

An Oil/Water/Gas Composition Meter based on Multiple Energy Gamma Ray Absorption (MEGRA) Measurement

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ABSTRACT

A class of multiphase flowmeters uses the principle of Dual Energy Gamma Ray Absorption (DEGRA) composition measurement to determine the individual water, oil and gas fractions. Under homogenous flow conditions the ultimate uncertainty in phase fractions achievable with this technique depends strongly on the choice of component hardware. The meter presented in this paper uses unique components optimised for water, oil and gas fraction measurement, yielding theoretical uncertainties of 2% in the fractions over a 1 second measurement period. Generally composition meters are sensitive to changes in production water salinity, causing significant systematic errors in the fraction and watercut measurements. A new measurement concept based on Multiple Energy Gamma Ray Absorption (MEGRA) which is insensitive to salinity variations is introduced. A multiphase flowmeter which employs the MEGRA concept does not require field calibration, a decisive advantage in subsea or marginal field developments.

1. INTRODUCTION

A multiphase flowmeter is a device, or a combination of devices, to measure the individual flow rates of water, oil and gas in a multiphase flow environment. The ultimate aim for multiphase flow meter technology is to replace the measurement function of the large, expensive, maintenance-intensive test separator. Multiphase metering should be considered as a means of providing measurements where conventional test separators would be either impractical or economically unattractive. The various measurement concepts used in multiphase meters have their specific areas of application; considerations such as flow rate, Gas Volume Fractions (GVF), watercut, flow regime and the uncertainties achievable under all prevailing conditions must be carefully considered (Ref. 1). In addition, operational aspects (e.g., calibration, use of radioactive sources, ease of installation) and costs (both capital and operating expenditures) should be given careful thought.

Most multiphase flowmeters consist of a total fluid (water, oil and gas) flow rate measurement combined with a composition measurement (Fig. 1). In homogeneous flow, these two measurements can be directly integrated resulting in individual water, oil and gas flow rates. In non-homogeneous flow, one needs either an advanced flow model, or some form of conditioning devices, such as a mixer or compact (in-line) separator upstream of the multiphase flowmeter.

Various types of multiphase composition meters are currently being developed. Most are based on either the measurement of electrical impedance or on gamma ray absorption. Use of gamma ray absorption has the advantage that it is able to cope with any oil-water ratio, in contrast to the impedance measurement. Also the non-intrusiveness of the method is an advantage.

2. COMPOSITION MEASUREMENT BASED ON DEGRA

As a further introduction, the basics of the Dual Energy Gamma Ray Absorption (DEGRA) measurement are explained here. The principle is based on the absorption of a narrow beam of γ - or X-rays of energies e_1 and e_2 . In a pipe, with inner diameter d , containing a water, oil and gas mixture with fractions α_w , α_o , α_g , the measured count rate $I_m(e)$ is :

$$I_m(e) = I_v(e) \cdot \exp\left[-\sum_{i=1}^3 \alpha_i \cdot \mu_i(e) \cdot d\right] \dots\dots\dots (1)$$

$I_v(e)$ is the count rate when the pipe is evacuated and μ_i represents the linear absorption coefficients for the water, oil and gas phases. For two energy levels, e_1 and e_2 , provided the linear absorption coefficients between water, oil and gas are sufficiently different, two independent equations are obtained. A third equation comes from the fact that the sum of the three fractions in a closed conduit should equal 1. A full set of linear equations is given below. R_w , R_o , R_g and R_m now represents the logarithm of the count rates for water, oil, gas and the mixture, respectively, at energies e_1 and e_2 .

The elements in the matrix are determined in a calibration process by filling the instrument with 100% water, 100% oil and 100% gas (air). Together with the measured count rates at the two energy levels from a multiphase mixture it is then possible to calculate the unknown phase fractions (Fig. 2).

$$\begin{bmatrix} R_w(e_1) & R_o(e_1) & R_g(e_1) \\ R_w(e_2) & R_o(e_2) & R_g(e_2) \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \alpha_w \\ \alpha_o \\ \alpha_g \end{bmatrix} = \begin{bmatrix} R_m(e_1) \\ R_m(e_2) \\ 1 \end{bmatrix} \dots\dots\dots (2)$$

In Fig. 3 the above is graphically presented with the logarithm of the count rates of the two energy levels plotted along the axis. The corners of the triangle are the water, oil and gas calibrations, and any point inside this triangle represents a particular composition of water, oil and gas. Combining the composition measurement with a conventional venturi measurement (Fig. 4) results in a complete three phase flow measurement for homogeneous flow regimes.

3. HARDWARE SELECTION AND DESIGN

Three important considerations must be addressed in the selection of hardware. These are the available energy levels (i.e. selection of radioactive source), the detection system (e.g. scintillation counters, solid state detectors, etc.), and a suitable pressure barrier (window) material.

3.1. Energy selection

The emission and absorption of γ - and X-rays are statistical processes, described by a Poisson distribution, therefore the measured count rate has an inherent uncertainty. For single energy γ - or X-ray absorption techniques, the following criterion is generally accepted (see Ref. 2).

$$\mu \cdot d = \left(\frac{\mu}{\rho}\right) \cdot \rho \cdot d = 2 \dots\dots\dots (3)$$

Here μ is the linear absorption coefficient and $[\mu/\rho]$ is the mass absorption coefficient. Note that μ is temperature and pressure dependent, while $[\mu/\rho]$ is independent of both. For a dual energy γ - and X-ray absorption technique the criteria for the selection of the two energies and their relative intensities have also been developed. In Ref. 3 it is demonstrated that the selection of the low energy level has a large influence on the uncertainty of the phase fraction measurement. Similar to Eq. 3, the uncertainty depends on the fluid parameters and pipe diameter. For a water, oil and gas system, the low energy level should preferably be in the range of 10-30 keV. The selection of the high energy level is not so critical, provided it is higher than 40-50 keV. Based on the above, Americium-241 (Am-241) with emissions at 13.9, 17.8, 21.5, 26.3, and 59.5 keV is a suitable source. These energy selection criteria will not be much different for the MEGRA measurement, to be introduced below.

The main disadvantages of Am-241 is that it is an alpha radiator, and has a relatively long half-life. Alternatives to Am-241 are being considered. In Fig. 5, an example of an Am-241 spectrum measured with a Si solid state detector is presented.

3.2. Window material

Applying low-energy gamma rays in this manner calls for strong, radiation-transparent wall material. Metal pipes are not suitable. Carbon fibers are known to be extremely strong and are transparent to low-energy gamma rays. Held in place by an epoxy matrix, Carbon Fiber Reinforced Epoxy (CFRE) is thus an attractive window material. With an effective tensile strength of approximately 1800 to 2000 MPa, it is 4 to 5 times stronger than steel. A CFRE cylinder with an internal diameter of 44 mm and a wall thickness of 2 mm was placed in a steel housing for pressure testing. The steel housing also contained two holes (15 mm diameter) required for gamma ray transmission. This combination was pressure tested successfully up to 120 MPa (1200 bar). In the prototype composition meters, CFRE has been used as window material.

3.3. Detector selection

Two important characteristics were considered in the detector selection process :

3.3.1. Resolution

The resolution of semiconductor diodes used as solid state gamma ray detectors is much better than that of the more commonly used sodium iodide (NaI) scintillation detectors or of gas filled detectors. As an example, for a Silicon (Si) solid state detector which operates at a temperature of around 5 °C, the resolution can be on the order of 1.5-2 keV for the low energy region (14-26 keV). Detector resolution also depends on the detector area, i.e. a small area detector has a better resolution than a large area detector. Considering the Am-241 energy spectrum, with the 4 energy peaks in the 14-26 keV region and the relatively large difference in μ in that region, a high resolution detector is required for adequate peak separation. For the fully separated energy level of 59.5 keV, the resolution is less critical.

3.3.2. Efficiency

The efficiency of NaI scintillation crystals, almost 100% for the lower gamma energy levels, is significantly better than that of Si solid state detectors, since in the latter, interactions between the photons and the detector take place in the very thin barrier (300 μm - 1 mm) between the n- and the p-regions of the semiconductor. As an example, for a Si detector the efficiency is approximately 40% for the 18 keV energy level and on the order of only a few percent at 59.5 keV. In particular for the 59.5 keV peak, larger area detectors are needed to compensate for the poor efficiency and to obtain sufficiently high count rates.

3.4. Dual area solid state detector

The above considerations on resolution and efficiency resulted in the design of a "dual-area" solid state detector, consisting of one 14 mm² and one 100 mm² detector combined on a single chip. The small area detector, having a resolution of 1.7 keV, is used for the low gamma energy levels (14-26 keV). The large area detector, having a resolution of approximately 5 keV, is used for the higher gamma energy level (59.5 keV). These resolutions are for a detector temperature of 5 °C, which is achieved by means of a Peltier cooling element directly attached to the detector. The total power consumption required to achieve this temperature, with an ambient temperature of 40 °C and fluid temperature of 60 °C, is approximately 1 watt.

The gas spectra of the two detectors with the relevant count rates for the five energy levels of Am-241 are presented in Fig. 6. A drawback of the 100 mm² high-energy detector is that it contains a significant number of irrelevant low-energy counts. This has a negative impact on the "deadtime" of the counting electronics. By using a 100 μm -thick copper foil as a filter, this low energy radiation is almost completely absorbed with a only small effect on the 59.5 keV count rate. Fig. 7 presents a sketch of the combined 14/100 mm² detector, including the 100 μm thick copper filter and the Peltier cooling element. Fig. 8 shows the gas spectra of the 14 and 100 mm² detectors with the copper filter; the relevant count rates for the 5 energy levels are also presented. Thus, a solid state detector with both sufficient resolution for the low energies and sufficient efficiency for the high energy has been obtained.

3.5. Accuracy considerations

The uncertainty in the calculation of phase fractions is due to the statistical behaviour of the radioactive decay. It can be demonstrated that the absolute uncertainty in the oil fraction, when compared with those of water and gas, is always largest (Ref. 3). It is also obvious that the maximum absolute uncertainty in oil fraction occurs with the lowest count rate, e.g. with 100% water. In Fig. 9 this maximum absolute uncertainty in oil fraction is indicated as a function of the salinity and the fluid path over which the absorption takes place. The graph is

valid for a specific configuration, i.e. a 6,475 MBq (175 mCi) Am-241 source, the 14/100 mm² dual-area Si solid state detector of 300 µm thickness, 2 mm CFRE wall thickness and a relatively short counting time of only 1 second.

The fraction uncertainty is large for a small fluid path length, as there is insufficient contrast in the absorption between the oil and the water phases, but decreases as the fluid path is extended. However, beyond a certain fluid path the uncertainty again increases because increased absorption results in count rates which are too low. The salinity also has an effect on the optimum fluid path, since with increasing salinity the optimum fluid path is reduced. For a fluid path of 15-20 mm the uncertainty in the phase fractions is not greatly influenced by salinity, hence accurate fraction measurements can be made over the full range of 0-300 kg/m³ salt (NaCl) concentration.

3.6. Concentric Venturi

The DEGRA composition meter can be used as stand-alone device only or can be integrated with any total fluid meter (e.g. a venturi plus differential pressure device) to make up a full multiphase flowmeter. With a venturi applied to homogeneous flow, the total fluid volume flow rate (Q_{tot}) can be calculated if the differential pressure (Δp) over the venturi and density of the multiphase fluid mixture (ρ_m) are known.

$$Q_{tot} = C \cdot \sqrt{\frac{\Delta p}{\rho_m}} \dots\dots\dots (4)$$

C is a geometrical constant multiplied by the discharge coefficient. Using the measured phase fractions α_w , α_o , and α_g , the base densities ρ_w , ρ_o , and ρ_g , and the measured temperature and pressure, one can calculate the actual density of the multiphase fluid mixture, ρ_m . Subsequently, the actual total fluid volume flow rate can be calculated, and with α_w , α_o , and α_g the individual water, oil and gas actual volume flow rates can be determined.

For flow rates on the order of 100 to several 1000 m³/day, a venturi throat diameter (fluid path length) of 15-20 mm is highly impractical because of the large pressure drop. However, with the introduction of a concentric venturi it is possible to achieve a fluid absorption path length of 15-20 mm and at the same time almost any desired cross sectional area for the fluid flow. In Fig. 10 a schematic drawing of a concentric configuration for very high salinity concentration (saturated brine with a concentration of 300 kg/m³) is presented. The conical body in the centre of the pipe contains the radiation source. The effective cross sectional area of the concentric throat, with inner and outer diameters of 30 and 58 mm respectively, is equivalent to that of a normal venturi with a throat diameter of 50 mm.

3.7. Influence of fluid parameters

The 100% water reference count rates for the lower energies required in the DEGRA calibration are strongly dependent on the salinity of the production water, since salt has a high absorption coefficient compared to water. Systematic errors in the measured water, oil and gas fractions will occur if the salinity of the production water changes and the 100% water reference count rate is not corrected. In many potential multiphase metering applications, the salinity of the production water will indeed vary in time, and could be different for each well drilled in the same reservoir. In water injection reservoirs, for example, the salinity will vary between that of formation water and that of injection water. In Fig. 11 the production water salinity for the wells of a North Sea reservoir are shown as measured in January and June 1993. It not only shows that salinity is different for each well in the same reservoir, but also that in a 6 month period the salinity for some wells has changed by more than 10 kg/m³. Also horizontal and/or vertical gradients in formation water salinity across the reservoir may occur. Ref. 4 presents an example where such gradients can lead to salinity variations much larger than 10 kg/m³. In Fig. 12 the relative change in watercut ($\Delta \text{watercut}/\text{watercut}$) is indicated for a change in salinity of 10 kg/m³ from the calibration salinity. In this example, at a 50 kg/m³ salinity and a salinity change of 10 kg/m³ results in a ($\Delta \text{watercut}/\text{watercut}$) of 8%. At a watercut level of 50% this equals a 4% absolute error in watercut and an 8% relative error in net-oil production.

The curve in Fig. 12 is almost independent of the energy levels used. Multiphase meters using a Barium-133 source (30 and 360 keV) or a combination of Am-241 and Cesium-137 sources (60 keV and 660 keV) will suffer from the same errors in watercut due to a change in salinity. It should be noted that the problem of

salinity changes is not unique to the gamma ray absorption technique. Conductivity measurement techniques, often used in situations of water external emulsions, are also influenced by salinity changes (Ref. 5).

4. COMPOSITION MEASUREMENT BASED ON TEGRA

When two energy levels are used it is possible to calculate the three phase fractions in a mixture. When three energy levels are applied (TEGRA, or Triple Energy Gamma Ray Absorption), it is possible to calculate one additional parameter; in the case presented here, the parameter of interest is salinity. In the measured water, oil and gas calibration spectra (Fig. 5), it can be seen that 13.9, 21.5 and 26.3 keV energy levels are also available. The 26.3 keV level was chosen for the calculation.

4.1. Exact solution of TEGRA

It will be shown that the new set of equations is very sensitive to small measurement errors or to the statistical uncertainty in the measured count rates. The 4x4 matrix, similar to the 3x3 matrix of Eq. 2, is very poorly conditioned and small variations in the measured count rates will lead to large fluctuations in estimates of phase fractions and salinity. In a computer simulation, with $\alpha_w = \alpha_o = 0.15$, $\alpha_g = 0.70$, $S = 100 \text{ kg/m}^3$ and applying the Poisson-type of statistical fluctuations, the exact solution of the set of equations for each measurement shows enormous fluctuations in the calculated α_w , α_o , α_g and S . In Fig. 13 it is shown that the calculated fractions are even outside the region of 0 to 1, and salinity estimates vary from -600 to +600 kg/m^3 . Hence, solving the equations for each measurement (one calculation per second) will not result in an acceptable composition measurement.

4.2. Constant salinity approach

As indicated above, salinity typically changes either on a time scale of months (gradual change from formation water to injected water) or perhaps on a time scales of days (sudden injection water breakthrough). In the time span of a few hours the salinity can be assumed constant; an improved calculation scheme based on this assumption has been developed. After imposing this constraint to the algorithms, it is no longer possible to solve the set of 4 equations exactly, but instead a solution can be found which is optimal in a chi-square minimisation sense. The outcome of this minimisation process is a set of individual phase fractions for each measurement, and one salinity figure for all measurements. The previous simulation was repeated with this new algorithm and the results are presented in Fig. 14. The calculated phase fractions demonstrate acceptable variations, and the calculated salinity equals the input value.

The chi-square minimisation algorithm is not limited to 3 energy levels. When more energy levels are added to the algorithm, e.g., 13.9 and 21.5 keV, the minimum acquisition time is reduced and the accuracy of the composition measurement is further improved. Hence, a composition measurement based on Multiple Energy Gamma Ray Absorption (MEGRA) has been created.

4.3. Salt composition changes

The TEGRA or MEGRA algorithms cannot distinguish between salinity changes or salt composition changes. Heavier salt components, e.g. potassium or calcium based salts, have higher absorption coefficients than the more commonly occurring NaCl. However, a sensitivity analysis showed that salt composition changes affect only the calculated salinity, and that the errors in the calculated phase fractions are negligible - less than 1% absolute error in phase fraction for a worst case of 100% water with a salinity concentration of 100 kg/m^3 .

5. CALIBRATION FREE OPERATION USING MEGRA

The entire purpose of the DEGRA calibration is to determine the matrix elements of Eq. 2, i.e. to measure the reference count rates of (saline) water, oil and gas at two gamma energy levels. With TEGRA it is possible to measure the salinity concentration in-situ. The absorption coefficients of fresh water are well known (Ref. 6) so it is possible to calculate the reference saline water count rate from the empty-pipe count rate. A similar procedure can be followed for the oil reference count rates, for which the density and composition of the oil needs to be known. A sensitivity analysis shows that the errors in phase fractions resulting from density and composition changes are small. For example, a relatively large change of 10 kg/m^3 in oil density results in a maximum absolute error of approximately 1% in any phase fraction. Hence, all the reference rates can be

calculated from the empty-pipe count rates, assumed oil composition and density, and tabulated absorption coefficients. The measured spectra, the empty-pipe spectrum, and the mixture spectrum are each a linear combination of the peaks occurring in Am-241, fluorescence peaks for materials in the vicinity of the detector, sum peaks, Compton scattering and build-up contributions.

This approach of calibration free operation (Fig. 15) has been verified with a prototype meter, which was evaluated in the Shell test loop and subsequently transported to an oil field. In Fig. 16, the phase fractions from the meter as measured for a particular well are presented. These fractions have been calculated with on-site calibration, i.e. the DEGRA concept and filling the meter first with saline production water and then with oil. The average watercut in the period between 1600-4000 seconds was measured to be 78%.

All the measured spectra over the above period were then re-processed, but this time the MEGRA algorithm, the empty-pipe count rate from the earlier testloop evaluation, and the tabulated, known, absorption coefficients were used. The resulting phase fractions are presented in Fig. 17 and the average watercut estimate over the same period used above was 76%. It is concluded that calibration free composition is practically possible if correction of the various distorting effects on the measured spectra is under control.

6. AREAS OF APPLICATION

A composition meter which uses MEGRA without flow models is only applicable to homogeneous flows, i.e. when (1) there is no velocity difference between the individual phases, (2) the individual phases are homogeneous, and (3) there are no variations in composition during a measurement period (for the MEGRA, within the 1 second measurement time). Equation 2 contains the mean logarithm of the count rate, but the actual measurement gives the logarithm of the mean count rate; these two are not equal in the case of non-homogeneous or varying compositions. In Fig. 18 a worst case situation of this phenomenon is schematically presented. Theoretically it can be demonstrated that in such a situation, or in any slug flow regime, the composition measurement always yields an under-reading of the watercut. This was further demonstrated in a testloop evaluation in which mixing intensity could be controlled (Fig. 19). The higher the mixing intensity, the better was the watercut measurement.

An overview of the various MEGRA applications in a multiphase flow measurement and classified by Gas Volume Fraction (GVF) is treated here.

6.1. Gassy liquid streams

Gas might be present in drainlines of separators because of excessive pressure loss causing gas breakout in the drainline or insufficient gas/liquid separation. Both phenomena result in fairly homogeneous "gassy liquid" streams (low GVF multiphase flows). Fig. 20 is an example which presents the watercut reading of a prototype MEGRA. The GVF of the mixture during these measurements was between 0 and 30%. This prototype MEGRA is currently undergoing a field evaluation on an offshore platform in the South China Sea.

6.2. Moderate Gas Volume Fraction streams

Naturally occurring flow streams with GVFs between 20% and 80% are ordinarily not homogeneous. Mixing of the multiphase flow is required upstream of the MEGRA to eliminate the velocity slip and reduce the variations in composition. This approach is already commercially available (Ref. 7-8).

6.3. High Gas Volume Fraction streams

At very high GVFs, i.e. GVFs higher than approximately 80%, it is difficult to achieve a slip-free and homogeneous mixture. Here the liquid and gas might be roughly separated using a small and simple separator followed by a measurement of the "gassy liquid" and "wet-gas" streams (Fig. 21). The "gassy liquid" stream can be measured with a MEGRA/venturi combination. This approach has been tested in the field recently; the well test package is commercially available.

7. FURTHER DEVELOPMENT OF MEGRA

In May of 1995 Shell awarded an exclusive License to Daniel Industries, Inc. to commercialize the MEGRA technology world-wide. As an initial step in the development of this product, Daniel designed and built several

prototype meters, the first of which was the unit currently located in the South China Sea and referenced above. This unit is also the one which produced the results shown in Fig. 20 from measurements made in the Shell multiphase flow loop.

In May of 1996, Daniel Industries, Inc. and Framo Engineering AS announced an agreement to cooperate as partners in the development, manufacture, and marketing of multiphase flow meters world-wide. Thus, once the MEGRA concept is proved through the deployment of prototype meters in various regions of the World, it will be integrated as the composition measurement of choice in the Daniel-Framo line of multiphase meters.

8. CONCLUSIONS

Accuracy considerations showed that the lower gamma energy levels of a composition meter based on DEGRA (TEGRA or MEGRA) should be in the range of 10-30 keV, and that the high energy level is not so critical provided it is above 40-50 keV. Am-241 proved to be a very attractive source from a measurement point of view.

The introduction of a unique dual-area solid state detector, with a small area detector providing good resolution for the various low energy levels (14-26 keV), and a large area detector with reduced resolution for the isolated high energy level (59.5 keV) of Am-241, is ideal for the MEGRA concept.

A sensitivity analysis for a combination of Am-241 and the dual-area solid state detector showed that with a fluid path length of 20 mm, the uncertainty of the measurement becomes almost independent of the salinity. Uncertainty in phase fractions are of the order of 2% if counting periods of 1 second are applied.

With a concentric configuration, having the Am-241 source in the centre of the pipe, the optimum 20 mm fluid path length can be selected without serious restriction in the fluid flow throughput.

Salinity changes, more than density and molecular composition changes, have a significant impact on the calculated phase fraction and watercut. With the introduction of a third energy level and an advanced calculation method, it is possible to calculate phase fractions and production water salinity with acceptable accuracy.

Calibration free composition measurement, which does not require field calibration with reference fluids, is feasible. For this only spectra for an empty-pipe, fresh water, and a "well defined" oil need be measured, and these only once. A subsequent analysis of the various background contributions will then result in instrument constants. All this can be done in the factory, and once installed in the field only a rough estimate of the salt composition and of the densities and molecular compositions of the oil and gas are required.

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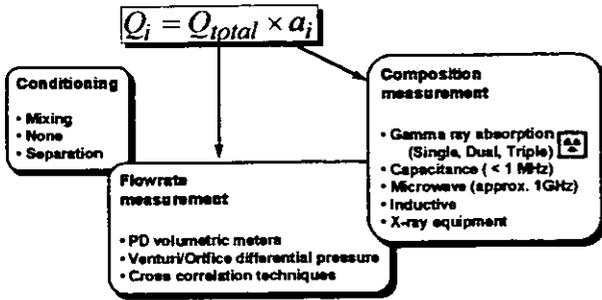


Fig. 1 - Building blocks of a multiphase flowmetering system. At higher Gas Volume Fractions, conditioning devices are required to reduce velocity slip between the gas/liquid phase or to remove the bulk of the gas. Alternatively advanced flow models might be used.

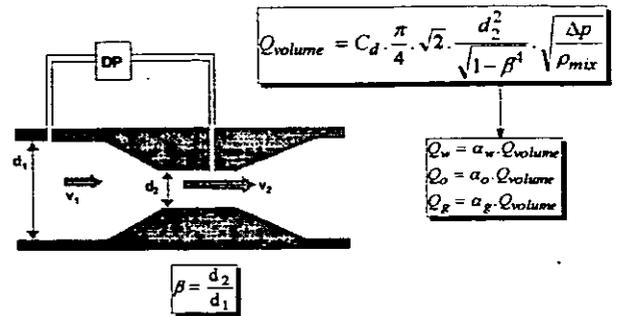


Fig. 4 - Venturi application in multiphase flow measurement. Density ρ_{mix} and the fractions α_i are measured with the gamma ray absorption technique.

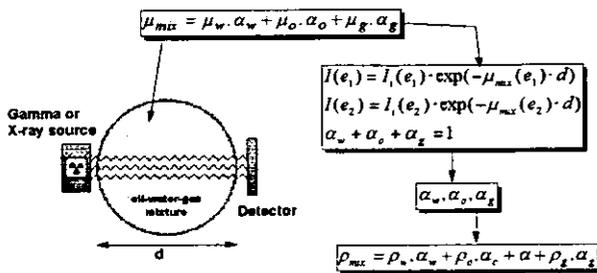


Fig. 2 - Principle of the Dual Energy Gamma Ray Absorption (DEGRA) technique.

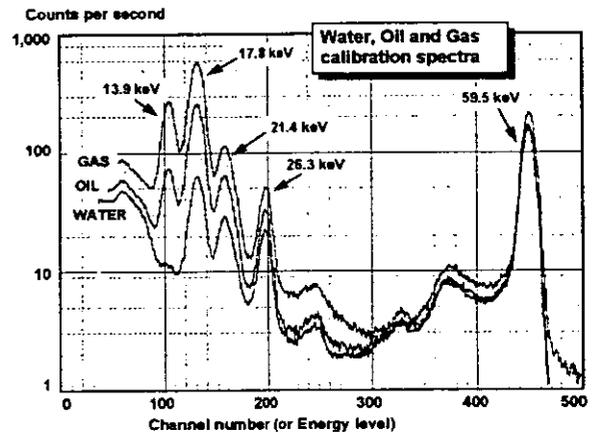


Fig. 5 - Water, oil and gas calibration spectra from a 6.475 GBq (175 mCi) Am-241 source as measured with a 14 mm² Si solid state detector cooled to 5°C.

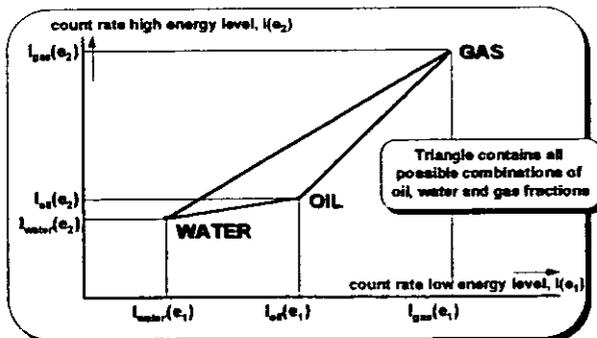


Fig. 3 - Graphical presentation of the DEGRA concept. The corner points of the triangle are the water, oil and gas calibration points.

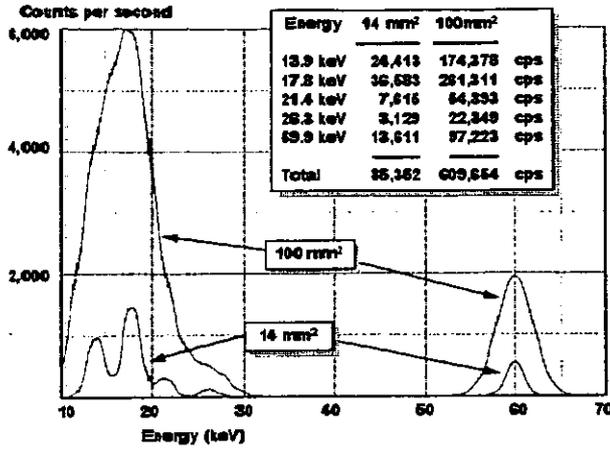


Fig. 6 - Gas spectra from two separate Si solid state detectors. The 14 mm² detector provides acceptable resolution and efficiency for the 14-26 keV energy levels. The 100 mm² is used to compensate for the poor efficiency at 59.5 keV.

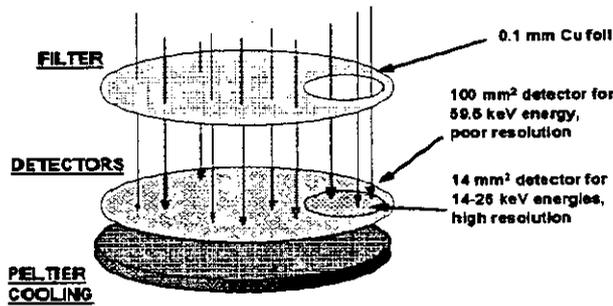


Fig. 7 - The "dual area Si solid state" detector. The 100 µm copper foil filters out the low energy gamma rays before they reach the 100 mm² detector. This large detector, having poor resolution, is dedicated to counting the 59.5 keV events.

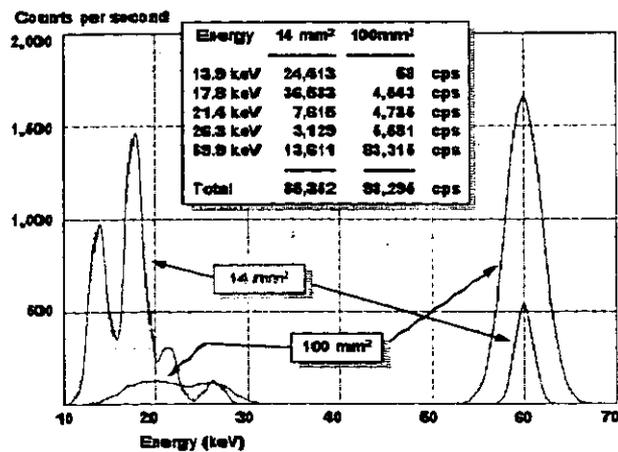


Fig. 8 - Gas spectra from the "dual area solid state" detector and the 100 µm copper filter. Low energy count rates on the 100 mm² detector have been reduced significantly with this filter.

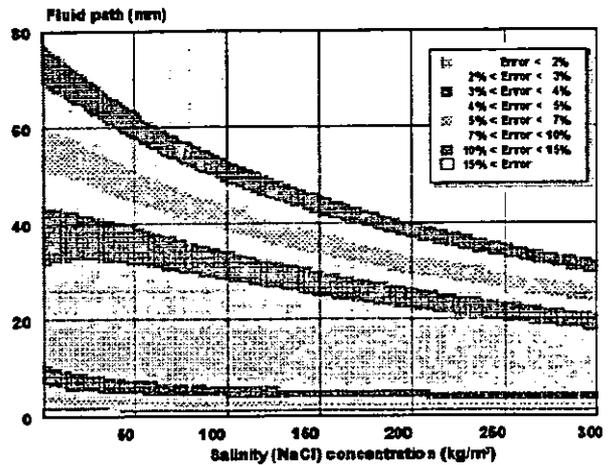


Fig. 9 - Uncertainty in the fraction calculation as a function of salinity and fluid path length. The plot is valid for a 6,475 MBq (175 mCi) Am-241 source, two 2 mm Carbon Fiber Reinforced Epoxy windows, and the 14/100 mm² "dual area solid state" detector shown in Fig. 7. Above plot for 100% water is a worst case situation (lowest count rate).

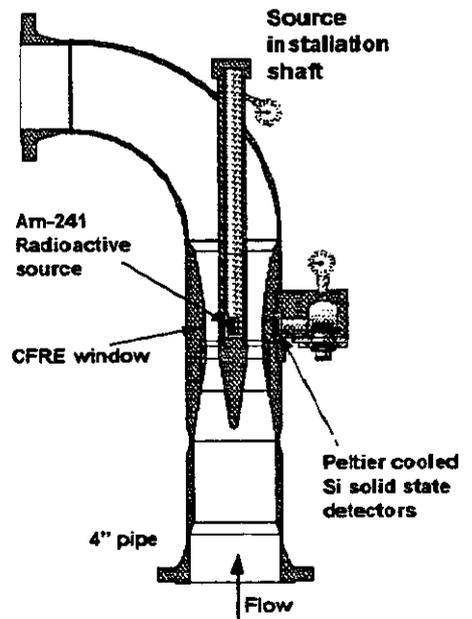


Fig. 10 - Schematic drawing of the concentric MEGRA. The source is installed in the centre of the pipe and a set of concentric Carbon Fiber Reinforced Epoxy cylinders are used as window material.

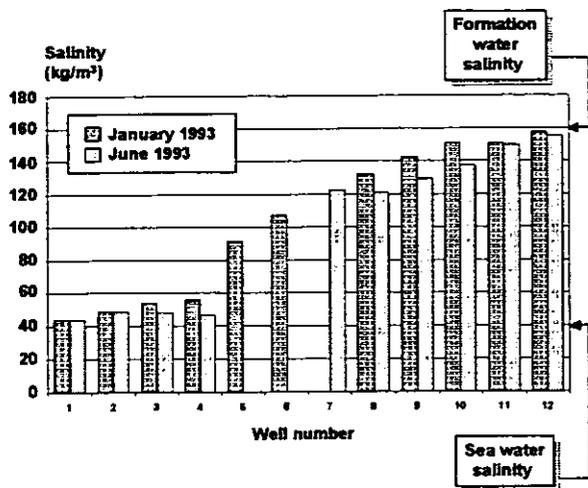


Fig. - 11 - The salinities of various wells from one North Sea field as measured in January and June 1993. The formation water salinity is 160 kg/m^3 while the sea water salinity is 35 kg/m^3 . The salinity measured changes gradually from that of the formation water to that of the sea water.

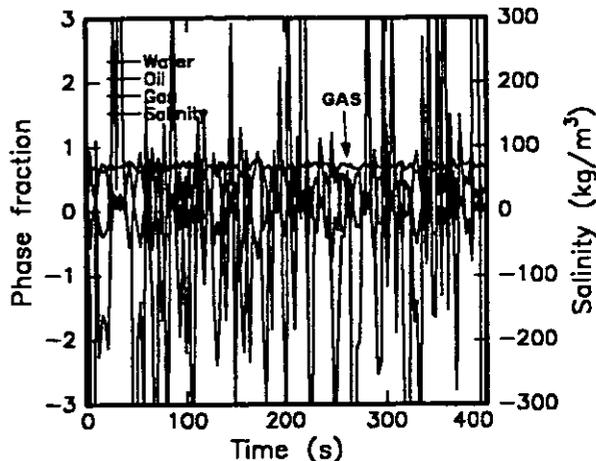


Fig. - 13 - Phase fractions and salinity obtained from the computer simulated count rates by directly solving the matrix equations. The left hand scale is valid for the phase fractions and the right hand for salinity. Input values are $\alpha_w=0.15$, $\alpha_o=0.15$, $\alpha_g=0.70$ and $S=100 \text{ kg/m}^3$. While the gas fraction calculation is acceptable, the oil and water fractions calculations and the salinity estimate are not acceptable.

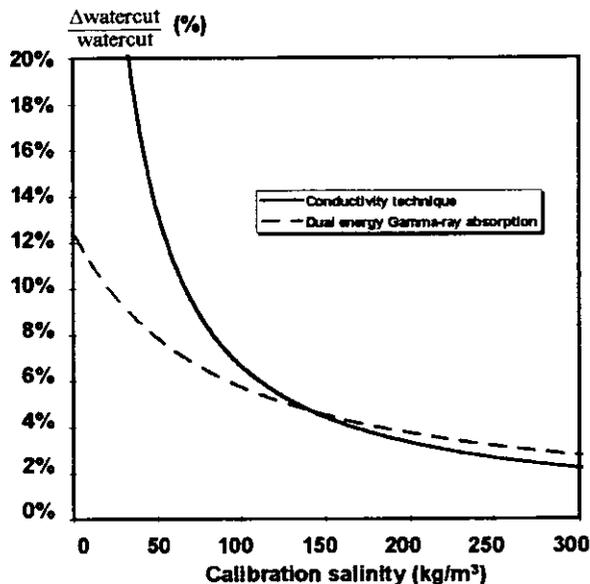


Fig. - 12 - The relative error in watercut as function of salinity for a change in salinity of 10 kg/m^3 .

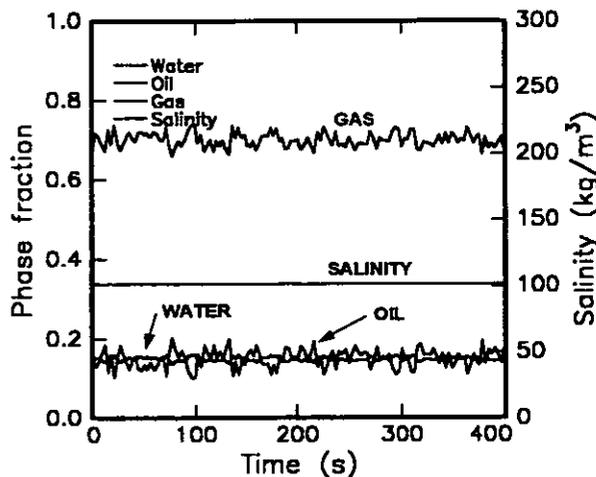


Fig. - 14 - Phase fractions and salinity obtained from the chi-square minimisation algorithm, where the same computer simulated count rates as in the previous figure were used as input. The left hand scale is valid for the phase fractions, that on the right for salinity. Input values are $\alpha_w=0.15$, $\alpha_o=0.15$, $\alpha_g=0.70$ and $S=100 \text{ kg/m}^3$. This new algorithm results in a statistically acceptable composition measurement and a proper estimation of the salinity.

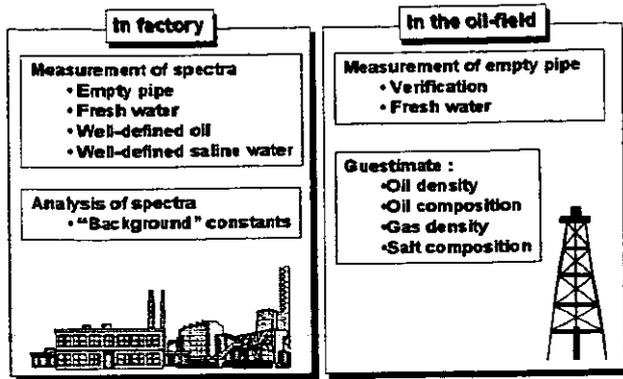


Fig. 15 - Principle of calibration free operation. No water, oil and gas calibration is required in the field.

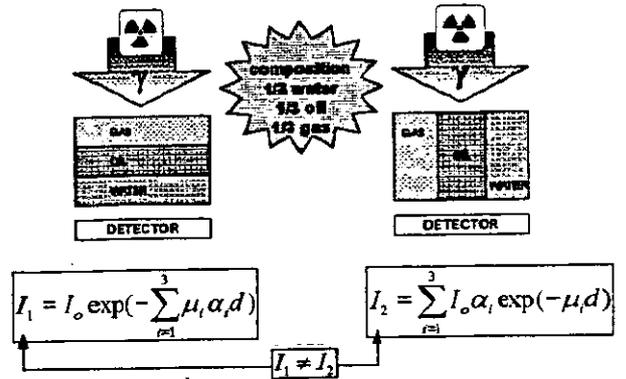


Fig. 18. - Count rates measured in these two situations are not equal, although the fractions in both are the same. If variations in time occur (second situation), the result is systematic underreading of the watercut.

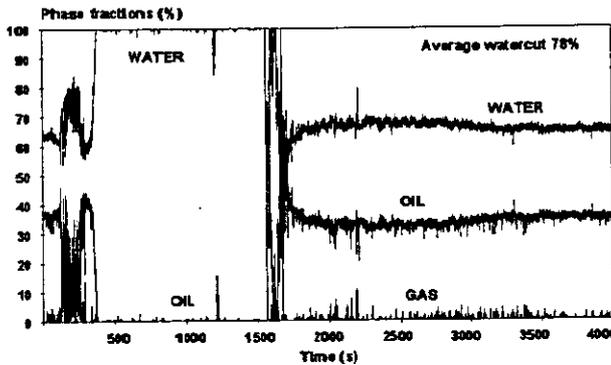


Fig. 16 - Fractions obtained using conventional calibration and the DEGRA calculation method. Saline water and oil reference count rates as measured in the oil field are used.

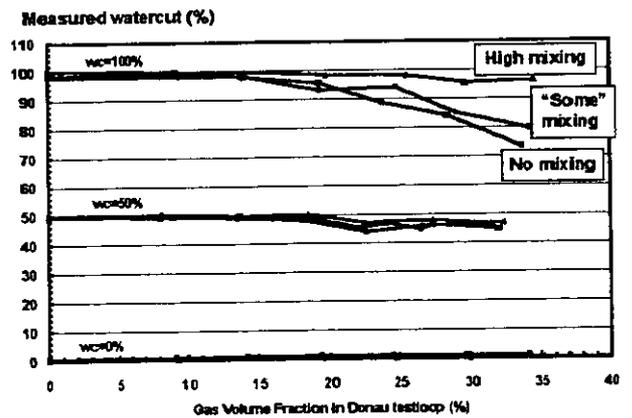


Fig. 19 - Watercut reading as a function of Gas Volume Fraction. Mixing is required above 20% GVF to avoid systematic errors in the composition measurement.

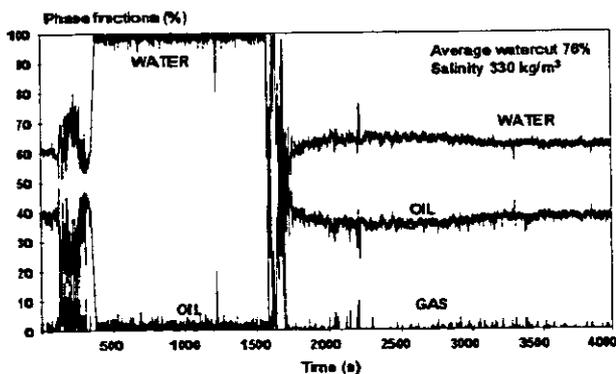


Fig. 17 - Fractions obtained using the calibration free concept plus the MEGRA algorithm. No reference spectra from the field are used, only spectra from the testloop evaluation.

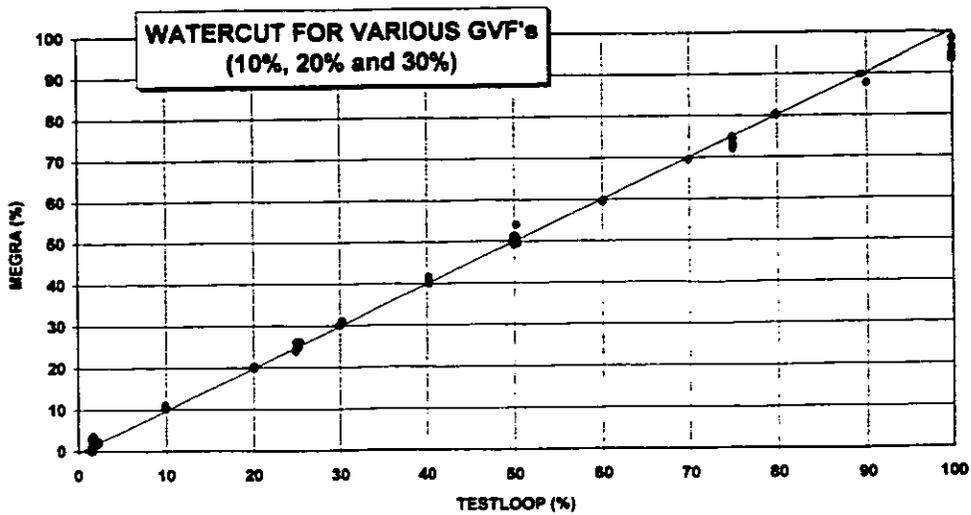


Fig. 20^a - Watercut reading of the Daniel prototype MEGRA versus the test loop reference measurement

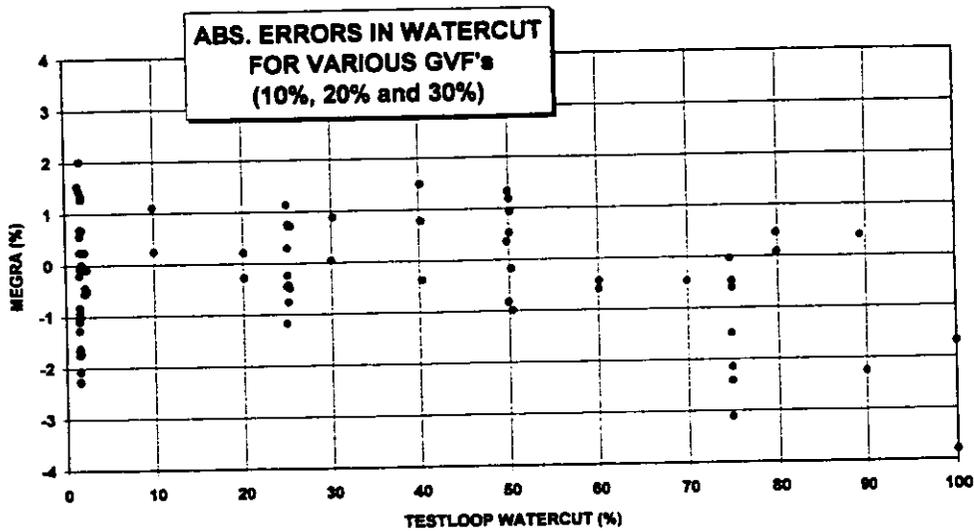


Fig. 20^b - Absolute error in watercut reading of the Daniel prototype MEGRA versus the reference measurement.

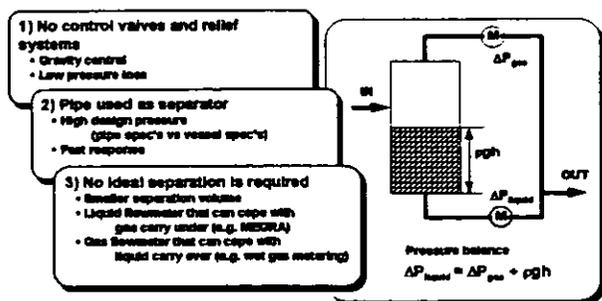


Fig. - 21 - A simple In-Line Conditioner (ILC) to remove the bulk of the gas from a high GVF multi-phase flow. MEGRA can be applied in the "gassy liquid" drainline, a "wet gas" meter in the gas line