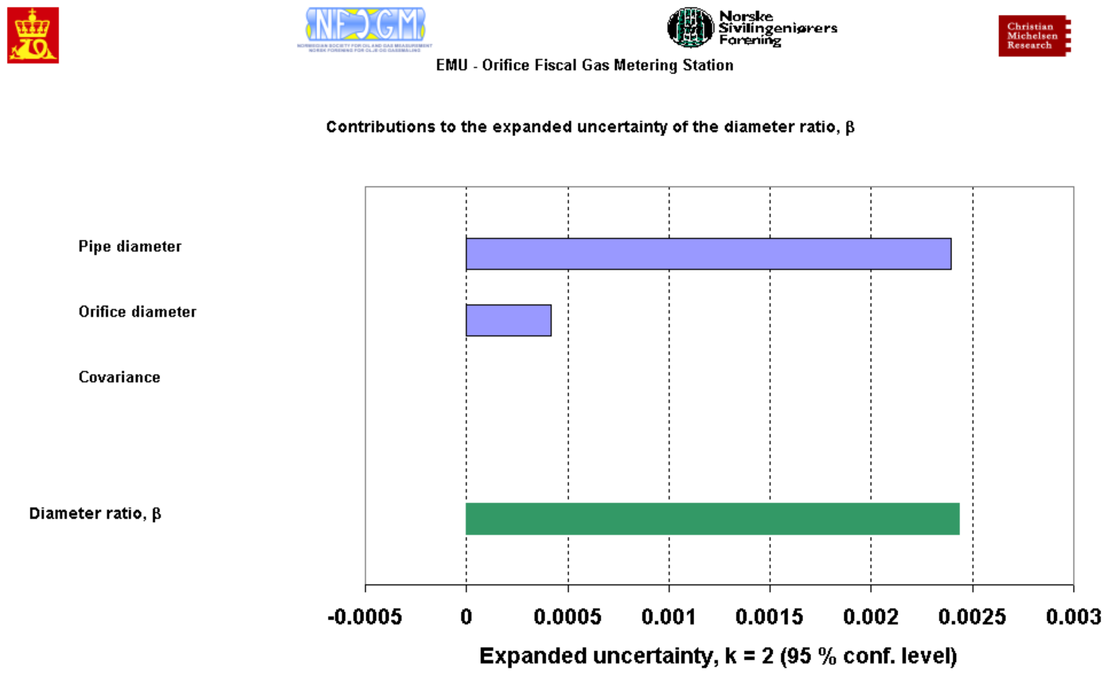


Figure 6.22 The "Beta-chart" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.13.2.7 Expansibility factor

The *Expansibility factor* calculation bar chart is given in the "*Exp-chart*" worksheet. Figure 6.23 shows an example where the contributions to the expanded uncertainty of the Expansibility diameter calculation are plotted (blue), together with the expanded uncertainty of the Expansibility factor (green).

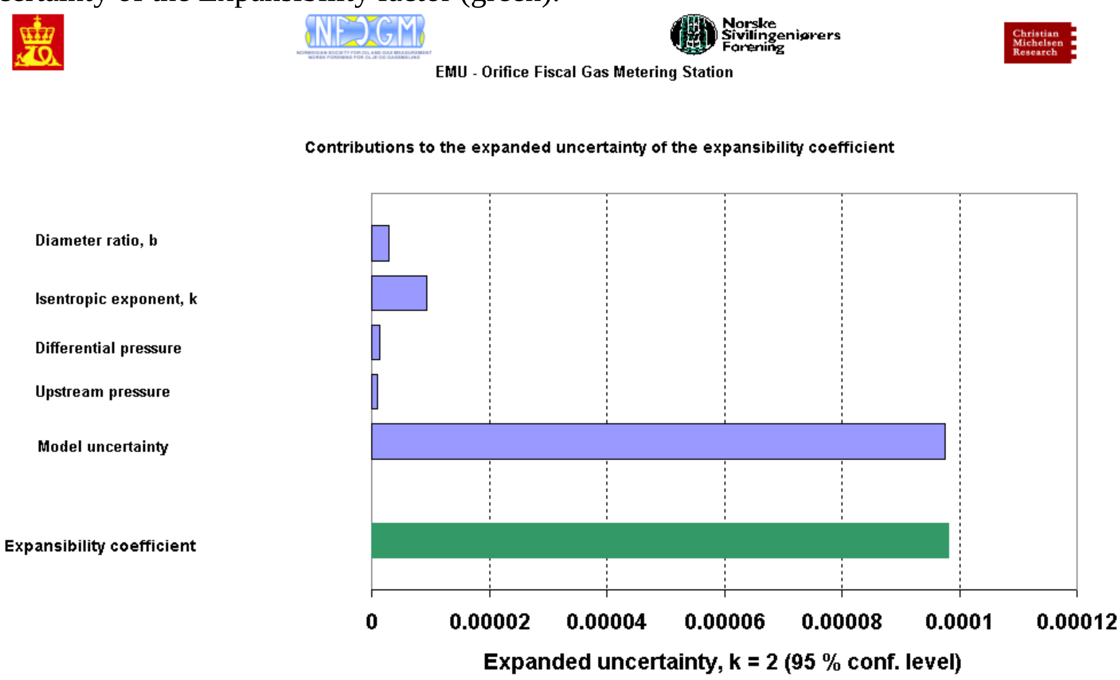


Figure 6.23 The "Exp-chart" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.13.2.8 Gas metering station

The gas metering station bar chart is given in the "*MetStat-chart*" worksheet. Figure 6.24 shows an example where the contributions to the expanded uncertainty of the actual mass flow rate are plotted (blue), together with the expanded uncertainty of the actual mass flow rate (green).

EMU - Orifice Fiscal Gas Metering Station

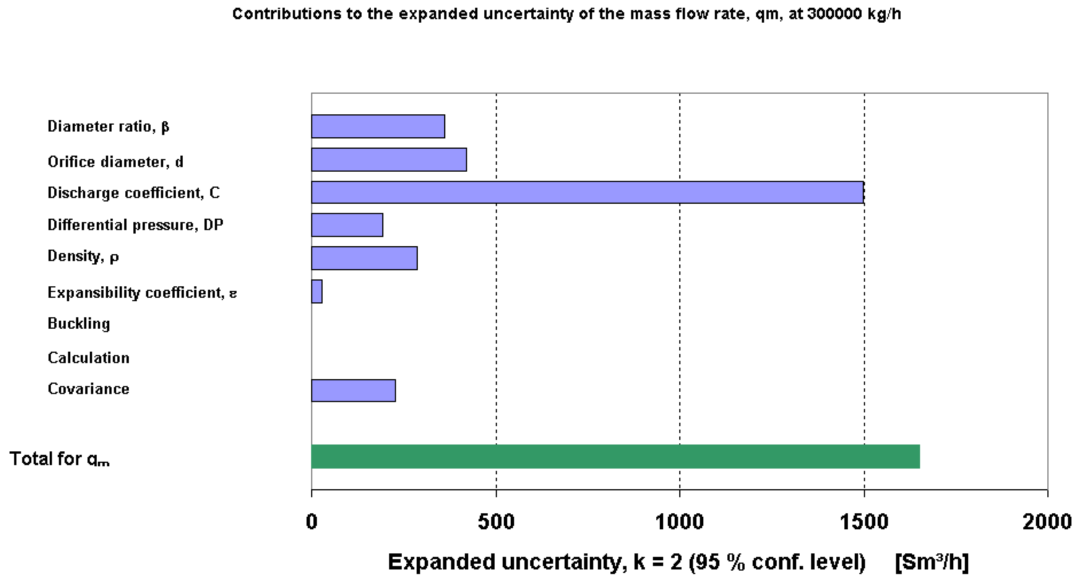


Figure 6.24 The "MetStat-chart" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

6.14 Summary report - Expanded uncertainty of the Orifice fiscal gas metering station

A "*Report*" worksheet is available in the program *EMU - Orifice Fiscal Gas Metering Station* to provide a condensed report of the calculated expanded uncertainty of the Orifice fiscal gas metering station. For documentation purposes, this one-page report can be used alone, or together with printout of other worksheets in the program.

Blank fields are available for filling in program user information and other comments. Also some of the settings of the "*Gas parameter*" worksheet is included for documentation purposes.

Norske Sivilingeniørers Forening

Christian Michelsen Research

EMU - Orifice Fiscal Gas Metering Station

Uncertainty evaluation report

Calculation performed by: ______________________

Date: 12-Mar-2003

OPERATING CONDITIONS, METER RUN	
Line pressure (static), P	100 bara
Line temperature, T	50 °C
Viscosity, μ	1.05E-05 Ns/m²
Isentropic exponent, κ	1.18
Gas density, ρ	81.62 kg/m³
Ambient (air) temperature, T_{air}	0 °C

DENSITOMETER CONDITIONS	
Temperature at density transducer, T_d	48 °C
Velocity of sound, c_d	415.24 m/s
Indicated (uncorrected) gas density at dens. transd., ρ_u	82.443 kg/m³
Calibration temperature, T_c	15 °C
Calibration velocity of sound (VOS), c_c	350 m/s

User comments:

Mass flow rate, q_m: 300000 kg/h

Flow velocity, v_A: 6.579437 m/s

	Unit	Value	Standard Uncertainty	Rel. Expanded Uncertainty (95 % c. l., k=2)	Contribution to k Eqm
Diameter ratio, β	-	0.59910111	0.0012	0.4061 %	**0.1200 %**
Orifice diameter, d	mm	266.333063	0.0933	0.0701 %	**0.1400 %**
Discharge coefficient, C	-	0.60266119	0.0015	0.5000 %	**0.4997 %**
Differential pressure, ΔP	mbar	329.501284	0.2121	0.1288 %	**0.0643 %**
Density, ρ	kg/m³	81.62	0.0780	0.1913 %	**0.0956 %**
Expansibility coefficient, ε	-	0.9988844	0.0000	0.0098 %	**0.0098 %**
Buckling	-	-	0.0000	-	**0.0000 %**
Calculation	-	-	0.0000	-	**0.0000 %**
Covariance	-	-	-	-	**0.0762 %**
Mass flow rate, qm	**kg/h**	**300000**	**825.4890329**	**0.5503 %**	**0.5503 %**

Figure 6.25 The "Report" *worksheet in the program EMU - Orifice Fiscal Gas Metering Station.*

6.15 Listing of plot data

A worksheet is available in the program *EMU - Orifice Fiscal Gas Metering Station* to provide listing of data involved in the uncertainty evaluation.

EMU - Orifice Fiscal Gas Metering Station

Plot data

Plot data for the "Graph" - sheet

First column: Differential pressure, [mbar]
Second column: Rel. exp. uncertainty of mass flow rate [%] (95 % confidence level)

36.4749	0.901349
101.4545	0.604139
199.0836	0.562018
329.5013	0.552268
492.8869	0.549234
689.4627	0.548185
919.4946	0.547924

Plot data for the "Met-stat-chart" - sheet
All data: expanded uncertainty (k=2) (Sm^3/h)

Diameter ratio, b	360.0667241
Orifice diameter, d	420.0837355
Discharge coefficient, C	1499.011138
Differential pressure, DP	193.0248343
Density, r	286.6872727
Expansibility coefficient, e	29.4547315
Buckling	0
Calculation	0
Covariance	228.6045279
Total	1650.978066

Plot data for the "T-chart" - sheet
All data: expanded uncertainty (k=2) (°C)

Element and transmitter uncertainty	0.066666667
Stability, transmitter	0.107716667
RFI effects, transmitter	0.066666667
Ambient temperature effect, transmitter	0.02
Stability, temperature element	0.05
Miscellaneous	0
Total	0.15294368

Plot data for the "T-density-chart" - sheet
All data: expanded uncertainty (k=2) (°C)

Element and transmitter uncertainty	0.066666667
Stability, transmitter	0.107716667
RFI effects, transmitter	0.066666667
Ambient temperature effect, transmitter	0.02
Stability, temperature element	0.05
Miscellaneous	0
Total	0.15294368

Plot data for the "P-chart" - sheet
All data: expanded uncertainty (k=2) (bar)

Transmitter uncertainty	0.023333333
Stability, transmitter	0.023
RFI effects	0.046666667
Ambient temperature effect, transmitter	0.013942857
Atmospheric pressure	0.06
Miscellaneous	0
Total	0.083938224

Plot data for the "D-chart" - sheet
All data: expanded uncertainty (k=2) (kg/m^3)

Densitometer accuracy	0.122388634
Repeatability	0.04
Calibration temperature, Tcal	2.74488E-05
Line temperature, T	0.038629934
Densitometer temperature, Td	0.038828525
Line pressure, P	1.36993E-05
Press. difference, densitometer to line, DPd	0.018845562
VOS, calibration gas, cc	0.004550078
VOS, densitometer gas, cd	0.002731424
Periodic time, t	7.05124E-05
VOS correction constant, Kd	0.045833081
Temperature correction model	0.048
Miscellaneous	0
Total	0.156099008

Plot data for the "DP-chart" - sheet
All data: expanded uncertainty (k=2) (mbar)

Transmitter uncertainty	0.183333333
Stability, transmitter	0.051833333
RFI effects	0.366666667
Ambient temperature effects, transmitter	0.096342857
Miscellaneous	0
Total	0.424292583

Plot data for the "Pipe-chart" - sheet
All data: expanded uncertainty (k=2) (mm)

Initial measured pipe diameter, D(T0)	1.778217805
Line temperature, T	0.000237942
Temperature for measurement of diam., T0	0.001586865
Thermal coefficient of the pipe	0.00466725
Total	1.778224654

Plot data for the "Orifice-chart" - sheet
All data: expanded uncertainty (k=2) (mm)

Initial measured orifice diameter, d(T0)	0.186504384
Line temperature	0.000651379
Temperature for measurement of diam., T0	0.004344123
Thermal coefficient of orifice plate material	0.003726576
Total	0.186593323

Plot data for the "Beta-chart" - sheet
All data: expanded uncertainty (k=2)

Pipe diameter	0.002396414
Orifice diameter	0.000419731
Covariance	-9.69377E-07
Total	0.002432894

Plot data for the "Exp-chart" - sheet
All data: expanded uncertainty (k=2)

Diameter ratio, b	2.89676E-06
Isentropic exponent, k	9.44099E-06
Differential pressure	1.43689E-06
Upstream pressure	9.36648E-07
Model uncertainty	9.76244E-05
Total	9.81376E-05

Figure 6.26 The "Plot Data" worksheet in the program EMU - Orifice Fiscal Gas Metering Station.

The "*Plot data*" worksheet gives a listing of all data used and plotted in the "*Graph*" and "*NN-chart*" worksheets, cf. Figure 6.26. Such a listing may be useful for reporting purposes, and in case the user needs to present the data in a form not directly available in the program *EMU - Orifice Fiscal Gas Metering Station.* Note that the contents of the "plot data" sheet will change with the settings used in the "Graph menu" sheet.

6.16 Program information

Two worksheets are available to provide information on the program. These are the "About" and the "Readme" worksheets.

The "About" worksheet, which is displayed at start-up of the program *EMU - Orifice Fiscal Gas Metering Station*, can be activated at any time and gives general information about the program. The "Readme" worksheet gives regulations and conditions for the distribution of the *Handbook* and the program, etc.

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