EuroLoop: Metrological concepts for efficient calibrations and primary realization of accurate reference values in flow

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Abstract

In a previous introductory paper [1], the ranges, possibilities and operation practice of the new calibration facilities for Natural Gas and several Oil products in Europe, are depicted.
The stringent claim on CMC or 'Calibration and Measurement Capability' is the driving force for criteria set for process stability, day-to-day reproducibility, long-term behavior of working standards and finally accuracy of the international linked reference value at the position of the device under test. The superb CMC claims imply highest demands in innovative designing.
This paper focuses on a 'metrological engineering' concept in which via an iterative process a balance is found between: optimal piping configuration, smallest uncertainties, sustainable traceability maintenance at one side and effective operation, lowest operational and capital expenses on the other.
The International traceability of the Hydro Carbon calibration facility (HyCal) will be realized by unique piston provers covering a range up to 5000 m^3/h. Theoretic and empirical correction methods will be avoided and most 'sensitive' parameters will be determined on the spot to increase credibility of estimated uncertainty sources. For instance, e.g. seal leakage, line-pack effects, diameter change will be measured and processed.
International acceptability of these rather small uncertainties will increase when uncertainty estimations are supported by 'on scale demonstration of auxiliary instrument performance' therefore a significant set of tests is scheduled in the near future.
The design of the intelligent piston will be shown as well as simulations of the piston behavior related to pump performance, inertia's, control characteristics of valves etc.
The primary realization will be intrinsic in the piston prover itself and changes of the reference volumes due to pressure, temperature and oil movement will be measured on line.
Traceability of the HP Gas Calibration laboratory will be based upon a Gas Oil Piston Prover and the Dutch-German-French Harmonized Reference Value. The prover was built in 2001 together with a multiplier and carrier of reference values, embodying the new traceability chain. The paper also focuses on the methods and steps to validate and certify such large Natural Gas calibration loop. In due coarse, the public will be informed regularly through series publications.

INTRODUCTION

In the past decade it became clear that the need for test facilities that offer primary standards for large flows in the oil and gas working field is still expanding. New metering principles like Ultrasonic-, Coriolis, Clamp-on US and pipe wall vibration sensing principles seem to always need at least one or repeated validation measurements somewhere in the life-cycle of the instrument, even when manufacturers claim the 'dry-calibration is sufficient' philosophy. The economics of valuable goods on the 'downstream oil and gas side' demands smaller uncertainties and comparable reference values between buyers and sellers (third party access..). For the 'upstream side' the demand focuses upon behavior of instruments, higher MTBF, smaller pressure drops, reliability and scaling of meter behavior at difficult process conditions. NMi has been working over 40 years in the field of large flow HP Gas and intermediate flow hydrocarbons and water for the up- and downstream fields. Round the millennium, manufacturers and end-users communicated concerns about the security of supply of the popular large gas test facilities of ‘Bergum’ (due to the discontinuous ‘gas-sink’: the electricity plant) and ‘Westerbork’ of Gasunie (due to seasonal restrictions) and the lack of test facilities for large hydrocarbon flows with several viscosities in Europe. NMi’s answer to that challenge is found in ‘EuroLoop’: one multiple large flow calibration and test facility offered to the up- and downstream oil and gas field, operational in 2008 (HyCal) and 2009 (GasCal).

What is ‘EuroLoop’?
EuroLoop is a ‘Center for flow technology’ and a ‘European facility for testing under industrial conditions’. It is located in the harbors of Rotterdam, close to refineries and a broad infrastructure. The separate facilities are distinguished in three sections:

1) ‘HyCal’, Hydrocarbon Calibration facility;
2) ‘GasCal’, Gas Calibration facility;
3) ‘GasSep’, Gas Separation test facility (which details will be presented in another publication).

The facilities are partially owned/partially rented by NMi. NMi will be responsible for the operational management, plant facilities, marketing and order intake and planning, service, metrological status and -maintenance. This modus of operandi was chosen to certain the three ‘Cornerstones’ of a National Metrology Institute: absolute independency, -impartiality and -integrity.
Obviously, putting the three facilities together at one site, optimal synergy in client- and operation facilitation is obtained.

Overview of the ranges:

HyCal: Calibration facilities for Oil and Oil products

Overview of specs:

Type	Closed circuit, master meter method and provering method
Flow	10 – 5000 m^3/h
Line sizes	4" – 24"
Traceability	Piston prover, on-line geometric
Medium	several oil products
Viscosity	1, 10, 100 cSt (1200 cSt)
Piston Provers	2 (40 meters long, $U_{k=2} \leq 0.02\%$)
Master Meters	18 ($U_{k=2} < 0.05\%$)
Temperature stability	better than 0.5 ^oC
Line pressure	Up to 10 bara
Line temperature	19 – 35 ^oC (freely adjustable)
Number of test runs	6 (2 per test liquid, simultaneous operation of six metering runs possible)
Capacity	600 calibrations per year

GasCal: Calibration facilities for Low to High pressure Natural Gas

Overview of specs:

Type	Closed circuit, master meter method
Flow	5 – 30 000 m^3/h at working pressure
	5 – 1 800 000 m_0^3/h equivalent atmospheric conditions
Line sizes	2" - 30"
Medium	Air, Natural Gas, CO_2, variable mixtures (like H_2/CH_4 in the future)
Traceability ladder	Gas Oil Piston Prover and step up flow
Line pressure	1 – 78 bara (freely adjustable)
Line temperature	5 – 35 ^oC (freely adjustable)
Uncertainty	better than 0.20%, 0.15% typical, 0.10% possible (k=2)
Temperature stability	better than 0.05 ^oC
Pressure stability	better than 5 mbar
Number of test runs	5
Capacity	800 – 1500 calibrations per year

Metrological designing

The design process that is used in EuroLoop is shown in a simplified flowchart in Figure 1.
The main feedback loops are:

- Metrologic (re) designing, an iterative process of innovative thinking, feasibility study of uncertainty claim, conservative estimation of uncertainty budgets;
- Front-end engineering, Process and instrumentation diagrams, calculation of operating points, defining rotation equipment, heat exchangers, and other critical equipment (long lead items);
- Capital Expenses calculation, decision point whether to simplify the design, to accept a higher CMC or to find extra funding;
- Detail engineering with process simulations to prevent from process instabilities leading to lower reproducibility of the measurements;
- Realization, commissioning and fine tuning;
- Commissioning, 1st calibration, certification and acceptance;

The grand loop at the right side (Metrological acceptance procedure) is also dependent on international acceptance which can only be achieved after participation in one or more ‘Key Comparison programms’ organized by the BIPM, the ultimate ‘examination board’ for National Measurement Institutes.

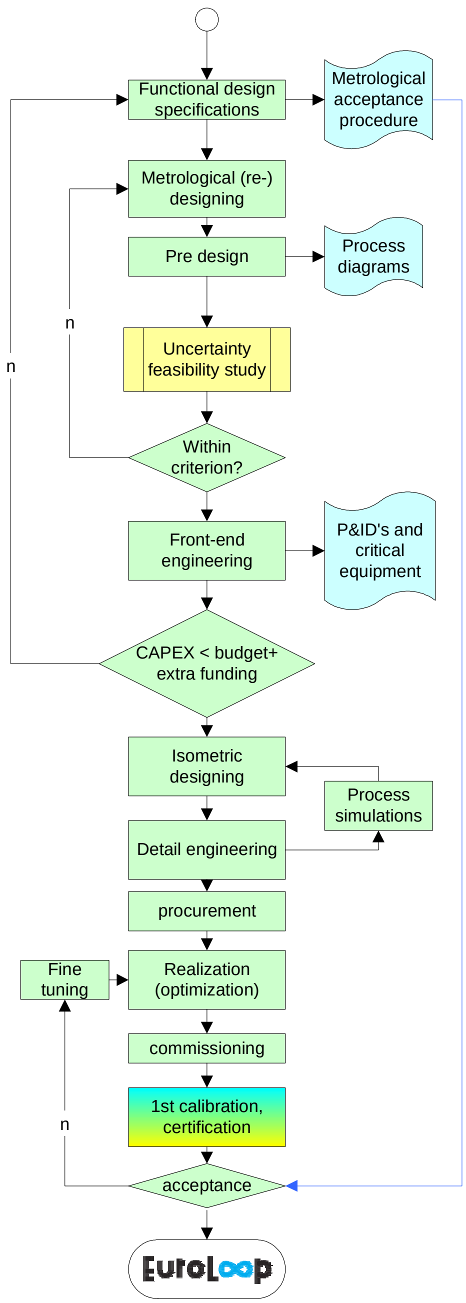


Figure 1: Euroloop Flowchart

Feasibility study claimed Calibration and Measurement Capability

As depicted in the previous section, the feasibility study of uncertainty budgets is crucial to prevent from disappointments or to put lost efforts in parameters that does hardly play a role and vice versa.
In this example, the uncertainty analyses of the HyCal facility is given as an example because related to GasCal in HyCal, more innovations had to be examined. In the modeling phase, the departure point is the mass balance that in all cases will remain stable during the measurement process ('quasi stationary flow').
The main dependencies are:

A) Provers' displaced reference liquid volume is related to:

- Length between switches (base travel length of the piston);
- Average Diameter of the prover (base area);
- Prover wall temperature (expansion of the prover due to temperature);
- Mixed cup temperature of the liquid between the switch sensors (density of the liquid);
- Gauge pressure in the prover (expansion of the prover cylinder due to pressure);
- Absolute pressure inside the prover (compression of the liquid and thus density);
- Prover wall gauge (expansion of the cylinder area);
- Young's modulus (elasticity of the wall material);
- Cubic expansion factor of prover material (temperature) ;
- Cubic expansion factor of liquid;
- Compressibility factor of the liquid.

B) The base volume determined at the reference point of the meter under test is related to:

- Temperature change in the dead volumes between piston prover and DuT during test run;
- Mixed cup temperature at the reference point of the DuT;
- Leakage between DuT and prover (e.g. through piston sealing);
- Geometry of the pipe length, -diameter, -wall gauge (elasticity and thermal expansion during test);

Some aspects like vapor bubbles inside the system will cause extra line pack effects due to instable process pressure 'in- and expiration' effects that are hardly calculable. It is of crucial importance to keep this amount of uncontrolled vapor as small as possible for it will lead to a decrease in repeatability.
The basics of uncertainty analyses read like:

$U = \sqrt{\sum_{par=1}^{par=n} \left(\frac{\delta V_{ref}}{\delta x} * \Delta x\right)^2}$, in other words: the effect of each individual parameter on the final uncertainty in reference volume (at the reference point of the DuT) is the square root sum of all individual contributions. The sensitivity factors are determined either analytical or numerical. For complicated models, often the numerical method is used and is presented in table 1

The sensitivity factors $\frac{\delta V_{ref}}{\delta x}$ are shown in the table as a percentage of Volume equivalence for easy comparison and to get a feeling which parameter is significant and which is not.

In this example, the small prover design is scrutinized on uncertainty budgets and crucial parameters can be appointed and further optimized if needed.

Parameter	value	unit	uncertainty (k=2) dX	unit	sensitivity factor	uncertainty in volume (k=2)	Impact on Vref %
					% / dX	%	
						0.017	100.0
Length between switches	20	m	0.002	m	5.000E+00	0.010	33.1
Diameter prover	0.564	m	0.0000123	m	3.546E+02	0.0044	6.3
Q operation	1200	m3/h					0.0
E mod	2.00E+11	kPa	2.00E+10	kPa	-1.283E-14	-0.00026	0.0
Wall gauge	0.05	m	0.2	mm	-1.128E-02	-0.002	1.7
Operation pressure	500000	Pa	1000	Pa	9.106E-08	0.0000911	0.0
Rho ref	800	kg/m3	2	kg/m3	-1.238E-04	-0.00025	0.0
Cub exp prover gamma	2.23E-05	C-1	2.23E-06	C^-1	1.360E+00	0.000003	0.0
T prover	15.00	C	0.10	C	-9.038E-02	-0.009	27.0
Pressure dead vol @ time 1	400000	Pa	1000	Pa	-1.119E-07	-0.00011	0.0
Press rise/min	500	Pa					0.0
Pressure dead vol @ time 2	400125	Pa	1000	Pa	1.119E-07	0.00011	0.0
T dead vol @ time 1	18	C	0.1	C	9.922E-02	0.002	1.6
dT dead volume netto			0.02	C			
Temp rise/ min	0.05	C/min					0.0
T dead vol @ time 2	18.01	C	0.02	C	-9.922E-02	-0.002	1.6
Dia connectionpipe	0.3048	m	0.005	m	-8.100E-03	-0.000041	0.0
Length connect pipe	**75**	m	1	m	-1.634E-05	-0.000016	0.0
Wall thickness dead v	0.01	m	0.001	m	-1.822E-04	-0.0000002	0.0
Pressure at DuT	1.00E+05	Pa	200	Pa	-8.539E-08	-0.000017	0.0
T at DuT	15.00	C	0.10	C	9.285E-02	0.009	28.5
Repr,due to mech. instability			0.00	%	1.000E+00	0.00	0.0
Leakage			0.00	%	1.000E+00	0.00	0.0

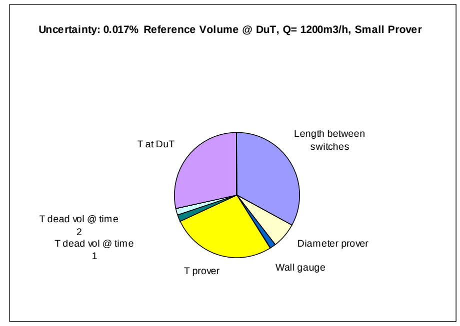


Figure 2: Impact of several uncertainty budgets

Table 1: 0.017% feasible uncertainty

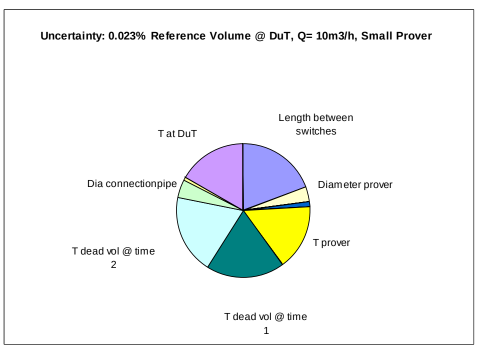


Figure 3: ‘balancing’ uncertainty

In the example, the feasible Best Measurement Capability of the Small prover at a flow rate of 1200 m^3/h is 0.017%
The significant parameters are apparently:
Length, diameter and the temperatures of the liquid in the prover and DuT. A remarkable fact is that the temperature measurement of the dead volumes does hardly play a role of importance. However when the flow rate is decreased to 10 m^3/h other parameters start to play a larger role like the dead volumes and every related parameter to that (temperature of dead volumes, diameter of connection pipes) and uncertainty tends to 0.023%.

What do we learn from these exercises?

1) For reaching highest accuracies, temperature effects need to be determined with small uncertainties. This is not a surprise; volume flow measurements are highly depending on temperatures as we see in gas as well as liquid metering. Temperature effects (unknown, uncorrected) often cause measurement noise.
2) It is not necessary at this stage to improve diameter accuracy (‘on line diameter determination’), it won’t help to improve the final uncertainty at this stage unless parameters length, and several temperature are improved first.

Note that the uncertainty budgets for reproducibility (a.o. due to axial vibration of the prover) and leakage are set to zero. See section ‘Added value of an intelligent prover’ for the motivation.

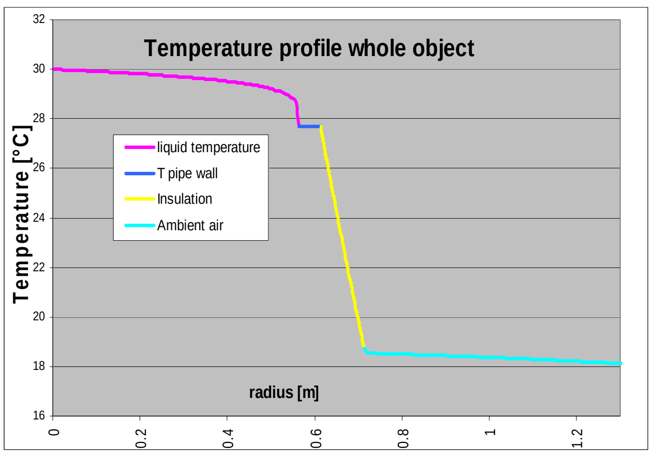
Such a high accuracy claim in metering 'mixed cup temperature' is this realistic for large pipes?

Temperature metrology in general is a rather strange working field. In fact measuring temperature of a substance is done by measuring the temperature of the tip of the sensor assuming that this tip is representing the representative (in liquid sometimes referred to 'mixed cup') temperature, which hardly ever will be the case. This is exactly the problem with temperature determination of large volumes, what does the profile look like?
The mixed cup temperature is defined as the temperature that would be read if the amount of passing liquid had been stirred. Mathematically it looks like:

$$T_{mixed} = \frac{2}{R^2}\int_{r=0}^{r=R} T_r \cdot r \cdot \delta r$$

Especially at the low flow rates/small turbulence (small Reynolds numbers) the temperature gradient in the liquid follows can be quite steep due to heat flow through the pipe wall via the stem of the thermo well. In the next graph, an example of a theoretical temperature profile is depicted. The study focuses on the large piston prover: Diameter prover cylinder 1.127 meter, pipe wall gauge 50 mm, ambient temperature 18°C, ambient air velocity 1 m/s, liquid temperature in center of the pipe 30 °C , flow rate 70 m^3/h and pipe insulation: 100 mm of mineral wool.

The left graph represents the cross section of the prover pipe in the temperature domain. The other graph focuses on the detail temperature profile inside the prover pipe and shows the deviation of the measured temperature related to the real liquid temperature. The temperature reference point position (sensor tips) is indicated by the red dots on the graph. The difference amounts about 0.25°C (see arrows) which would be a disaster considering the high accuracy claims.



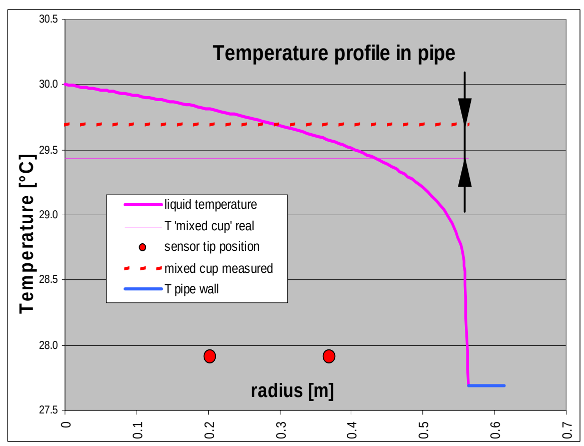


Figure 4: Temperature profiles

Fortunately the temperature profile will be less violent as in this theory, because of higher turbulence due to lots of bends in the closed circuits. However it is hard to estimate the uncertainty budget of this deviation and therefore NMi decided to put efforts in a system that could minimize these measurement deviations (See next section).

Mixed cup temperature measurement with ultrasound techniques.

In general, the speed of sound of a fluid is defined by: $c = \sqrt{\frac{B}{\rho}}$ m/s in which B is the 'Bulk modulus' or volumetric elasticity defined as: $B = \frac{\delta P}{\delta V / V}$ (reciprocal of compressibility of the fluid). In the following section, the speed of sound is presented as a function of reference density of the fluid and the mixed cup temperature.

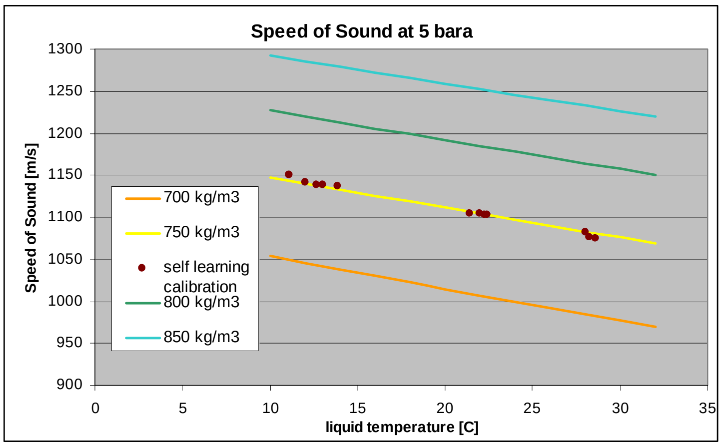


Figure 5: Speed Sound at 5 bara

The decay in speed of sound (slope) is roughly 3.5~4 m/s/°C.
For the indicated small temperature range, the relationship T=f(SoS) can be given by the linear relation: T=*a*+*b**SoS.

In HyCal, both factors *a* and *b* will be determined on site with an on line 'SoS calibrator'. The working principle is depicted in the next diagram.
It is of crucial importance to have a high resolution in the timing parameters of the ultrasound signal.

For the 1.127 diameter prover, the traveling time difference (resolution) of the ultrasound signal at a 0.01 °C temperature change of the fluid amounts 25 ns at minimum. For the small prover, the timing becomes more critical: 6 ns. Fortunately state of the art ultrasonic timing techniques offer these claims easily. In HyCal, the reference density will be stable for a certain period in time while circulated in the calibration loop. The loop will be provided with a 'self learning calibrator' to find the SoS for a given process condition (the a and b coefficients).

The SoS will be related to a high precision temperature reference standard in an on line passive thermostatic bath (see Figure 6). At the start up, factor b (slope) will be based upon literature and factor *a* ('zero shift') will be determined on the spot.

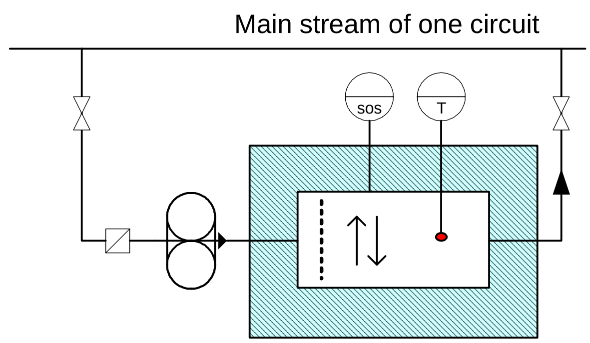


Figure 6: online T=f(SoS) calibrator

Design Details 'HyCal'

In this section, the design of the hydrocarbon liquid calibration facility 'HyCal' will be discussed.

Process flow diagram

The design consists of the following parts (see Figure 7):

- Three separate circuits (only circuit 1 has been drawn in Figure 7) for 3 types hydrocarbon liquids with viscosities in the order of 1, 10 and 100 cSt;
- A large and a small piston prover, that can be alternated to each circuit;
- Crossover headers for primary calibration enabling to put the small and large reference runs and metering runs in series;

Per circuit:

- One small and one large reference loop (6", 10" and 16" multipath ultrasonic meters);
- Two meterruns (12"and 24");
- A set of pump trains, variable speed drives, heat exchanger, flow regulating valves each loop;
- One automatic liquid expansion/pressure control system that works also as an analyser for line pack effects.

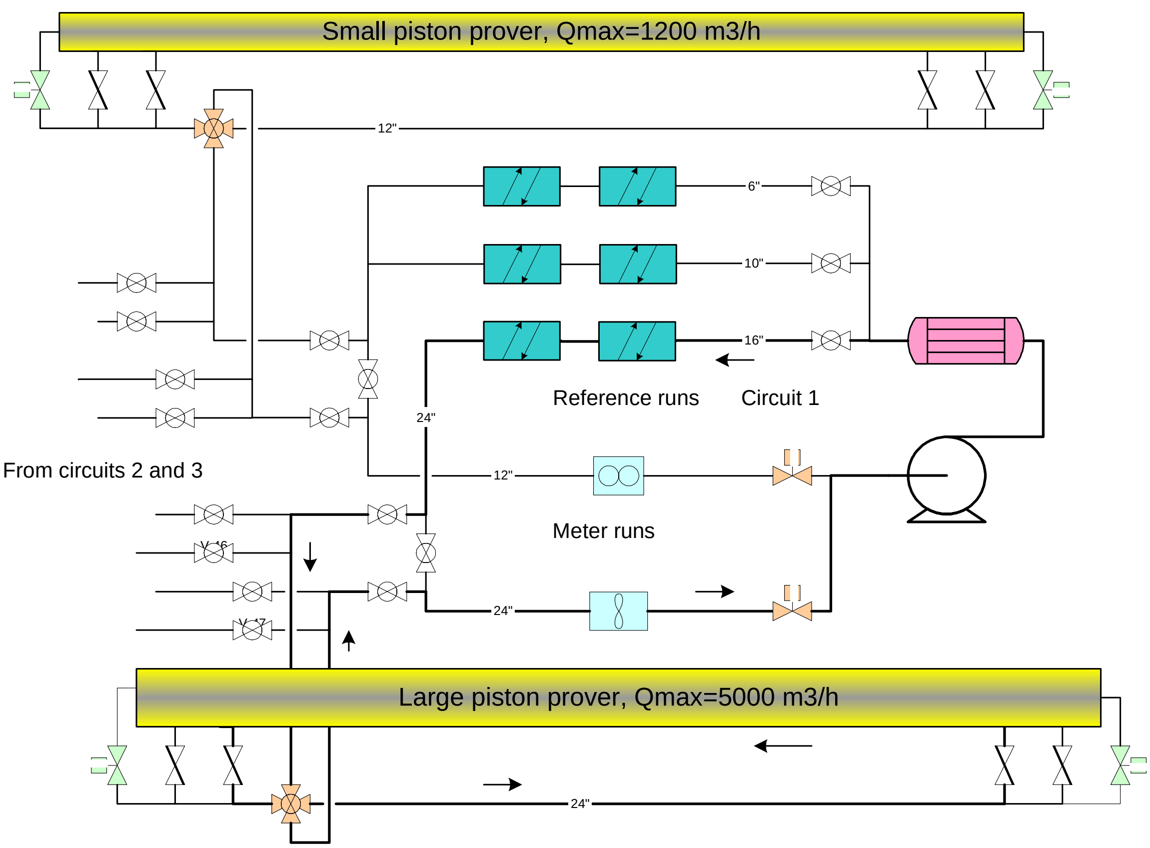


Figure 7: Simplified process flow diagram

A focus point in this design is to have all circuits connected and considering as small dead volumes as possible between DuT, reference meters and piston provers. Most globe valves are double block and bleed types for the obvious reason to prevent from the smallest internal leakage.

Piston provers
The two 40-meter long bi-directional piston provers respectively 1127 and 564 mm in diameter are provided with intelligent pistons (see below). The main challenge in the design lies in the way the pistons are to be launched and stopped at the desired position.
Extensive simulation studies have shown that three in- and outlets were needed for each of the provers to get full control over the dynamics. Furthermore, the in- and outlet grating patterns needed optimization in order to reduce pressure peaks when operating in piston launch- and decelerate modes, especially when taking water hammer into account on a prover containing almost 40 tons of liquid.

Simulation of the acceleration and the deceleration process of the pistons
The following issues were taken into account in the design process:

- The piston has to reach a steady velocity before the first ‘start sensor’ is reached;
- Water hammer needs to be avoided at all times;
- Cavitation needs to be avoided at all times;
- The acceleration and deceleration strokes need to be as short as possible to reduce investments on high precision pipe;
- The acceleration and deceleration strokes need to be as short as possible to reduce precious waiting time;
- The piston must have a slow speed when the end buffer is approached and a 3-point calibration of the proximity sensors can be achieved each piston stroke (see section ‘intelligent piston’).
- The deceleration shall be ‘fail safe’ e.g. when choking valves fail to close down during the run

Traceability chain, HyCal

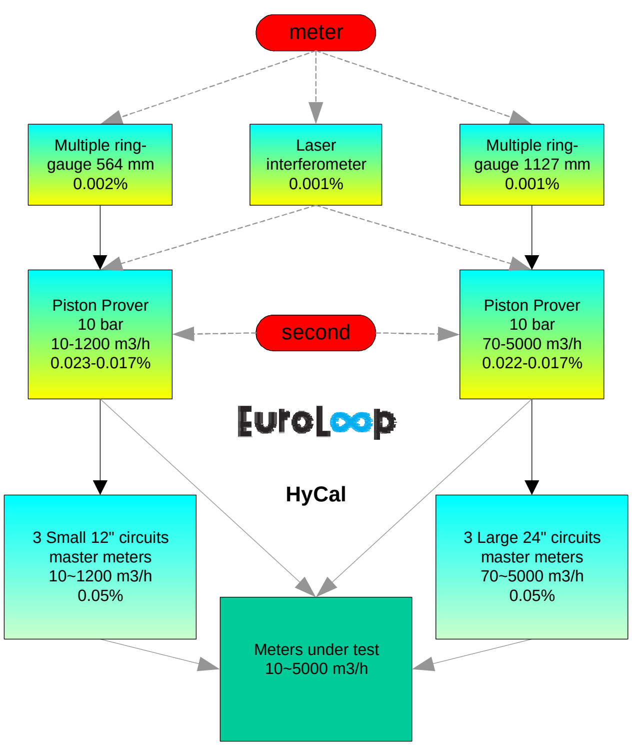


Figure 8: Traceability scheme HyCal

In the next traceability chart the dissemination of SI-units throughout the range of ‘HyCal’ is based upon geometric determination of reference volume by online diameter comparison of the cylinders with a multi-step ring gauge (diameter) and with a laser interferometer (length between the switches). The complete rangeability is based upon the intelligent piston provers without interference of step up TRMs or multiplier techniques. Advantage of that is:

- Transparent uncertainty analyses;
- Small uncertainties;
- Efficient full range recalibration of the master meters;
- No down times for the calibration of prover diameters.

Simulation backgrounds and results of the piston movement to assure safe and stable operation

A pre-study of the piston movement was necessary for two reasons.

- The piston must have a stable velocity before reaching the first inductive timer switch to enhance mechanical reproducibility;
- The piston must decelerate in a controlled and safe way.

The basics of the simulations were as follows:

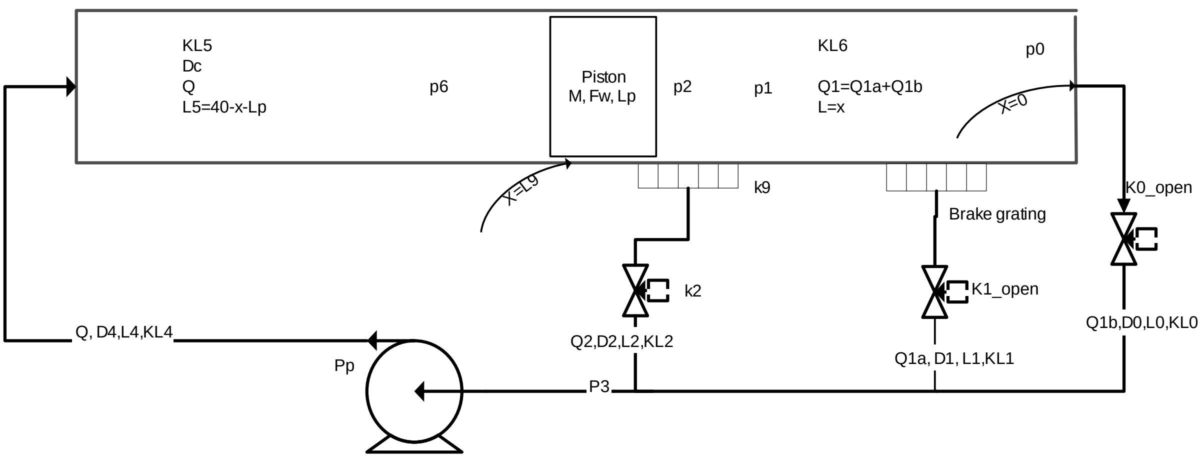


Figure 9: Simulation of the decelerating mode of the piston approaching the terminal

General:

A=Area in m^2

$dP_{pipeline} = \xi \bullet \frac{L}{D} \bullet 1/2 \bullet \rho \bullet \frac{Q^2}{A^2}$ or simplified $dP_{pipeline} = k_L \bullet Q^2$

$dP_{acceleration} = \frac{L}{A} \bullet \rho \bullet Q'$ (with $Q' = \frac{\delta Q}{\delta \tau}$) or simplified $dP_{acceleration} = I \bullet Q'$

Phase 1: assume Q1b=0 (valve K0 is closed) so that Q1a=Q1

$Q = Q_1 + Q_2 = \text{Constant}$ (1)

so that

$Q' = Q_1' + Q_2' = 0$ therefore $Q_1' = -Q_2'$ (2)

<u>Pressure relations focusing differential pressure p2-p3:</u>

counter clockwise

$p_3 = p_2 - k_9 \bullet Q_2^2 - k_2 \bullet Q_2^2 - k_{L2} \bullet Q_2^2 - I_2 \bullet Q_2'$ => $p_3 = p_2 - (k_9 + k_2 + k_{L2}) \bullet Q_2^2 - I_2 \bullet Q_2'$

or simplified $p_3 = p_2 - X \bullet Q_2^2 - I_2 \bullet Q_2'$ (3)

clockwise $p_3 = p_2 - (k_6 + k_1 + k_{1\_open} + k_{L1}) \bullet Q_1^2 - I_1 \bullet Q_1'$

or simplified $p_3 = p_2 - Y \bullet Q_1^2 - I_1 \bullet Q_1'$ (4)

from (3) and (4) $X \bullet Q_2^2 + I_2 \bullet Q_2' = Y \bullet Q_1^2 + I_1 \bullet Q_1'$ (5)

from (5), (1) and (2): $X \bullet Q_2^2 + I_2 \bullet Q_2' = Y \bullet (Q - Q_2)^2 - I_1 \bullet Q_2'$ (6)

leads to $(X - Y) \bullet Q_2^2 - Y \bullet Q^2 + 2 \bullet Y \bullet Q \bullet Q_2 = -(I_2 + I_1) \bullet Q_2'$ (7)

combining the constants: $a=(X-Y)$, $b= -YQ^2$, $c=2YQ$ and $d= -(I_2+I_1)$ (8)

=> $aQ_2^2 + b + cQ_2 = dQ_2'$ (9)

Goal is to solve Q_2 and Q'_2 for this step at time τ_n calculation.

$$Q_2' = \frac{(Q_{2,n} - Q_{2,n-1})}{\Delta\tau} \quad (10)$$

in which $\Delta\tau$=time step per calculation and n = calculation step in progress
Because the previous calculation (n-1) is finished, $Q_{2,n-1}$ was solved and used as input.
Combining (9) and (10) leads to

$$\frac{a}{d}Q_2^2 + (\frac{c}{d} - \frac{1}{\Delta\tau})Q_2 + (\frac{b}{d} + \frac{Q_{2,n-1}}{\Delta\tau}) = 0 \quad (12)$$

From which Q_2 can be solved with the quadratic equation:

$$Q_{2,n\,(I,II)} = \frac{-(\frac{c}{d} - \frac{1}{\Delta\tau}) \pm \sqrt{(\frac{c}{d} - \frac{1}{\Delta\tau})^2 - 4\frac{a}{d}(\frac{b}{d} + \frac{Q_{2,n-1}}{\Delta\tau})}}{2\frac{a}{d}} \quad (13)$$

for the n^{th} calculation step.
If two solutions for $Q_{2,n}$ are present, the one closest to $Q_{2,n-1}$ will be used.

Phase 2:
As soon as the piston approaches brake grating k1, k0 will be opened gradually (in the calculation.)
In normal conditions, k0 is open during the whole run to a certain degree to ascertain a maximum fixed braking flow rate and inherent piston velocity <0.1 m/s

Given: $Q_1=Q_{1A}+Q_{1B}$ (14) And $K_A \bullet \frac{Q_{1A}^2}{A_A^2} = K_B \bullet \frac{Q_{1B}^2}{A_B^2}$ (15)

from which the ratio between the two streams can be calculated:
(Assumption: $Q'_{1B}=0$) (14) and (15) leads to

$$Q_{1A} = \frac{Q_1}{1 + \frac{A_B}{A_A}\sqrt{\frac{K_A}{K_B}}} \quad \text{and} \quad Q_{1B} = \frac{Q_1}{1 + \frac{A_A}{A_B}\sqrt{\frac{K_B}{K_A}}} \quad (16)$$

<u>Position and progress of the piston:</u>

If the piston is at the left side of k9 grating: $x = x - \frac{Q}{A} \bullet \Delta\tau$

If piston on the right side of k9 grating and left side of k1 grating: $x = x - \frac{Q_1}{A} \bullet \Delta\tau$

If piston on the right side of k1 grating: $x = x - \frac{Q_{1B}}{A} \bullet \Delta\tau$

If the friction pressure of the piston (due to the seals) exceeds dP over line 1 or line 2 (dependant on position of the piston) then the piston will not move anymore (x will remain constant)

<u>Equivalent k-factor of route 1, bypassed by bottom pipe line</u>
The equivalent k-factor due to parallel configuration of line 1_A and 1_B that should be used in formula (4) is calculated according to:

$$K_{equivalent} = \left(\frac{A_c\sqrt{K_a}\sqrt{K_b}}{A_a\sqrt{Kb} + A_b\sqrt{K_a}}\right)^2 \qquad (17)$$

Ka = k_pipeline1 + k1(grating) + k1(valve)
Kb = k_pipeline0 + k0(grating)

Results simulated deceleration of the piston, water hammer and cavitation prevented?
The results of the simulations made clear that the wall gratings should have a smooth k-value as a function of passing (‘plugging’) piston. Besides possible damage of the delicate electronics inside the piston a large water hammer effect due to the intense deceleration crossing grating k9 would appear at the cylinder bottom and the piston. Secondly, the sudden flow reduction in pipeline L2 would definitely lead to cavitation (see graph below, smallest piston prover at 1200 m^3/h):

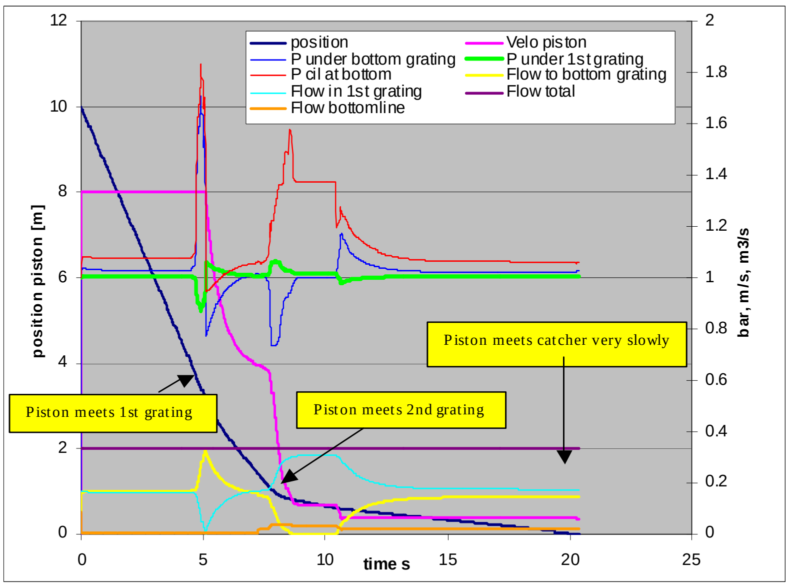


Figure 10: Simulation of the braking process of the piston inside the prover

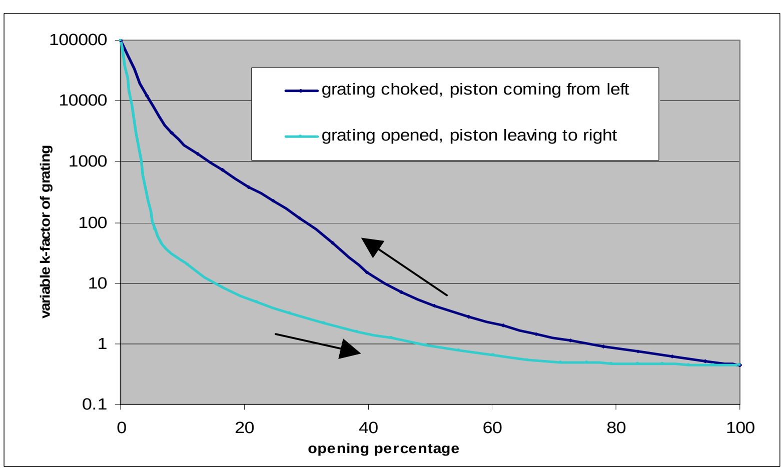


Figure 11: non symmetric grating characteristics

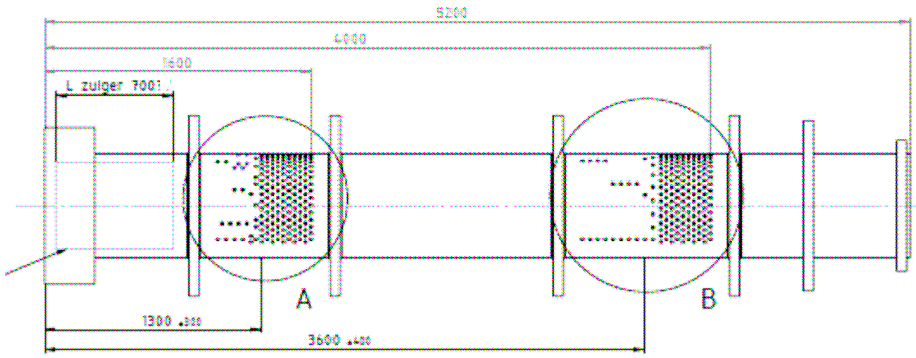
Transients of most important parameters at the phase where the piston approaches the two gratings (piston moves from left to right) are:

- Two small water hammer transients at 1st and 2nd block off
- Two under pressure peaks at both block offs.

These ‘friendly’ transients could only be achieved when the gratings were fine tuned to the process, see design in Figure 12.

Mind that the average process pressure is put at 1 bara, in operation, this pressure would be around 8 bara to avoid any cavitation, decrease volume of vapor bubbles etc.

The grating/piston (piston serves as a plug) combination is used as fail safe (hydraulic) controlled valve during the deceleration process. Interesting to see that the valve has a very asymmetric curve. The ‘valve’ smoothes the movement of the piston running into the right direction. As soon as the ‘valve’ opens again, the average flow rate will not exceed Q_{max}/2 and thanks to the



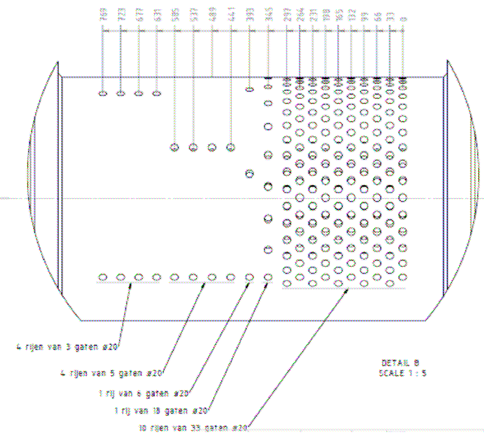


Figure 12: Detail design of the remarkable gratings (small prover)

liquid inertia in line 2, the flow builds up slowly despite the sudden ‘nasty’ opening of the grating.

Launching the piston and keeping the start-up transients under control enhancing calibration stability

The launching mode of the piston prover differs completely from the deceleration mode. In opposite to the later, launching the piston requires the following functionality:
- The stationary flow equilibrium and inherently response of the meter under test may not significantly be affected. (Deviation curve of meter under test is often very much related to actual flow rate)
- The piston should travel with a steady velocity when passing the first and successive inductive timing switches. (Enhancing the repeatability of the piston/run timing configuration)

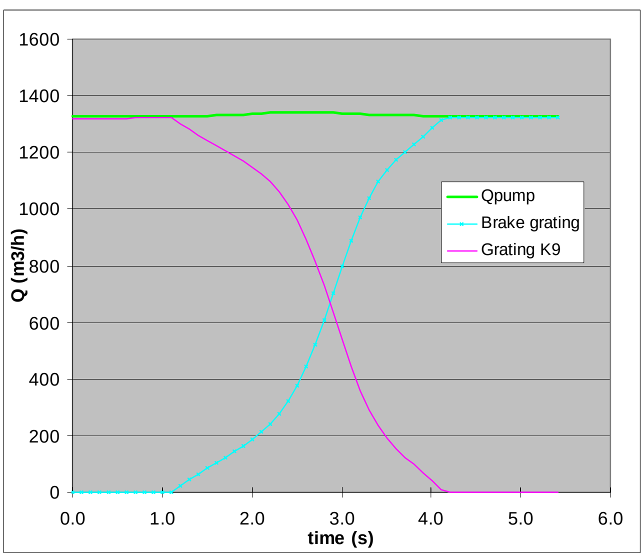


Figure 13: Simulation of the piston launch mode

During startup phase, the prover wall grating hydraulic friction is kept constant and the flows will only be controlled by motor operated fast control valves.
In Figure 13, the wall grating valves (butterfly types) are closed vice versa opened with a constant rotational speed of the valve stem within 3 seconds. Depending on the delay times between the two valves and the friction-factor as a function of opening ratio, the flow rate stability can be optimized so that the piston velocity is as stable as possible when passing the start timer switch.

What is the added value of an intelligent piston?

After some feasibility studies related to uncertainty budgets, NMi concluded that the only way to reach such demanding accuracies was to get a continuous online geometric calibration of the piston switch volumes available for each measuring run. (See section 'feasibility uncertainty')

Furthermore, a National Measurement Institute has to offer transparency in uncertainty analyses, which means that there is a constant strive to determine the amplitude of each uncertainty source rather then proposing estimates of uncertainty budgets and wait for endless discussions such as:

- How can the uncertainty budget of seal leakage be quantified?
- How can be proven that the piston is traveling at a steady velocity?
- What is the real expansion of the prover under the given process pressure?
- What is the real deformation of the prover due to irregular mechanical load?
- What is the real diameter expansion of the prover, due to temperature differences along the 40 m long provers?

Expected deformation of the precision prover pipes after on site assembling and positioning

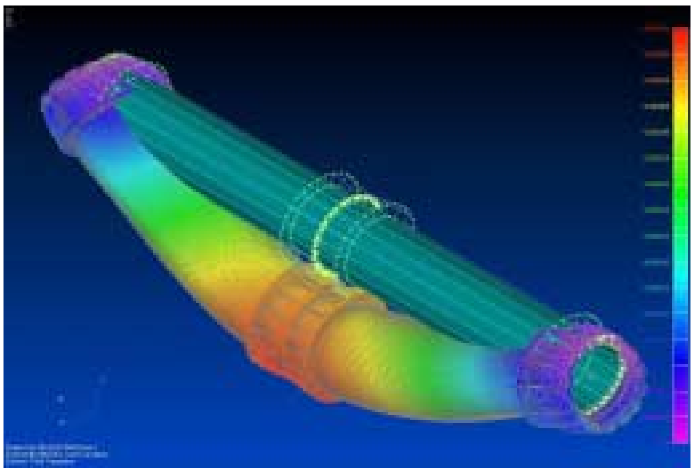


Figure 14: deformation of the precision prover pipes

The piston provers are very long and relatively thin. Various finite element calculations showed that special care should be taken at the design of the joint flanges to secure mechanical stiffness to reduce deformations at the joints. However, there is no guarantee for perfect regular mechanical support along the measurement partition. In the next figure, a case was analyzed assuming that some of the support piles were subsided only a few tenths of a millimeter in the soft soil of the site. The resulting forces bring about a considerable deviation of the cylinder circularity that should be taken into account.

With the online multipoint diameter gauge, this unknown non-circularity will be observed and compensated for.

The following schematic diagram depicts the several features of the intelligent pistons like:

- Diameter comparison with a primary ring gauge at the piston terminal, this is the most important feature. Twelve proximity sensors mounted on a rigid Invar base ring are used to detect the variation in prover diameter related to the ring gauge. (See section below for details);
- Pressure difference and leak flow detection, used for validation of the run related to seal wear or seal damage and inherent seal leakage;
- Several temperature sensors for correction purpose and safety checks (e.g. power consumption electronics)
- Acceleration sensor, to prove piston steady velocity within the calibration time window. The acceleration signal will be analyzed to calculate delta velocity (For details, see below);
- Radial angle sensor, to check for consistency of the piston position related to wearing of the sliding strips.
- Processor, inductive battery charger, HF transceiver

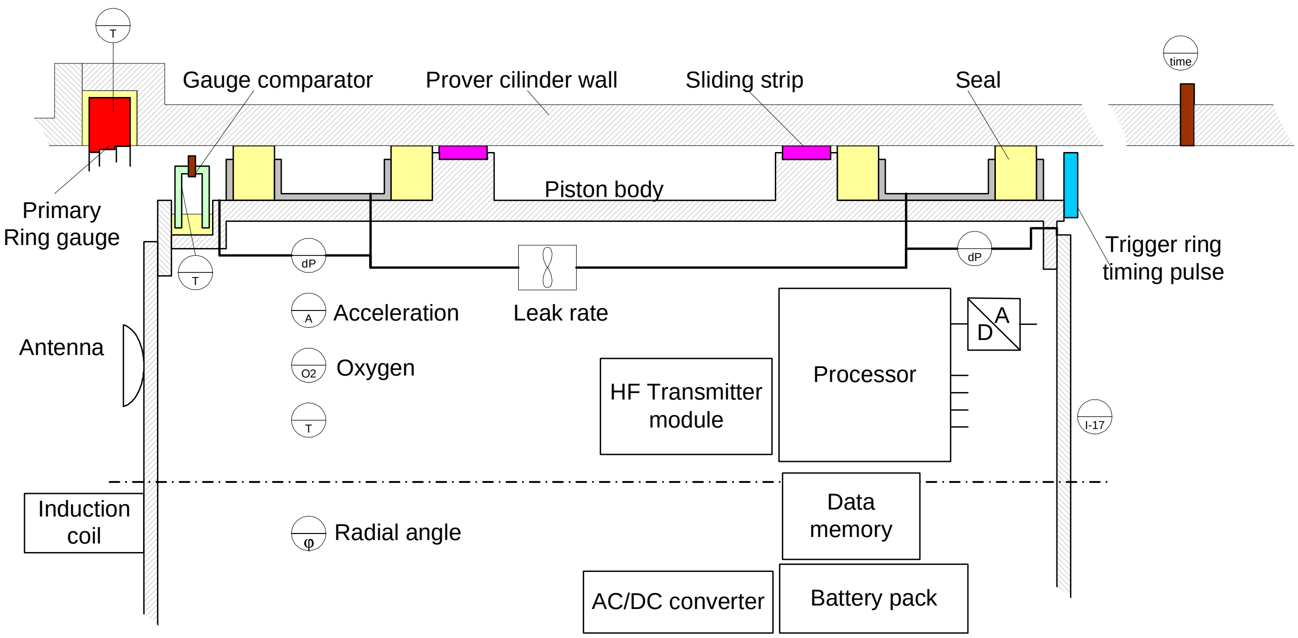


Figure 15: Overview of the piston's intelligent features

Gauge comparator: High resolution proximity sensors for 6 diametral on line measurement of geometry

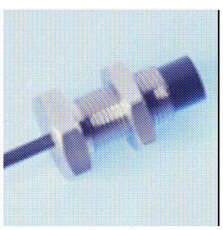


Fig. 16: proximity sensor (Ø 12mm)

The high-resolution inductive sensors are sensitive for the change in impedance of the coil distance related to the gap span to be determined. The impedance is also highly dependant on the material type of the 'conductor', which is the pipe wall. 12 of these sensors will be positioned at a rigged Invar support ring that travels along with the piston. The gap between the 'artifact' Invar support ring related to the prover wall is compared with a Primary Ring gauge (manufactured from the prover wall material) in order to disseminate the international unit of length along the prover wall. The temperature sensitivity of the inductive sensors is approximately 1 µm per °C.

Bearing in mind that the system is based upon analogue electronic techniques (long term drift), it was decided to design this piston-run cyclic calibration procedure to prevent from what metrologists call 'information loss'. The total range of the slit measurement is fixed at 3.5 mm for the large and 2 mm for the small prover. The resolution of the sensor/instrumentation amplifier is 0.12 respectively 0.08 µm at a refreshing rate of 1ms. At highest speed, the diameter could be determined nearly every 1 mm of piston travel at that speed. Each sensor will be calibrated when traveling along the three steps ladder ring gauge during the last couple of seconds when the piston arrives slowly at his terminal.

Figure 17: Example of a ring gauge

Calibration of inductive switch positions

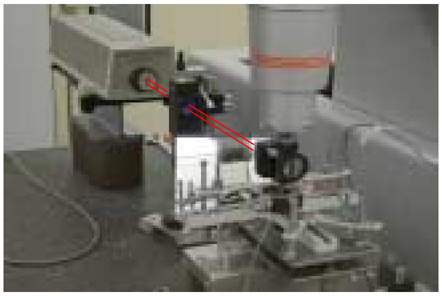


Figure 18:Laser interferometer

The inductive switches are triggered by the ferrous metal ring attached to the piston (blue ring on Figure 15). The base reference volume sections of the pistons are dependant on the trigger moments of the inductive sensors attached in the prover wall.
The exact trigger positions of the inductive sensors will be calibrated with the aid of an artificial sliding piston with a laser reflector cube attached on the center line of that piston. A laser interferometer will be attached at the bottom of the prover and serves as a reference differential-length related pulse generator when the artificial piston is mechanically pulled through the open prover. When the inductive sensors are passed, the coinciding pulse is 'stamped' with the interferometers' position pulse counts. With this procedure, an accurate calibration of the length scale is realized. However, unfortunately the refractive index of air in the test site together with the reproducibility of the inductive sensors compels to estimate the accuracy at 0.5 mm per sensor. An extensive test program is schedules for the coming months to study the effects when an inductive sensor is replaced or when it is not completely mounted at the bottom of its thread hole. For this moment a rather high uncertainty budget of 2 mm is estimated as a total for 20 meters length (See uncertainty analyses)

Acceleration metering: advantageous for what?

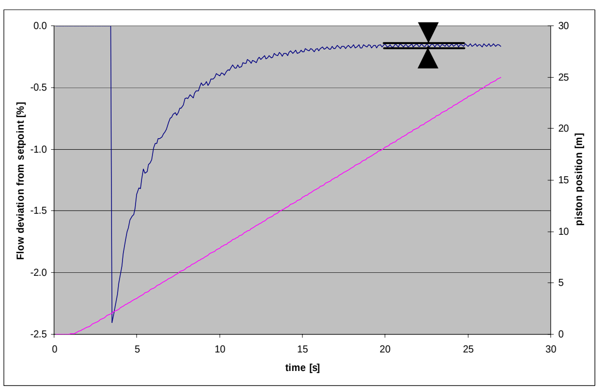


Figure 19: Piston approaching first trigger sensor

From the launching simulation, the observed maximum ripple of flow rate (and thus piston movement) is in the order of 0.025% (amplitude) at a frequency of 2.5 Hz and average flow rate of 5000 m^3/h.

At a diameter of 1127 mm (Large prover), the superposed velocity amplitude of the piston (dL/dt) and attached trigger ring for the timing pulses can be calculated at 0.35 mm/s. The smallest discrete switch length is 5 meter out of 4 times 5m total number of sections within 20meter net prover length. The effect of this ripple at the first and last timestamp will generate a standard deviation of dL/L*100=0.007% each 5 m sections. For the two timestamps combined (total travel time of the piston between the time sensor) it will generate $\sqrt{0.007^2 + 0.007^2} = 0.01\%$ 'noise' (or type A according to the GUM [2]) as additional uncertainty. It is obvious that the advantage of the accelerometer reading is that the reproducibility of the piston can be directly calculated in stead of waiting for another complete metering run. It can be concluded also that using the other metering sections as well, the standard deviation will be reduced by the square of the number of sections reducing to $0.01\% / \sqrt{4} = 0.005\%$. As a thumb rule one should keep the acceleration signal at the metering run below $\omega dL/dt = 2\pi f . dL/dt$ is 5.5 mm/s^2 or 5.10^{-4} times gravity. Inherently the accelerometer should be a low noise/high output type and should be able to handle transients at small frequencies down to DC such as e.g. Brüel and Kjaer offers.

Design details ‘GasCal’

In this section, the design of the High Pressure Gas calibration facility ‘GasCal’ will be discussed. The metrological principle of large conventional gas calibration facilities is mostly based upon a relatively long traceability chain, which inherently loses ‘information’ due to many intermediate step-up calibrations at different flow- and pressure ranges. This is not an option for the GasCal design. The facilities reference values will be based upon a very short and transparent traceability chain, leading to small uncertainties and straightforward uncertainty analyses. Small uncertainties are advantageous for society and short traceability chains are advantageous for the operational costs (‘maintaining traceability’) of GasCal.

Process flow diagram

GasCal can be distinguished into five parts:

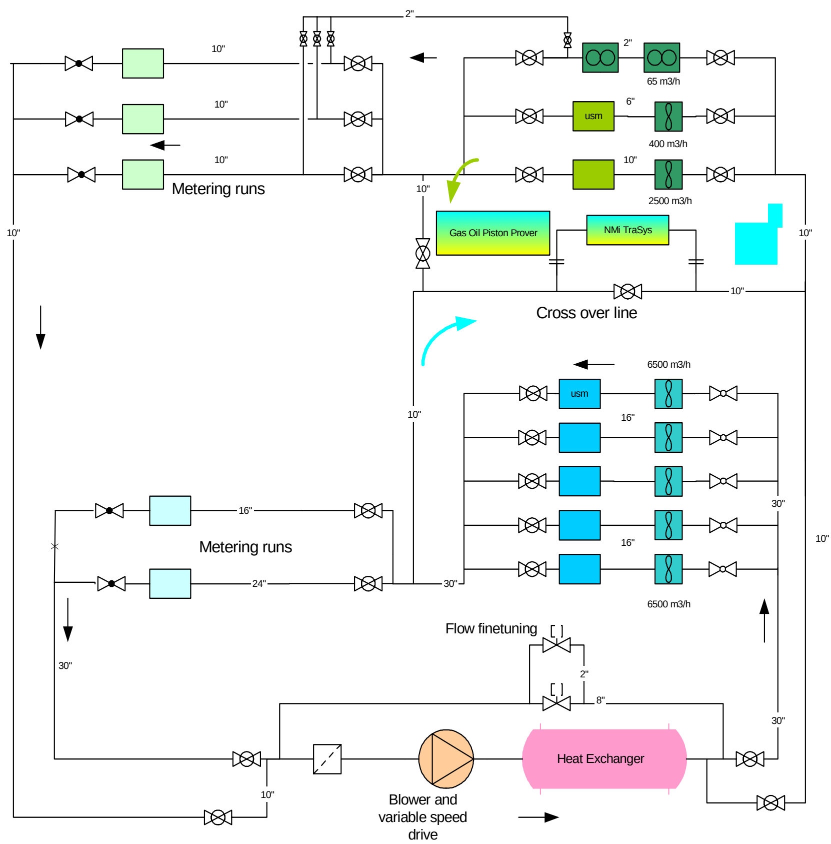


Figure 20: Process flow diagram

- 5 identical large reference runs, each consisting of one turbine reference meter and one ultrasonic monitoring meter, Q max 5 x 6500 m3/h. Total flow rate ads up theoretically to 32500 m^3/h and is depends on gas density.
- 3 small to very small reference runs, consisting of various reference meters and monitoring meters. Total flow rate up to nearly 3000 m^3/h
- Three identical metering runs for 12” and smaller meters
- Crossover for primary calibration (see section traceability chains) enabling to put the small and large reference runs in series for calibration maintenance, crosschecking etc. (see blue arrows).
- Variable speed drive, blower, flow fine tuning valves, filter and heat exchanger.

The design is such that dead volumes have been avoided as much as possible to reduce uncontrollable in- and expiratory effects (line pack) that might introduce poor repeatability.
The main transport line is a 30” diameter pipe, this extra large pipe is chosen to reduce pressure drop along the total circuit (energy consumption) and to minimize risk of low frequent oscillation effects and pulsations.
The monitoring meters (ultrasonic meters) are used to constantly monitor the behavior of the reference turbine meters but do not contribute in the determination of the reference value at the spot of the meter under test. Consistency has to be met during the calibration time frame. The question may arise why these meters are used while the reproducibility and repeatability cannot (yet?) compete with modern precision turbine metering. The answer to that is obvious, two turbine meters in series would be preferable from the metrologists’ perspective, but for the sake of ‘no’ extra pressure drop ultrasonic meters will be installed.

NMi concluded that this type of facility (closed loop with blower) is the best solution in the Netherlands to cope with the conflicting requirements of having a large gas flow at various pressure stages, reliability (risk of supply), no seasonal effects, stable flow and free of pulsations.
The drawback of this type facility is the energy consumption at large flow rates and the more complicated operation efforts, gas logistics etc. On the other hand, the enormous positive effect is found in the fact that the gas composition is absolutely constant and operation conditions are fully under control which lead to a considerable decrease in measurement uncertainty of reference mass flow.

Temperature stability: a prerequisite for high precision (gas) flow metering.

One of the challenges of the GasCal design is to keep the temperature variations within control.
The good news is that the facility’s process conditions are hardly depending on weather and/or ground conditions of the gas such as the case in conventional ‘tied-in’ test facilities. The laboratory hall has excellent temperature control. However, most important issues in gas metering related to temperature effects are a.o.:

- Unknown temperature variations in dead volumes between meter under test and reference meters (line pack effects); The past decades, NMi learn a lot from the facilities ‘Bergum’ and ‘Westerbork’ (owned by Gasunie). One of the best remedies are to use a large number of temperature transmitters in the dead volumes to determine the slow temperature transients during the calibration timeframe and to correct for the effects.
- Temperature stratification, especially at low flow rates in the long 24”and 16”metering runs; the phenomena was studied extensively by Gasunie and NMi[7]. GasCal will be provided with twin temperature measurements, both at the top of the pipe and at the bottom of the pipe.
- Unknown temperature profile of the fluid over the cross section, leading to wrong determination of ‘mixed cup temperature’ (See section before related to HyCal). Although this effect is not as large as in high viscous fluid circuits, the GasCal piping will be insulated anyhow to prevent from this risk. Mind that the process conditions can be quite different from the laboratory conditions.

Conventional and new traceability chain for the reference values for High Pressure Natural Gas Volume

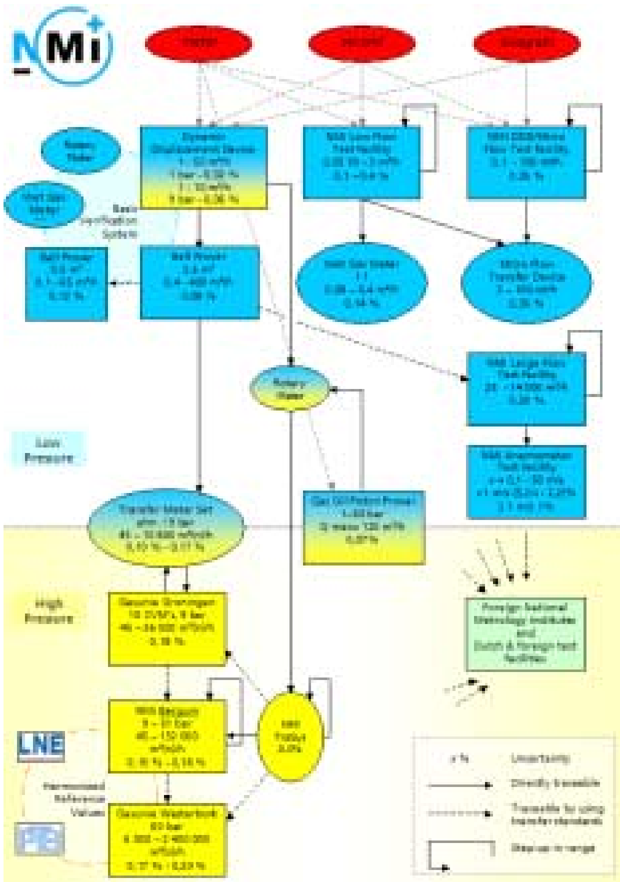


Figure 21: Situation until 2010

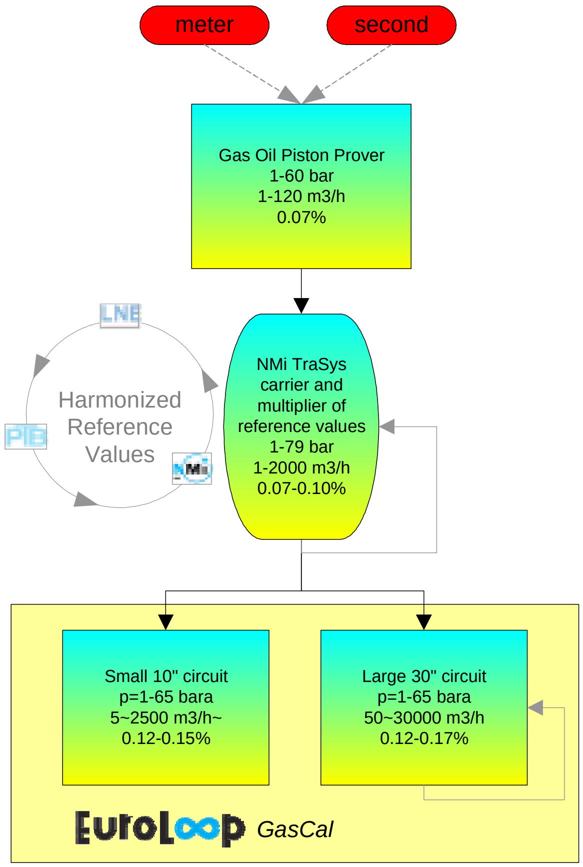


Figure 22: Situation commencing 2009

In the two presented traceability charts of ‘old’ and ‘new’ situation it is quite clearly that the dissemination of SI-units throughout the range of ‘GasCal’ is straight forward and will be realized in only a few steps. The main sources of these improvements are:

- The complete rangeability is placed under one roof, no dragging around with traveling reference meters (TRMs) to pressure and/or range restricted facilities.
- The primary realization will not be based upon the time consuming ‘pressure step up system’ but one Gas Oil Piston Prover together with traceability ‘booster’ called ‘NMi TraSys’ (‘*Traceability System’*).

These separate ‘mobile primary reference generators’ will be situated in the laboratory hall of GasCal. In the next figures, the operating principles are shown, for details see [3],[6]

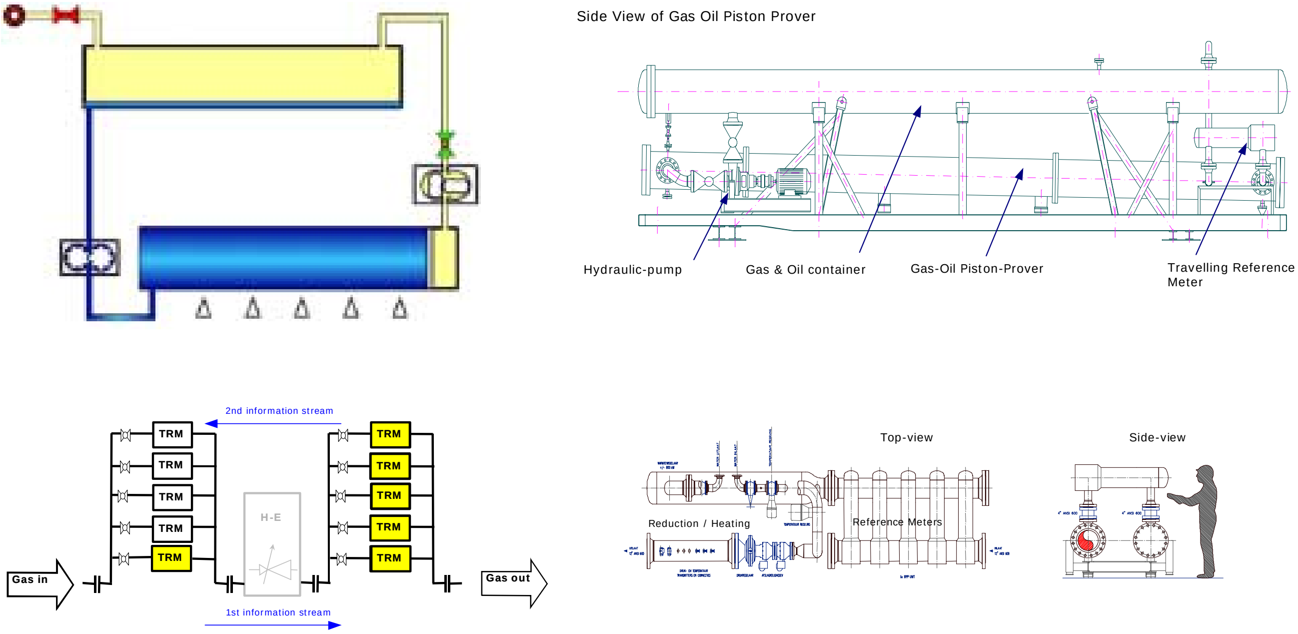


Figure 23: Primary and multiplied reference values, realized by the Gas Oil Piston Prover and TraSys

The left upper figure represents the Hydraulic driven Gas-Oil Piston Prover in a ‘closed circuit’ configuration for gas applications and will soon embody the national reference value for the volume of high-pressure gas. The advantage of the system is its process pressure independency. Another advantage is the stable operation of the piston as a result of the hydraulic smooth drive, resulting in small reproducibility figures.

Due to the restricted flow range of ‘GOPP’ another instrument is being used to boost up the flow range up to 2000 m^3/h which is carried out by NMi TraSys.

Obviously, the facilities ‘Bergum’ and ‘Westerbork’ will stay open until GasCal has been proven ‘stable’ and ‘consistent’ i.e. holding reference values that do not differ from earlier realized reference values.

The ultimate fine-tune procedure to diminish differences between (inter) national reference values is done by the ‘Harmonization Process’ which means that more independent national reference value attribute to realize the Global reference value for Natural Gas Volume [8]. This reference value that is currently realized by NMi, PTB and LNE will finally be embodied in EuroLoop GasCal for further dissemination of traceability with small uncertainties.

Sustainable operations: Low energy consumption and full recycling of Natural Gas

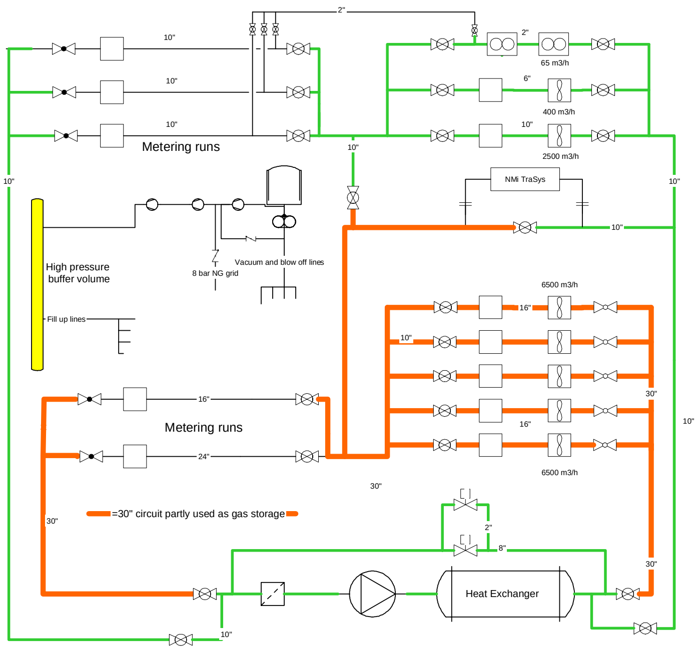


Figure 24: High pressure buffering and logistics

Recycling Natural Gas.

NMi values sustainable operations at her facilities and decided to avoid any (Natural) Gas spillage.
Mounting and dismounting the meters under test requires a complete meter run blow off containing up to 10 m^3 at 60 bar, equivalent to approximately 670 Nm^3. This amount of gas will be directed to either the 30" part or to the external high-pressure buffer volume. Complete removal will be done by vacumizing down to 20 mBar after which the spool pipe will be vented. For efficient operations, it is required to be able to blow off and to fill up again in a short time. An operation management study on gas logistics shows that four buffer volumes will work efficiently.

1. A small atmospheric gas holder as an intermediate storage for vacumized spool pipe gas;
2. The 30"loop partly used as temporary buffer (orange);
3. A separate High Pressure Volume (dead end pipeline, yellow);
4. The 10"circuit in operation mode (green, variable pressure)

The optimum operation sequence is to have batches of calibration of roughly the same pressure and to start operations at low-pressure ranges, climbing up during the week up to the highest pressures. The advantage of this cycle is to use the downtimes (e.g. weekends, overnights) to re-transport the gas into the high-pressure cavities.

Energy consumption by a large process blower.

In the design stage of the flow generating system, the energy consumption and related cooling power was one of the main considerations.

Two options are available:

- The blower/compressor has a fixed speed, electromotor and gearbox configuration with anti surge vanes at the inlet to control the smaller flow rates at high dP;
- The blower/compressor has a variable speed drive.

NMi opted for the variable speed drive to cover the complete range and maintaining high efficiency of the blower (durability). The maximum power at the blower shaft is 2400 kW at the full 30000 m^3/h actual flow rate, pressure difference of 2.5 bar across in- and outlet at 61 bara for Natural Gas. The system is suited for various other gases as well.
The installation will be fitted with a cooling system allowing the medium to be cooled to temperatures down to 5 and 10 ^oC. The main cooling power will be obtained from the river water that is available at about 50 meters outside the fence.

Conclusions
In the course of 2008 and 2009, two calibration facilities ‘under one roof’ will become available that are unique in their combination of line size, flow range, viscosity, pressure, temperature and measurement uncertainties.
As a National institute for Standards in Measurement, NMi VSL has a function to provide industry and society with applicable expertise and knowledge in Metrology, usually delivered as "Traceability Services". A prerequisite to this function for the Metrology of Flow is e.g., the capability to generate reliable reference values for measurement of large high-pressure gas flow and large mineral products flow.
EuroLoop is the creation of straightforward traceability-chains by innovative metrological concepts, realizing reference values covering wide ranges in pressure and flow-rates gas and liquid types.
Extending its capabilities NMi VSL keeps its dedication on track to reduce uncertainties in flow measurements and in this new facility specifically contributing to improvements in the Oil and Gas sector, at your service.

Acknowledgements

We have spend a couple of interesting hours together, dreaming, sparring and aiming for superb results, thank you folks, keep on bringing flow metrology onto a higher level:
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Anneke, Ewout, Judith and Levi: thanks for supporting me again during this hectic but exciting period!

List of used symbols:

Symbol	Legend	unit	Symbol	Legend	unit
Q	Volume flow rate	m^3/h			
L	Length, pipe	m	τ	time	s
P	pressure	Bar, Pa	φ	Angle or meter deviation	Rad, %
dP	Delta pressure	bar	μ	micro	-
K	Loss coëfficiënt, in $dP=K \frac{1}{2} \rho Q^2$	[1]	ω	Radial velocity	Rad/s
v	Velocity	m/s	ρ	Density	Kg/m^3
v’	Velocity derivative	m/s^2	T	temperature	K, °C
Q’	Flow derivative	m^3/s^2	R,r	Radius	Rad
I	Inertia		δ, Δ, d	Differential operator	-
A	Acceleration	m/s^2	D	Diameter	m
f	Pipeline friction factor according to Darcy-Weisbach	[1]	E	Young’s modulus	Pa
B	Bulk elasticity	Pa			

Abbreviations:

DuT	Device under test
MuT	Meter under test
SoS	Speed of Sound
TRM	Traveling Reference Meter
GOPP	Gas Oil Piston Prover
TraSys	Traceability System

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