Reproducibility of the Bernoulli laboratory in Westerbork

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Summary

This paper explains the way in which the traceability of the Bernoulli laboratory in Westerbork is organised and shows the reproducibility that is determined from the measurement results involved.

1. Introduction to the Bernoulli laboratory (internationally known as *Westerbork*[1])

Gasunie[2] owns the pipeline network for the transportation of natural gas in the Netherlands and has an annual throughput of approximately 80 billion m^3_n. Annually, 160 billion m^3_n are measured at entry points and exit points together. Because neither buyer nor seller likes to bear the risk of measurement errors, a measurement policy has been developed. This policy is based on two principles: perform measurements with zero systematic error and do so with the lowest achievable and affordable uncertainty. To this, Gasunie Research[3] owns and operates the internationally well-known *Bernoulli laboratory* in Westerbork. This laboratory, constructed in 1978, is among the three biggest calibration facilities in the world for high-pressure large capacity natural gas flow meters. The traceability to international standards is provided by NMi-VSL[4].

NMi-VSL is appointed by Dutch Law and by Royal Decision as the National Standards institute. For physical standards, NMi-VSL is the top of the traceability-chain in the Netherlands in ultimately linking calibrations, verifications, and other results of measurement to SI units. The flow department realizes the primary standards for gas and liquid flow volume measurements and has many installations for the calibration of flow measurement equipment.

2. The importance of calibrating gas meters at their operating pressure

Turbine gas meters are common for the measurement of gas volumes in custody transfer. In the early seventies, it was discovered that the reading of gas meters (flow) was dependent on the type of gas, its density and its viscosity. This is illustrated in figure 1. It was then decided that gas meters should be calibrated at their operating conditions, as far as possible. This is the main reason why a number of high-pressure natural gas test facilities were founded in the Netherlands, with the Bernoulli laboratory in Westerbork at the high end.

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[1] *Westerbork is the name of the village in the Netherlands where the laboratory is located*

[2] *Gasunie, short for N.V. Nederlandse Gasunie, consists of Gasunie Trade & Supply and Gasunie Assets & Technology.*

[3] *Gasunie Research is part of Gasunie Assets & Technology.*

[4] *The NMi (Netherlands Measurements institute) is the institute of Metrology in the Netherlands. NMi Van Swinden Laboratory B.V. (NMi-VSL) is part of NMi.*

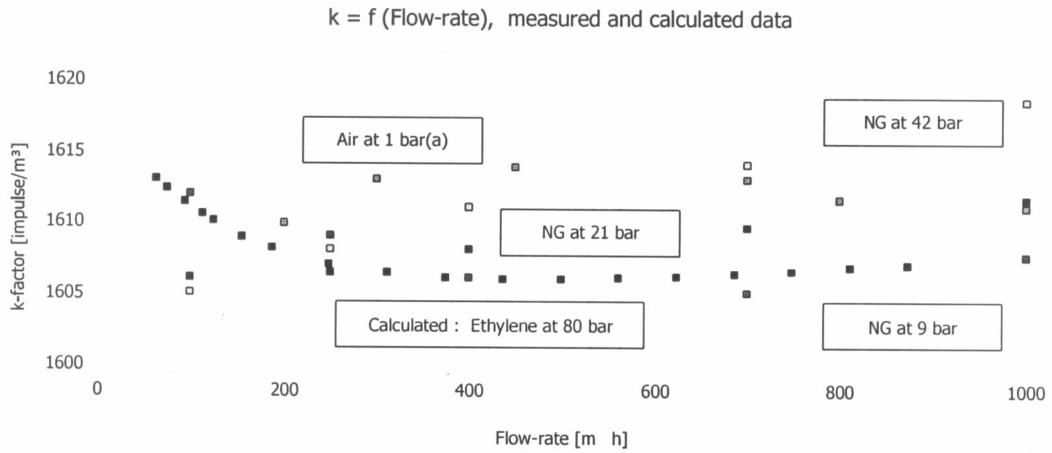


Figure 1: The K-factor of a turbine gas meter at different operating conditions (NG=Natural Gas).

Before entering upon the subject traceability a short description of the facility is given.

3. Description of the Bernoulli laboratory

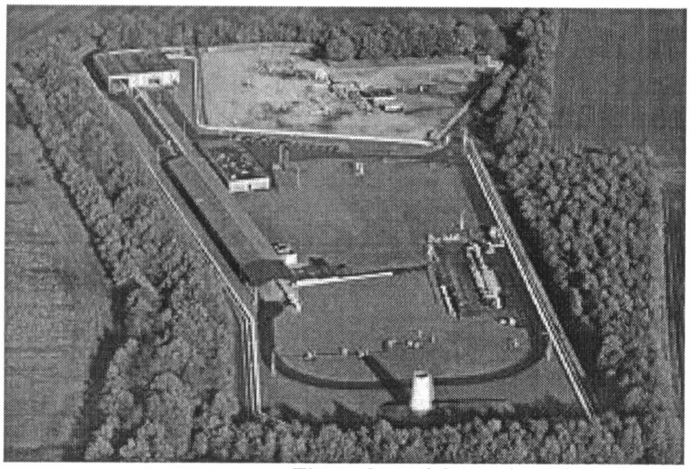


Figure 2: Aerial overview of the Bernoulli laboratory

The Bernoulli laboratory was built in 1978 as a by-pass on the 68-bar gas transport pipeline from the Groningen field to the first downstream compressor station in the village of Ommen. By shutting a valve in the main transport pipe, Gasunie Research can direct the gas flow through one or more of the laboratory's reference meters and then through the meter to be calibrated. The Bernoulli Laboratory has two test sections at its disposal, for pipe diameters between 100 and 750 mm.

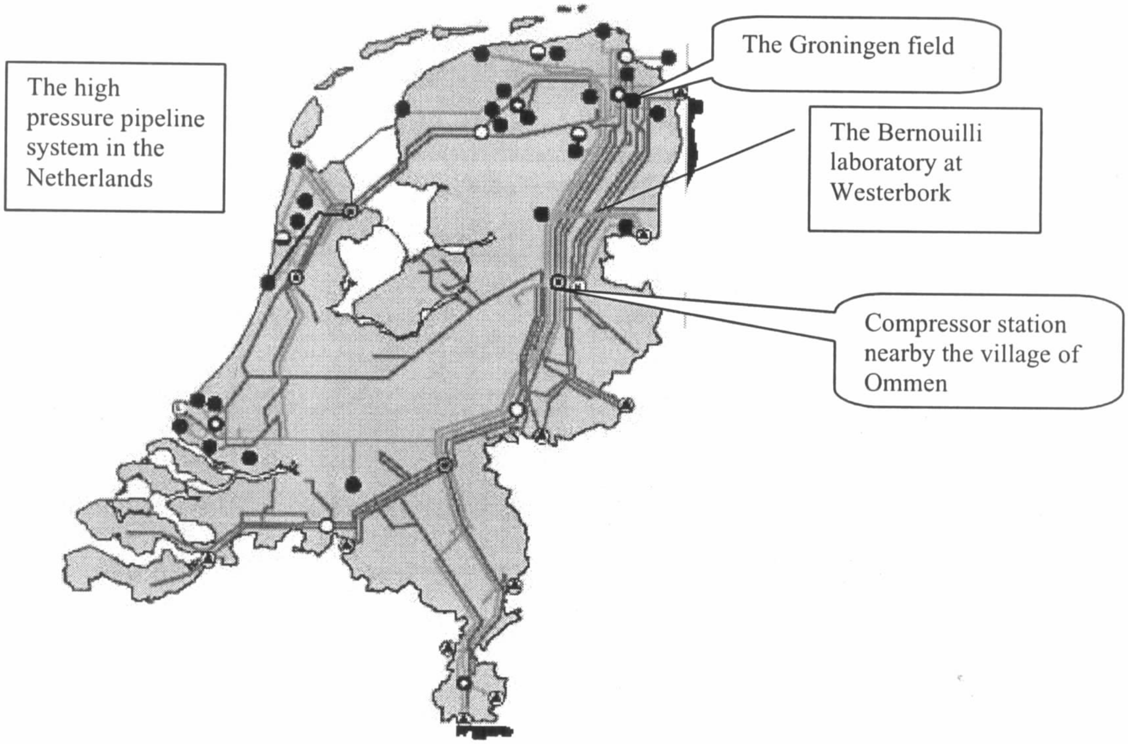


Figure3: The high-pressure pipeline system in the Netherlands

During winter the gas flow of the Bernoulli laboratory can be varied between 100 and 28,000 m^3/h at ~62 bar and ~10°C. At any time at least one third is available, which means that the laboratory is one of the largest high-pressure flow test facilities in the world. Largely due to its favourable position in the Dutch gas transport network (the distance between Westerbork and the compressor stations being approximately 50 km) the influence of pulsations in the gas flow can be neglected.

The long straight pipe length of both test sections is favourable for arranging gas meters at reference flow conditions (free from any flow disturbance). Taking all aspects into account, the Bernoulli laboratory offers exceptionally stable circumstances for calibrations and tests.

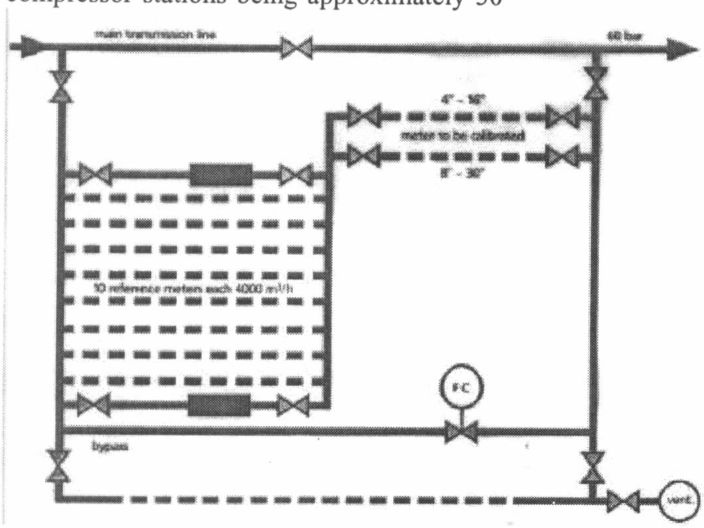


Figure 4: Schematic overview of the facility

4. The importance of traceability to international standards

In general, traceability is intended to achieve equal measurement results independent of when, where and how it was achieved. Only when this can be assured, fair trade can take place. Formally, a traceable measurement is one for which all steps from its derivation from the primary realization of its unit, together with the uncertainty contributions in each of the steps, are known and well established. The methods applied in the Netherlands for the traceability of the Bernoulli laboratory are described below.

5. How to trace the measurement of gas volumes to the kilogram in Paris.

For measured volumes, traceability to international standards means that the commercial gas meter is calibrated against a standard. This standard is calibrated against a higher standard and that second standard is calibrated against an even higher standard until the international standards of mass, time and length are reached. The realisation of the unit of volume in the Netherlands follows the reverse route, from Paris, where the kg is kept, via Delft where the primary units of length and time are realised, via Dordrecht, where the first realization of a flowing m^3 is done, and finally to Westerbork. This process is named "Retracement". In a nutshell these steps are:

1. The kilogram in **Delft** (headquarters of NMi-VSL) is calibrated against the kilogram in **Paris**.
2. The units of length and time are realized in **Delft** using their physical principles, according to the international appointments initiated by the BIPM.
3. The first realization of a flowing m^3 of Natural Gas is done in **Dordrecht** by using the so-called Dynamic Displacement Device (DDD). The DDD is operated with a liquid, allowing displaced volumes to be weighed. Heart of the DDD is a floater in a vessel which separates gas from liquid but at the same time transfers liquid flow into gas flow. An accurate density determination on the liquid links mass with volume. The traceability of the density measurement and its relation to different temperatures is a story of its own, performed by NMi-VSL in Dordrecht and Delft.
4. The small prover and the large bell prover are calibrated using de DDD.
5. The CVM-cart, consisting of 3 CVM-meters, is calibrated against the large bell prover and transferred to Groningen. The capacity is 3 times 400 m3/h at 1 bar absolute.
6. In **Groningen**, the CVM-Set, consisting of 10 CVM-meters, and a series of traveling standards are calibrated. Traceability is delivered by the CVM-Cart calibrated in Dordrecht as in step 5. Using the bootstrapping[5] procedure flows between 5 and 4000 m^3/h and pressures between 8 and 35 bar (g) are reached (max 36000 $m3_n/h$).
7. In **Bergum**, a similar procedure as in Groningen is followed. The working standards of Bergum and a series of traveling standards are calibrated. Traceability is delivered by the traveling standards calibrated in Groningen as in step 6. Using the bootstrapping procedure flows between 5 and 4000 m3/h and pressures between 8 and 50 bar are reached (max 132000 $m3_n/h$). A special set of traveling standards is prepared using the Reynolds balancing procedure[6] for the calibration of the Bernoulli laboratory at ~60 bar.
8. In **Westerbork**, the 10 working standards are calibrated by using the bootstrapping procedure and the special set of Reynolds balanced traveling standards calibrated in

[5] Bootstrapping procedure: Using multiple parallel mounted standards, calibrated individually, the calibration capacity is multiplied with the number of standards. The multiplication may either regard pressure or flow rate.

[6] Reynolds balancing: A 60 bar calibration curve is determined by interpolation between calibration curves established at 8, 20, 35 and 50 bars at equal Reynoldsnumbers.

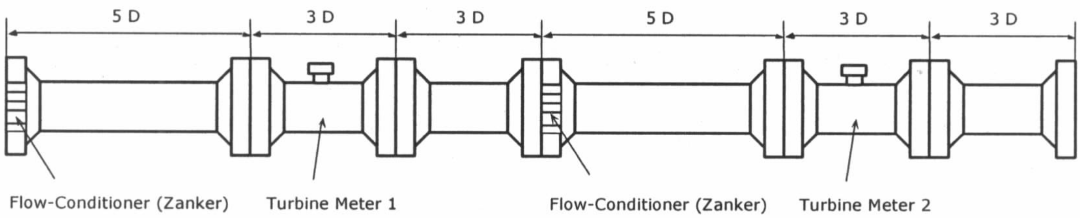
Bergum as in step 7 (max 1500000 $m3_n/h$).

9. **Filtering procedure**: To improve the long-term stability, the results of the last five retracements are taken into account to determine the new m^3. This is done by weighing the retracement results with the factors 1/2, 1/4, 1/8, 1/16 and 1/32 respectively, decreasing factors with age. The sequence is normalized to give 100%.
10. **Harmonisation**: In June 1999, NMi VSL of The Netherlands and PTB of Germany, have agreed to disseminate the same reference value of a cubic meter for Natural Gas. BNM of France, joined as well on May 4th 2004. By calibrating a special set of harmonisation traveling standards in the involved calibration facilities, the in-between difference is determined. The in-between difference is divided according to the "weight" of the facility set by the square of its uncertainty specification, resulting a "harmonisation factor" for each facility. Each facility adjusts its standards by its own harmonisation factor.

6. Re-calibration cycle of the Bernoulli laboratory

The previous chapter illustrated the long trace from the unit of mass in Paris to the calibration facilities in Groningen, Bergum and Westerbork. It takes about three months to complete the procedure. To avoid bias and to keep accuracy under tight control instrument-checks and procedures have been developed for every step in the process.

The ten reference (working) standards of the Bernoulli laboratory are compared individually by using several sets of turbine meter packages, using their universal deviation curve as a carrier of traceability. Obviously the deviation of the values read from a working standard compared to the values read from each of the traveling reference meters need to be identical ('consistency checking'). The traveling reference meters are mounted in a tandem configuration: flow straightener - inlet pipe (5D) - turbine meter - outlet pipe (3D), followed by an identical second package.



Despite the fact that the facility has ideal flow conditions, eventual installation effects like a non-uniform flow profile and swirl are completely isolated from the traveling reference meters by using flow-conditioners.

In the following graph, typical results are shown from a calibrated (working) standard of the Bernoulli laboratory.

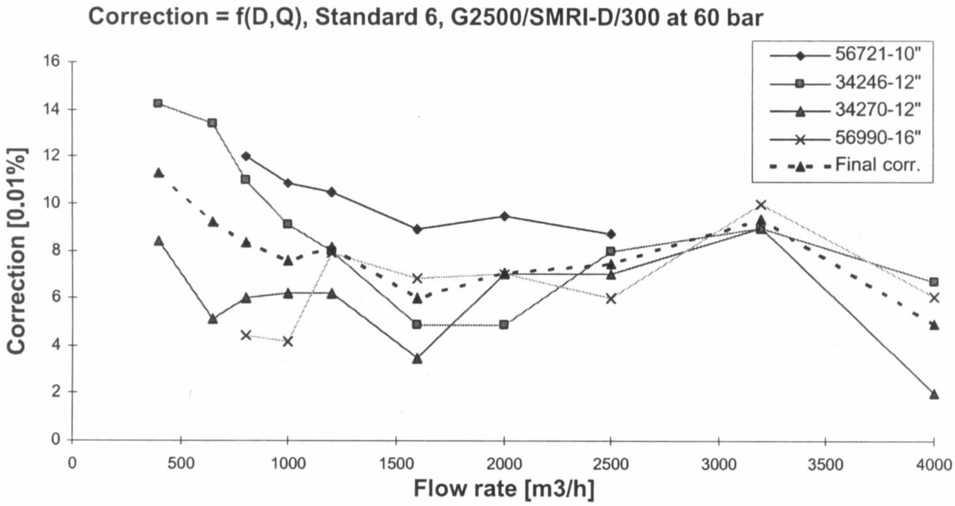


Figure 5. Correction factor of (working) standard 6 determined from four different traveling reference meters

For each standard the average correction curve from all traveling reference meters ("Final" correction in fig 5) will be passed to the filtering procedure and the harmonisation procedure. After completion of these procedures, the filtered and harmonised correction curve is determined and the standards are adjusted accordingly. The adjustment is implemented as a 'Straatsma' model of polynomial correction in the data acquisition computer of the facility.

7. Maintenance of the calibration status of the Bernoulli laboratory

It is vital to check the metrological status of the working standards of the Bernoulli laboratory on a regular basis. An extensive procedure was developed to keep track of the individual status of each reference meter.

Three monthly extensive crosschecking

At an interval of three months, a so called 'quarterly check' is carried out with one or two transfer packages. At each quarterly check, other transfer packages are used (different diameters). The procedure for crosschecking runs as follows:

The transfer package (tandem turbine configuration) is brought into position.
Both turbine meters are calibrated at a pre-defined set of flow rates, as if they were 'meters under test', using every working standard of the Bernoulli laboratory.
The determined deviation curve of each 'meter under test' is compared to the deviation curve that should have been found (the 'Harmonized reference deviation curve').
These substantial amounts of data along the deviation curves are consolidated to two representative figures: one for the flow range from 20% up to 100% and another one for the range 0% to 20% of Q-max (maximum flow of the meter).
The non-conformities are evaluated. Deltas smaller than 0.1% are acceptable and higher deltas are subjected to closer review in the technical expert team of Gasunie and NMi VSL.

If the delta's turn out to be more than 0.1%, the working standard under review is subjected to internal inspection or other tests. If the standard shows insignificant abnormalities, the deviation curve will be adjusted (new polynomial coefficients), otherwise the standard will be overhauled. See figure 6 for a typical result of a quarterly check.

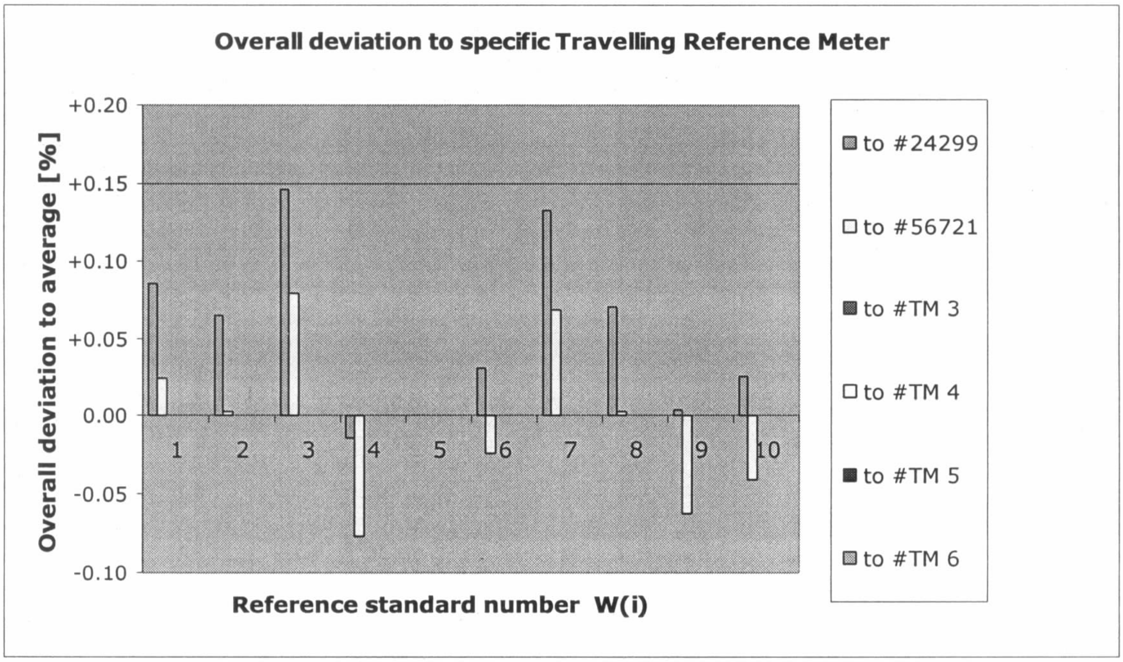


Figure 6 Result of three-monthly check; up to six traveling reference meters may be used, in this example, only two are used (24299 and 56721); The ten working standards are referred to as W(i).

Figure 6 shows that working standard number 3 (W3) must be inspected since the average deviation using both traveling reference meters exceeds 0.1%. This is not the case for W7 despite the deviation >0.1% against one of the traveling reference meters. The strongest possible consistency would be the case when the light blue bars and the dark blue bars are of equal length and show numbers close to zero.

Two weekly single flow rate testing.

Another crosschecking method that is used on a regular basis is the single flow rate procedure. The procedure of this simplified crosschecking method is as follows:

An arbitrary device under test, that was already mounted in one of the two metering runs, is used. At only one pre-defined flow rate, the device under test is calibrated against each working standard of the Bernoulli laboratory. The determined calibration results (one for each of the 10 working standards) are averaged to get the best-known reference value at that moment. The individual deviations may not differ by more than 0.1% from the average. If a standard exceeds that limit, it is treated as in the procedure for the quarterly check. See figure 7 for a typical result of a two weekly crosscheck.

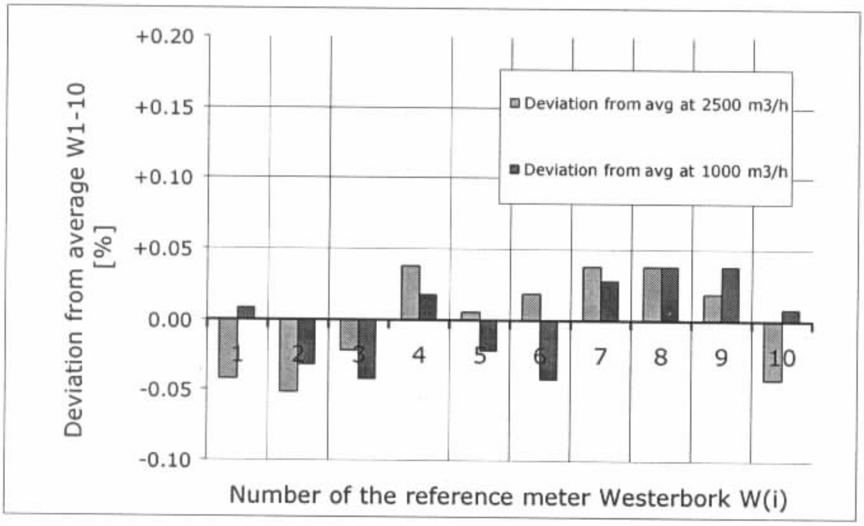


Figure7 Result of Two-weekly check

Figure 7 shows that no single standard requires inspection.

Continuous 'Watchdog checking'

The conglomeration of several test facilities in the Netherlands is ideal from perspective of intercomparing calibration results of single meters that have visited two or more test facilities in a short time. Meters that have been calibrated at different pressure stages are designated 'Watch dog meters'. The procedure starts to 'bark' when during the evaluation of the test results in the Reynolds domain a growing difference between the test facilities appears. Among others, the Bernoulli laboratory is subjected to this procedure continuously.
Obviously, only 'Reynolds-balanced' gas meters, e.g. turbine meters, vortex meters and orifice plates, are used for watchdog checking. Rotary gas meters are rarely calibrated in 'Westerbork' due to their restricted capacity. Therefore, they are excluded from this type of consistency checking. The use of Ultrasonic- and Coriolis gas meters is under consideration since confidence in their reproducibility is growing.

8. Short- and long-term behaviour of the reference meters, Calibration and Measurement Capability

As a result of the extensive two-weekly consistency tests and the three monthly intermediate calibrations of the reference meters, the short and long-term behaviour of the reference meters has very well been observed throughout the past decade

From laboratory tests it is shown that the intrinsic average drift of highly qualified turbine meters is 0.02% per year. This can only be proven by using extremely stable reference standards like Piston provers or Bell provers. Apparently, this figure depends highly on the degree of operation and other environmental conditions (like mechanical and pneumatic vibrations, sudden temperature variations, contamination etc.)

The reproducibility figures in the following table include all (random) variation results of secondary parameters, like temperature, pressure, supercompressibility factors, timing, and pulse counting. They are favoured by the advantageous operational conditions of the Bernoulli laboratory and the thorough inspection-, revalidation- and maintenance procedures. The figures are presented as two times standard deviation.

	Flow rate < 1000 m^3/h	Flow rate > 1000 m^3/h
Short term reproducibility, hourly stability, using only one reference meter 1)	0.06%	0.02%
Intermediate term reproducibility, day to day stability 1)	0.12%	0.06%
Long term stability, up to 3 years 2)	0.22%~0.16 %	0.06%~0.10%
Reduced baseline uncertainty profiting from the Harmonized Reference Values NMi/PTB/BNM 3)	0.16 %	

Source:
1) Intercomparison Exercise of High Pressure Test Facilities Within GERG, GERG TM12 2001
2) Uncertainty analyses of the Bernoulli laboratory, re-calibration cycle of 2003/2004.
3) Calculation of the Harmonized reference Value for High Pressure Natural Gas based upon the 'Annex-1 procedure' of the contract that is accepted by NMi/PTB and BNM, see also section 3.9 'The Harmonization process; the 'European reference value for High -pressure gas volume measurements'.

Figure 8 shows an overview of the determined reproducibility and uncertainty. The accumulated uncertainties of all steps preceding the retracement of the Bernoulli laboratory is represented by $U_{(harmonized)}$=0.16%. The reproducibility of the reference standards and the secondary equipment is added to determine the two CMC values (CMC=Calibration and Measurement Capability).

The coloured lines in figure 8 represent the individual long term reproducibility of the 10 reference meters. The two reference meters that are used for small flow rates are mounted closest to the 'Device under Test', preventing too much dead volume between the meters. The other eight reference meters are not used at flow rates smaller than 800 m^3/h actual.

The reproducibility (long term stability) is based upon the observed drift of each reference meter after a full retracement cycle. This figure is pessimistic since the information of the watchdog system is not included. In figure 8 this uncertainty budget is marked as: Max $u_{long\ term}$

When using two or more reference meters in parallel, the compound reproducibility improves compared to the use of a single standard; these figures will be indicated as $CMC_{using\ two\ ref.meters\ in\ parallel}$ and $CMC_{using\ one\ ref.meter}$ respectively.

The total Calibration and Measurement Capability or 'CMC' is calculated with the Root Sum Square method including a 'near ideal meter' to be calibrated. In metrology, it is a normal practice to regard 'CMC' as the uncertainty that is normally offered to the user 'when he is calling today'. Obviously, when a 'Device under Test' shows a bad reproducibility, the Total uncertainty will increase inherently.

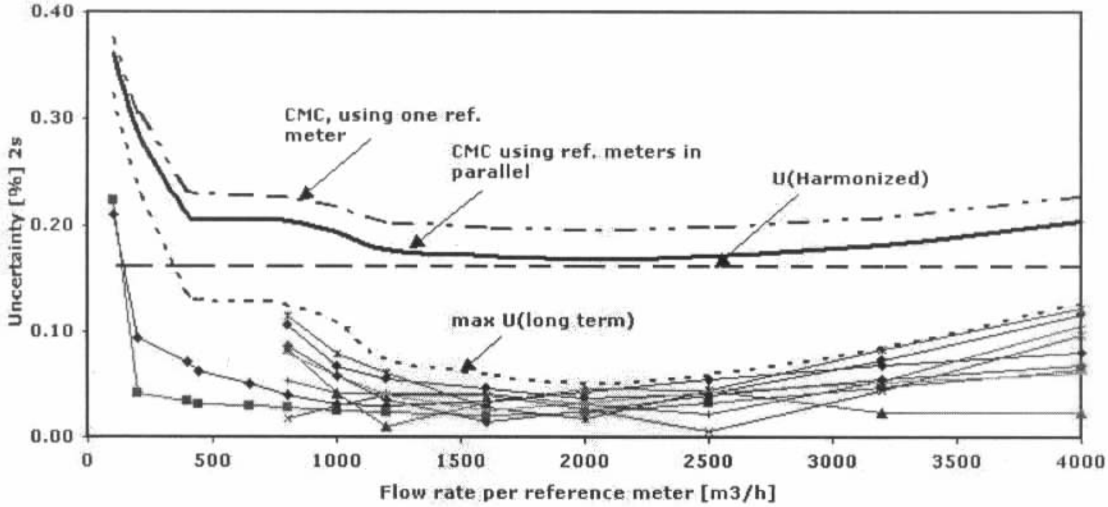


Figure8: Uncertainty and CMC of the Bernoulli laboratory

9 International treaties and ISO 17025 Accreditation

The technical side of traceability has been elaborated in the previous sections, but there is also a legal side to traceability.

The legal side involves international treaties, international organisations and national bodies. In this field, the meter convention of 1870 should be mentioned as well as the International Committee of Weights and Measures (CIPM) and its executive body, the International Bureau of Weights and Measures (BIPM). In the Netherlands, NMi-VSL is appointed by Dutch Law and by Royal Decision as the National Standards Institute. NMi-VSL and other national standards institutes (members of the Meter Convention) have signed an arrangement of recognition (Mutual Recognition Arrangement, the so-called MRA).

The measurement standards institutes must have an operational quality system that demonstrably fulfils the requirements of ISO/IEC 17025. NMi-VSL works accordingly and is accredited by the Dutch authority for laboratory accreditation ('Raad van Accreditatie' or 'RvA') on the basis of ISO-17025 for all calibration activities. The accreditation is checked for competence every year by the RvA by means of the Quality System and technical audits.

Calibration certificates issued directly by NMi-VSL comply with the highest standards of traceability and are 'globally' valid on the basis of international treaties and the EA MultiLateral Agreement of mutual equivalence and recognition (MLA) and MRA.

10 Conclusion

The maintenance of the traceability and the calibration status of the Bernoulli laboratory are done with great care. The reproducibility surveys a 25-year period in which a value between 0.06% and 0.10% has been established. Favoured by the harmonisation of the reference values for high-pressure natural gas between NMi-VSL, PTB and BNM, the CMC is below 0.2%.
NMi-VSL and Gasunie Research are continuously searching for ways to improve the reproducibility and reduce the uncertainty of the Bernoulli laboratory.

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