

CALIBRATION OF GAS DENSITY TRANSDUCERS  
USING NATURAL GAS

by

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DANTEST

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PAPER 1.2

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## CALIBRATION OF DENSITY METERS WITH NATURAL GAS

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### 1. BACKGROUND FOR THE WORK WITH GAS DENSITY

#### 1.1. The Danish Natural Gas System

During the last ten years Denmark has built a system for distribution of natural gas coming foremost from the North Sea Thyra Field.

The main pipelines are distributed as seen on fig. 1. Along these pipelines 28 major stations are situated for quantity measurement of gas with turbine meters and density meters. The gas is measured in mass as follows (mass = Volume × density).

$$m = V \times \rho$$

Every station has two measuring sections each with a turbine meter and a density meter. Density will be measured at 16-40 bar and at 5 °C. The total number of density meters in Denmark is expected to be around 70, and these meters require a relevant calibration, which is the main subject of this paper.

#### 1.2. Dantest involvement in natural gas metering

Dantest was formed as an independent institute the 1 January, 1980 merging together the National Institute for Testing Materials and the main part of of the National Bureau of Weights and Measures. Dantest has carried on to take care of mass and volume measurement in Denmark.

The density measurement of gas was therefore a natural continuation of this work, and over the past 4 years we have worked with several projects for the Technology Board/Agency of Technology (Government Organisation) concerning gas measurement.

To meet the need for calibration, Dantest has built a laboratory for calibration of density meters and for examination of the influence of the gas composition and calibration conditions on calibration results.

Dantest has furthermore laboratories for gas-chromatography and for calibration of smaller gas meters (diaphragm meters) with or without temperature compensation.

#### 1.3. Traditional calibration methods

Traditionally gas density meters are calibrated introducing a known pure gas such as N<sub>2</sub> in the meter at controlled temperature and pressure conditions. The gas density is found from international accepted tables.

Then correlating the signal from the meter and the density of the gas a calibration point is achieved. Having several points, it is possible to evaluate an approximation for the density as a function of the vibration period,  $\tau$ , of the density meter:  $\rho = f(\tau)$ . Where  $f$  usually is a 2. order polynomium in  $\tau$ .

$$\rho = A\tau^2 + B\tau + C$$

As the calibration is made with a pure gas the question rises, how the density meter reacts on other gases such as natural gas containing many heavy hydrocarbons.

As an approach to this problem Solartron has as a manufacturer introduced their "velocity of sound correction" to be used for other gases than the calibration gas. The problem here is the lack of published documentation, and therefore it is difficult for the authorities to accept.

#### 1.4. Calibration method with natural gas

Documentation for the necessary correction using a density meter calibrated with a pure gas to measure density of any natural gas is achieved by establishing

$$\rho_{\text{cal.gas}} = f_1(\tau) \quad \rho_{\text{nat.gas}} = f_2(\tau)$$

This implies, that it is more direct to use a natural gas or a corresponding synthetic gas for calibration, instead of producing numerous corrections.

This was the main reason for Dantest in 1981 to build the already mentioned density laboratory.

In our laboratory we have established calibration curves for nitrogen-ethane mixtures, multi-component synthetic gas mixtures, and natural gas.

## 2. MEASUREMENT OF GAS DENSITY AND THE LABORATORY FACILITIES

The laboratory is primarily equipped for measuring density of gas with the object of calibrating density meters. In this process it was also necessary to create facilities for determination of the compressibility factor of any gas. In this way it is possible to examine, if existing tables such as AGA NX 19 are suitable for North Sea gas.

### 2.1. Determination of gas density

Density of gas can be determined in two ways. Fig. 2.

I By direct mass and volume determination

$$\rho_g = m/V$$

## II By using the gas law

$$\rho_g = \frac{\rho}{Z \times R \times T}$$

$\rho_g$  : density

p : pressure

Z : compressibility factor

R : gas constant (universal gas constant divided by mole mass)

T : temperature (in K)

m : mass

V : volume

In our laboratory density can be determined by both methods.

### 2.2. The layout of the laboratory

Fig. 3 shows a sketch of the laboratory.

The laboratory is divided into four sections.

a) Gas supply section

b) Compressibility factor measurement

c) Density measurement  $\rho_g = m/v$  (method I)

d) Density measurement  $\rho_g = \frac{\rho}{Z \times R \times T}$

(method II)

Item a)

The gas supply comprises a gas reservoir (gas bottles + regulator 300/150) plus a Desgranges & Huot deadweight-tester ① .

The deadweight-tester is used to stabilise and determine the working pressure for the other three sections. It has been calibrated by LNE\*, and has a measurement range of 0.4 bar to 200 bar with a relative tolerance of 0.01 %. With the aid of a quick connection at ②, the "gas supply" can be connected to the three sections in turn.

Item b)

Comprises a Desgranges & Huot compressibility factor meter ④ (referred to as a Z-meter) and a Heto thermal bath which stabilises the temperature in the Z-meter. The Z-meter is calibrated with the aid of a known gas and the measurement range and accuracy are determined by the calibration. Dantest uses nitrogen with a purity of 99.9992 % and NBS tables for

\* Laboratoire National d'Essais

nitrogen. The Z-meter is actually calibrated in the range 3 to 80 bar, and the use is limited to 90 bar.

Item c)

The section for determining the density according to method I comprises a pressure vessel ②, specially designed to calibrate density meters. This vessel can be used in the range 0 to 80 bar and can be used for most types of gas. The accuracy when determining density is between 0.05 % and 0.1 % depending on the pressure level and the type of gas. The vessel is equipped with measuring devices for pressure and temperature. The nominal volume is 12 litres.

Item d)

The section for determining the density according to method II comprises a thermal cabinet in which it is possible to place density meters. Each density meter is individually fitted with a Pt 100 resistance so that the temperature can be measured with an accuracy of  $\pm 0.1$  °C. The thermal cabinet ③ can be adjusted from 0 to 40 °C.

### 3. ACTUAL CALIBRATION PROCEDURES

This section describes briefly how the two methods for determining density are used for calibration of density meters. Fig. 4.

#### 3.1. Determining density according to method I:

$$\rho_g = \frac{m}{V}$$

##### Calibration

Knowing the volume of the system (vessel + density meter) as a function of pressure and temperature, a calibration point ( $\rho$ ,  $\tau$ ) can be found by weighing.

The mass of the gas is determined performing 3 steps:

- 1) Weighing the total system while it is empty.
- 2) Filling the system with gas. (After each filling/emptying, the vessel is stabilized for at least 3 hours).
- 3) The vessel is weighed.

Temperature, pressure and the density meter signal are noted before and after weighing.

##### System volume

The total volume of the system (pressure vessel + density meter) is calibrated by a gravimetric method. The measurement is a combination of nitrogen and water weighing. The volume of the vessel is determined by weighing the content of water. Experiments showed that it was necessary to determine

the volume at 60 bar since air bubbles disturb measurement at lower pressures. Further the volumetric pressure expansion coefficient for the vessel was found weighing the nitrogen content at three different pressures.

The volume of the density meter was determined by nitrogen weighing since the instrument could not tolerate water. It can be shown that the effect of the pressure expansion of the density meter is insignificant compared to the level of system accuracy.

### 3.2. Determining density according to method II:

$$\rho_g = \frac{P}{Z \times R \times T}$$

#### Calibration

The density meters are placed in a thermal cabinet and connected in series to the gas supply system. The temperature regulation is set to the required value and after stabilisation the calibration can begin.

The density meters are purged and filled with the calibration gas to the required pressure. Because of compression, a further stabilizing period of approximately 20 minutes is required.

Pressure, temperature and density meter signals are recorded continuously during stabilization and during the final read off.

The density meters are then filled/emptied for the next pressure stage until the required pressure is completed.

#### Compressibility, Z, and gas constant, R

Z can be determined according to tables, such as NBS tables for nitrogen and methane, or for other gases with the aid of the Z meter.

The gas constant, R, can be determined by calculation or by experiment. By calculation the known composition of the gas is used. The gas usually needs to be mixed gravimetrically in order to achieve sufficient accuracy, if the number of the components exceeds 2-3.

R can also be determined by measuring the density according to method I, and measuring the compressibility factor with the Z meter. Then R is calculated according to

$$R = \frac{P}{\rho \times Z \times T}$$

#### The Z meter

A sketch of the meter is shown in fig. 5. Since knowledge of the Z-value is a necessary basis for the use of natural gas or multicomponent gas mixtures for calibration of density meters, a more

detailed description is given of the measurement procedure.

The Z meter comprises two chambers with a pressure transducer placed in the largest chamber, three pneumatic valves A, B, and C, and two resistance thermometers.

#### Measurement procedure

Two valve positions are possible:

Valve position	Valve A	Valve B	Valve C
1	open	closed	open
2	closed	open	closed

In valve position 1 gas is filled in V<sub>1</sub> to the required pressure and stabilised by the deadweight-tester. After a period of stabilisation the pressure transducer signal and temperature are noted.

In valve position 2, after the gas is distributed in the two chambers, the pressure transducer signal and temperature are noted again.

#### Determination of Z

The basis for calculating the compressibility factor Z is the real gas equation :  $pV = ZnRT$ .

#### Position 1

$$p_1V_1 = Z_1n_1RM$$

$$p_2V_2 = Z_2n_2RM$$

#### Position 2

$$p_3(V_1 + V_2) = Z_3(n_1 + n_2)RM$$

$p_1, p_2$  : Pressure in V<sub>1</sub> and V<sub>2</sub> respectively

$p_3$  : Pressure in V<sub>3</sub> = V<sub>1</sub> + V<sub>2</sub>

T : Temperature (held constant)

$Z_1, Z_2$  : Compressibility factor for the two states (V<sub>1</sub>, p<sub>1</sub>, T) and (V<sub>2</sub>, p<sub>2</sub>, T).

$Z_3$  : Compressibility factor for state (V<sub>1</sub> + V<sub>2</sub>, p<sub>3</sub>, T)

$n_1, n_2$  : Number of moles of gas in V<sub>1</sub> and V<sub>2</sub> respectively

With these three equations we get an expression for the compressibility factor for the unknown gas, Z<sub>1</sub>:

$$Z_1 = \frac{p_1}{\frac{p_3 \times (1 + A)}{Z_3} - \frac{p_2 \times A}{Z_2}}$$

A is the volume ratio V<sub>2</sub>/V<sub>1</sub>, measured by the manufacturer.

$p_2$  is the barometric pressure.

$p_1$  is the sum of the barometric pressure and pressure from the deadweight-tester.

$p_3$  can be determined after calibrating the pressure transducer. For this purpose a gas which properties are known from internationally recognised tables, e.g. nitrogen, is used.

Since  $Z_2$  and  $Z_3$  are unknown, the linear relationship between  $Z$  and  $p$  is used:

$$Z = 1 - k \times p$$

This applies to gases at pressures below 20 bar.

The gas constant,  $k$ , is determined, e.g. by iteration between the following two expressions:

$$1. \quad Z_1 = \frac{p_1}{\frac{p_3 \times (A + 1)}{1 - k \times p_3} - \frac{p_2 \times A}{1 - k \times p_2}}$$

$$2. \quad k = (1 - Z_1)/p_1$$

#### 4. PRESENT STATE AND FURTHER DEVELOPMENT

##### 4.1. Present state

###### Gas composition

It is important to have a good knowledge of the expected average composition of the gas to be measured.

From this composition a calibration gas is chosen. It can be either a sample of natural gas or a good synthetic reference gas.

###### Compressibility, $Z$ , and gas constant, $R$

$Z$  is measured at the temperatures and pressures ( $T$ ,  $p$ ) which are going to be used for calibration.

$R$  is found with the highest accuracy by weighing, and  $Z$  determination. Another possibility is to calculate  $R$  from the gas composition found by gas-chromatography if the achieved accuracy is acceptable. If the gas composition is known with sufficient accuracy from the mixing process, this composition might be used, but we have had some problems using this way, in getting an official certificate of the composition.

###### Calibration

For each bottle of gas  $Z$  and  $R$  must be determined as described above. But as the gas consumption for calibration of density meters is small, the same bottle can be used again and again without new determinations of  $Z$  and  $R$ .

##### 4.2 Development

At the moment the pressure is limited to 90 bar



in the Dantest laboratory because of the Z meter. In order to meet the off-shore demands a new Z-meter is under construction.

It should be able to operate up to 150 bars. This Z meter which is shown in fig. 6. consists of two pressure vessels of 0.3 l and 3 l. Here we have the advantage, that we can calibrate the volume of the two vessels individually with airfree distilled water, and thus the Z-values will be independent of any existing gas tables. These tables will then be used for control of the Z meter.

With the new instrument it will be possible to calibrate density meters using natural gas in the off-shore pressure range too.

## 5. RESULTS

In this paper we are publishing some of our results for pure gases and synthetic gas mixtures representing expected natural gas compositions. Later we hope to publish results for natural gas too.

### 5.1. Measurements with nitrogen

To establish reliability of the laboratory and to estimate the accuracy level, nitrogen results were compared to NBS tables in the following way.

- Comparison of density measured by method I,  $\rho = m/V$ , with NBS tables showed a correspondance within 0.05 %.
- Comparison between method I and II using nitrogen showed deviations less than 0.06 %. The density meter signals (period) obtained in method I were introduced in the calibration curve obtained by method II, and the densities thus calculated were compared to the measured density  $\rho = m/V$ .

### 5.2 Measurements with methane and synthetic gas mixtures

The gases which have been used in the laboratory can be divided into 4 groups:

- methane
- two component methane/ethane mixtures
- synthetic gas mixtures (reference gases for natural gas)
- natural gas (not included here)

We have focused on the expected Danish gas composition and in the following typical results are given. Further results are given in the Dantest report for TR-project 133/360-81.368, "Calibration and examination of gas density meters".

Fig. 7 shows results obtained with a Solartron 7810 density meter for two gas mixtures. These two gas mixtures were chosen as reference gases for the

expected Danish gas composition. The figure shows the relative difference between the "true density" of the gas and the density determined from the density meter signal using the calibration constants obtained with nitrogen. "True density" is here achieved from  $\rho = p/R \times Z \times T$ . Abscissa is the above mentioned density obtained from the density meter using the calibration constants obtained with nitrogen. This is the resulting error, when a density meter calibrated using nitrogen is used for measurements on another gas.

The deviations up to 1 % show, that a correction is needed.

Table 1.

	Fraction of volume	
	"Natural" Gas 1	"Natural" Gas 2
CH <sub>4</sub>	0.8956	0.9079
C <sub>2</sub> H <sub>6</sub>	0.0573	0.0491
C <sub>3</sub> H <sub>8</sub>	0.0223	0.0164
C <sub>4</sub> H <sub>10</sub> , i	0.0076	0.0074
C <sub>4</sub> H <sub>10</sub> , n	0.0059	0.0055
CO <sub>2</sub>	0.0059	0.0059
N <sub>2</sub>	0.0054	0.0078

Fig. 8 shows furthermore corresponding results for methane and methane/ethane mixtures. The results indicate, that a mixture with 6 % or 8 % ethane in methane might be used as a calibration gas instead of mixture 1 or 2.

The result for pure methane shows, that using methane as calibration gas, a correction is needed.

Fig. 9 corresponds to fig. 8, and it shows the similarity of two density meters of the same type Solartron 7810. As seen they agree within 0.05 %, which is under their calibration accuracy of 0.1 %.

We have very few data concerning temperature influence but in fig. 10 some results are compared to the Solartron temperature correction. The deviation is within the stated accuracy of the results.  $\rho_{20^{\circ}\text{C}}$  is calculated from the calibration constants established at 20 °C and the signal given metering on the same gas at 5 °C.  $\rho_{5^{\circ}\text{C}}$  is the gas density at 5 °C determined from  $p$ ,  $Z$ ,  $R$  and  $T$ .

## 6. ACCURACY AND TRACEABILITY

### 6.1 Accuracy

#### Z-measurement

Comparing the Dantest Z-results for methane with the corresponding values from the NBS tables gives an estimate of 0.05 % for the systematic uncertainty of Z. Having a random uncertainty of 0.024 %, we get an estimate for the uncertainty of Z of

$$100 \times \frac{e_Z}{Z} = \sqrt{0.05^2 + 0.025^2} \% = \underline{0.06 \%}$$

This gives a reasonable basis to estimate 0.1 % as our general Z-uncertainty.

#### Density measurement

For the pressure the uncertainty is 0.01 % and for temperature 0.024 % based on certificates for the equipment. For R measured 0.06 %.

The estimate for the systematic uncertainty for  $\rho$  is then

$$\sqrt{0.06^2 + 0.01^2 + 0.024^2 + 0.06^2} \% = 0.09 \%$$

The random uncertainty is 0.014 % and then the estimate for the total uncertainty of  $\rho$  is  $\approx 0.1 \%$ .

This gives the basis to estimate 0.15 % as the general uncertainty of the density calculated from the calibration curve because we normally only see deviations around 0.02 % between the value of  $\rho$  calculated from the calibration curve and  $\rho$  measured.

### 6.2 Traceability

It is important, that all equipment is calibrated in a proper way. At Dantest we have used the following institutes, which all are traceable to international accepted standards.

<u>Instrument</u>	<u>Institute</u>	<u>Intervals</u>
Deadweight-tester	LNE	2 years
Pt 100	RISØ	1 year
Barometer	SAS	1 year
Z-meter	Dantest, NBS tables	1 year
Electronic scale	Dantest	1 year
Weights	Dantest	1 year

### 6.3 Control procedures

The Z-meter is calibrated using the NBS-tables for nitrogen. The Z-meter is then used to measure Z-values for methane, and these values are compared with the NBS methane tables. Typical deviations are in the range of 0.03 - 0.08 %.

When calibrating density meters one or two known Dantest reference meters are inserted in series with the meters to be calibrated. The signal from the reference density meters are compared with their calibration curves before calibration of the unknown density meters.

Readings of all instruments are performed according to stabilization criterias, developed from experience and the desired accuracy of the measurements.

## 7. CONCLUSION

Our conclusion is, that the most direct way for calibrating density meters, is to use a representative gas mixture for the gas to be measured.

It is better to use such a gas for calibration of density meters, than to use it to find a correction for another calibration gas. The same measurements have to be done.

This procedure gives the highest probability for a good measurement, and it is possible in this way to obtain an uncertainty of the density as small as 0.15 % or even smaller.

It presents of course some safety problems, but they are reasonable to handle.

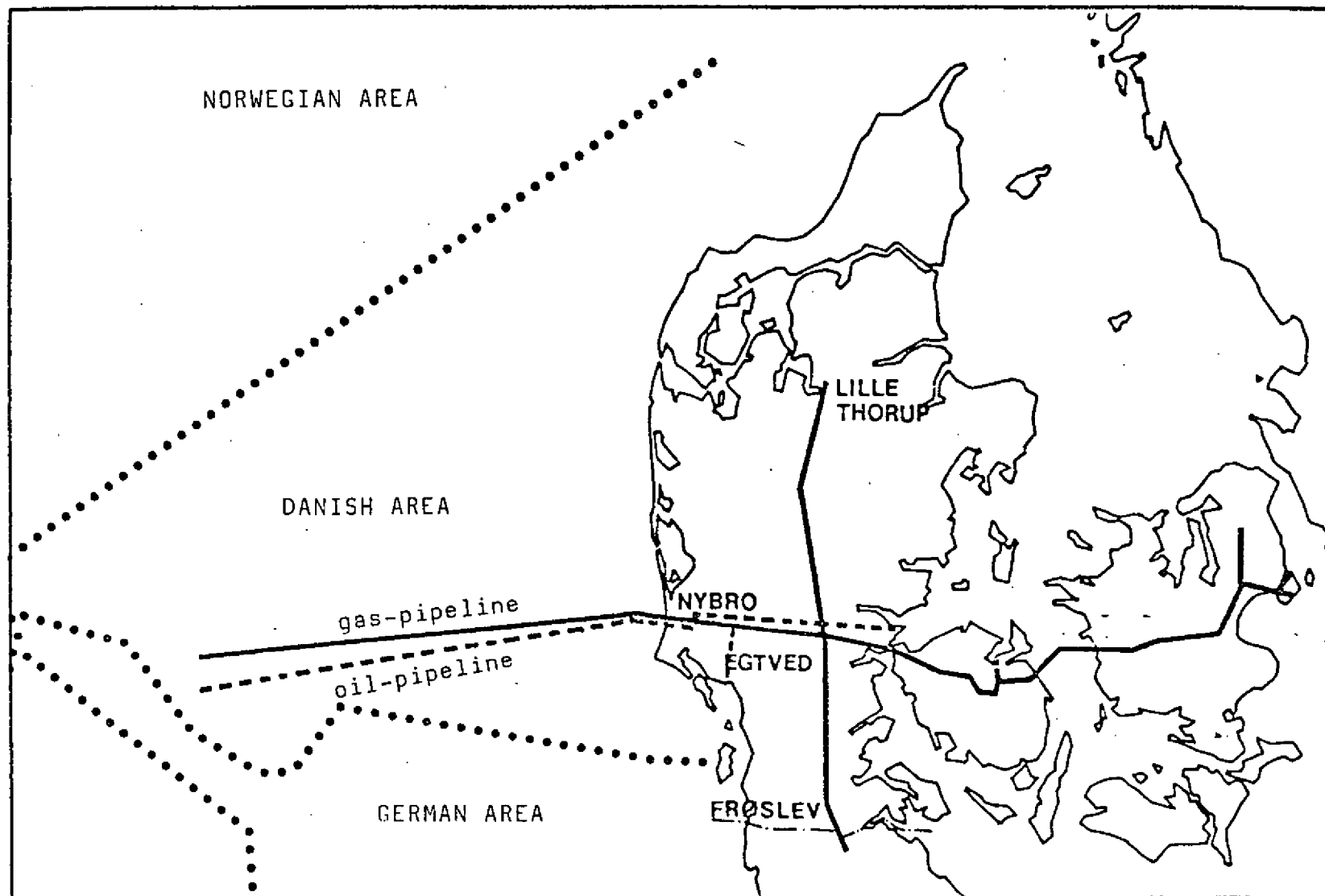


Fig. 1 The danish natural gas system

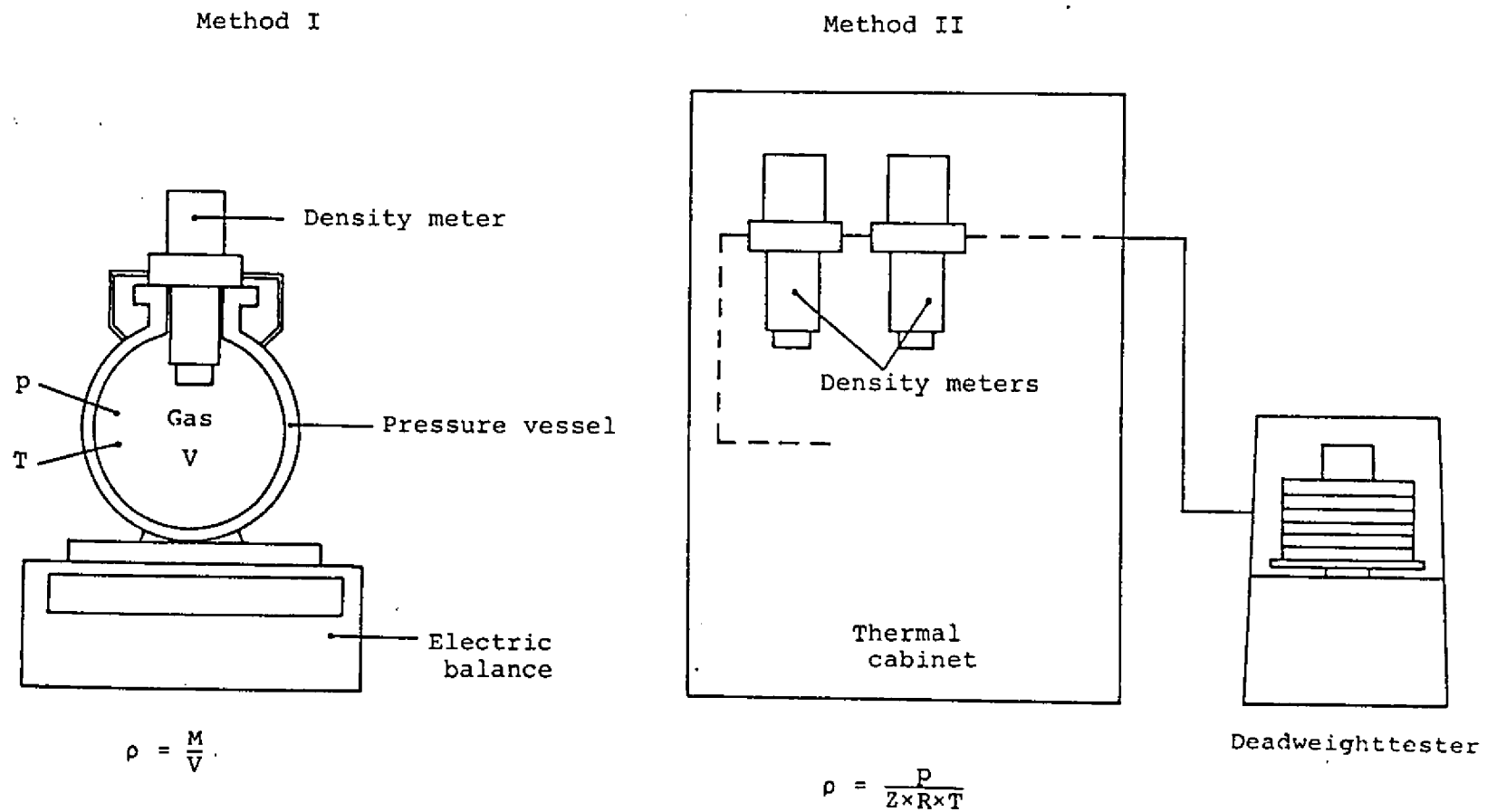


Fig. 2 Schematic figure of the two methods for measuring gas density in the laboratory of Dantest.

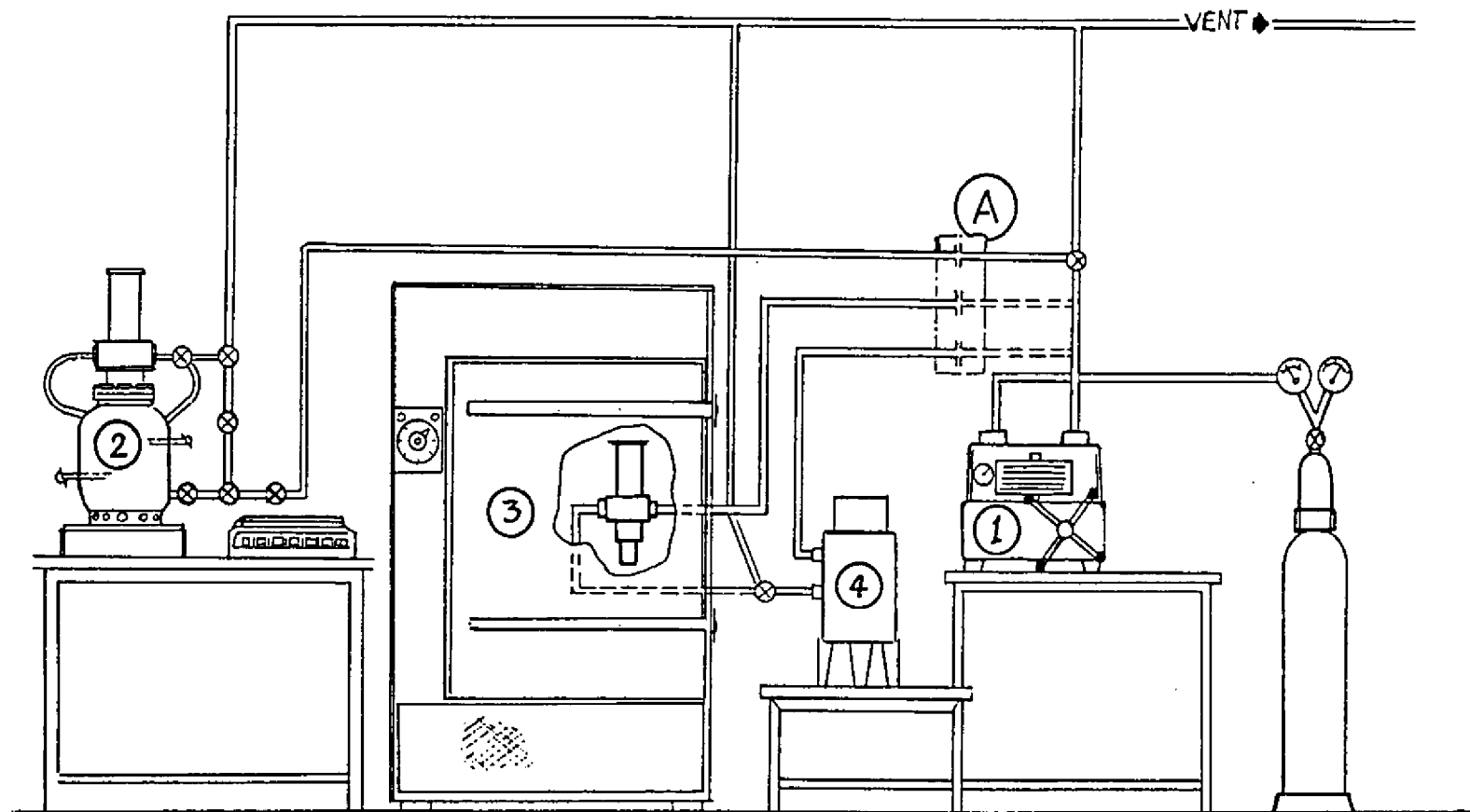
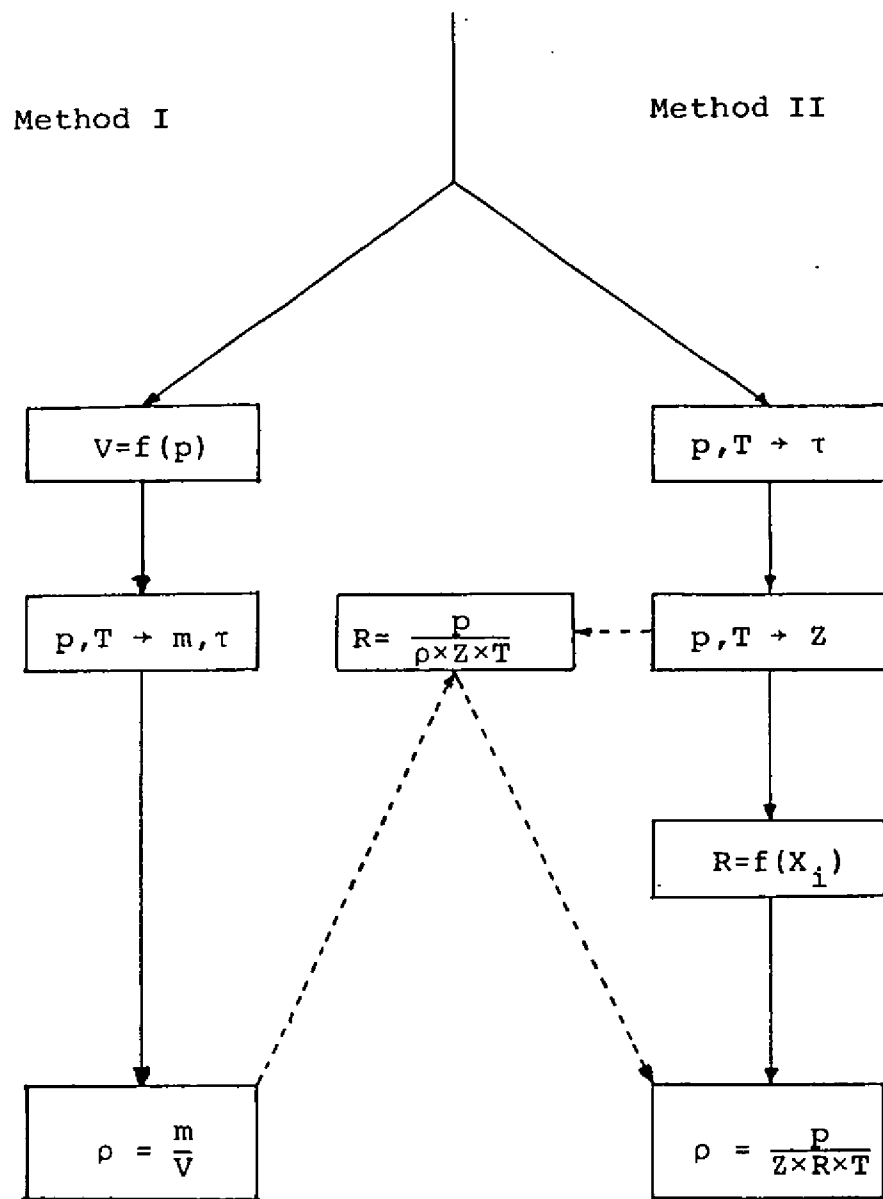


Fig. 3 Scetch of the laboratory.

Fig. 4 Measuring the density of gas





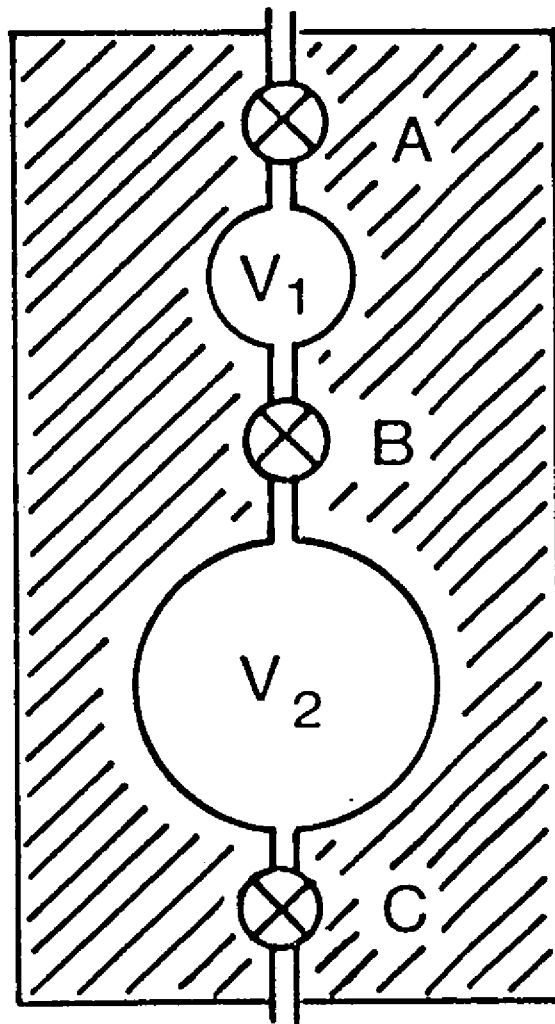


Fig. 5 Schematic drawing of a Desgranges and Huot Z-meter. Pressure range: up to 90 bar.

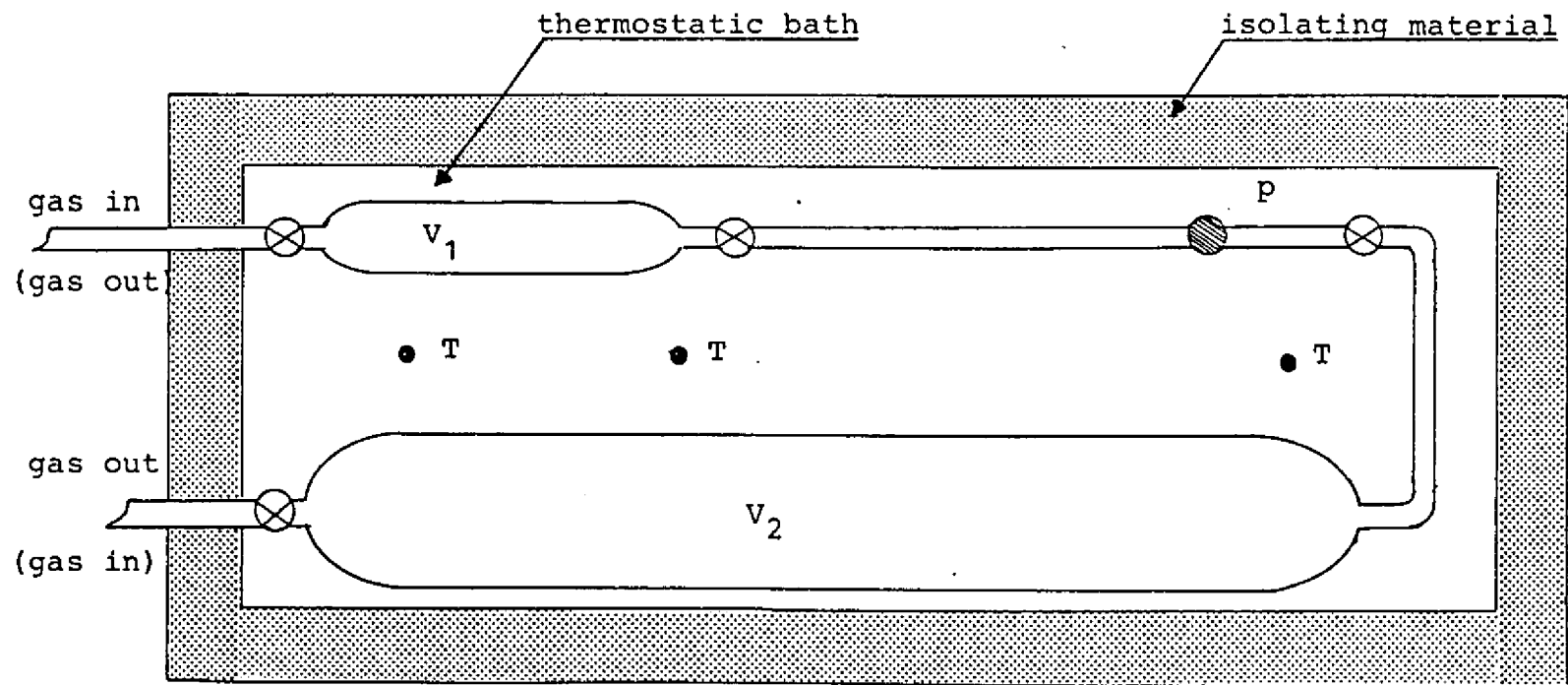


Fig. 6 Schematic drawing of the Z-meter Dantest has built. Pressure range: 50-150 bar

Fig. 7 THE RELATIVE DEVIATION BETWEEN "TRUE DENSITY" (DETERMINED FROM p, T, Z AND R) AND DENSITY CALCULATED USING CONSTANTS DETERMINED BY THE NITROGEN CALIBRATION

DENSITY METER TYPE : SOLARTRON 7810 no. 6343

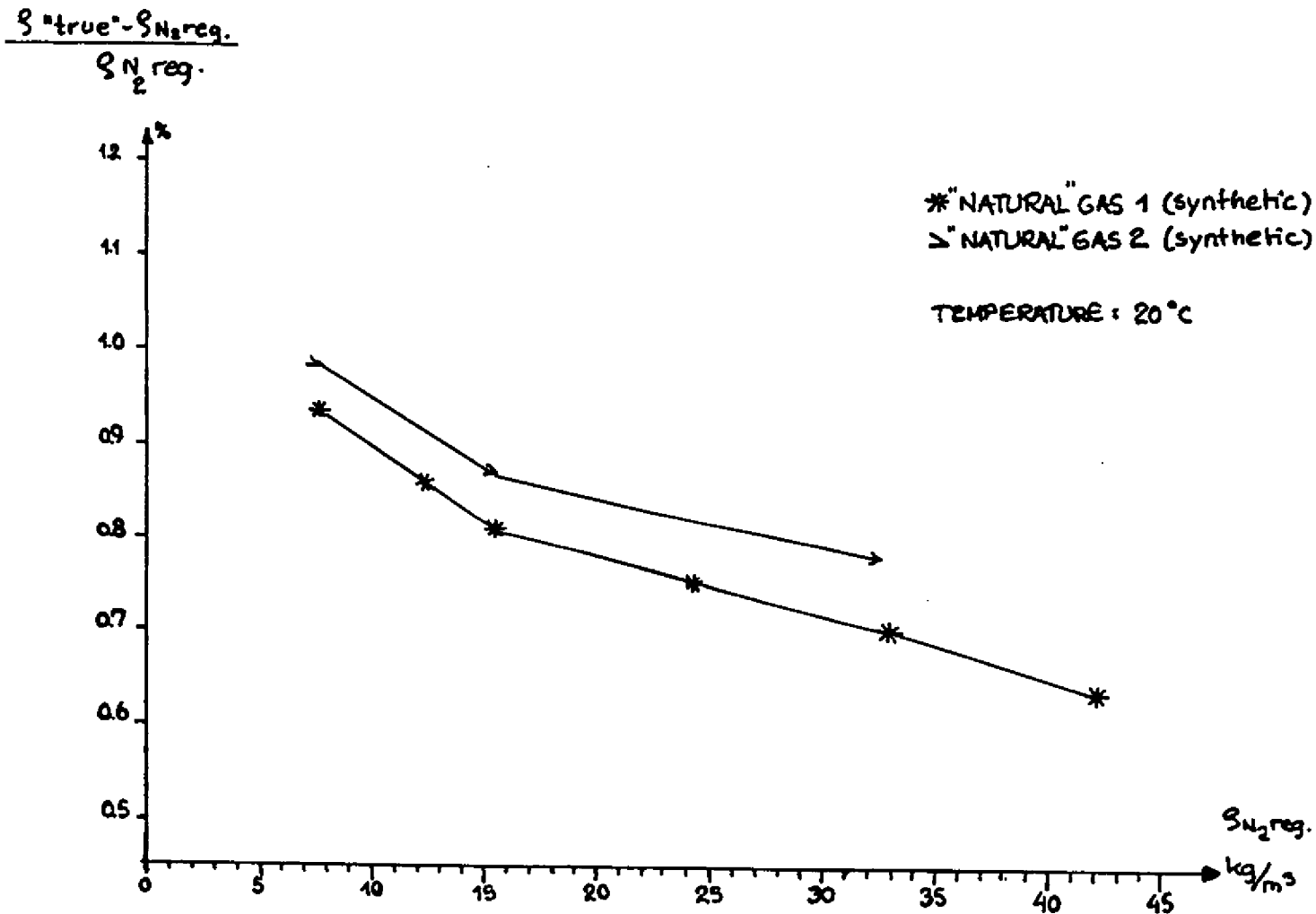


Fig. 8 THE RELATIVE DEVIATION BETWEEN "TRUE DENSITY" (DETERMINED FROM p, T, Z AND R) AND DENSITY CALCULATED USING CONSTANTS DETERMINED BY THE NITROGEN CALIBRATION.

DENSITY METER TYPE : SOLARTRON 7810 NO. 6343

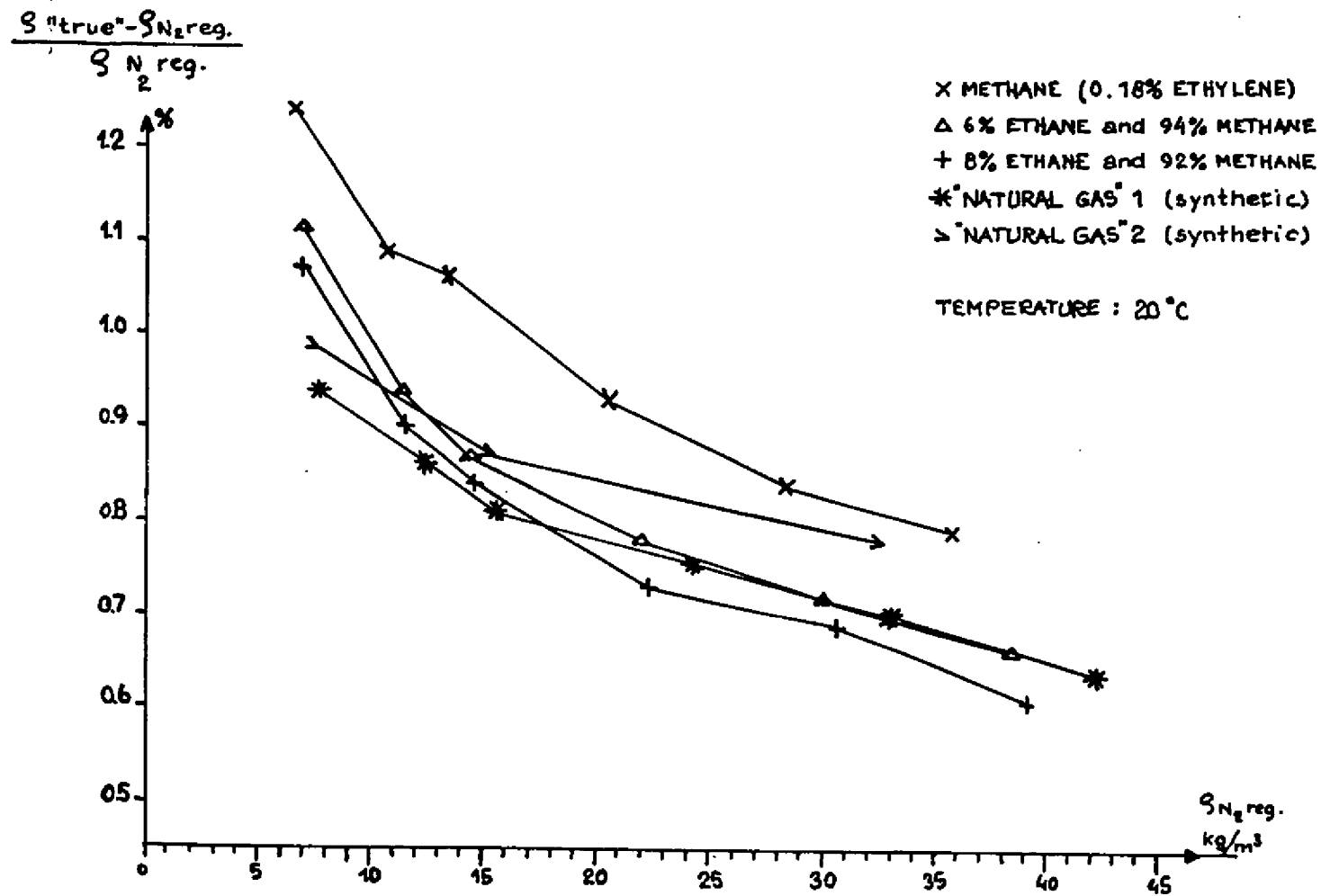


Fig. 9 COMPARISON BETWEEN TWO DENSITY METERS SHOWING THE RELATIVE DEVIATION BETWEEN "TRUE DENSITY" (DETERMINED FROM p, T, Z AND R) AND DENSITY CALCULATED USING CONSTANTS DETERMINED BY THE NITROGEN CALIBRATION.

DENSITY METER TYPE : SOLARTRON 7810 no. 6343 AND no. 6357

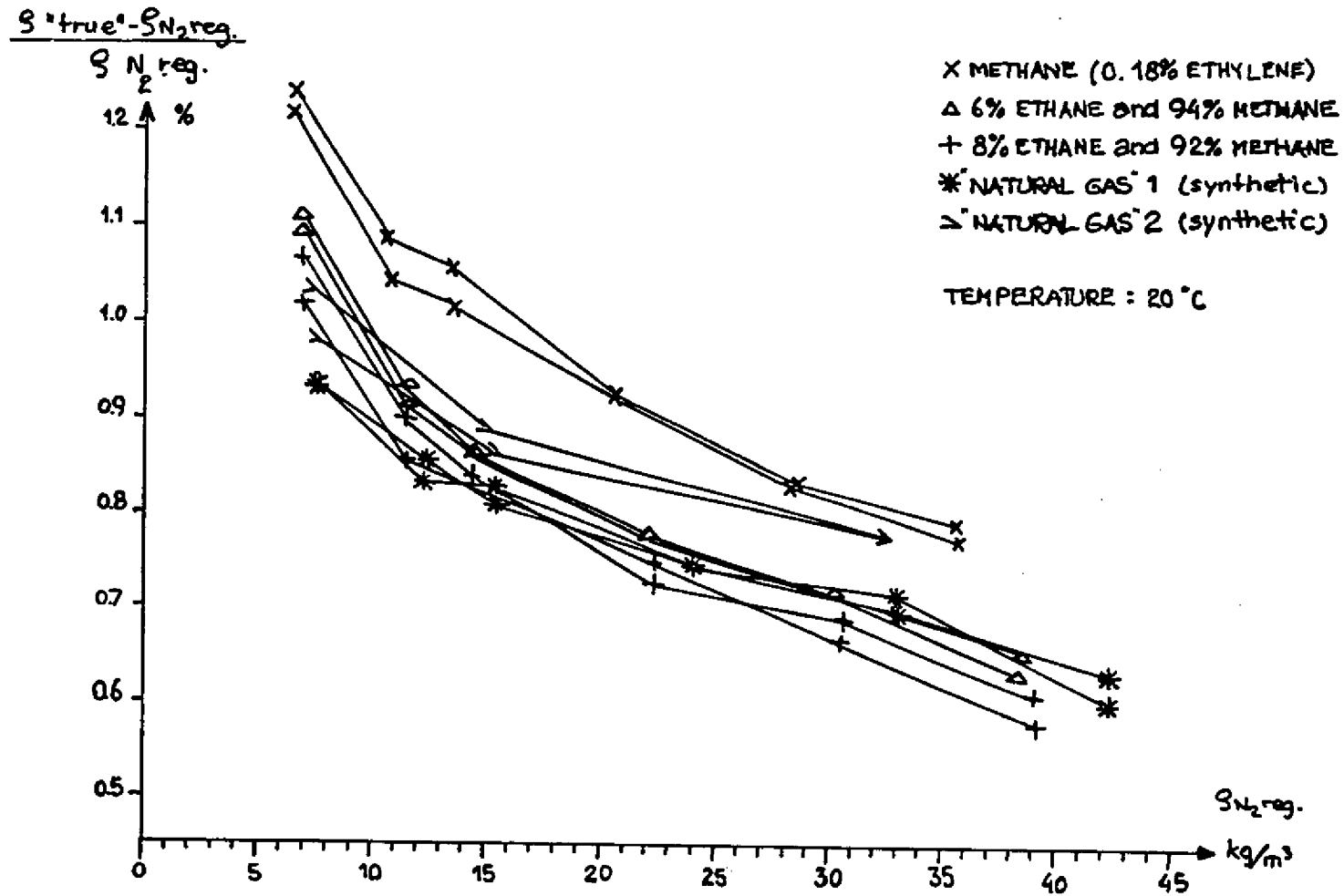
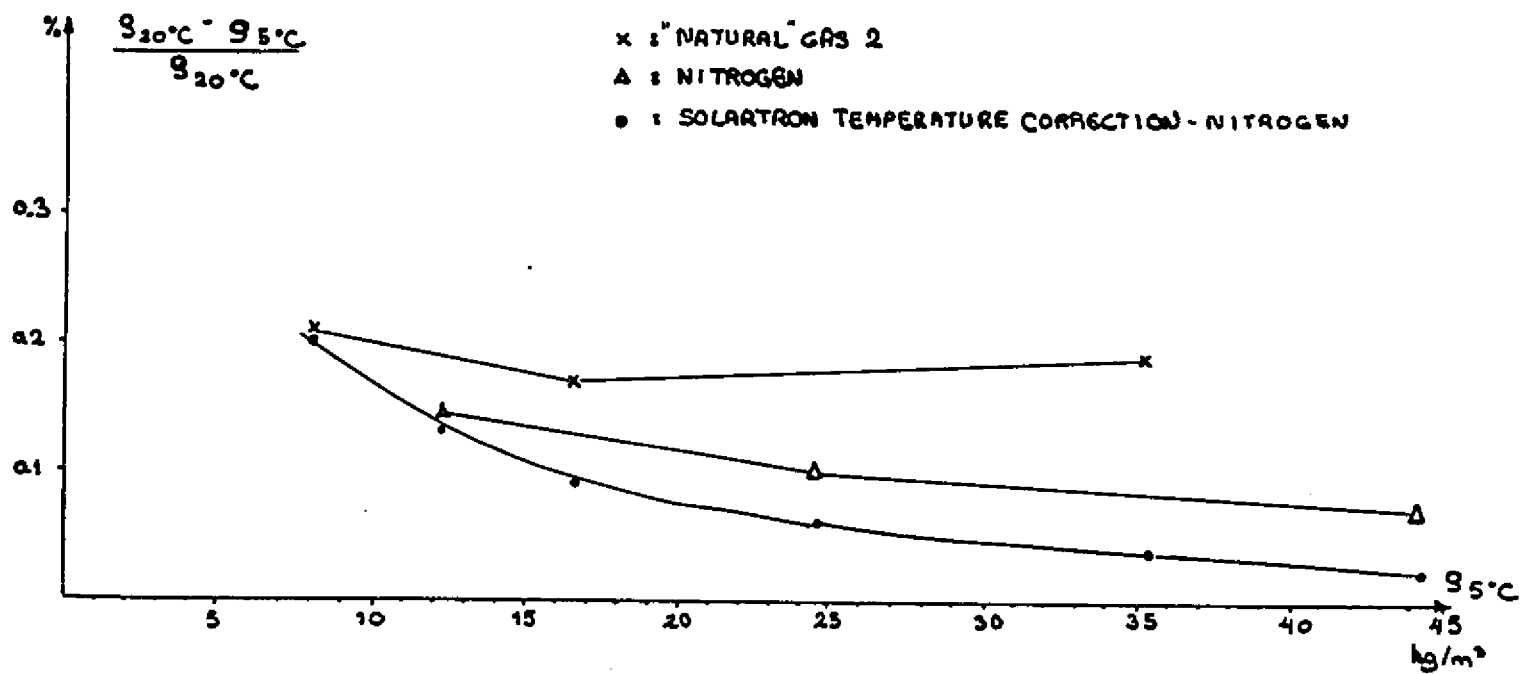


Fig. 10 TEMPERATURE CORRECTION FOR NATURAL GAS 2 (SYNTH.) AND NITROGEN, BASE TEMPERATURE: 20°C.  
 EXPERIMENTAL TEMPERATURE: 5°C. DENSITY METER TYPE : SOLARTRON 7810 no. 6357



## References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.