UNIT OF VOLUME FOR NATURAL GAS AT OPERATIONAL CONDITIONS, PTB AND NMi VSL DISSEMINATE "HARMONIZED REFERENCE VALUES"

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SUMMARY
Since November 1999, PTB and NMi VSL have established and disseminate Harmonized Reference Values for the Unit of Volume of Natural Gas [1-6]. These Reference Values for Natural Gas at operational conditions are applied, not only in the test facilities at which they originate but are installed and applied as well in other test-facilities [7] and have a wide application in Custody Transfer Measurements [8]. The paper describes backgrounds and procedures that have been developed and that are currently in use in Germany and The Netherlands. The prerequisites of the harmonization process, the underlying procedures, results obtained so far as well as the economic benefits for the European market will be pointed out. The "harmonization" can be considered as the first factual step towards the realization of a European unit of volume for Natural Gas at operational conditions.

INTRODUCTION OF NMi VSL

Reference Values for gas-flow measurements under operational conditions have been established in The Netherlands since the seventies [9] together with the rapid development of gas-transport and gas-distribution in the region. In those days, a pressure-dependency of turbine-meters not related to differences in operating conditions was observed. This non-ideal behaviour leads ultimately to different invoicing for the same quantity of gas (if e.g. related to kilo's).

Gasunie decided in 1973 that reliable gas-flow measurements, for all operational conditions, were necessary for an adequate "Gas-balance" at all times. Moreover, it would create a situation with neither advantages, nor disadvantages for users caused by metering-principles, operating pressures or meter-sizes. In close co-operation with "IJkwezen" (at that time responsible for the Dutch measurement Standards), three high-pressure test-installations in Groningen (1973), Bergum (1975) and Westerbork (1978) respectively, have been put into operation. The facilities at Bergum (since 1989 property of NMi) and Westerbork (Gasunie) are since many years now, in use for research, testing, verification and calibration of gas-meters under operational conditions.

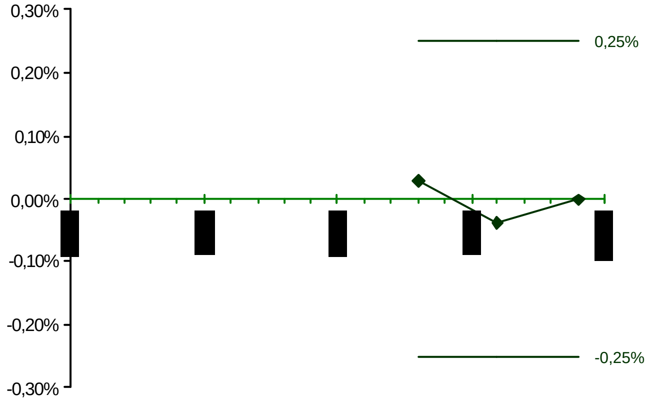
The long traceability-chain with numerous calibrations to realize Reference Values ranging from atmospheric till 60 bar, showed a disadvantage. A re-calibration of the total chain could easily give at the end, a change in Reference Value of 0,1%. Today strong efforts are made through developments in technology, viz. "Dynamic Displacement Device - 2000", "Gas-Oil Piston-Prover", "NMi TraSys" together with "Z/Z-meter" to improve the overall stability of the Reference Values of the traceability-chain and to reduce their uncertainty to 0,1% for 4.000 m^3/h at 60 bar [10, 11].

INTRODUCTION OF *PIGSAR*-PTB

In the early nineties a new high-pressure test-facility under auspices of Ruhrgas has been founded in Dorsten, Germany, called *pigsar*, "Prüfinstitut für Gaszähler, Ein Service Angebot der Ruhrgas AG".

PIGSAR operates a Piston-Prover (for Volume comparison) under supervision of PTB, for the realization of Reference Values [12]. An attractive short traceability-chain is created. The Reference Value of the last re-calibration constitutes the German "Best Known Reference Value", see Figure 1.
At *pigsar*-PTB, Laser-Doppler Anemometry (LDA) is being developed for application in the realization of the high-pressure Unit of Volume. Results of experience with an optical primary standard for Air [13] as well as of the application of LDA in high-pressure Gas have been published [14, 15].

Historic Reference Values (50 bar), *pigsar* -PTB



Last Re-calibration for "Best Known Reference Value"

Figure 1

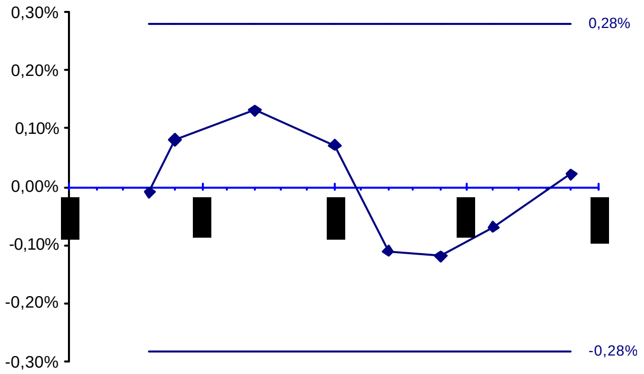
STABILITY OF REFERENCE VALUES

After the opening of *pigsar*, customers of NMi VSL "Bergum" and *pigsar*-PTB soon observed small, but more or less constant differences between the two facilities, i.e. a 'cubic metre' of Gas offered at Bergum was always somewhat smaller than the one obtainable at Dorsten.

The differences between the two facilities varied, depending on pressure, flow and the diameter of the meter under observation. Also small differences have an economic impact and the clever "Homo Economicus", driven by economic benefits only, started to select calibration at "Bergum" for 'selling' metering-stations and calibration at *pigsar* for meters with 'buying' purposes.

Since the seventies, we have seen an increasing use of Natural Gas as a source of energy; and in Europe, a vast network (gas-grid) has been constructed. In this growing grid more and more points of transfer of ownership of the transported gas are installed, leading ultimately to increasing demand for reliable and stable Reference Values for high-pressure gas-flow measurements. The principle of Third Party Access (TPA), supported in the future by direct invoicing of energy-shipment, makes it of vital importance that Gas-transport organizations have at all times a clear knowledge about the contents of their transport-grid. Therefore, stability of measurement values in time is gaining importance and sudden variations in Reference Values, are certainly not acceptable.
As an illustration, the maximum observed difference of ca. 0,3% represented in 2002 for The Netherlands, an economic value of ca. 18 M.EURO.

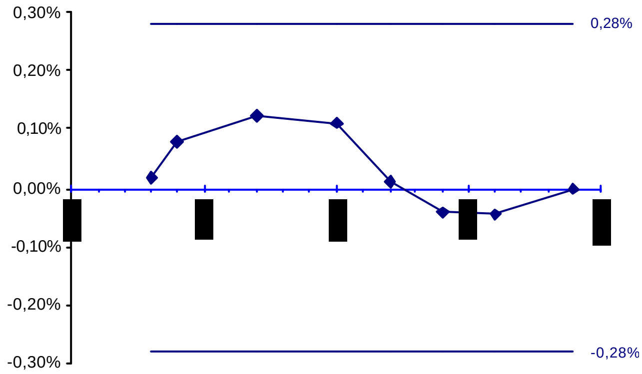
Historic Reference Values (50 bar), NMi VSL



Historic Average as "Best Known Reference Value"

Figure 2

"Smoothened" Reference Values (50 bar), NMi VSL



Weighed Average for "Best Known Reference Value"

Figure 3

In the light of the described developments in transport and distribution, variations in Reference Values have to be brought to a technical minimum. As a first step, NMi VSL has, at its re-calibration in 1999, adapted its methodology and has included historic re-calibration data to obtain a "smoothening" of the variations of the Reference Values [2]. The results are presented in Figure 2 and 3.

UNCERTAINTY AS A QUANTIFICATION OF QUALITY

With the increasing knowledge about the measurement process, the concept "uncertainty of measurement" has taken over the notion "accuracy" [16] and nowadays, uncertainty is conceived as a measure for the quality of a measurement result. The uncertainty-budget quantifies "the lack of information". Uncertainty thus defines the band in which to expect the "best known reference value" of the SI-unit in relation (deviation) to the indicated value of the measuring instrument.

The basic uncertainty of a calibration and test-facility is named CMC - Calibration and Measurement Capability and defined as "the highest level of calibration or measurement normally offered to clients, expressed in terms of a confidence level of 95%, sometimes referred to as best measurement capability".

Following the same concept, uncertainty and CMC can be used to define the "degree of equivalency" between two sets of measurement results, or between two sets of reference values, or even between two calibration-facilities that disseminate reference values [17].

In Figure 4 an illustration is given how the principle of uncertainty is applied as the quantification of equivalency and to establish a 'weighed' average between the two sets of measurement results. Let us assume two sets of values RV1 and RV2 that differ 0,25% and that have uncertainties of U_{RV1} of 0,2% and U_{RV2} of 0,3%, respectively. In a first step the uncertainties are applied to assure that RV1 and RV2 represent the same SI-unit, i.e. do not differ significantly from one another and a ? $_{\text{permitted}}$ is defined. The result shows a permissible difference of 0,36%. As the actual difference is 0,25% we are allowed to proceed. Now, we go to determine the equivalency of the two sets and to calculate the weighed average of the two sets, via the calculation of factors W_1 and W_2, respectively. The two calculated factors are W_1 = 0,31 and W_2 = 0,69. Finally, the uncertainty of the new Reference Value is calculated.

$$\Delta_{\text{permitted}} \leq \sqrt{u_{RV1}{}^2 + u_{RV2}{}^2}$$

$$W_1 = \frac{1}{1 + \left(\frac{u_2}{u_1}\right)^2}$$

$$u_{\text{harmonized}} = \sqrt{W_1^2 * u_2^2 + W_2^2 * u_1^2 + u_{\text{comparison}}^2}$$

Assuming an uncertainty of 0,1% for the comparison-process, an uncertainty for the harmonized reference values of $u_{\text{harmonized}}$ = 0,19% is found. Figure 4 presents an overview and illustration.

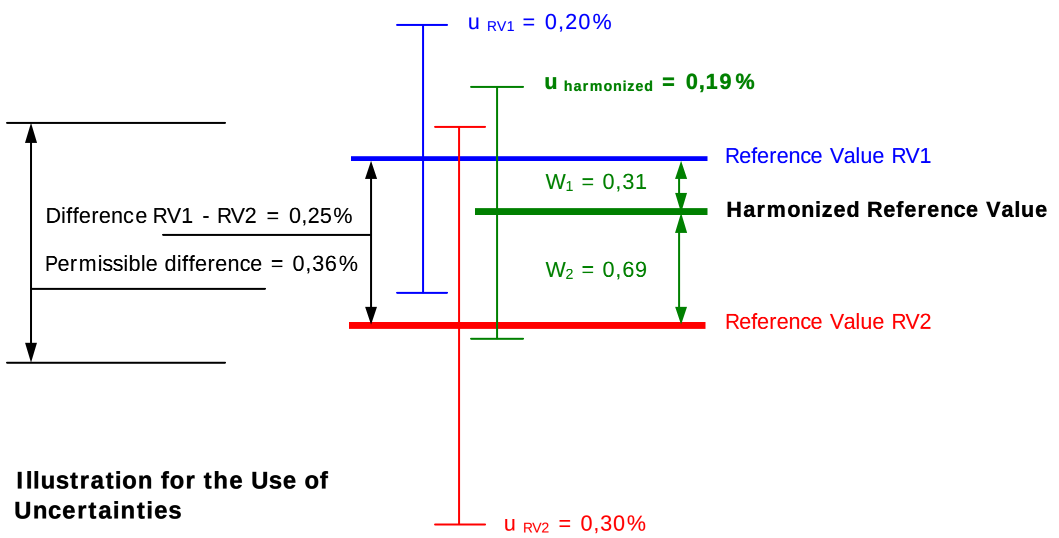


Figure 4

So, in the actual situation we have two different realization principles leading to almost the same measurement results and within one another's uncertainty levels. Is that a good enough base to organize Harmonized Reference Values with the desired properties, viz. increased stability in time (reproducibility) and reduced uncertainty ?

METHODOLOGY TO ELIMINATE DIFFERENCES

In June 1999, two National institutes of metrology, NMi VSL of The Netherlands and PTB of Germany, have agreed to disseminate the same realization of a cubic meter for Natural Gas. At the ceremony of signing the agreement, an explanation on the background and the procedures was given to a gathered "Flow-Community" in Dordrecht, The Netherlands, invited to witness the event [18, 19].
Harmonized Reference Values is an illustration of progress in applied Methodology of high-pressure gas-flow measurements.
The signed contract includes an Annex-II, drawn up by a Team of Experts, containing all the steps necessary to come to long term Harmonized Reference Values.
In the next chapters the basic procedures as well as technical requirements are overviewed.

HARMONIZATION PROCEDURES

The applied Methodology is based upon a set of six (6) prerequisite conditions. These conditions have been discussed and agreed upon before the actual comparisons have been organized to avoid results of comparisons having an impact on the discussion.

1. Two independently realized *) Sets of Reference Values
- ✓ At NMi VSL, a system based on mass-comparison of gas-flows is in use to realize high-pressure Reference Values over a full pressure range from atmospheric till 60 bar.
- ✓ The German National facility for high-pressure gas-flow standards, *pigsar*, operates a Traceability-Chain linked to a Piston-Prover for direct Volume comparisons at three discrete pressures, under supervision of PTB.

*) A Traceability-Chain is called "independent" if no direct link in the realization of the Unit of Volume exists between the two high-pressure traceability-chains with reference to equipment, procedures and personnel. The only common ground consists of the International primary standards for time, length, mass and temperature.

2. Sets of Reference Values, used to establish Harmonized Reference Values have overlapping flow-rates and similar pressures, i.e. the same operational conditions.
- ✓ NMi VSL- "Bergum" : 9-51 bar(a) and 100-132.000 m^3/h *)
- ✓ *pigsar*-PTB : 16-51 bar(a) and 144-300.000 m^3/h *)

For practical reasons, the Harmonization refers to conditions at 21 and 51 bar(a) and to flows ranging from 2.000-130.000 m^3/h *)

*) All volumes relate to 15 ^{0}C and 1,01325 bar

3. The uncertainty-budget for each of the Sets is fully known, understood and accepted.
A Team of Experts, consisting of Staff of PTB and NMi VSL responsible for the Harmonization, have scrutinized all the uncertainties involved in the realization of the Sets of Reference Values that have become part of the Harmonized Reference Values. Misunderstandings and unclear situations have been clarified, some amendments were necessary and corrective actions have been executed. Finally, full consent of the Team has been obtained.

4. The observed differences between the two sets are smaller than the Root Square Sum of the corresponding uncertainties (2σ), i.e. differences are not significant and therefore permitted.
In the case at hand the initial uncertainties of the two Sets at 50 bar had at that time been established at 0,25% and 0,28%, respectively, giving rise to a permitted difference of 0,375%. In these two Sets the actual differences established, varied from 0,15-0,35%, allowing the Harmonization to proceed.

5. The stability, i.e. the reproducibility of the Reference Values over the years, for each of the Sets is demonstrated.
Again, the Team of Experts looked into the available historic data of the two organizations.
In Figure 2, the Set of NMi VSL of the period 1983 till 1999 is given. The Reference Values are presented against the historic average of the period together with the band of the established uncertainty. It is clear that the Traceability-Chain at NMi suffers from variations in its capability to produce stable reference values [2]. Weighed averaging of historic reference values was introduced in 1998 to eliminate the extremes, but it was clear that NMi VSL-Flow needed improvements in applied technology as well [10-11]. Figure 3 presents the results of the weighed averaging (smoothening) for NMi VSL-Flow over the same period.
Finally, Figure 4 gives the Reference Values of *pigsar*-PTB, presented against its own historic average. Though a much shorter period is involved, it seems that the initial uncertainty with respect to the shown stability over the years is conservative.

6. The Degree of Equivalency is established, based on historic performance and accepted uncertainties.
At this moment the original uncertainties of the Sets of Reference Values expressed as CMC start to play a major role. First the uncertainties were applied, as was explained before, to divide the difference between the two Sets, applying the determined equivalency. The searched for Best Known Reference Value is based on the information obtained from the combined facilities and its value is closer to the original value of that facility with the smallest CMC.
Figure 5 gives the combined Traceability-Chains and Harmonized Reference Value of November 1999, reflected against the last harmonization of January 2003 with its Best Known Reference Values (Figure 6).

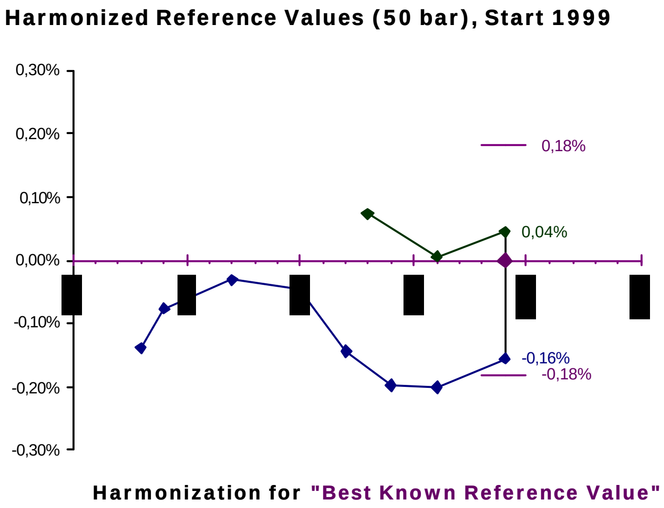


Figure 5

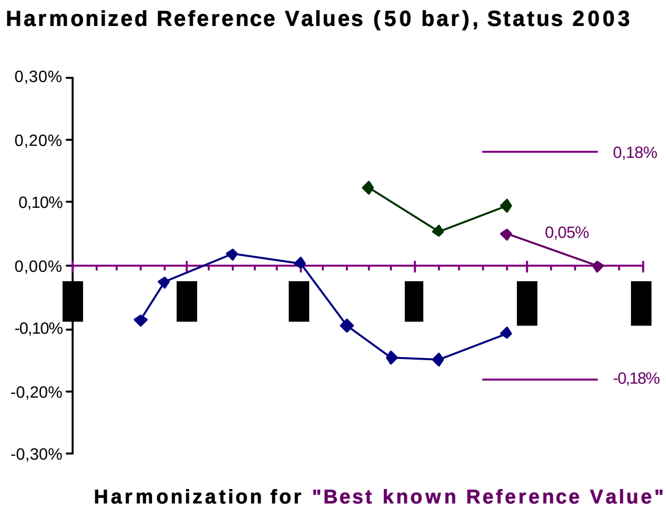


Figure 6

FIRST CONCLUSION
The graph of Figure 5 shows the impact of the Harmonization on the change in Reference Values for the two facilities in 1999. Figure 6 shows the change in Reference Values resulting from the Harmonization in 2003. A change in Harmonized Reference Value of 0,05% has occurred. As a first new value, a major improvement in stability has been accomplished. Historic consistency is demonstrated.

TECHNICAL INFORMATION

PTB and NMi VSL have applied three sets of different turbine meters (two in series) to allow a maximum of overlap in flow-range. Within the reproducibility of the results, no significant discontinuity could be observed although three different meter sizes (100 Ø, 250 Ø and 400 Ø) and two different pressure stages (20 and 50 bar) for each size were used.

The uncertainties (k = 2) are graphically shown (Figure 1 and 3), clarifying the claimed and accepted uncertainties at *pigsar* and NMi VSL. The results of the various comparisons are used to calculate Harmonized Reference Values, applying a method of "quadratic weighing". In this way common "best-known reference values" for the two facilities are established.

TESTS OF COMPARISON

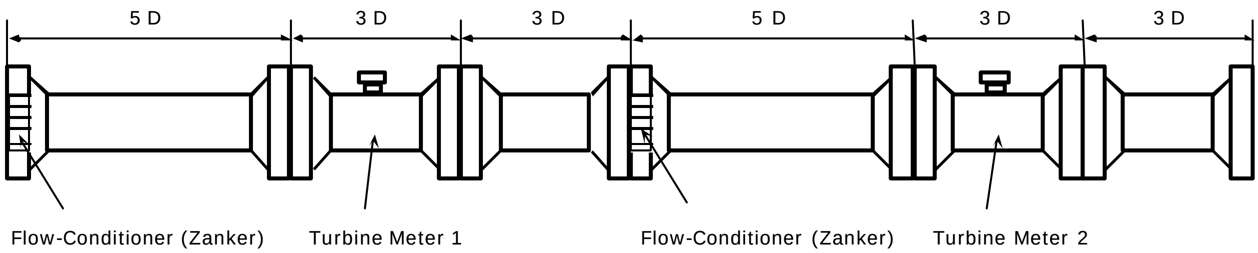
Introduction

At the initial tests of comparison some technical peculiarities tampering the ability to reproduce similar measurement data for similar conditions have been discovered and amended. It concerned mainly the instrument with which comparisons were performed. After some research, special transfer packages were developed that were able to reproduce measurement data in a satisfactory way. Please note that in the uncertainty of the Harmonized Values a contribution of the comparison process is included. It is easy to see that doubling this uncertainty contribution (see illustration, Figure 4) to 0,2% will lead to an $u_{harmonized}$ = 0,26% and will undo part of the claimed advantages (reduction of uncertainty).

Lay-out of Transfer Packages

Harmonized Values are established with, and will reside (for the time being) in, three transfer-packages (100 Ø, 250 Ø and 400 Ø) defined in this section.

Each package used for the comparisons has the layout presented in the next sketch.



A package consist of a 5-D inlet-section with Zanker-straightener, a Turbine-meter (#1), a 3-D outlet-section, again a 5-D inlet-section with Zanker-straightener, a Turbine-meter (#2) and a final 3-D outlet-section.

Zanker-straighteners have been added to nullify installation-effects and are also applied in the normal calibration procedures. 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 are used. Each twin package consists of two different type turbine meters with the stated, applied actual flow-rates :

Two G-250 turbine meters (4", 100 Ø), with a flow range of 100-400 m^3/h actual;

Two G-1.600 turbine meters (10", 250 Ø), with a flow range of 300–2.500 m^3/h actual;

Two G-4.000 turbine meters (16", 400 Ø), with a flow range of 600–6.000 m^3/h actual.

Test-matrix
The presented test-matrix has been established and followed for the comparison between the two facilities.

Test-Matrix	NMi VSL-"Bergum"		PTB - *pigsar*	
	20 bar	50 bar	20 bar	50 bar
100 Ø	4 points	4 points	4 points	4 points
250 Ø	6 points	6 points	6 points	6 points
400 Ø	7 points	3 points	7 points	3 (7) points

Each measurement (comparison against the measurement-standard of the facility) 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 measured actual flow-rate ranges from 100 up to 6.000 m^3/h (2.500 m^3/h actual at 50 bar), and the pressures are 20 and 50 bar. In total 30 points (in duplo) have been examined. Thus 60 deviations together with their uncertainties have been established. Of those, 5 flow-rates overlap between meter-sizes and insight is obtained of differences in behaviour connected to meter-size. Flow-rates have been plotted as Reynolds-values to allow for comparisons of conditions that are for technical reasons, not completely identical.

Determination of weighing factors
After completion of the uncertainty analysis of each Test Facility, the uncertainties of the "Actual HP m^3" are known at various flow-rates and at the two selected pressures. For easiness of calculation the uncertainties are determined as a function of Reynolds, and CMC's are established. Subsequently, the weighed average of individual "Actual HP m^3" of each chain was calculated.

Introduction of the Harmonization factor
The difference of each test result with respect to the weighed average curve is established, and after completion of the individual harmonized deviation curves, the differences between the participating laboratories and the "Harmonized Value" (as a function of Reynolds number) is determined for each comparable Reynolds number and for each individual meter and each pressure.

The Harmonization factor (H) is defined as $H_{x,i} = \varphi_{x,i} - \varphi_{x,c}$

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

The huge amount of data is plotted in a transparent way so that the Team of Experts could easily evaluate the Comparison results at a final "Comparison Evaluation Meeting".

Maximum permitted differences
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.:

$$\left| L_i - L_j \right| \leq \sqrt{u_i^2 + u_j^2} \quad \text{for all } i, j \quad \text{where } i \neq j$$

L_i = (Smoothened) HP Value of participant-i
u (CMC) = uncertainty of participant-i

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

<u>Nota Bene</u>, at this point a go/no-go decision has to be made. All test results must fall within a pre-required tolerance level. If the permitted difference is exceeded, a process of trouble-shooting is initiated by the Team of Experts, resulting in or, the elimination of this road-block or, a halt in the harmonization-process.

Introduction of Harmonization factor in each Facility
Each participant will correct the "original, independent" values, "(Smoothened) HP values", by means of the "correction model".
Once the weighing factors and the harmonization factors are known according to the previous steps, the correction model has to be developed to a simple and transparent algorithm.
Each laboratory processes the Harmonization factor into each standard that is used to disseminate traceability to Society. Harmonization factors will not be processed to the results of a Meter-under-Test at the specific laboratory and are not available to the public.
Finally the uncertainty of the harmonized m^3 is calculated, according to :

$$u_c = \sqrt{\sum_{i=1}^{m} w_i^2 u_i^2 + u_{AVG}^2}$$

u_{AVG} is the experimental standard deviation of the average.

As the amount of data is large, this uncertainty contribution is small (2s = 0,05% typical).
The feedback process is a purely mathematical process (corrections applied to the deviation curves of a standard meter of the "national level") and no extra uncertainty contributions need to be added.

The harmonization has created an improvement in uncertainty of ca. 30% (compare Figures 1, 2 and 3 with Figures 5 and 6) without any technical improvement in any of the two both Traceability-Chains. The synergy of the combination of two independent chains becomes very clear at this stage.

Sustaining harmonized reference values
Obviously, the harmonization process is not a "once-in-a-life-time" activity. The parties have agreed to continuously check the National reference values as incorporated in the standards, with respect to the harmonized reference values.
A system of periodic re-calibration as well as periodic verification is defined. This checking-loop is has a half-yearly interval. The check is organized with the same transfer-packages (Watch-dogs) as used in the harmonization process. The transfer-packages are kept apart for this purpose.

Sustaining National Reference Values as the basis for Harmonization
In the two National facilities a three-yearly re-calibration cycle is sustained according to the running procedures of each individual institute to keep the foundation of the harmonization intact.

CONCLUSION
pigsar-PTB and NMi VSL-Flow share common, harmonized reference values. The differences in measurement values between *pigsar* and NMi VSL-Flow are minimized, but the uncertainty in the repeatability of the installations remains. The combination of the two independently realized and equivalent traceability-chains has given a considerable reduction in the CMC (uncertainty) of the two facilities in view of the initial uncertainties.
The looked after increased stability of the measurement values, passed-on to society, could indeed be established, compared to observed variations in the past.

POTENTIAL DISADVANTAGES
- The two Traceability-Chains need to be kept in operation and the knowledge and expertise about the two systems kept alive and continuously extended.
- The re-calibration programs of the two systems should be synchronized.
- A punctual checking scheme and procedures are required and need to be followed.
- The two involved flow-organizations have in fact lost their completely independent status, since one organization depends on the realized traceability of the other for its own, but shared, Harmonized traceability.

IMPORTANT LESSON SINCE 1999

At the start of the harmonization the Reynolds-concept was believed to be the big 'equalizer' making it possible to compare results taken from conditions that were not quite similar and so to include also data from the facility "Westerbork" (Gasunie), since this facility was part of the Traceability-Chain of NMi VSL and would thus be able to compensate for the region that "Bergum" and *pigsar* did not have in common. In reality it proved to lead to insecure validation processes and today the region of harmonization is strictly limited to equal pressures and equal flows.
Operating in different conditions could result in various harmonization processes. The demand for independent data is determining and remains a prerequisite.

DEVELOPMENTS IN TECHNOLOGY

Programmes for technical improvements of each individual Traceability Chain are initiated and will reduce uncertainties, together with an enhanced stability in the future even more. Of the undertaken developments we name for NMi VSL, NMi TraSys & Z/Z-meter, GOPP and a new Dynamic Displacement Device. For *pigsar*-PTB we mention the implementation of Laser-Doppler Anemometry (LDA).

HARMONIZATION AGREEMENT

The agreement on harmonization between PTB and NMi VSL is open to others. Other National Metrology Institutes or even other calibration laboratories that operate a demonstrated, independently realized set of reference values are acceptable. All six prerequisite conditions are to be met and an additional decrease in harmonized uncertainty together with a gain in stability should be offered.

BENEFITS FOR INDUSTRY AND SOCIETY

As National institutes for Measurement Standards, NMi VSL as well as PTB, have a function to provide society with reliable sources of traceability. A prerequisite to this function is the ability to generate and to improve the reference values themselves as well as the knowledge about reference values of high-pressure gas-flow measurements.
The minimization of observed differences between *pigsar* and NMi VSL-Flow, together with the realization of enhanced stability in Reference Values is of economic importance.
Improved uncertainties are a distinct additional benefit of the Harmonization process.

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[7] Among these facilities are :
- ? Instromet (8 bar) – Utrecht, The Netherlands
- ? Gasunie, Bernoulli-Laboratory (60 bar) - Westerbork, The Netherlands
- ? Gasunie, High-Pressure Test-Facility (8-40 bar) – Groningen, The Netherlands
- ? TransCanada Calibrations (65 bar) – Winnipeg, Canada

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List of definitions, symbols and abbreviations

? "HP m^3" is referred to as the (original) Reference Value of a high-pressure m^3 of Natural Gas, established during one re-calibration (cycle) of an independent Traceability-Chain

? "Traceability-Chain" is an original, coherent Set of Reference Values at various pressures.

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

? "Smoothened HP m^3" is referred to as the "Actual HP m^3", if originating from more than one re-calibration cycle, i.e. into which a number of most recent "HP m^3" values have been amalgamated in a well-defined way. In the applied procedure the number of "HP m^3" as well as the weighing-method (contribution to "Smoothened HP m^3") are laid down.

? "Harmonized HP m^3" is referred to as the weighed averaged Reference Value of a high-pressure m^3 of Natural Gas derived from the "Actual (or Smoothened) HP m^3" of two, independently realized, Traceability-Chains (sets of Reference Values), here PTB and NMi VSL.

? "Harmonization coefficient" is referred to as the factor, applied to "Actual HP m^3" to give the "Harmonized HP m^3"

? "Reynolds-number" refers to a dimensionless Figure, characterizing the gas-flow condition, commonly defined at gas-flow measurements as : $Re = \frac{v * ? * D}{\mu}$ in which :

v = (average) velocity of the gas in the pipe;
ρ = actual density of the gas;
D = pipe-diameter at the entrance of the gas-meter;
μ = actual dynamic viscosity of the gas.