The Harmonization of Reference Values for high-pressure Gas-Flow Measurements

Procedure for Common Reference Values at PIGSAR-PTB and NMi VSL

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INTRODUCTION

At the beginning of 1997, a discussion between NMi VSL, Ruhrgas and PTB has been initiated with the purpose to search for possibilities and to eventually eliminate the observed differences in measurement values, existing between the test-facilities of PIGSAR in Dorsten (DE) and NMi VSL-Flow in Bergum (NL).

During the following meetings, the next questions arose :

- What are the differences in realization between the low-pressure traceability-chains of PTB and NMi VSL-Flow ?
- What are the differences in realization between the high-pressure traceability-chains of PIGSAR and NMi VSL-Flow ?
- What are the differences in deviation and corresponding uncertainties between these traceability-chains ?
- Are the observed differences significant from a metrology point-of-view ?
- Would there be a need for 'metrological' co-operation between the parties and if yes, how could that be accomplished ?
- Would it then eventually be possible, through close co-operation, to enhance the comparability of the traceability-chains and thereby create a higher reliability and stability of the Reference Values used in both facilities for high-pressure gas-flow measurements, calibrations and verifications ?

An initial comparison between the two high-pressure facilities in 1997 confirmed that differences in measurement values between the two sets of Reference Values did exist. Moreover, the observed differences proved to be systematic, although not significant from metrology point-of-view.
In addition, in the summer of 1997, a comparison between PTB and NMi VSL, with respect to low-pressure gas-flow measurements, showed very reproducible and comparable results in reference levels and uncertainties, and no systematic differences. It was then decided to repeat the high-pressure comparisons with transfer-packages that were hardly sensitive for so-called 'installation-effects', so often 'observed' between high-pressure test-facilities.
The differences were smaller than in the first comparison, in most cases not significant, but still large enough to prevent good 'traceability services' to Society [1].

Taking the economic importance of high-pressure gas-flow measurements in consideration, and although having different backgrounds, incentives and specialities, the involved organizations of the two test-facilities shared a common view with respect to equivalent and impartial services to Society. So, all parties were triggered to "have a hard look into one another's kitchen" and to come up with ideas for improvement.
A working-group has been established with the objectives : "to create Common Reference Values for high-pressure Gas-Flow Measurements of Natural Gas", "to get rid of most of the differences in Measurement Values", and "to improve the uncertainty levels of both high-pressure test-facilities".

The results of the working-group are presented here as a Procedure and are attached as an Annex to the Agreement.

This procedure sets the rules about how the information included in two, or more, independently organized and equivalent high-pressure gas-flow traceability-chains can be combined.

SITUATION

The observed differences between PIGSAR and NMi VSL-Flow are schematically represented in Figure 1.

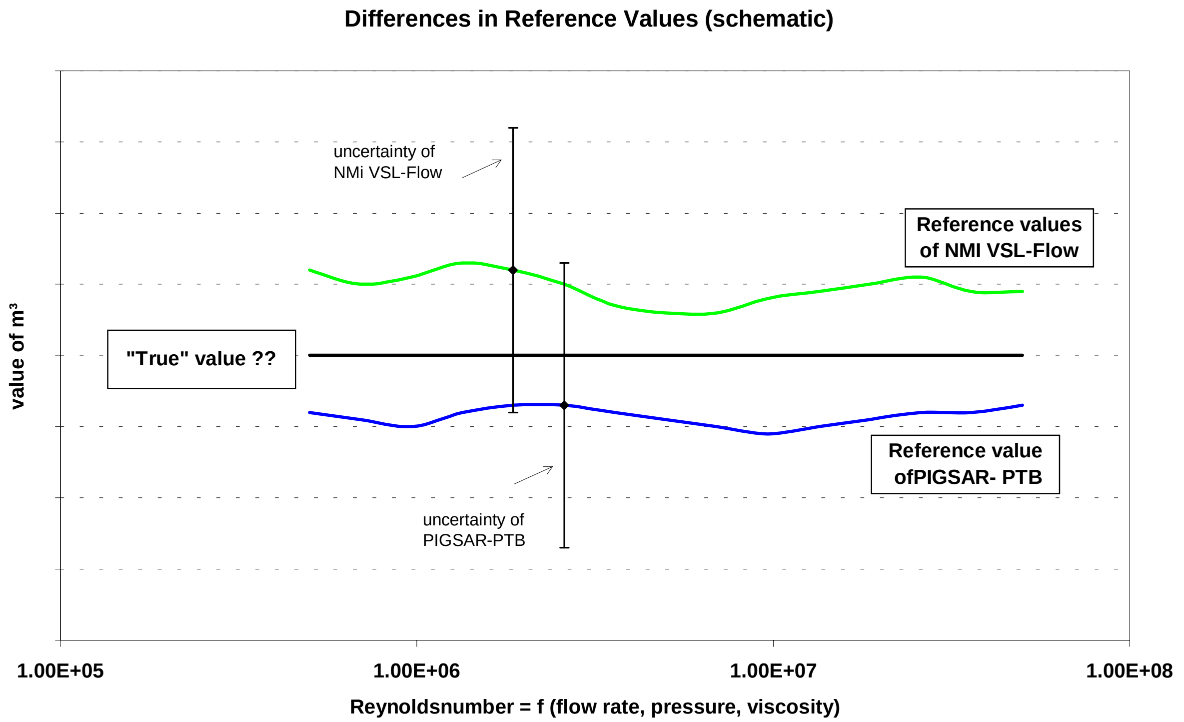
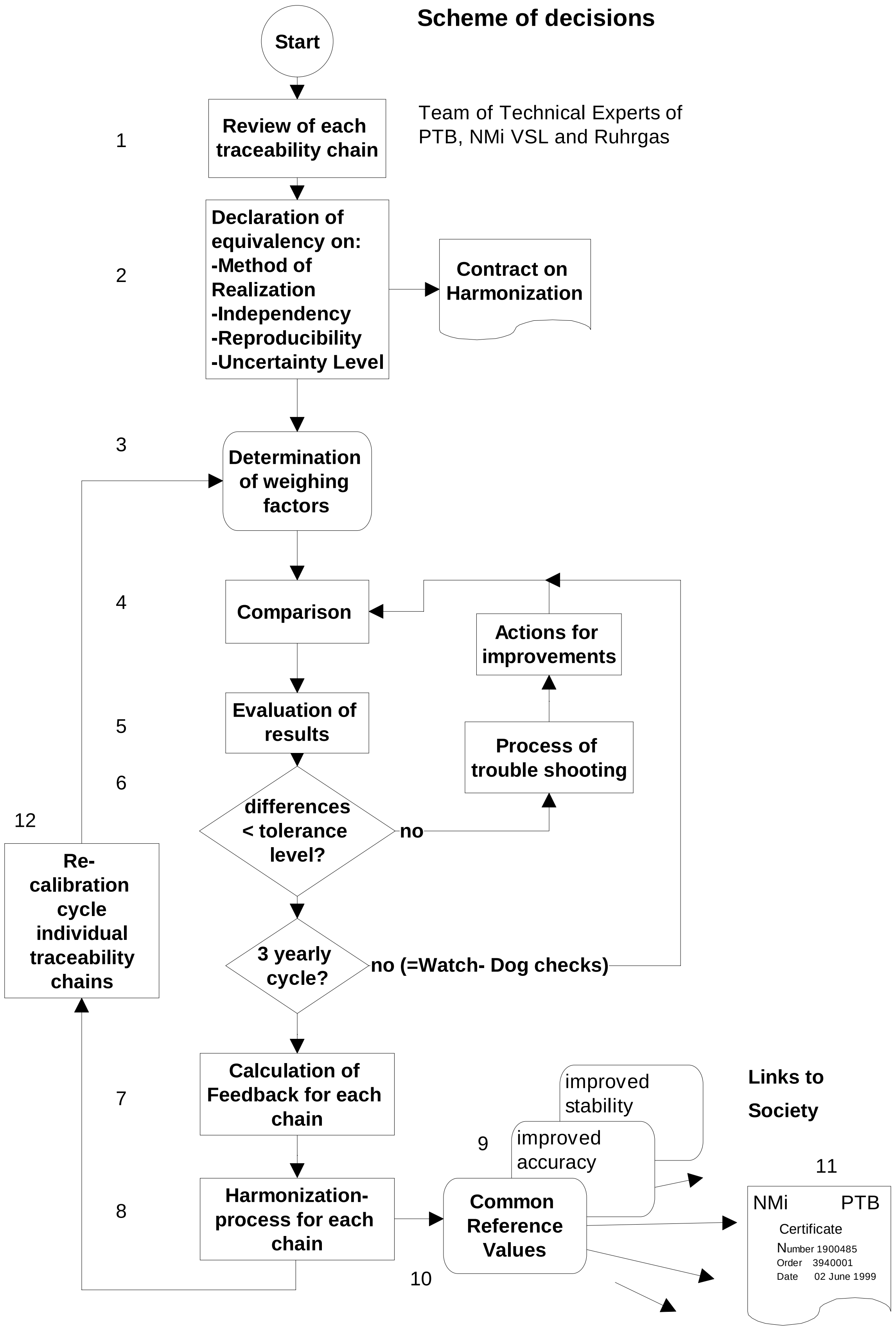


FIGURE 1. Differences between high-pressure test-facilities may be small and insignificant from metrology point-of-view, for Society the situation is not understood, nor accepted.

PROCEDURAL SCHEME

The process has started with the appointment of the Team of Technical Experts. Each party is represented by at least one expert. In the Team, technical evaluations and assessments are being made. Decisions have to be taken unanimously.

FIGURE 2. Flow chart of the Harmonization Process.



Step 1- Prerequisites.

-Independent systems

* At PIGSAR, under supervision of PTB, Reference Values are realized based on a fully independent Piston-Prover system (Volume comparisons).
* At NMi VSL-Flow a traceability-chain with its Reference Values based on mass-comparison of gas-flow under quasi-stationary conditions, is realized in an independent way;

A system is called “independent” if no direct exists links between the different HIGH-PRESSURE TRACEABILITY-CHAIN’s that in origin do not share common reference values for the unity “volume”, but only for the International primary standards for time, length, mass and temperature.

-Equivalency of the Traceability Chains

* Stability of each of the realization methods is demonstrated. Stability refers to the reproducibility of the Reference Values over the years.
* The uncertainty-budget of each of the systems is known, understood and accepted.
* The level of confidence that the differences between the two systems are not significant, is established and accepted.
* Degree of Equivalency, based on historic performance and uncertainty-level, is established and accepted.

Step 2- Declaration of equivalency and co-operation

In the undersigned contract, drawn up by the Team of Technical Experts, all the steps necessary to come to long term Common Reference Values are included.

Step 3- Determination of weighing factors

After completing the uncertainty analyses of each Test Facility, the uncertainty levels of the “Actual HP m^3” are known as a function of Reynolds. The Common Reference Values are based upon the weighed average of the individual “Actual HP m^3” of each chain.
The calculation of the weighing- or impact factor of each traceability-chain is based upon the “ratio of the squares” of the uncertainty level of each traceability-chain according to:

$$w_1 = \frac{1}{1+\frac{u_1^2}{u_2^2}} \quad \text{and} \quad w_2 = \frac{1}{1+\frac{u_2^2}{u_1^2}}$$

In which subscript 1 and 2 refer to the different parties.

As an example, when the uncertainty level of one point in the chain amounts to 0.2% (u_1) and at the comparable point in the other chain 0.3% (u_2), then the impact (w1) of chain nr. 11 at that particular point becomes 69%, whereas w_2 of chain nr. 2 amounts to 31%.

Step 4- Comparison tests

-Layout of Transfer Package

Unified Values are established with, and will reside (for the time being) in, three transfer-packages defined in this section.

Each package used for the comparison test has the following layout:

(5-D inlet with Zanker)-(Turbine #1)-(3-D outlet)-(5-D inlet with Zanker)-(Turbine #2)-(3-D outlet)
The Zanker-straighteners have been added to nullify installation-effects. The 3-D outlet pipe is provided with a thermo-element at 1-D from the outlet of the turbine meter.

A total of three ‘twin’ packages with increasing flow capacity will be used. Each twin package consists of two different type turbine meters:
Two G 250 turbine meters (4”), with a flow range of 100-400 m^3/h actual;
Two G 1600 turbine meters (10”), with a flow range of 400–2.500 m^3/h actual;
Two G 4000 turbine meters (16”), with a flow range of 600–6.500 m^3/h actual.

-Test matrix
The following comparison tests shall be carried out:
The deviation of each individual meter of 3 transfer packages will be determined at the following process points at each participating laboratory:

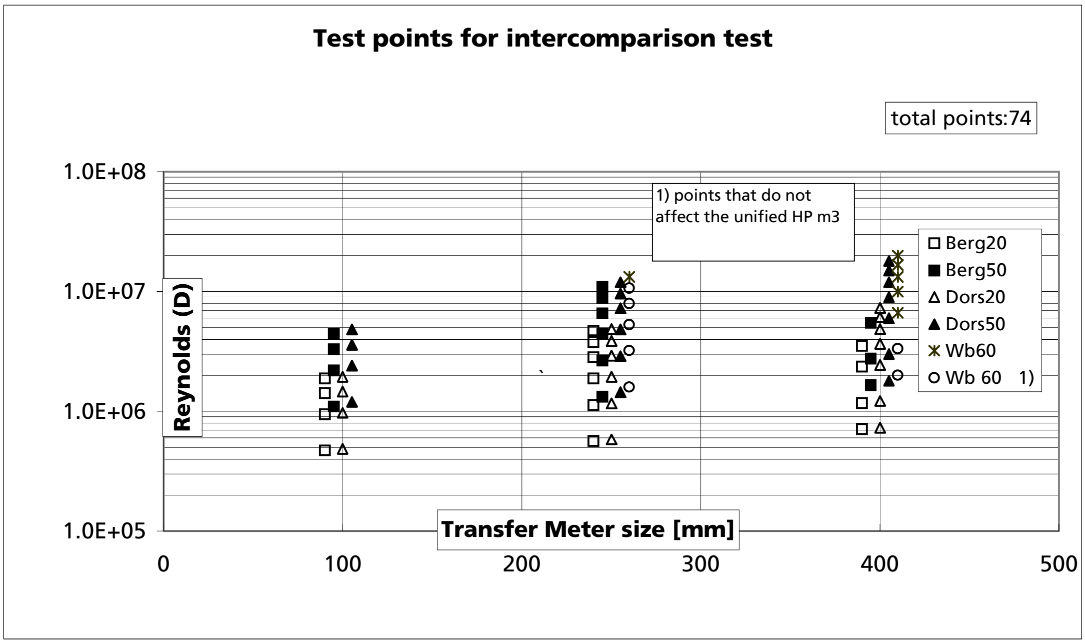


FIGURE 3. Graphical overview of the test points in the Reynolds domain

Each measurement is carried out at least three times for each turbine meter in the packages (6 pieces). A broad range in operating points is covered i.e. the actual flow rate ranges from 100 up to 6.000 m^3/h, and the pressure ranges from 20 up to 60 bar.

Step 5- Evaluation of Comparison Test Results

The test results of each individual turbine meter are presented as a function of Reynolds number in figure 4.

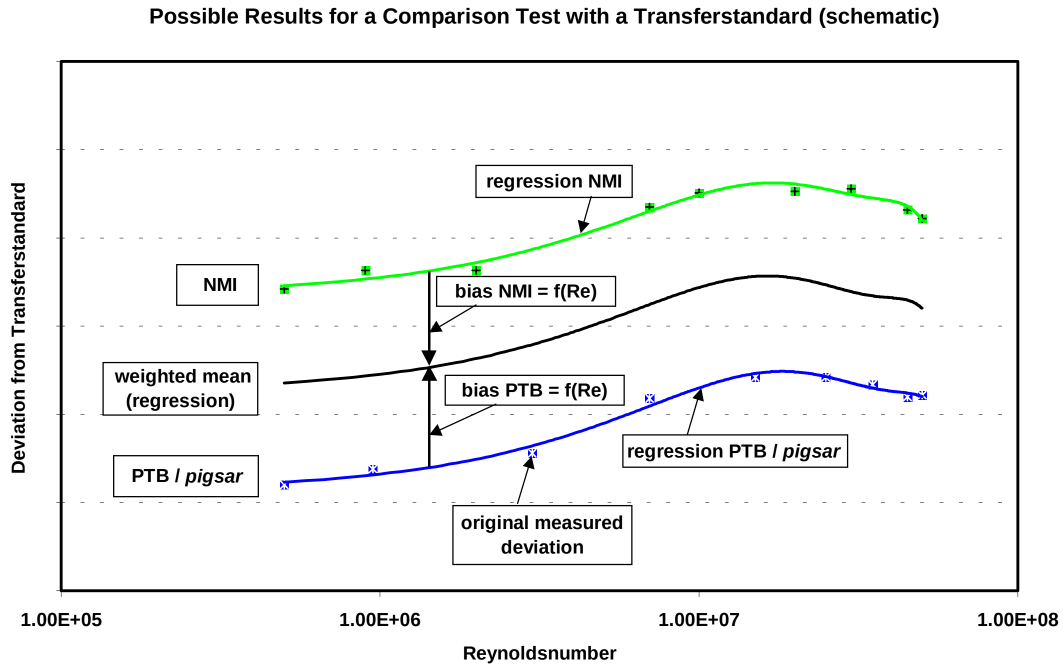


FIGURE 4. Possible differences between measurement results of the Comparison test

In reality, the Reynolds numbers may not exactly overlap (due to different conditions of the gases), so that the weighed average curve of each meter has to be developed from the polynomial equation of both test results of NMi VSL and PIGSAR. Remember that the weighing factors were already calculated from the uncertainty levels of the two independent systems in step 4.

The deviation curve of each individual meter is expressed as a polynomial equation related to the Reynolds number (Note: the aim is to make the procedure not sensitive with respect to pressure levels) i.e.:

Test results Lab “1”, turbine meter “x”: $\varphi_{x,1} = a_{0,1} + a_{1,1}Re + a_{2,1}Re^2 + a_{3,1}Re^3 + ...$

Test results Lab “2”, turbine meter “x”: $\varphi_{x,2} = a_{0,2} + a_{1,2}Re + a_{2,2}Re^2 + a_{3,2}Re^3 + ...$

in which Re = Reynolds number related to pipeline diameter /10^5

The weighed mean deviation curve of the individual transfer meter is calculated according to :

$$\varphi_{x,c} = \sum_{i=1}^{i=m} w_i * (a_{0,i} + a_{1,i}Re + a_{2,i}Re^2 + a_{3,i}Re^3 + ...)$$ in which c= common level

Step 5 continued- Calculation of the bias of each test result with respect to the weighed average curve

After completion of the individual unified deviation curves, the differences (bias) between the participating laboratories and the “Unified level” (L_c) as a function of Reynolds number will determined for each comparable Reynolds number and for each individual meter (see figure 5).

The Bias is defined as: $Bias_{x,i} = \varphi_{x,i} - \varphi_{x,c}$

in which i= laboratory number and c= common reference value.and x = specific turbine meter.

In the example, only three sets of measurement results have been plotted.
In reality, the amount of information is twice as much (6 turbine meters) .

The huge amount of data is plotted in a transparent way so that the Team of Technical Experts can still easily evaluate the Comparison results at a “Comparison Evaluation Meeting”.

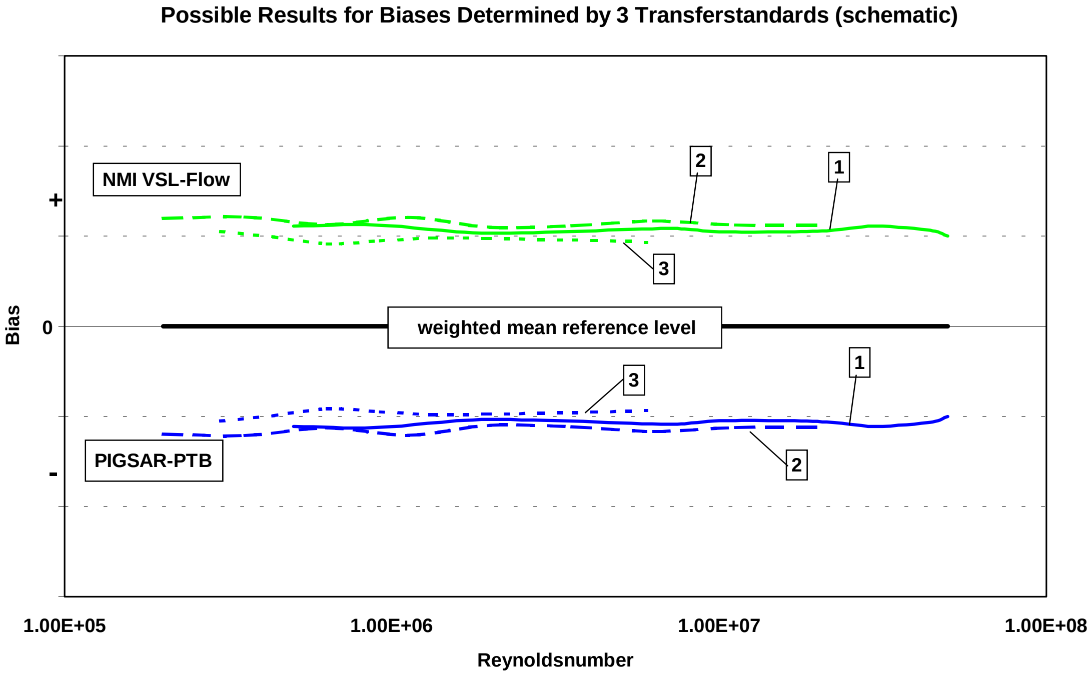


FIGURE 5. Example of possible results of the biases

Step 6- Maximum permissible difference between the chains

The deviation of the measuring result between the partners (or potential partner) may not exceed the Root Square Sum of both individual uncertainty levels i.e.:

$|L_i - L_j| \leq \sqrt{u_i^2 + u_j^2}$ for all i, j where $i \neq j$ and L_i= (Smoothed) HP level of participant-i

L_j= (Smoothed) HP level of participant-j
u= total uncertainty level of participant

The deviations are based upon the subtraction of the polynomial equations as calculated in the previous section.

Nota Bene, at this point a go/no-go decision has to be made (See flowchart in figure 2). All test results must fall within a pre-required tolerance level. If the tolerance level is exceeded, a process of trouble-shooting will be initiated by the Team of Technical Experts.

Step 7: Calculation of Feedback for each individual Traceability Chain

Each participant will correct the “original, independent” level (or eventually the “Smoothed HP level”) by means of the “correction model”.
Once the weighing factors and the bias model are known according to the previous steps, the correction model has to be developed to a simple and transparent algorithm according to:

$$bias_{est,i} = a_{0,i} + a_{1,i} Re + a_{2,i} Re^2 \quad [\%]$$

in which $bias_{est,I}$ = estimated bias related to the unified level for laboratory number “i” ,
$a_{0..2,i}$ = constants for laboratory number “i” and
Re = Reynolds number related to nominal pipe diameter / 10^5

The feed-back correction of each the individual reference meter in each laboratory is simply calculated from: $feedback_i = -bias_{est,i} \quad [\%]$

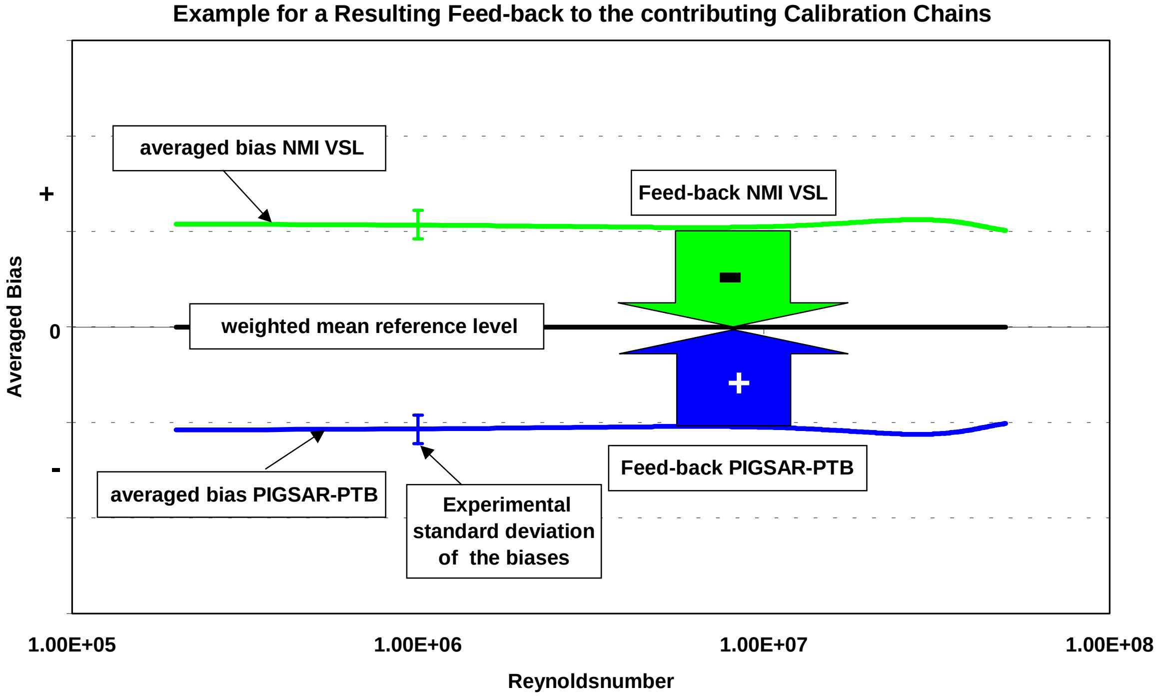


FIGURE 6. The Harmonization process

Each laboratory shall process this Feedback component into each standard which is- or will be- used to disseminate traceability to Society. This process runs through calibrations, testing and verification services.
The Feedback component will by no means be processed directly to the results of a meter under test at the specific laboratory (e.g. a “correction factor to calibration results”).

Total uncertainty of unified m^3 and resulting uncertainty of the participating chain

The total uncertainty level of the unified m^3 is calculated according to:

$$u_c = \sqrt{\sum_{i=1}^{m} w_i^{\,2}(u_i^{\,2} + u_{A\,bias,i}^{\,2})}$$

in which : $u_{A\ bias,i}$ is the experimental standard deviation of the average. As the amount of data is large, this uncertainty budget is small (2s=0.05% typical).
As the feedback process is a purely mathematical process (bias-corrections applied to the deviation curves of a standard meter of the “national level”) no extra uncertainty component needs to be added.

For all participating chains at the same Reynolds number:
$u_{c,i} = u_c$

in which :
$u_{c,i}$ = The uncertainty level of the individual chain after completion of the feedback process.

For example : Assume that both uncertainty levels ($u_{1,2}$) are equal : 0.3%, and the experimental standard deviation of the biases is 0.05% (2s) at laboratory-1 and 0.04% at laboratory-2 then the total uncertainty level of the unified reference values at a certain Reynolds-number amounts to:

$$u_c = \sqrt{0.5^2 * (0.3^2 + 0.05^2) + 0.5^2 * (0.3^2 + 0.04^2)} = 0.21\%$$

The uncertainty level is enhanced by 30% (From 0.3 to 0.21%) without any direct use of technical improvement in one or both Traceability-Chains. The synergy of combining two independent chains becomes very clear at this stage.

Loop at step 4- maintaining the unified reference values

Obviously, the unification process is not a “once-in-a-life-time” activity. The parties are obliged to continuously check the level of the national reference meters (standards) with respect to the unified level.
A system of periodic re-calibration as well as periodic verification is defined as shown in figure 2. The check loop is running to maintain a half-yearly comparison check. This check is carried out by means of the same transfer-packages (Watch-dogs) used in the unification process and which are kept apart for this purpose.

Step 8,9 and 10- Settling the Harmonized values in each reference meter

At each point in the Traceability Chains from which the unified reference value is disseminated to society will be treated according to this procedure. The procedure uses the most accurate test-facilities as a basis of the calculation of the Feedback. This is the case when two or more chains exist that are not independent like the overlapping capacities of the Bergum and Westerbork test-facilities. In that particular case, only the data of the comparison results of “Bergum” will be used. Now that a common reference value is established, the service of bringing one single reference value to society becomes a fact. The double logo at the calibration certificates guarantees that all used standards are traceable to this unified value (See step 11 in figure 2.).

Step 12- Maintaining the national level as a basis for the unification process

The return-loop in figure 2. represents the three-yearly re-calibration cycle at NMi VSL-Flow and at PIGSAR-PTB. This re-calibration cycle is carried out according to the normal running procedures of each individual Institute.

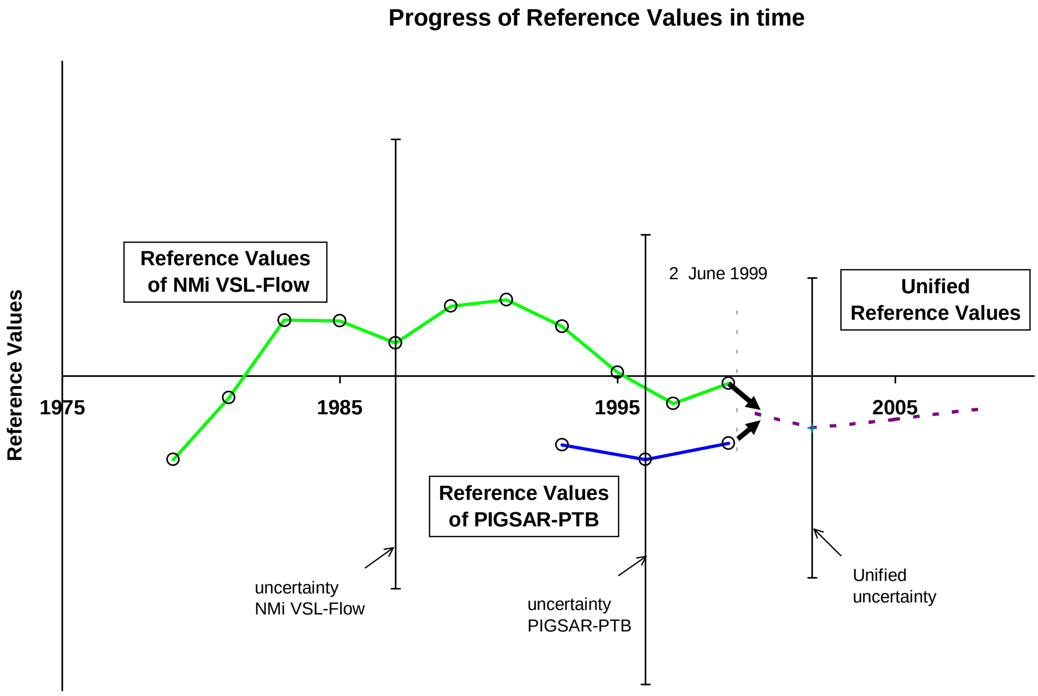


Figure 7. The service of bringing one single reference value to society becomes fact..

CONCLUSION

+ Common and shared reference values. The differences in measurement values between PIGSAR and NMi VSL-Flow are minimized (the uncertainty of the repeatability of the installations remain).
+ The procedure to establish Common Reference Values is based on the degree of equivalency (using the established weighing factors, stemming from the total uncertainties of the original Reference Values);
+ Together with Common Reference Values, corresponding uncertainty levels are established;
+ By combining independent and equivalent traceability chains, considerable reduction in uncertainty levels is obtained;
+ Programmes for technical improvement of each individual Traceability Chain are initiated and will reduce uncertainty levels in the future even more;
+ International co-operation in the field of establishing unified reference values has another spin-off: Shared Research projects in Metrology;
+ By combining independent and equivalent traceability chains the stability of the Reference Values is enhanced;
+ International Society may enjoy more stable, more accurate reference values by the combination of the two independent and equivalent traceability chains. For the first time in history, the two Metrological Institutes share one, unified, and more reliable reference value for high-pressure gas volume measurements.

REFERENCES

[1] M.P. van der Beek and I.J. Landheer (1998),
The Acceptance of Variations in Reference Values of Gas-Flow Measurements,
Proceedings of Flomeko, June 1998, LUND, Sweden

List of Definitions, Symbols and Abbreviations

The "HP m^3" is referred to as the reference value of a high-pressure m^3 of Natural Gas, established during one re-calibration cycle of an independent traceability-chain.

The "Actual HP m^3" is the most recent value of a "HP m^3 ".

The "Smoothed HP m^3" is referred to as the reference value of a high-pressure m^3 of Natural Gas originating from more than one re-calibration cycle, i.e. into which previous "HP m^3" values have been incorporated in a well-defined way. The amalgamation of the selected group of most recent "HP m^3" values into the "Smoothed HP m^3" is depending of the applied procedure. The number of re-calibration cycles as well as the weighing-method of the "HP m^3" values effect the "Actual Smoothed HP m^3".

The "Unified HP m^3" is referred to as the reference value of a high-pressure m^3 of Natural Gas derived from the "Actual (Smoothed) HP m^3" of at least two independent and equivalent traceability-chains.

The "Reynolds-number" refers to a dimensionless figure, characterizing the gas
In the field of gas-flow measurements it is commonly defined as : $Re = \frac{v * \rho * D}{\mu}$

in which : v = velocity of the gas in the pipeline;
ρ = actual density of the gas;
D = pipeline-diameter at the entrance of the gas-meter;
μ = actual dynamic viscosity of the gas.

Symbol	Quantity, Description	unit
ν	Degrees of freedom in the mathematical model of the bias	[1]
A	Polynomial constant	[var.]
F	Weighing factor, dependent on number of cycle	[1]
M	Number of participating traceability-chains	[1]
N	Number of re-calibration cycles, used to calculate the Smoothed HP m^3	[1]
N	Total number of test-points for the determination of the bias	[1]
W	Weighing factor (impact of the traceability-chain on the unified m^3)	[1]
X	Virtual value of a m^3 at a cycle related to the progressing average through time	[%]
Avg	Average	[var.]
C	Unified m^3	[m^3]
i	Counter i	[1]
j	Counter j	[1]