CONTINUOUS ON-LINE WATER MEASUREMENT

by

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CONTINUOUS MEASUREMENT OF THE WATER CONTENT OF CRUDE OIL USING ELECTRICAL CAPACITANCE TECHNIQUES - DEVELOPMENT AND APPLICATIONS

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SYNOPSIS

Accurate measurement of crude oil water content has become a very important fiscal measurement, for offshore platforms and terminals and for refineries. The established practice uses flow proportioned automatic samplers, but this approach poses some difficult problems especially for spiked crude and for high pressure pipelines. Another matter often debated is the incidence and significance of high water content transients and therefore the grab frequency required for an automatic sampler to ensure taking a representative composite sample.

The first part of this paper describes the development of a continuous monitor, using the well-known electrical capacitance technique, aiming to measure the water content of crude oil transfers to an accuracy comparable with established fiscal measurement practices. It is equally applicable to high pressure and spiked crudes and eliminates any concern for water transients.

The second part of the paper describes how a prototype capacitance monitor was used to study the water content profiles during discharge of VLCCs. The results indicate - inter alia - that despite large water transients being common, automatic sampling with a grab frequency of only one grab per minute or even lower would collect a representative sample. The importance of accurate flow proportioning is also highlighted. Another application for the capacitance technique which is described is for pipeline water profile studies, to give real time display of the profile and avoid tedious manual sampling and lab. testing.

1. DEVELOPMENT OF A CONTINUOUS ANALYSER

1.1 Introduction

Accurate measurement of water content has become a very important fiscal measurement for crude oils. The approach currently recognised internationally is to use an automatic sampler to derive a representative bulk sample of each transfer and test this sample in a laboratory.

This approach has many limitations, both in concept and in practice. The problems are particularly acute when applied to hot, high pressure and high vapour pressure crudes, as arise in production pipelines and offshore platforms. Results from sampling/testing are often too slow for operational benefit.

Clearly, there is a very strong incentive to provide the means to measure crude oil water content continuously on-line, i.e. in real time. Using the change in dielectric constant of an oil/water mixture to measure water content has been used for many years. However, it has generally been applied only in a simplistic manner and with little knowledge of the important parameters: consequently accuracy has been very poor and credibility low.

Since 1979, we have been studying the capacitance technique in the belief that it might offer the way to measure water in crude oils on-line, in the fiscal context. The technique has many practical advantages in that it is essentially very simple and is readily applicable to hot/high pressure/spiked crudes for which the existing sampler techniques are unattractive.

Our earlier work used some proprietary capacitance electrodes and conventional ac bridge electronics of the type supplied for level sensing. The overall system was rather elementary and lacked sensitivity, yet the results were highly satisfactory as a basis to progress the technique further.

About that time, Endress and Hauser Ltd who had provided the initial equipment for our tests, developed a new technique for measuring capacitance. It combined very high sensitivity with excellent stability and high immunity to resistive effects - characteristics all eminently suitable for the water content measurement.

Endress and Hauser became convinced that water content measurement by the capacitance technique could become a viable commercial prospect. Therefore they agreed to collaborate with us in its development.

1.2 Design Details

1.2.1 Flow Cell Design

The basis of the capacitance method for water content measurement is the flow cell, comprising an outer tube with connections for oil in and out and a central electrode. The tube and electrode form an electrical capacitor whose capacitance varies with the dielectric constant of the flowing oil/water mixture.

The capacitance between two plates is directly proportional to the plate area and inversely proportional to their distance apart. Thus the preferred design is to use a long large diameter tube with a concentric electrode whose diameter is just less than the tube ID.

In practice, the length and diameter of the flow cell tube are constrained by what can easily be handled and installed. The separation between the two cylinders must be large enough to cope with dirty crude/water mixtures, without risk of blockages. The cross sectional area of the flow annulus needs to be small enough to ensure that the fluid velocity for practical sampling rates is high enough to keep any water particles in suspension. Otherwise flow rate does not affect the measurement.

Our preliminary work had shown that temperature compensation would be essential for fiscal measurements. Therefore, a temperature sensor is required within the flow cell.

For low water contents, the oil/water mixture is non-conducting and therefore uninsulated electrodes would suffice. However, in practice, flow cells will experience short periods of high water contents (above say 40% volume water) and such mixtures would short circuit an uninsulated cell. A cell design with insulated electrodes is therefore preferred, but the insulator must be very thin to minimise its effect of reducing the active capacitance.

The flow cell tubing and the electrode connections must of course be designed to the pressure rating appropriate to the application. For refinery offsites service this is commonly Class 150, but for offshore/terminals/pipelines, it may be as high as Class 1500 (i.e. working pressures up to 245 bar, 3600 psig).

For fiscal applications, one special design factor arises. An established practice for other fiscal measurements (e.g. turbine meters and densitometers) is to have a dual measurement with in-build discrepancy alarm, to enhance the system's integrity. We therefore conceived the novel arrangement to incorporate two capacitance measurements within the same flow cell, using an electrode in each end of a single flow tube.

Based on the above criteria and in collaboration with Endress and Hauser, dual measurement flow cells for Class 150 and Class 900 applications have been designed and manufactured. These are shown in Figs.1 and 2.

The low pressure cell, Fig.1, has an overall length of 1 metre. The outer tubular electrode has an internal diameter of 65 mm and the gap between the two electrodes is 6 mm. The effective length of each cell is approx. 200 mm. The central electrode is hollow to reduce its weight.

Both electrodes have an insulating coating to reduce the effect of conductivity at high water contents. This coating is an oven baked epoxy material approx. 0.004" thick (0.1 mm). To improve the adhesion of the coating the cell is manufactured from carbon steel.

In order to obtain high sensitivity and stability care must be taken to minimise the effect of stray capacitance at the cell ends where the central electrodes are mounted. This has been catered for by the shape of the central electrode, by the use of insulating materials and by the provision of a guard ring. The central electrode is a large diameter tube mounted by an insulator on a small diameter shaft, thus reducing the electrode surface area at the end of the cell. The end boss is further insulated. The guard ring provides a screen between the active electrode and earth, thereby reducing the standing capacitance at the boss. It is driven by a voltage of identical waveform to the measuring electrode but is not included in the measurement.

Each cell has an active capacitance ca 160 pF when full of dry crude oil. The change of capacitance between dry oil and 5% water/oil mixture is approx. 22 pF.

The high pressure cell, Fig.2, is of a similar design but built to Class 900 specification. The cell is made from 3" dia. Schedule 80 pipe requiring some changes in the dimensions of the electrode system.

As this cell is intended for high pressure production line application the specification is less demanding, in that only one 0-5% range is required. This together with the more difficult design of electrical connection seals has led to the ground ring being omitted. To compensate for this the insulated support rod of the central electrode has been extended giving increased separation between the active area and the end of the cell.

The central electrode is open to fluid, to eliminate any distortion due to pressure. The contents of this electrode have no influence on the measurement.

1.2.2 Electronics Design

The measuring technique used is the same for both the low and high pressure cells. It is a pulsed dc measurement whereby the capacitor that is the cell is charged to a fixed voltage simultaneously with a reference capacitor. These two capacitors are then switched such that their charges are integrated and compared to provide a difference signal.

The switching is accomplished with CMOS bilaterial switches at a maximum rate of 240 kHz. Varying this switching frequency provides a means of changing the span, increasing the frequency increases the sensitivity.

Various options are available or envisaged. The simplest option provides an output of instantaneous water content as a non linearised signal, together with temperature. As the water content signal is fairly linear over the limited range 0-5% it is possible to add a display to this verison to give a self contained single range unit. When more sophisticated facilities are required the above output and display circuit will need to be replaced by a micro computer package. Such a package is under development by Endress and Hauser Ltd. and is expected to be available by the end of this year.

1.2.3 Temperature Coefficient

Our results for temperature coefficients were very encouraging for the seven crude oils (and one lub. oil), as shown in Table 1.

Each coefficient was linear over the temperature range tested (15^{o} to $40^{o}C$) and all the crude oils had sensibly identical coefficients, at $-0.0020/^{o}C$.

Expressed in terms of equivalent water content, the coefficient is -0.027% volume water per degree C.

The significance of these findings is that, being linear, the temperature correction is easy to apply in practice: being the same for all crudes allows the correction to be factory set.

In the practical applications for the equipment, the crude oil temperature - either crude discharges or offshore pipelines - does not change greatly over a measurement period: probably by less than 5°C. In that case, appreciable difference in the temperature coefficient from the value we determined would have little effect upon the overall measurement. Note from Table 1 that the coefficient for lub oil was very close to that for the seven crude oils.

The temperature coefficients measured relate to dry crude only. Theoretical considerations would indicate that temperature would have no significant effect upon the sensitivity of the capacitance system to water content changes. However, in future studies, this assumption might be re-examined.

1.2.4 Dry Oil Dielectric Constants

From the outset of our work on capacitance techniques applied to measure crude oil water content, it has been recognised that the dry oil dielectric constand (ϵ) is a major factor. The ϵ value increases with density and aromaticity. Differences in ϵ values are small in absolute terms, but large in relation to the effects of small quantities of water.

Literature references sugges that the ϵ value for crudes ranges from 2.05 to 2.7.

The crudes tested were Forties, Ninian, Kuwait, Kirkuk, Arab Medium, Basrah and Zuluf. A lub oil basic grade (BG20S) was tested for comparison. The dry oil dielectric constants are shown in Table 1, referred to 20°C.

The spread is from 2.235 (Basrah) to 2.476 (Zuluf) much less than suggested by the literature but measured for only a few crudes of interest to BP. The ϵ values for the two North Sea crudes Forties and Ninian are very similar (2.301 and 2.280), as was expected for similar crudes.

1.2.5 Calibration for Water Content

The results from these tests are shown in Fig.3, but with the zero point for each crude shifted to a common value corresponding to a dry oil ϵ value of 2.2. Fig.3 shows that the calibration for all the oils tested was sensibly the same, excluding the shift in zero. For water contents below 40% v/v the calibration is independent of water salinity, for most practical applications.

From all our results, the relationship appears to have the form:

$$\mathrm{Ln}\,\epsilon_{\text{mixture}} = \mathrm{Ln}\,\epsilon_{\text{dry oil}} \times (1 - V) + \mathrm{Ln}\,\epsilon_{\text{water}} \times V$$

where Ln is the natural log

- ϵ is the dielectric constant of the stated material and taking the empirical value for water in this closed emulsion situation as 55.

- V is the volume fraction of water in the oil/water mixture, for values up to V = 0.4.

1.3 Accuracy Considerations

1.3.1 Target Accuracy

The equipment is intended to measure water in crude oil for fiscal applications. The aim therefore must be to attain the same or better accuracy (precision) as the alternative and presently accepted route using automatic samplers and laboratory testing of the composite sample.

The three standard IP/ASTM laboratory test procedures for water in crude oil are IP359/82 (= ASTM D.4007-81) Centrifuge method: IP358/82 (= ASTM D.4006-81) Dean & Stark Distillation method and IP356/82 Karl Fischer titration method (for North Sea crudes).

In view of the importance of this measurement, the laboratory test procedures have recently been reviewed (as indicated by the suffix dates) and their precision data revised. Now for both the centrifuge and distillation tests, the precision data cited applies only to water contents below 1% v/v. Repeatability and reproducibility are respectively 0.12%/0.28% v/v water for centrifuge and 0.08%/0.11% v/v water for distillation. The Karl Fischer precision is cited only up to the 1.5% water level, for which the figures are 0.02%/0.06% v/v water and better by a factor of two at the 0.5% water level. Internationally at this time, the centrifuge method is still very widely used, despite having the worst quoted precision of the three methods.

No data appears to be available for the overall accuracy of the measurement procedure involving automatic sampling/sample transfer/sample handling/sub-sampling/lab testing. Clearly, it cannot be better than the performance of the final lab test and all the qualitative evidence indicates that it is very much worse. Problems with sampling equipment and subsequent sample homogenisation have been widely reported. Spiked crudes present special problems.

Taking even the most optimistic view of the capabilities of existing sampling/lab testing systems, the **best** accuracy that is likely to be achieved is 0.05% v/v water. A more realistic figure, still with a good degree of optimism, is probably 0.1% v/v water, for relatively low water contents.

So, for the capacitance technique, our target was set initially at achieving 0.05% v/v accuracy at the 1% v/v water level for the bulk transfer, and being prepared to accept an accuracy of 0.1% v/v.

It is important to recognise and to emphasise that the capacitance technique is just as dependent as automatic samplers on drawing its primary sample from a fully representative location in the pipeline, and on the same equipment as samplers for flow proportioning the measurement.

An important and fundamental difference between samplers and the capacitance method is that the latter measures the instantaneous water content continuously and integrates the reading over the whole operational period. The capacitance equipment therefore has to be able to measure water contents from zero to 100% v/v (or more typically from zero to say 40% v/v) at any instant. These high water contents are of relatively short duration, since the overall parcel water content is generally less than 1% v/v. The accuracy required of the capacitance system at high water contents needs to be the same in relative terms as aimed for in the bulk average figure, namely a target of 5 percent of the amount present and prepared to accept up to around 10 percent of the amount. Thus, at the 40% v/v water transient level, an error of ± 2% v/v could be considered good and we could accept ± 4% v/v error.

1.3.2 Estimated Accuracy

The accuracy of the capacitance system in service depends on several factors, viz:

a) the ability of the mechanical/electronic assembly to measure electrical capacitance, accurately and reliably:

b) establishing the relationship between the dielectric constant and the water content of the crude oil mixture in the cell:

c) any extraneous effects from gas bubbles, wax deposition or water particle size/shape; also flow proportioning errors.

From our evidence so far, the measurement capability of the primary cell assembly/electronics is excellent. The sensitivity corresponds to better than 0.01% v/v water, with linearity of the same order. The temperature coefficient is negligible. Long term stability is good, with no discernible drift over several days.

Therefore, excluding any extraneous effects (below), the accuracy will depend almost entirely upon knowing the relationship between the water content of the crude oil mixture in the cell and the measured electrical capacitance.

Our work on a limited range of crudes has shown (Fig.3) that the change in capacitance with change of water content is very similar for all crudes, with a spread of only a few percent relative about the mean sensitivity. Since our target accuracy (+0.05% v/v in 1% v/v) corresponds to five percent relative, this spread of sensitivity should not be too significant and it is only pertinent to multi-crude service. More work is in hand to establish precision data in this area.

The dominant factor is the dielectric constant of the dry oil, which dictates the zero setting for the measurement. As shown in Table 1, different types of crude have constants which differ by amounts which are large when expressed in terms of equivalent water content. Therefore, on any application, the accuracy of the capacitance technique will be determined largely by the constancy of the dry oil dielectric constant (= crude oil type) during the measurement period.

For production applications - e.g. Forties Field - the crude oil type is expected to remain sensibly constant. This may also apply to many pipeline applications. If applied to a line with multiple field inputs with fluctuating proportions of different crudes/condensates, then problems could arise. In practice, such changes may be self-evident from the instrument reading, since a change of oil type would produce an apparently large and unexpected change in 'water content' in either the positive or negative sense. On-line density monitors may give useful guidance. For refinery import applications, the crude type is expected to change for each shipment and the calibration procedure proposed is described later. The assumption is made that each shipment is only one crude or a uniform mixture.

Any gas bubbles in the measured crude would depress the dielectric constant and produce an incorrect low reading. It may also produce a noisy signal and therefore its own diagnosis. Gas bubbles were not apparent during our prototype studies on VLCC discharges at a refinery.

Any wax deposition in the flow cell would reduce the active volume and thereby reduce the sensitivity to water and probably the zero point. We would expect the installation to be designed to avoid waxing: but if it occurs it is likely to affect each half of the dual cell assembly differently and therefore become evident by the discrepancy between the two independent channel measurements.

1.4 Potential Applications

1.4.1 Offshore and Production Pipelines

The capacitance technique is expected to be particularly attractive for off-shore duties on spiked and high pressure crude, both because of the importance of the water content measurement and the severe problems experienced with the automatic sampling technique.

BP is in course of installing a Class 900 system on an offshore platform.

This package, in common with our general approach for offshore equipment, will be as simple as possible to maximise reliability Fig.4.

It will be a dual cell, with each cell having a single range of 0 to 5% v/v water. Each cell will have its own dedicated electronics unit/output signal which will be connected to the platform's central recording facility. The unit will not be flow proportioned. The system will provide just the instantaneous water content, without integration.

For 0 to 5% range, the calibration will be assumed linear. The zero will be set on the platform, to suit the oil and the relatively high operating temperature of ca 50-60°C.

1.4.2 Refinery Import Lines

In many respects the refinery import duty is more demanding.

The equipment must cope with a wide variety of different crudes having different dielectric constants. The water content during the discharge can vary from zero to 100%. The oil flow rate also changes throughout the discharge, such that flow proportioning the water content measurement and continuously integrating the signal to give an overall cargo figure is essential.

Apart from the pressure rating of the cell, the primary equipment is the same as for the offshore duty, with the flow cell installed in a fast sample loop.

However, the electronics package associated with the flow cell would necessarily be more sophisticated, to perform the flow weighting and integration functions together with other facilities. Endress and Hauser are now producing such a package using microprocessor technology.

The refinery application poses two important questions, namely:

a) How to cope with the different crude oil types, each with a different base oil dielectric constant, hence instrument zero.

b) How to cope with water contents above the normal range for good capacitance measurements, i.e. above ca 40% v/v.

At this stage of the development, our approach to both these questions is dictated primarily by the need to retain simplicity, in order to ensure reliability and modest cost. Nevertheless, this approach may well be also the best in the longer term, though the possible alternative of using a differential (wet/dry) technique cannot be ignored.

To cope with different crudes, advantage is taken of the fact that the sensitivity to water is similar for all crudes: only the zero reading will be affected. Assuming that for each cargo the crude type is known and remains constant throughout the discharge, then the procedure would be as follows:

i) set the crude oil type into the controller: this data is or will be available. This sets the instrument zero at approximately the right point. (It need not be correct).

ii) During the main part of the discharge, when the water content is at its 'natural' low level (as indicated by the monitor itself), draw a spot sample and measure its water content by the standard test method, e.g. Karl Fischer. Compare the sample result with the monitor reading at the time the sample was drawn, to establish any zero error in the monitor.

iii) At the completion of discharge, apply the known zero error to the overall average reported by the monitor.

To cope with high water contents, above 40% v/v, our simple approach assumes that such high levels will be transitory and make little contribution to the average water content. This assumption is fully in line with our cargo studies described later.

Monitor readings above 40% v/v are greatly affected by the salinity of the water, which generally is an unknown factor. We therefore take the view that high readings will not be quantitative. Instead, we have proposed to E & H that the equipment be programmed in such a way that for all outputs beyond the normal range (40% v/v), a nominal value such as 60% v/v (selected by the user) would be applied automatically in calculating the overall average. We estimate from our studies that the error instroduced by this simple expedient will be negligible. In practice, water contents above 40% are far from common, even as transients.

1.5 Conclusions

The results to date are very encouraging and give clear indications of the potential capability of the capacitance technique to measure water in crude oils to the accuracy required for fiscal duties. Further on-line testing is now required to verify laboratory data and identify any operational problems.

A system is currently being installed for testing at a BP refinery - and its performance will be compared with the latest types of grab sampler.

2. PRACTICAL APPLICATIONS

2.1 Water Discharge Characteristics (Ship to Shore Transfers)

2.1.1 Introduction

When sampling crude oil for water content using automatic grab (discontinuous) samplers there is some doubt as to the overall representivity of the lab. sample if water has passed down the line in the form of transients (slugs). Computer simulations conducted in-house have demonstrated that transients could have significant effect if they formed the major contribution to the overall water content and their period of existence at the sampling point was equal to or less than the sampling grab interval. If such conditions existed then it would be essential to modify the sampling process to ensure that transients, as presented to the sampler were sampled representatively. The sampling process using conventional grab sampling techniques can be modified either by increasing grab frequency, or by modifying the transients with suitable sample conditioning (1 & 2).

Increasing the complexity of the sampling systems tends to result in reduced reliability. Unless it is known that transients affect results significantly extra sophistication is unnecessary and undesirable.

Consequently work was initiated on establishing the existence or non-existence of such transients and their importance to the overall sample representivity.

To do this we installed a continuous capacitance water in oil monitor in a fast loop of an existing Jiskoot Series 300 sampler on a 30 inch ship to shore crude import line.

Signals from the existing Detectronics Ultrasonic Doppler Flowmeter, which was used for the Jiskoot flow proportioning, were monitored together with the capacitance meter on a two pen recorder to give an overall picture of water content characteristics.

The initial intention of this work was to look solely at transient behaviour of the water content. However, the scope was extended to gain some experience on the continuous capacitance monitor as an alternative to discontinuous sampling.

2.1.2 Test Installation

The test installation is depicted in Fig.5. The sample probe and sample loop line sizing were chosen to present as large an area as possible to the main line whilst maintaining a good sample velocity. The probe was mounted vertically in the line with a minimum design velocity of 1.5 m/sec (i.e. using 10 mm ID tubing @ 7 litres/min.) to ensure no drop-out of water.

The probe was mounted in an area of high turbulence just downstream of a blanked Tee-section (Fig.6). The representivity of the sample at this point had previously been demonstrated by work done by others with manual sampling at this location and at the jetty head on the boom gantry.

The capacitance probe was mounted downstream of the sample extraction pump. The pump discharge pressure was around 30 psig above line pressure which reduces the probability of entrained gas affecting measurements. Also the pump was used to break-down any large water droplets and present a consistently mixed sample to the probe.

Signals from the capacitance meter and the flowmeter were fed to a two-pen flat bed recorder. The recorder traces were integrated manually to assess water contents, transient contributions and flowmeter performance. A PET computer was added at a later date to aid data integration.

The flowmeter signal was also being used to proportion the Jiskoot sampler. Thus any defect in the flow measurement affected the sampler and continuous measurements equally.

Nominal capacitance probe calibration is shown in Fig.7.

2.1.3 Water Profile Observations

Typical water content profiles associated with ship "free flow" discharge flow patterns are summarised in Fig.8 and relative quantities discharged for each stage are summarised in Tables 2 and 3.

Although the profiles are fairly predictable in appearance the relative quantities are by no means so. In two cases the initial line clearing operations accounted for 40 to 50% of the total water discharged and in one case 30% of the total water came over in the final strippings.

Line clearing (emptying of the lines of a previous cargo if of a different type) and stripping operations are generally carried out at lower flowrates than the main discharge. They represent less than 10% of the total quantity of cargo discharged but can contribute up to between 50 and 60% of the total water. This highlights the importance of good flowmeter performance over the operating range for consistent sample representivity. Also because such large quantities of water can be present during these periods good sample line mixing is essential. A water level of 100% was measured (manually sampled) and levels of around 20 to 40% were not uncommon.

Generally, our observations have shown that:

a) High water contents in the form of transients appear at the beginning of discharge and during tank stripping at the end of discharge.

b) Water transients will tend to occur when there is an abrupt change of flowrate due to pump failure/restart, suction changes, tank changes if not on common suction, etc.

c) During main discharges the water contents fall to values of 0.3% v/v and less as conditions stabilise and separated water is not picked up as in a) and b) above.

d) Normal practices of manual sampling at the jetty head and slumping of samples will invariably lead to erroneous estimations of water content due to the water discharge distributions and associated flow distributions.

e) For the range of ships observed flow meter readings varied between a minimum of 10% to a maximum of 90% range. A flowmeter with a turn-down of 10:1 is therefore necessary.

f) Because of the high water contents at low average flows and low water contents at the high average flows consistent accuracy of the flowmeter in terms of actual reading (not span) is necessary.

Typical water content traces against flow traces at different stages in the discharge are presented in Figs.9, 10, 11, 12.

2.1.4 Water Transient Characteristics

The Jiskoot sampler operates on an 86 second cycle (= 1000 cycles/24 hours). In order to arrive at a reasonable estimation of a water profile it is accepted that around 10 samples of each transient are required. For the purposes of this test we therefore looked at transients of 10 minutes or less as being capable of producing sampling errors.

Table 3 summarises these transient distributions and contributions during typical discharges. It is seen that in genral contributions are less than 0.04% v/v water which is insignificant in terms of other problems associated with sampling, sample handling and analysis. One example (not shown) of the contribution being 0.14% v/v water was recorded, however, consideration of 5 minute transients revealed the contribution was quartered to 0.04% v/v water. At the worst the Jiskoot could over estimate each transient by 1½ minutes which is approximately 30% (on a 5 minute basis) of 0.04% equal to 0.01% v/v water.

As contributions by 5 to 10 minute transients are of the above order it is difficult to justify:

a) transient time stretching techniques.

b) high frequency grab samplers with small grab volumes

Transients of less than 20 secs. were not observed and those of less than 1 minute were very infrequent, no more than 1 or 2 at most per discharge with negligible contribution to the cargo water content.

Statistically it is evident that the Jiskoot Series 300 type sampler only fails to catch representative samples in the presence of transients of less duration than the sample cycle time of 86 secs. and of such number/ magnitude to contribute a substantial proportion of the water content. These transient distributions are not evident.

2.1.5 Comparison of Continuous Monitor Results with the Grab Sampler

For this comparison it was not necessary to worry about representivity of sample from the line or accuracy of the flow proportioning flowmeter. This was because both "samplers" were on the same fast loop downstream of the pump and both used the same flowmeter signal.

However, the capacitance cell is known to be affected by the type of crude and temperature. It was therefore necessary to take manual samples at various times throughout each discharge to establish a calibration.

For the purposes of these tests, linear calibrations were considered sufficient and for each discharge zeros and sensitivities were established. Water contents were integrated with flow based on the nominal calibration (Fig.7) and then adjusted.

Where data was available in sufficient form to enable us to calibrate our probe against lab. samples (with due allowance for temperature effects) integrated mean water contents agreed fairly well with the Jiskoot results (see Table 2). These results were only obtained as an "aside" to the main objective of this work but serve to encourage us that continuous monitoring using capacitance techniques is a viable proposition.

It is interesting to note that on one occasion the grab sampler failed, but by this time we had sufficient confidence in the corrected continuous monitor result to use that for the refinery's official figures for water content received from the ship.

2.2 Water Profiling Tests

2.2.1 Introduction

At the end of 1981 it became apparent that in order to be able to specify economically and technically optimised solutions for the full range of BP's applications for automatic samplers, we would need to extend our knowledge and experience of the behaviour of water and crude oil mixtures in large pipelines. In particular we were interested to study the water/oil homogenising efficiency of in-pipe jet mixing systems.

2.2.2 Profiling Equipment

The aim of the test programme was to demonstrate that jet mixing could achieve homogeneity in the line and to measure the power required to do so. A key factor was to be able to simultaneously measure water contents of the mixture across the line profile at several locations beyond the jets. Based upon our separate development of the electrical capacitance technique for measuring water in crude, we decided to use this approach to monitor the water profiles at three positions. The alternative, of using manual sampling and testing, would have been very slow and tedious for the number of tests required. Absolute accuracy was not deemed important at this stage of the study.

Three sets of profiling probes, each with six offtakes spaced equidistant across the pipe were made, generally according to draft ISO 3171.

The offtake inlets were designed to face the flow and minimise end effects. Connecting lines between the probes and the capacitance cells were selected to ensure fast flows and minimise tendency to separate the oil and water before entry to the cells. Flow rates at the probe entries were arranged to be nominally isokinetic.

2.2.3 Capacitance Cells and Water Profile Display Arrangements

The water contents of the samples were measured using eighteen capacitance cells. These were frame mounted, and piped and wired in groups of six.

Outputs from the capacitance cells were fed into a Commodore computer and presented as an instantaneous graphic display of the water profile (Fig.14). This is a unique feature of the test system. Facilities were provided to change the display range from 0-5% water to 0-30% water, and to print out the resultant bar chart. Note that water contents greater than 30% volume would appear on the computer readout as nominal 30%. The computer software also included the facility to zero all probe outputs.

2.3 Discussion of Applications

2.3.1 Water Discharge Characteristic Testing

The application of a continuous monitor allowed us to monitor the water content of 17 cargoes discharged to a Refinery over the period February to June 1982. Cargoes (the majority of which were the final parts of "part cargoes") ranged from 47,000 to 118,000 tons of Arab Light and Medium, Forties and Kirkuk crudes with 0.1 to 1.3% volume water.

We found that transients were less frequent and less severe than generally expected and are not a problem. Automatic samplers with grab intervals as long as two minutes would take a representative sample. There was no evidence to support the current international proposal for taking at least 10,000 sample grabs for each transfer.

No transient less than 20 sec. was observed. Only one or two transients less than 1 min. occurred during each discharge and their contribution to the total water content was negligible (less than 0.01% vol). Even the total contribution of all transients up to 10 min. duration was on average less than 0.04% volume water, for the cargoes studied.

Oil discharged during line clearing and stripping is typically only 10% of the cargo but may contain up to 60% of the total water. As these operations combine low flow rates with high water contents (sometimes up to 100% volume water), the importance of accurate flow proportioning and good line mixing for the water measurement system are very obvious.

We were also able to compare the overall water content calculated from the continuous monitor with that obtained from the Jiskoot Series 300 sampler (Table 2).

Where data was available in sufficient form to enable us to calibrate our probe against lab. samples (with due allowance for pressure effects and temperature effects) integrated mean water contents agreed fairly well with the sampler results (see Table 2). The average error between the two measurements was only 0.06% vol. water. This is a useful validation for both techniques.

Whilst the foregoing confirms that transient behaviour in ship to shore discharges does not merit grab frequencies greater than one per minute and/or transient stretching techniques it does not contradict the argument for continuous monitors.

The advantages of continuous monitoring were shown in its ability to observe discharge conditions and give an instantaneous integrated value of water discharged at any time during operations. Calibrations, if necessary, can be verified very quickly against spot lab. samples and above all any discrepancies argued and agreed whilst the ship is still alongside.

Only one problem with continuous monitors was noted. If flow in the line stops the monitor will continue to give a reading that can drift around depending on the settling and recirculation going on in the sampling section. This is easily accounted for in the integrated values because the flow is zero.

2.3.2 Water Profiling Tests

This application demonstrated admirably the superiority of continuous techniques over discontinuous techniques in the ability to obtain simultaneous real-time information on water contents (Fig.14).

The data obtained during the mixing trails far exceeded that which would have been possible within the time scale if manual methods of water determination were employed.

This application was purely on instantaneous comparison of readings from each capacitance cell to ascertain water profiles. Absolute calibration was not essential and provided each cell's calibration was stable effects of varying crudes and temperature were inconsequential.

The technique has since been applied at a major VLCC terminal in Europe and will be applied to our own further studies shortly at a refinery.

'Automatic' profiling, e.g. using this capacitance technique is recognised in draft ISO 3171

2.4 References

1. a) General Review of Automatic Pipeline Sampling and Continuous Measurement Techniques for Determining the Water Content of Crude Oils by W.H. Topham.

   b) Development of a New Definitive Automatic Sampler for Crude Oils by R.C. Gold and M.B. Wilson.

   Papers presented at IMC Symposium on 3/5th November, 1981 entitled:

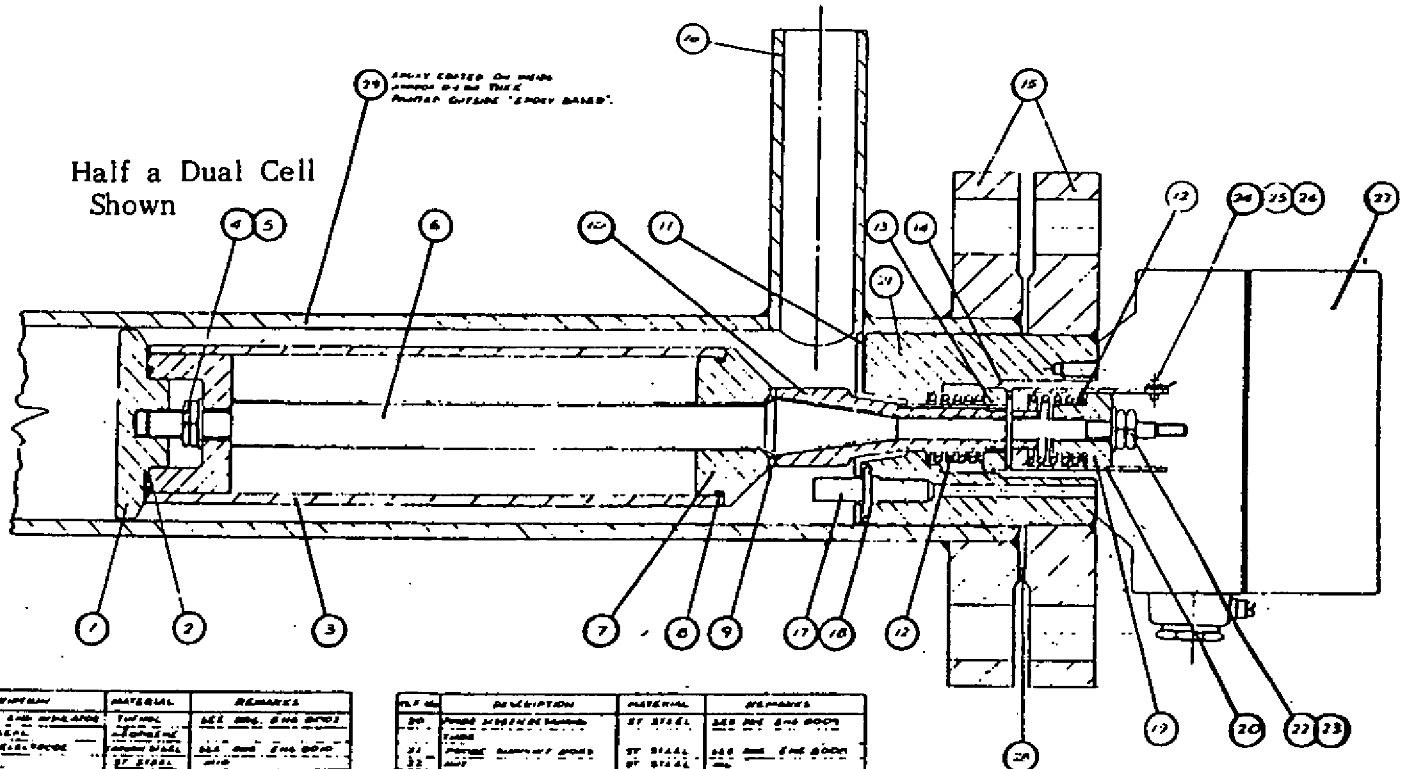
   "Automatic Sampling and Water Determination for Crude Oils".

2. UK Patent No. GB 2 106 408 Multi-Orifice Mixing Device

3. UK Patents Application No. 84 11147 Capacitance Cell for Measuring Water in Crude Oil

ACKNOWLEDGEMENT

Permission to publish this paper has been given by The British Petroleum Company p.l.c.

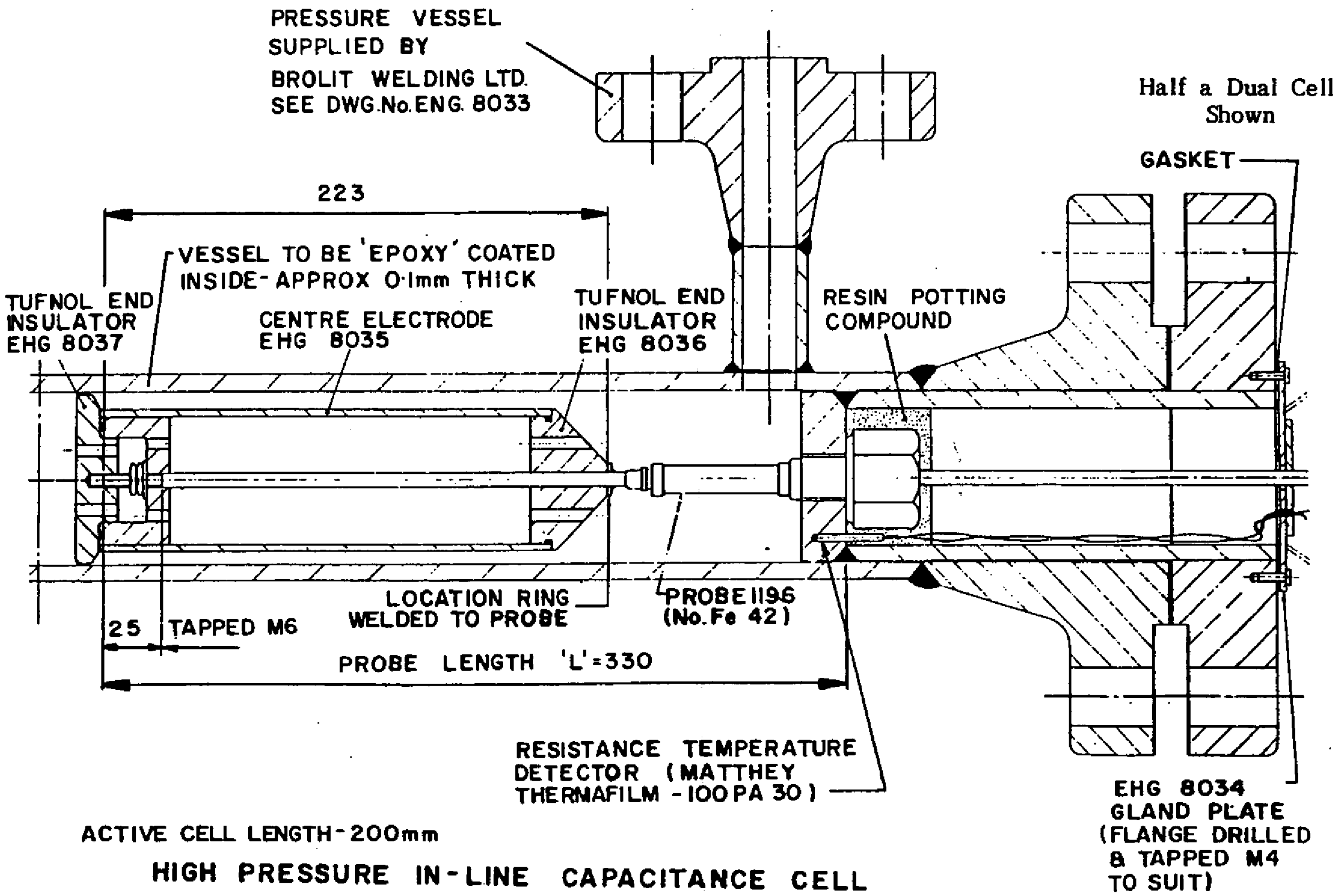


REF No	DESCRIPTION	MATERIAL	REMARKS
1	[illegible] END INSULATOR	TUFNOL	SEE DRG. [illegible]
2	'O' RING SEAL	NEOPRENE	
3	CENTRAL ELECTRODE	[illegible] STEEL	SEE DRG. [illegible]
4	NUT	ST. STEEL	M10
5	SPRING WASHER	ST. STEEL	[illegible] M10
6	CENTRE ELECTRODE SUPPORT ROD	ST. STEEL	SEE DRG. [illegible]
7	PROBE END INSULATOR	TUFNOL	SEE DRG. [illegible]
8	'O' RING SEAL	NEOPRENE	
9	SEALING GASKET		
10	SCREENING ELECTRODE	ST. STEEL	SEE DRG. [illegible]
11	[illegible]	P.T.F.E.	SEE DRG. [illegible]
12	SPRING	STEEL	SEE DRG. [illegible]
13	[illegible] RING	TUFNOL	SEE DRG. [illegible]
14	[illegible]	ST. STEEL	M10
15	[illegible] FLANGE	[illegible] STEEL	
16	INLET/OUTLET PIPE		[illegible]
17	[illegible] BULB		[illegible] @ 0°C
18	'O' RING SEAL	NEOPRENE	
19	INSULATING COLLAR	TUFNOL	SEE DRG. [illegible]

REF No	DESCRIPTION	MATERIAL	REMARKS
20	PROBE SCREENING TUBE	ST. STEEL	SEE DRG. [illegible]
21	PROBE SUPPORT [illegible]	ST. STEEL	SEE DRG. [illegible]
22	NUT	ST. STEEL	[illegible]
23	PLAIN WASHER	ST. STEEL	[illegible]
24	[illegible]		M3 [illegible]
25	SCREW - [illegible]		M3 [illegible]
26	SHAKEPROOF WASHER		M3 [illegible]
27	ELECTRONICS ENCLOSURE		
28	GASKET		[illegible]
29	OUTER ELECTRODE	CARBON STEEL	[illegible]

IN LINE CAPACITANCE CELL GENERAL ARRANGEMENT

FIG.1



ACTIVE CELL LENGTH - 200mm

HIGH PRESSURE IN-LINE CAPACITANCE CELL

FIG.2

CALIBRATION DATA FOR E & H SYSTEM FOR WATER CONTENT IN SEVEN CRUDE OILS.

The points shown for each crude are measured values, corrected to have the same zero point. Measurements were made in a circulating loop test rig.

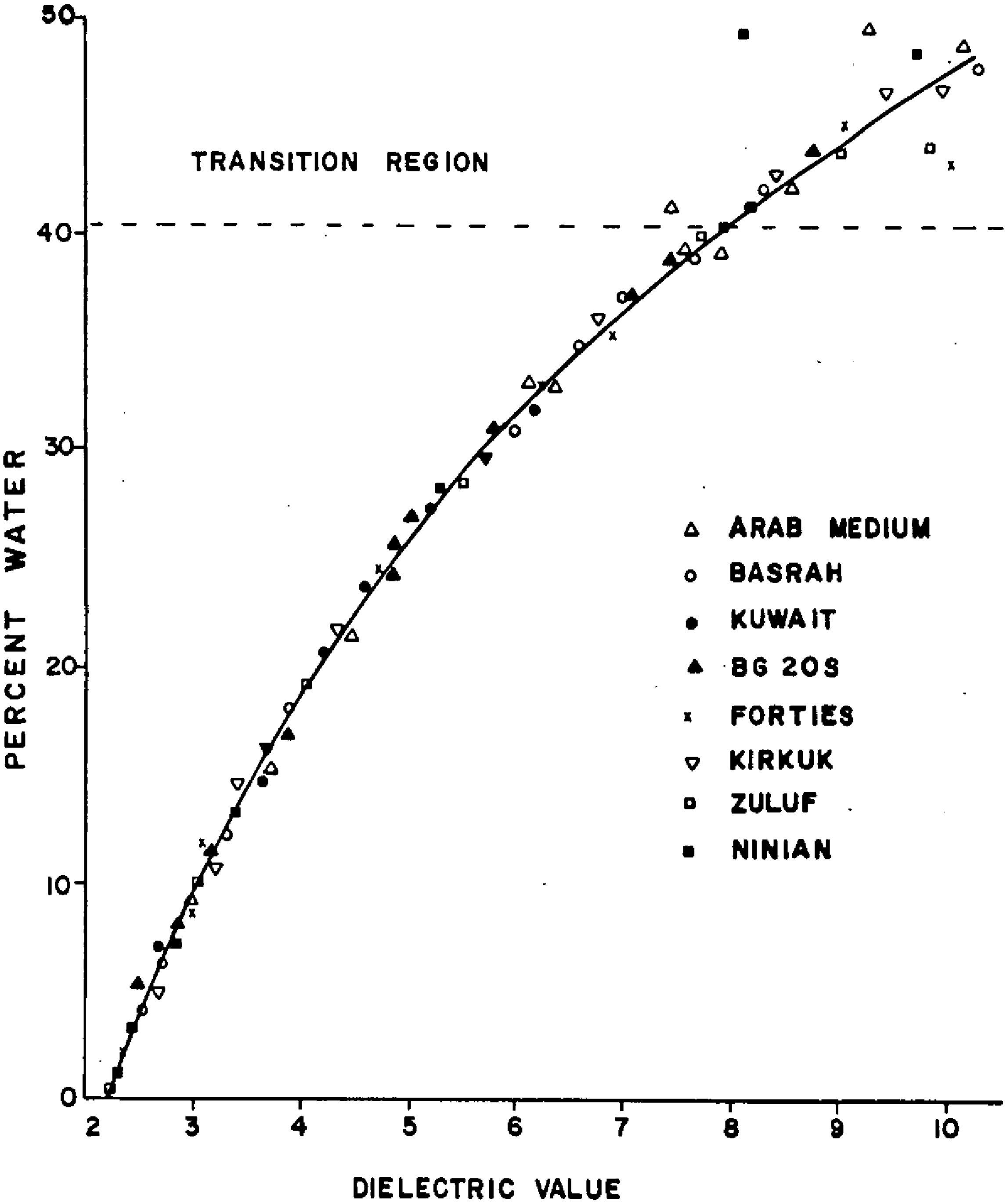
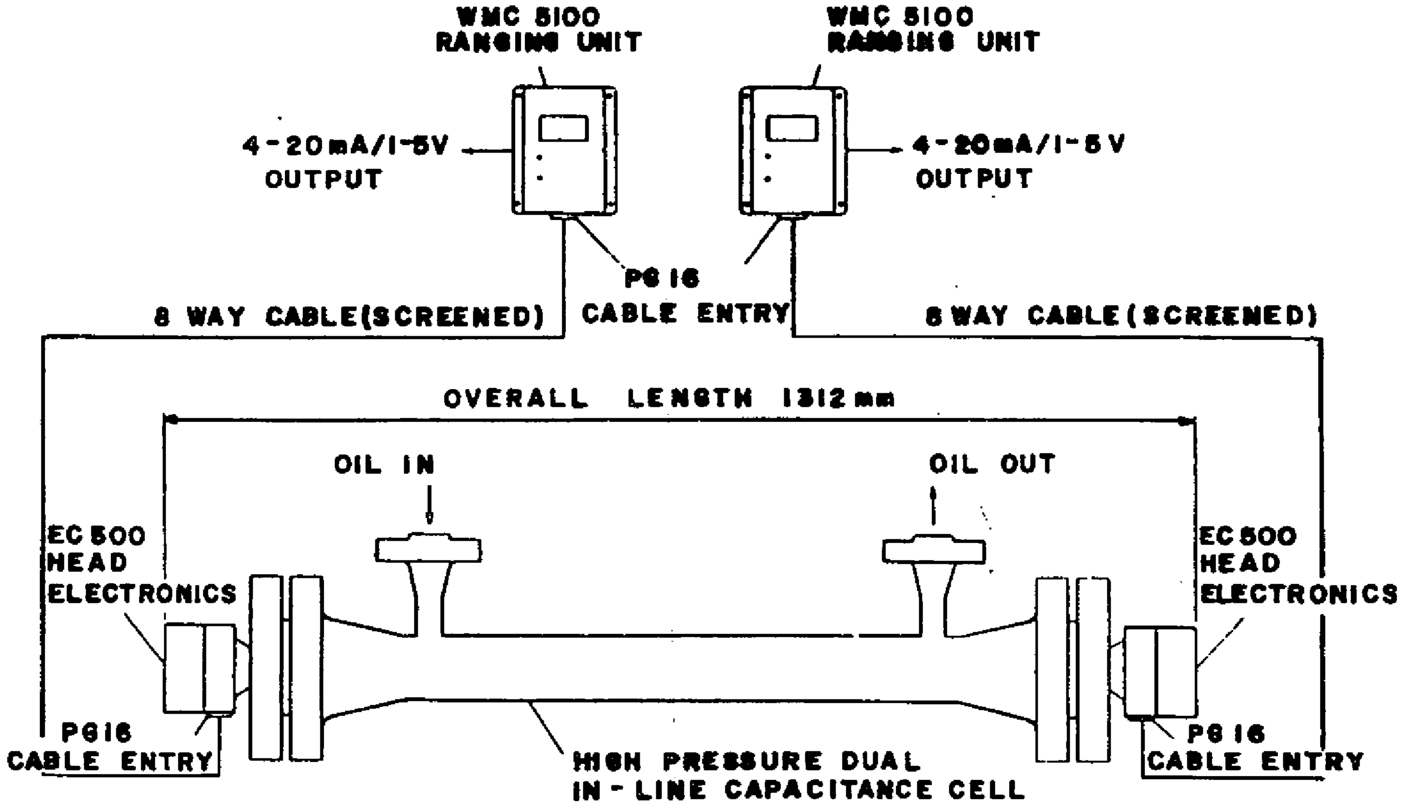


FIG.3



WATER IN OIL ANALYSIS SYSTEM

FIG.4

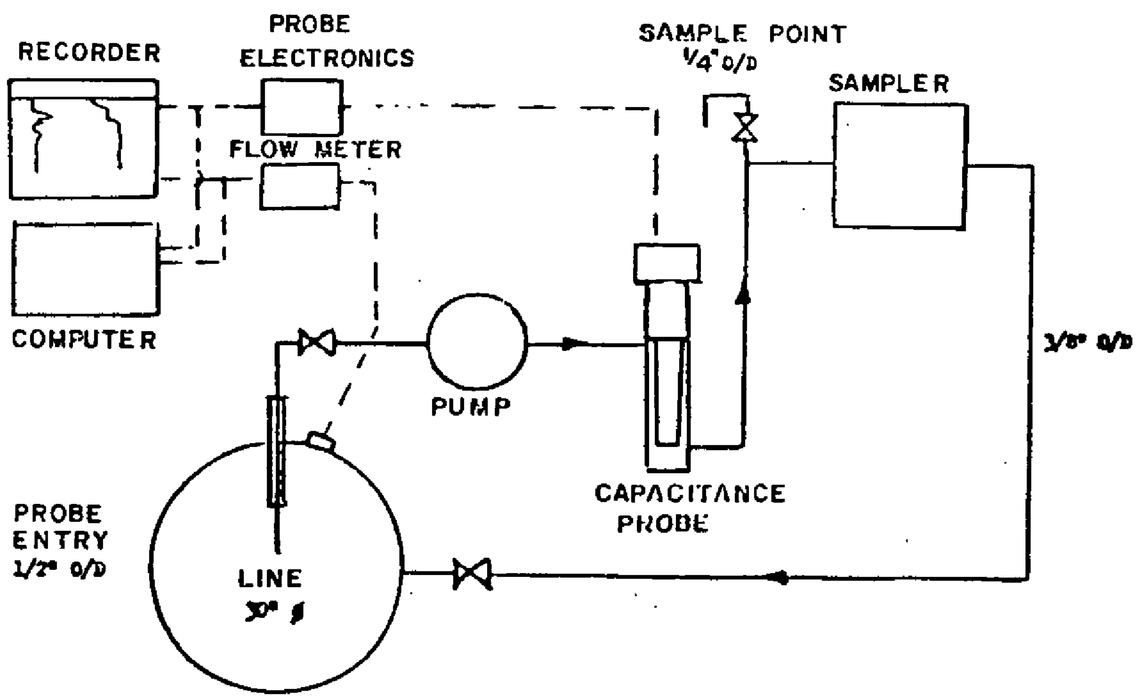
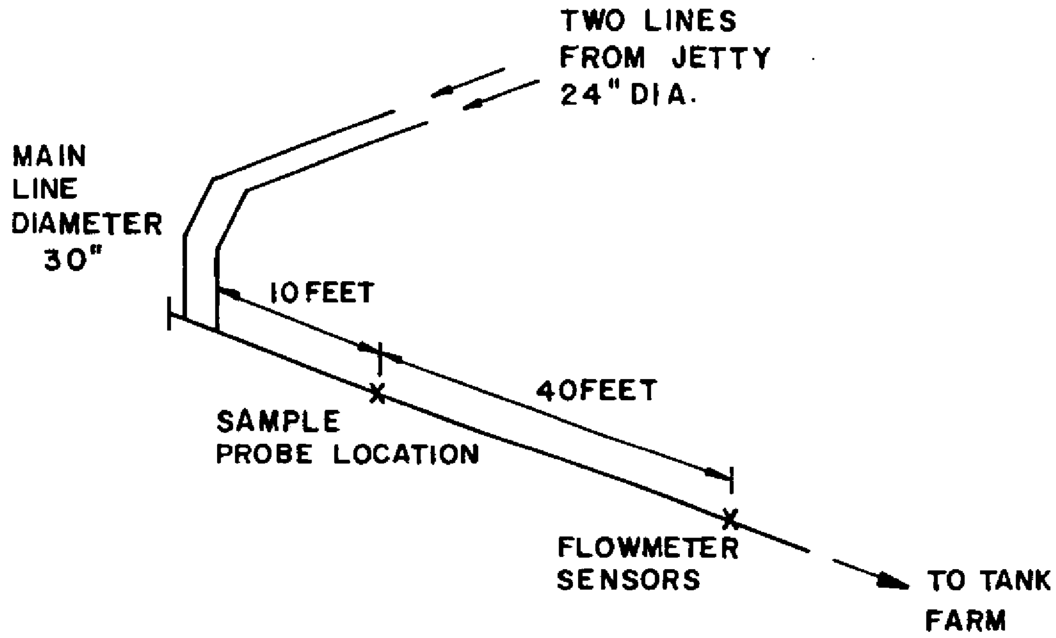


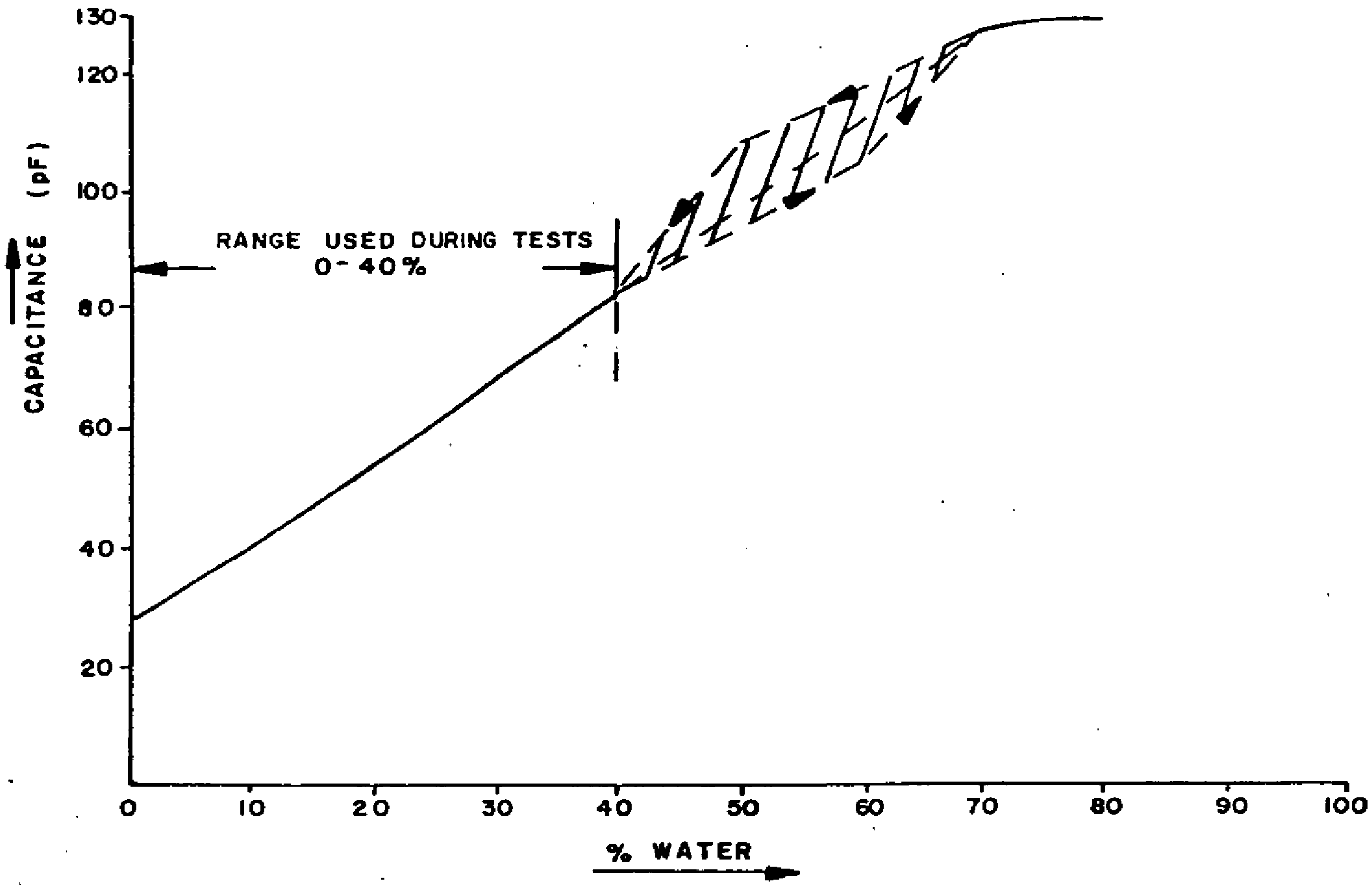
FIG.5

SAMPLE SYSTEM SCHEMATIC FOR A SINGLE CELL CAPACITANCE PROBE USED FOR WATER DISCHARGE CHARACTERISTIC STUDIES ON CRUDE IMPORT LINES



SAMPLE SYSTEM AND FLOWMETER LOCATIONS

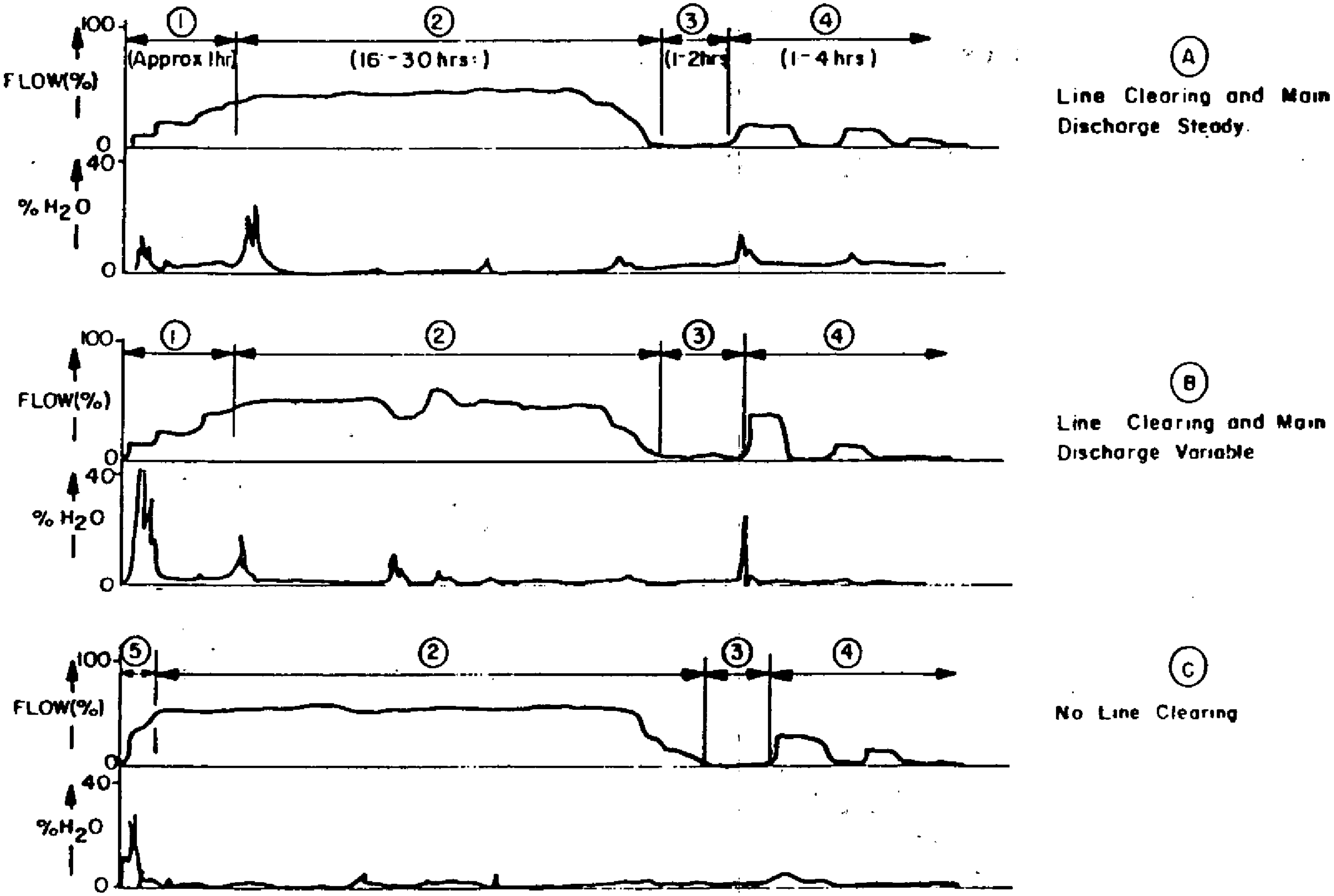
FIG.6



CAPACITANCE PROBE NOMINAL CALIBRATION

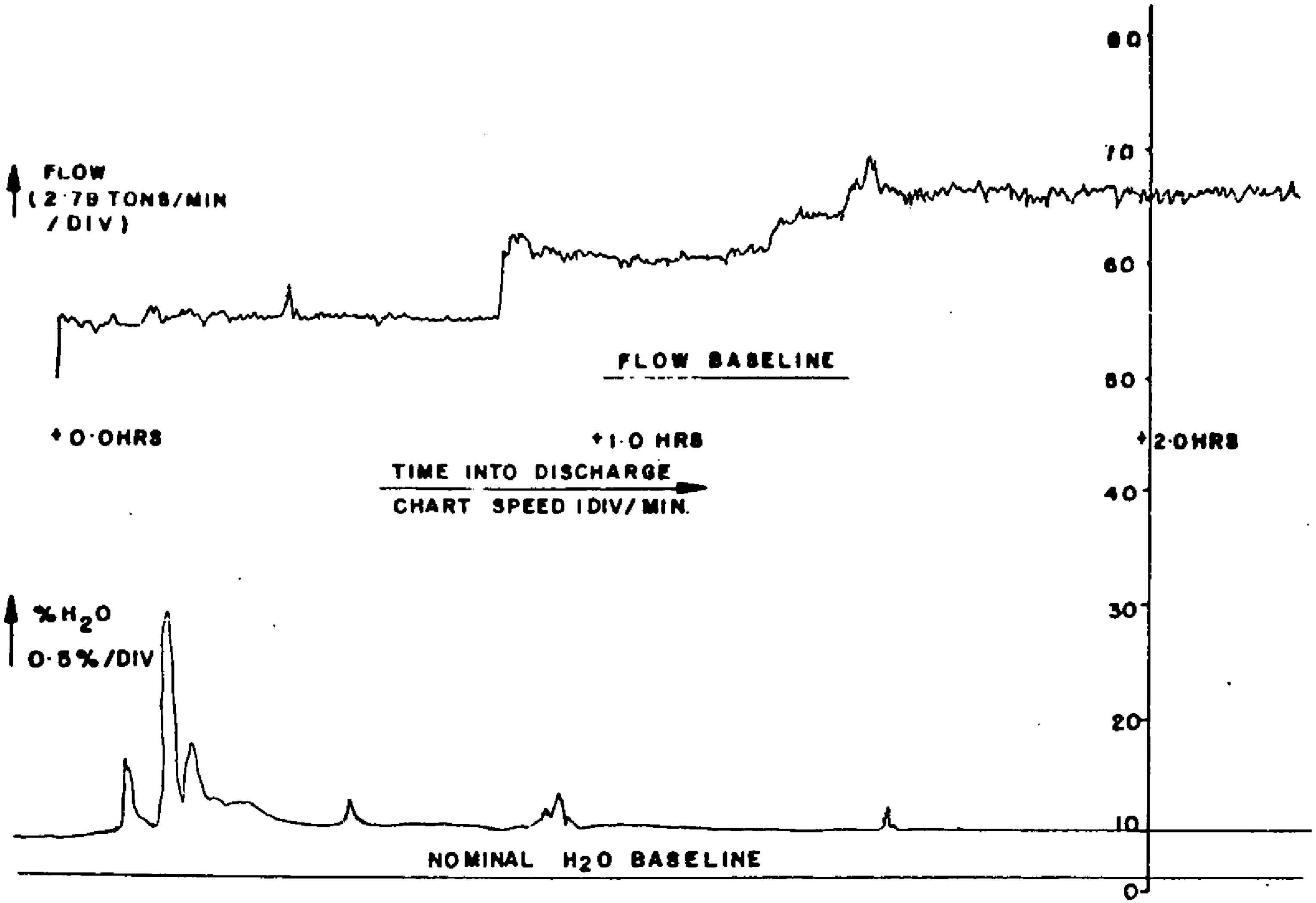
FIG.7

TYPICAL CRUDE FLOW & WATER CONTENT PROFILES DURING SHIP DISCHARGES



(1) Line Clearing
(2) Main Discharge
(3) Discharge Suspended for Crude Washing
(4) Tank Stripping + Discharge of Strippings
(5) No Line Clearing, Flow Raised to Main Discharge Levels Within 5-10 mins

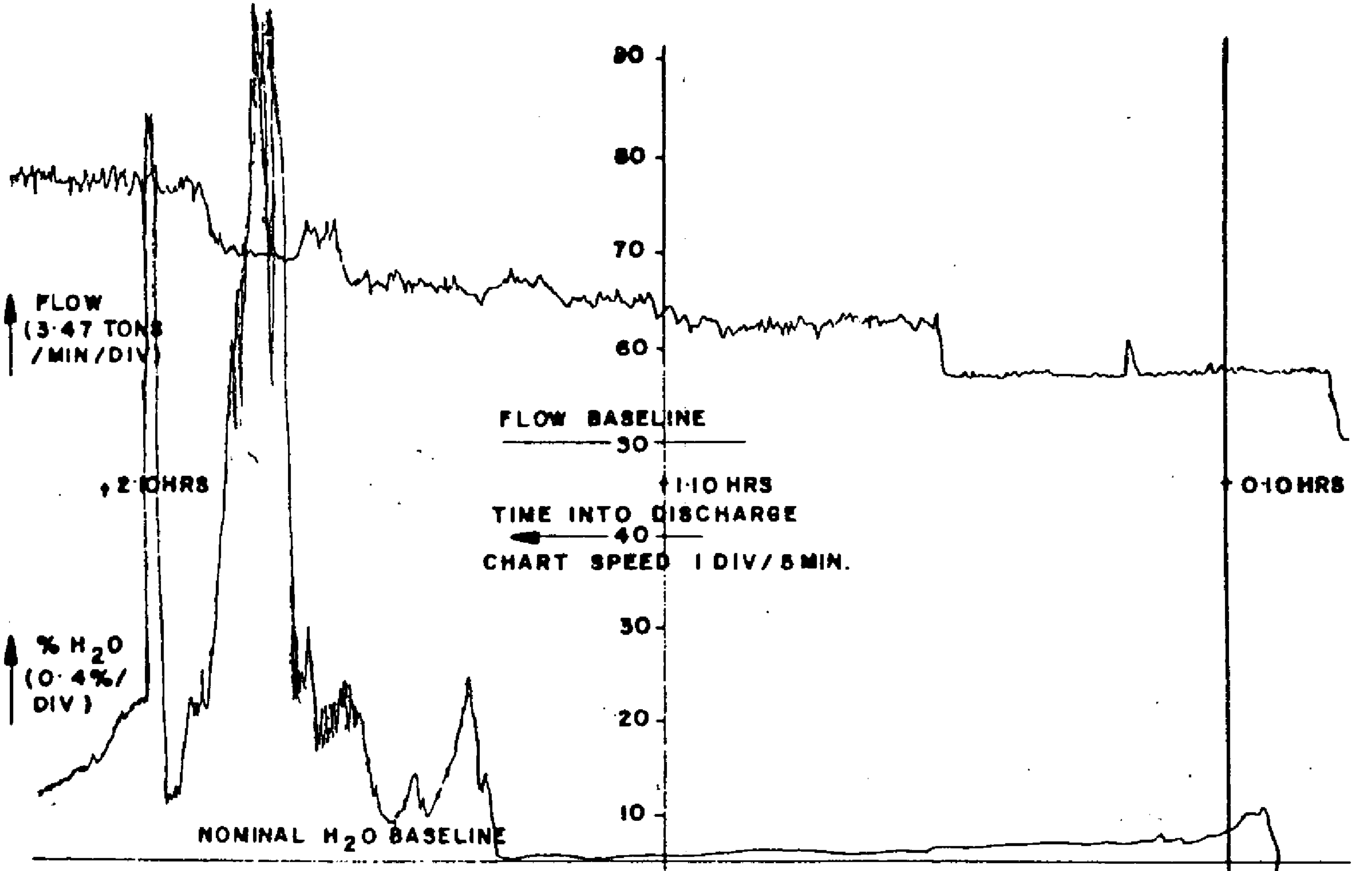
FIG.8



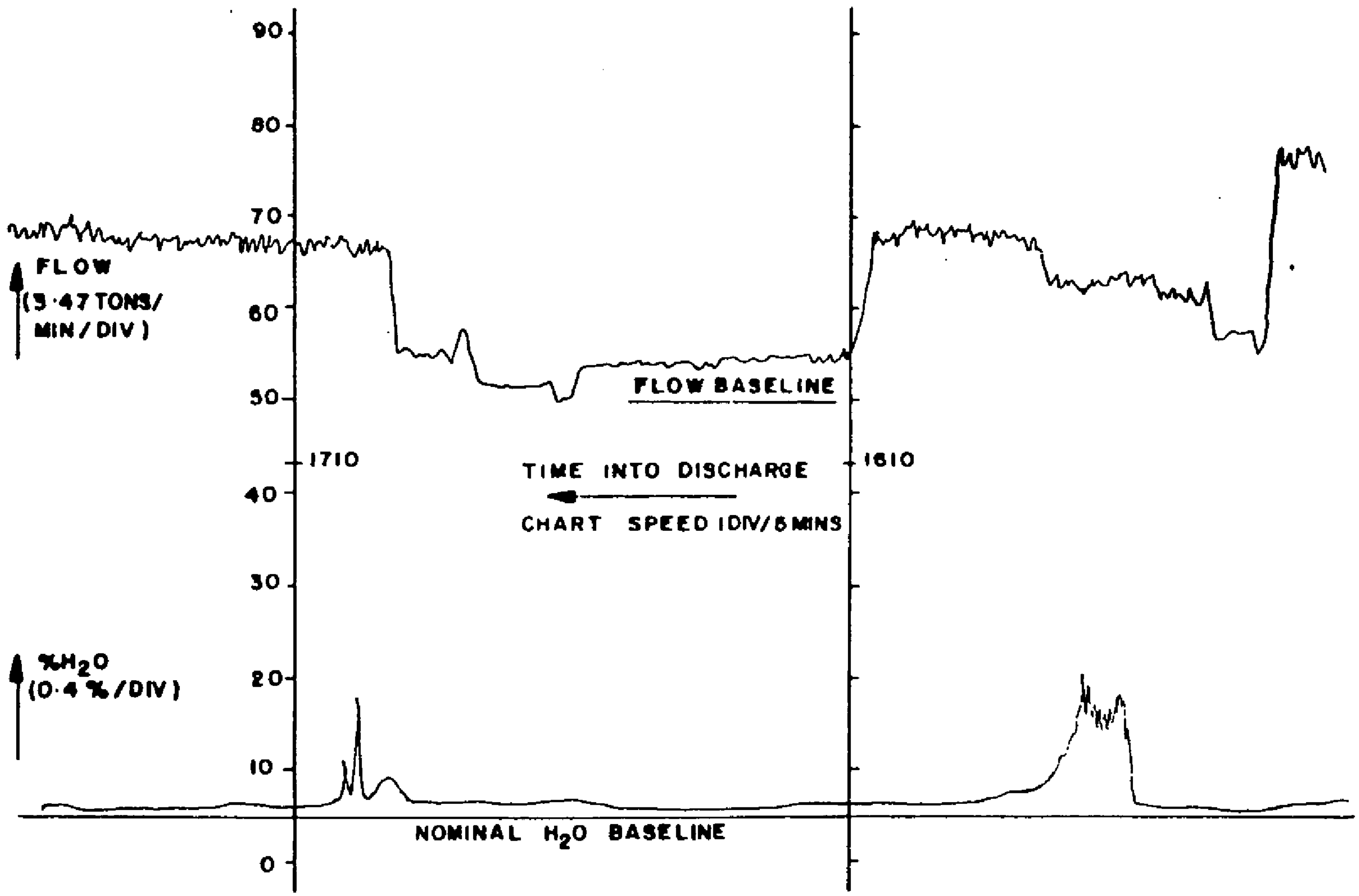
TYPICAL PROFILES FOR FLOW AND WATER AT BEGINNING OF A SHIP DISCHARGE

FIG.9

FIG.10



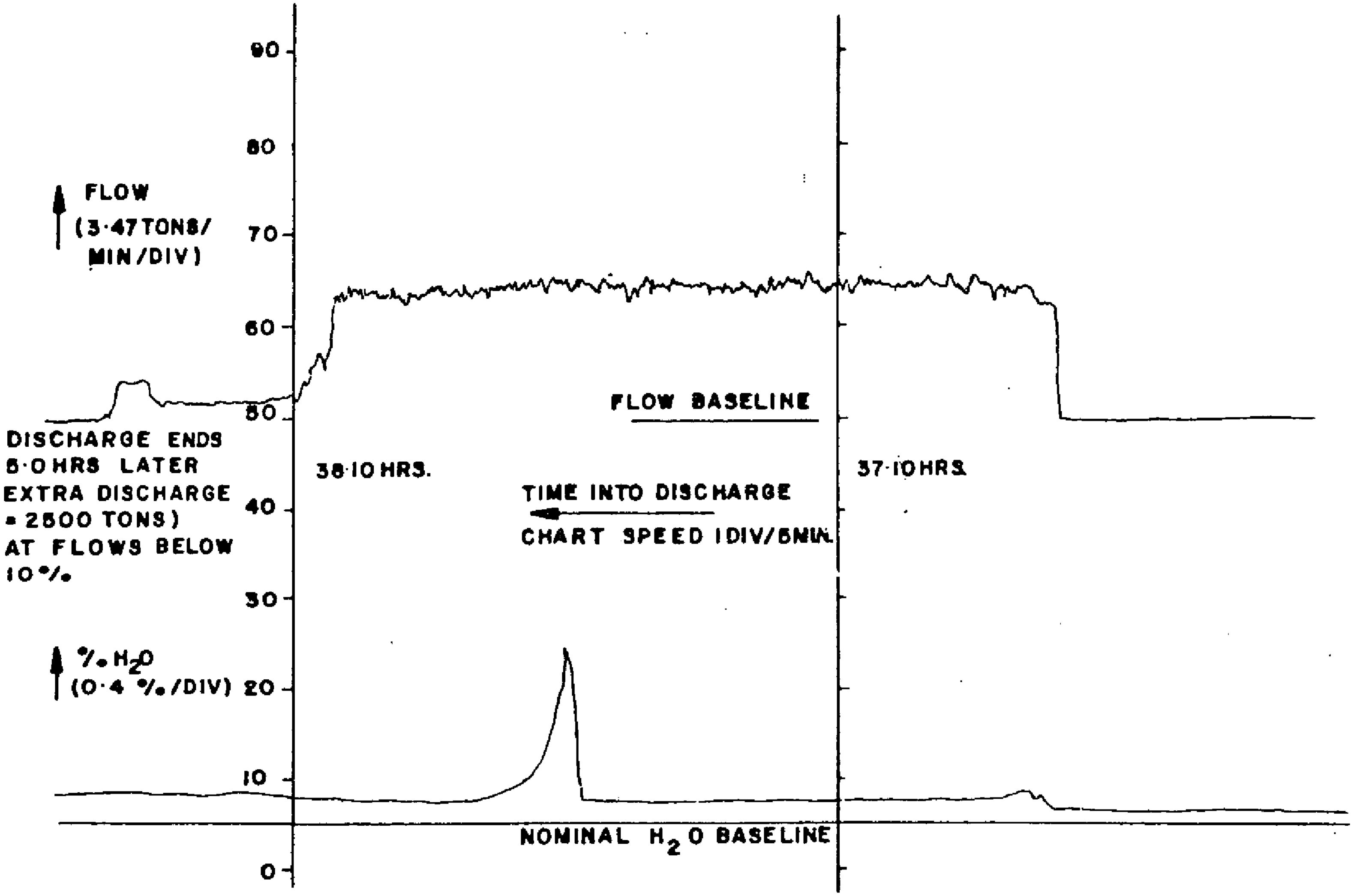
TYPICAL PROFILES FOR FLOW AND WATER AT BEGINNING OF A SHIP DISCHARGE



TYPICAL WATER PROFILE WITH CHANGES IN FLOW DURING A SHIP DISCHARGE

FIG.11

FIG.12



TYPICAL FLOW AND WATER PROFILES AT END OF A SHIP DISCHARGE

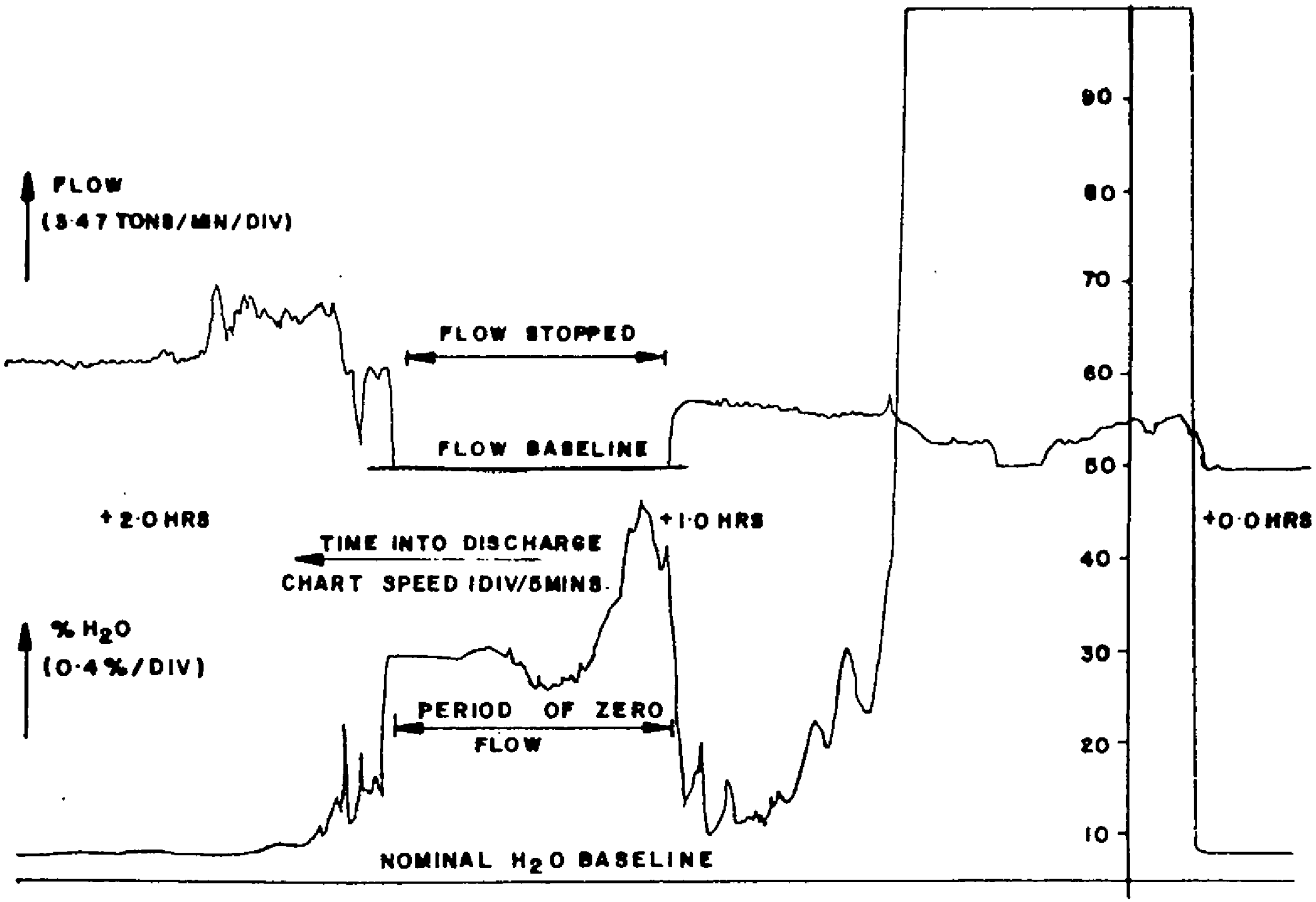


FIG.13

FLOW AND WATER PROFILE SHOWING RESPONSE OF CONTINUOUS MONITOR AT ZERO FLOW.

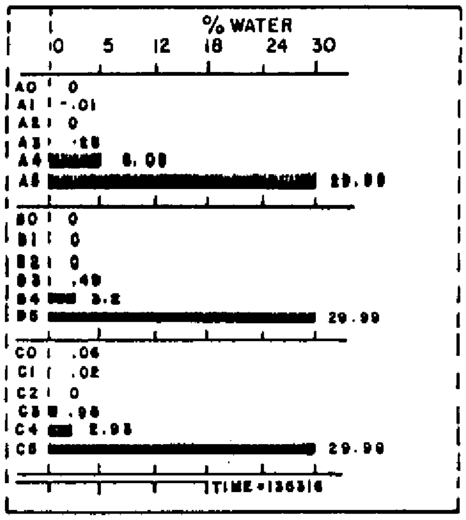
TYPICAL PROFILE PRINTOUTS FOR JET MIXING TRIALS

WATER - 9·6 %
FLOW - 1·6 m/s

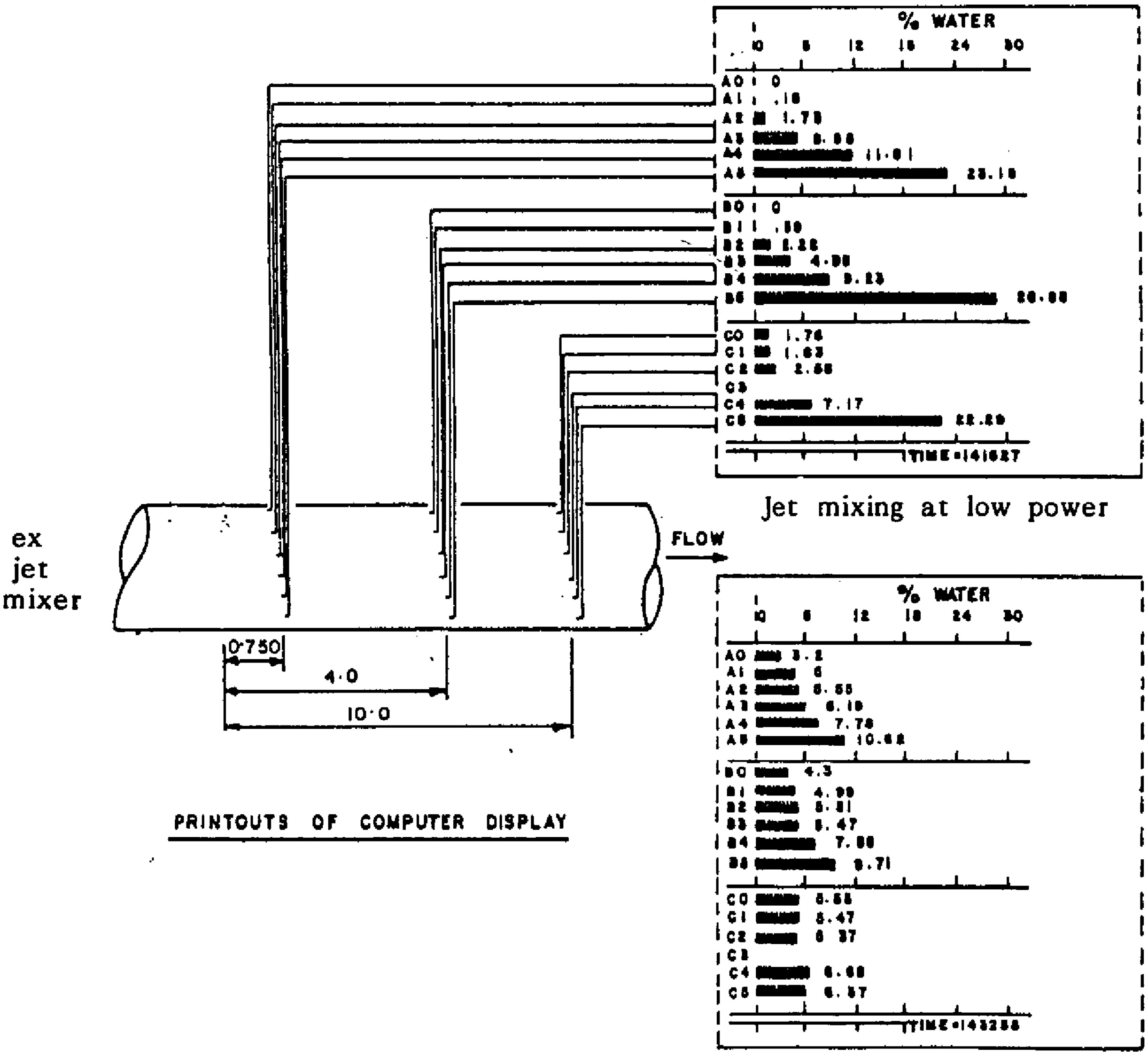
NOTES: 1. PROBE C3 FAILED MIDWAY THROUGH RUN.

2. MAXIMUM PROBE OUTPUT 29·99 %
∴ READING OF 29·99 % CAN REPRESENT WATER CONTENT TO 100%

3. PROBE CALIBRATION IN ERROR -
READING OF 6 % REPRESENTS WATER CONTENT OF APPROX. 10 %



No mixing



Jet mixing at low power

Jet mixing - power increased

PRINTOUTS OF COMPUTER DISPLAY

FIG.14

TABLE 1

CHARACTERISTICS OF VARIOUS TYPES OF CRUDE OILS

Crude type	Dry Oil Dielectric Constant (ε) @ 20°C	Temperature Coefficient of (ε) in absolute units	Temperature Coefficient in terms of % v/v water
BASRAH	2.235	-0.0020	-0.028
NINIAN	2.280	-0.0020	-0.027
KIRKUK	2.290	-0.0020	-0.027
FORTIES	2.301	-0.0020	-0.027
ARAB MEDIUM	2.341	-0.0021	-0.027
KUWAIT	2.441	-0.0021	-0.027
ZULUF (Arabian) blend	2.476	-0.0020	-0.027
BG 20S LUB OIL	2.152	-0.0021	-0.030

TABLE 2

COMPARISON OF THE CONTINUOUS CAPACITANCE MONITOR AGAINST THE JISKOOT SAMPLER ON MEAN WATER CONTENT

SHIP	DATE	CRUDE TYPE	TOTAL DISCHARGE (TONS)	TOTAL WATER (TONS)	MEAN % WATER	
					JISKOOT SAMPLER	CAPACITANCE MONITOR
A	3·2·82	KIRKUK	98,000	580	0·64	0·6
B	16·2·82	ARAB MEDIUM	67,000	132·5	0·18	0·20
C	22·2·82	FORTIES	100,000	1,210	1·3	1·21
D	25·2·82	ARAB LIGHT	65,000	269	0·35	0·41
E	16·4·82	ARAB LIGHT	64,000	67·2	0·12	0·10
F	26·4·82	FORTIES	47,000	96·4	0·35	0·20

TABLE 3

WATER DISCHARGE DISTRIBUTIONS AND TRANSIENT CONTRIBUTIONS

SHIP	DATE	WATER DISTRIBUTIONS			TRANSIENT CONTRIBUTIONS (1)			% WATER CONTRIBUTED BY TRANSIENTS (1)
		LINE CLEAR (TONS)	MAIN (TONS)	STRIPPING (TONS)	LINE CLEAR (TONS)	MAIN (TONS)	STRIPPING (TONS)	
A	3·2·82	50·1	333	169·9	27	0	6	0·034
B	16·2·82	19·7	106·5	6·3	16	1·6	0·2	0·0266
C	22·2·82	530·3	646·8	32·9	7	14	0	0·021
D	25·2·82	18·4	242	8·6	5	5·5	2·0	0·0192
E	16·4·82	2·3	61·7	3·2	0·42	0·13	0·03	0·0009
F	26·4·82	8·7	86·5	1·2	2·7	6·7	1·0	0·022

NOTES: 1) TRANSIENT CONTRIBUTIONS BASED ON TRANSIENT PERIODS OF UP TO 10 MINS.
2) NO TRANSIENT OF LESS THAN 20 SECONDS DURATION WAS OBSERVED. (TIME CONSTANT OF SAMPLING SYSTEM WAS APPROXIMATELY 5 SECONDS.)
3) TRANSIENTS OF LESS THAN 1 MINUTE WERE OBSERVED BUT WERE INSIGNIFICANT IN NUMBER & CONTRIBUTION.