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FIELD-BASED WATER-IN-OIL SAMPLING STUDIES

by

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S U M M A R Y

The paper describes the water-in-oil sampling field tests performed at a major European oil refinery. Metered supplies of water were injected into crude-carrying pipelines and the results monitored downstream by a bypass grab sampler, an in-the-line grab sampler, a capacitance device and a multi-probe profiler. The response of these instruments was monitored as crude type, flow velocity and water content were varied. Studies were also made of how pipe configurations affect the mixing of water and oil and the modification of slugs of water during passage through these configurations. The work was sponsored by the members of the NEL Automatic Sampling Project.

C O N T E N T S

N O T A T I O N

Symbol	Description	S.I. Unit
B	Background water, ie water already present in the crude oil flow before any water injection	per cent v/v
C	Calculated total water in oil flow = B + I	per cent v/v
I	Percentage of water injected into the main flow $= \frac{W_i}{W_i + K_i} \times 100$	per cent v/v
K_i	Crude oil flowrate	l/s
K_s	Volume of crude oil in the sample	ml
R	Rating sampling system[11] (only applicable if injected water content is > 1 per cent v/v water)	
	$= \frac{\text{Difference between sampled and calculated water content}}{\text{Injected + background water content}}$	
	$= \frac{S - C}{B + I} = \frac{S - C}{C}$	-
	R, rating = A if ratio $< \pm 0.05$ B if ratio $> \pm 0.05$ and $< \pm 0.10$ C if ratio $> \pm 0.10$ and $< \pm 0.15$ D if ratio $> \pm 0.15$	
	Prefix 'd' = uncertainty in measurement of variable prefixed.	
S	Percentage of water in a sample $\frac{W_s}{W_s + K_s} \times 100$	per cent v/v
W_i	Flowrate of water injected into the main flow	l/s
W_s	Measured volume of water in a sample	ml

1 INTRODUCTION

Since 1981 the NEL Automatic Sampling project has been supported by a consortium of between 14 and 18 member companies to perform research work to study and improve automatic water-in-oil sampling systems and methods[1,2]. The work has drawn upon three main resources: Firstly, and predominantly, it has used the purpose-built sampling test facility at the NEL[3,4,5]. Secondly, this has been supplemented by the use of computer simulations[6,7] and thirdly, the subject of this paper, a working refinery was utilised to conduct field test work. Although the field tests described were undertaken in 1985 and 1986[8] it is only now that confidentiality restrictions have been lifted and the results[9] can be presented in this paper.

The objectives of the field tests were to compare different sampling methods - notably In-the-line and External-loop sampling, to investigate the degree of mixing transients experienced and their effect on the different sampling methods, to verify the NEL's laboratory work on the effect of varying sampling flowrate through an External-loop sampler and to effect a comparison between laboratory and field sampling environments.

It should be noted that the results and conclusions arising from this work pertain to one particular situation at one refinery and may not be universally true.

2 SAMPLING FACILITY AND TESTING PROCEDURE

The field test facilities were made available to NEL by BP at their refinery in Europort near Rotterdam in the Netherlands. This location was chosen because BP had already established an experimental sampling facility at the refinery[10] and only a few pipework changes and hot taps were required to make it suitable for the NEL field tests.

2.1 Tests Performed

A total of 19 test 'runs' labelled A-S were performed on three separate occasions, with each occasion having a different type of crude oil. Delays were experienced in the testing programme due to difficulties in obtaining the preferred types of crude oil and problems in finding sufficient spare ullage for tank-to-tank transfers. In all, the tests took a year to complete and included a comprehensive programme of sampling flowrates, water transient studies and sampling comparisons. A summary of the tests performed is given in Table 1, with specific details given in Tables 2 and 3.

2.2 Pipework

The sampling facility was installed at a manifold where lines from the jetty, the tank farm and the refinery all joined together. In this location sampling tests could be conducted on tank-to-tank transfers using several pipe configurations. A schematic of the pipe configuration is given in Fig. 1 which shows the sampling station situated on the No 1 header about 2 m downstream of the jetty/header manifold. The internal diameter of the mainline pipe at the sampling station was 1.197 m. The approximate hold up volume between injection and sampling points on the direct route down the No 2 header, crossover via the No 3 line and up the No 1 header was calculated as 37m^3. Hold up between injection and sampling points via the No 2 header, down the No 3 jetty line, crossover at the jetty end, return by the No 2 jetty line and up the No 1 header was calculated as 379 m^3.

All instrumentation, computers, data loggers, Karl Fischer equipment etc was housed in a 'Portakabin' adjacent to the sampling station. A Commodore PET computer monitored all four flowmeters used and the 'Aquasyst' capacitance cell output and recorded them on disk and gave a hard copy both as a print-out and on a chart recorder.

2.3 Mainline Flowrate Measurement

The total quantity of crude oil transferred during a test was calculated by reading the exporting and receiving tank dip gauges. The maximum uncertainty in the measurement of flowrate calculated from the tank dips was calculated as ±12 l/s. The tank dips, however, did not give a measure of the flowrate at any moment during a test and for this reason a Maurer 'Cruflo' insertion turbine meter reading to ±40 l/s, normally used to pace the sampler, was situated downstream in the No 1 header and was used to monitor the constancy of the flowrate during the course of each test.

2.4 Injected Water Flowrate Measurement

Sea water from the refinery fire ring main was piped to the injection point by two 51 mm (2-inch) fire hoses, each of which was connected via a non-return valve and a ball valve to either the top or the lower injection point. A 51 mm (2-inch) calibrated turbine flowmeter was fitted in each line together with the requisite upstream and downstream lengths of straight steel pipe. Each flowmeter had a range of 4-50 l/s and the total uncertainty in the flow measurement system was calculated at ±0.26 l/s.

2.5 Sampling Instrumentation

The following sampling devices were used:

A Maurer In-the-line grab sampler and a Maurer External-loop grab sampler, both of the 'Maidstone' type, were fitted with identical internal mechanical systems and having their sample receivers immediately after the outlet port of the sampler. In order to obtain a workable sample volume in the minimum time the samplers were set to give the highest grab rate of 20 grabs per minute and each sample collection time was two minutes, giving a sample volume of 40 ml. The In-the-line sampler was mounted horizontally from the side of the mainline pipe, while the External-loop cell sampler was mounted below the main flow pipe in the external-loop which, because of piping complexity, had a sampling probe inserted vertically upwards into the mainline pipe. The sampling probe was of the NEL design as shown in Fig. 2.

The wall tapping, which was only used in the third set of tests, was mounted horizontally at the side of the pipe near the sampling station and consisted of a 50 mm dia. pipe, 315 mm long, with a blanking flange from which an axial 12 mm pipe, 130 mm long, led to the sample control valve.

The Profiler was designed in accordance with the recommendations contained in the Draft ISO Standard, 3171[11] and consisted of five equispaced NEL design sampling probes facing towards the direction of flow in the main line with the top and bottom probes each 20 mm from the pipe wall. All the probes were 9 mm o.d. and 6 mm i.d. with internally chamfered tips. There was also an additional probe facing vertically downwards to enable sampling from within the 5 mm bottom of the main line to check for any separate free water flowing along the bottom of the pipeline.

A dual cell 'Aquasyst' electrical capacitance water-in-oil measuring instrument manufactured by Endress and Hauser was inserted in the external-loop to monitor changes in water content and record the shape of the water transients reaching the sampling station[12].

3 WATER CONTENT MEASUREMENTS

3.1 Injected Water Content

Although the flowrate of crude oil transferred during a test could be measured by tank dips to within ±12 l/s, K_I, the actual flowrate at any moment during a test was assessed using the insertion flowmeter which, because of background fluctuations, could only be read to ±40 l/s. W_I was measured by calibrated turbine meters to within ±0.26 l/s. The total uncertainties associated with the injected water measurement I, was dependent on both K_I and W_I and was calculated for the individual tests to be:

Test(s)	A/B	C/D	E/F	G	H/I	J/K	L/M	N/O	P/Q	R	S
dI = ±	0.08	0.03	0.02	0.03	0.10	0.03	0.10	0.06	0.02	0.05	0.04

3.2 Background Water Content

Background water samples were taken before and after a testing period, usually at the same time as tank dip measurements were taken, ie before and after a change in flowrate or start up or close down of the pumps. Usually three samples were taken from a tapping on the external-loop together with three samples taken from the centre probe of the Profile to obtain each background water measurement. Throughout the tests the background water, with only a few exceptions, remained very constant. This was mainly achieved by the policy of either allowing the crude to remain for a period in the exporting tank before a test or by running tank mixers before and during the tests to ensure uniformity of background water.

3.3 Calculated Water Content

The total water present in the mainline flow during a sampling test was calculated from the sum of the injected water, I, and the background water, B. The uncertainty in measuring the calculated water content was, therefore, a combination of uncertainties due to measurement of both injected and background water contents and was calculated to have a maximum value of ±0.10 per cent v/v water.

3.4 Sampled Water Content

All samples taken were collected in disposable polythene bottles with screw caps. The sample volumes collected were of approximately 250 ml volume, except in the case of the Maurer grab samplers which were of 40 ml. Analysis of each sample was by potentiometric Karl Fischer titration performed volumetrically on 0.1 ml up to 1 ml subsamples taken from the homogenised contents of each 250 or 40 ml sample. Examination showed that the uncertainty of measurement associated with the volumetric Karl Fischer titration would be within the repeatability values given by the gravimetric IP 356/84 Standard. The maximum water content analysed in the field tests was 2.5 per cent v/v water, hence the maximum expected uncertainty in measurement by Karl Fischer analysis was ±0.03 per cent v/v water. For many tests and for the background water measurements the expected uncertainty would be much less because of the smaller percentages of water involved.

3.5 Difference between Calculated and Sampled Water Contents

Taking the uncertainty in the measurement of the calculated water content, ie Injected plus Background, as ±0.10 per cent v/v water and the uncertainty in the sampled water content as ±0.03 per cent v/v water then statistically any calculated and sampled water content measurements were significantly different when they differed by more than ±0.10 per cent v/v water.

4 PROFILE AND MIXING STUDIES

It was expected that all background and injected water would be well mixed in the transit through the bends and valves of the crossover manifold between injection and sampling points[13]. Further, the Reynolds number of the mainline flow at the sampling station varied from 33 000–380 000 so that a fully turbulent flow and an established velocity profile would always be expected to aid mixing. In addition, the water injection points gave the injected water an inlet velocity of about 5 m/s though this could have been higher because of possible constrictions in the hot taps.

In order to check that all background and injected water had been mixed uniformly, profiling measurements were conducted generally, in accordance with ISO DIS 3171, before tests A, C, E, G, H, J, L, N, P and R, using the six-point Profiler. An example of the results obtained is given in Table 4 which gives, in addition to each water content measured, the mean water content measured across the five forward-facing profile probes, the 95 per cent confidence limits of that mean and the 95 per cent confidence limits expressed as a percentage of the mean. The figures in brackets refer to the probe pointing vertically downwards to check for free water in the bottom of the pipe and these were not entered into the calculation of the means. It can be seen from these bracketed figures that no free water was detected at any time during this test and this was true for all the other tests. Beneath the profiling measurements, a similar mean, 95 per cent confidence limits and confidence limits expressed as a percentage of the mean are given for each sampling probe on the Profiler.

Analysis of the profiling results for all tests gave information in three main areas:

4.1 Compliance with ISO 3171

ISO 3171, Section 6 and Fig. 8[11] states that a water concentration profile across a pipeline is acceptable for sampling if the average water content at each position on the Profiler does not exceed ±5 per cent of the mean value. All water concentration profiles, and hence all the flow conditions used in the tests, were found to be well within the ISO recommendations.

4.2 Relative Mixing Characteristics

Statistical analysis of the profiling results for all the tests showed that there was no correlation between profile uniformity and pipeline velocity. Similarly, there was no significant correlation between profile uniformity and type of crude oil for the three crude oils studied.

The effect of pipeline length on mixing was demonstrated by comparing tests C/D, G, N/O and R. Test C/D conducted at 1.46 m/s on Statfiord crude, on the direct injection/sampling route, had a profile scatter of 1.3 per cent while test G ran at 1.43 m/s on the same crude but via the jetty route had a

profile scatter of 0.6 per cent, ie passage down the jetty seemed to further mix the water. However, a similar comparison on the mixed crude with test N/O run at 1.20 m/s on the direct route gave a profile scatter of 1.5 per cent, identical with that of test R run at 1.17 m/s on the same crude via the jetty although in the case of test R the degree of scatter was calculated from only three profiles.

The overall conclusion was that in these cases the background water and injected water was so well mixed that differences in pipeline velocity, type of crude or pipeline mixing length had little effect.

4.3 Sampling System Uncertainties

4.3.1 Random errors

The results of the profiling tests presented an opportunity to evaluate the repeatability of the complete sampling system in measuring water content in that, for each set of profile results, samples were obtained consecutively from the same probe and analysed by the same procedure. The repeatability would also include the random fluctuations in the water content of the crude oil flowing in the pipeline during the time each set of profile measurements were made.

To illustrate this opportunity, the figures below the line in Table 4 show, in addition to the mean water content at each probe position, the 95 per cent confidence limits of the values obtained at that probe position expressed in water content and as a percentage of the mean water content. The average value of the 95 per cent confidence limits for all the profile data for individual probe positions was found to be $\pm$0.12 per cent v/v water.

Examination of individual sets of profile measurements showed some profiles such as H/I had average confidence limits of $\pm$0.04 per cent v/v water while others, such as J/K, had average confidence limits of $\pm$0.25 per cent v/v water. The former value approached the repeatability of the Karl Fischer analysis, while the latter value may reflect the repeatability of obtaining a representative sample from a flow of varying water content.

4.3.2 Systematic errors

The figures given in the box of Table 4 include an overall mean of S, the sampled water content and C, the calculated water content. These values were determined for each set of profiling measurements so the random fluctuations described above would have been removed. It was seen that the values of S generally exceeded C with a maximum difference (test J/K) of 0.16 per cent v/v water. The mean difference of S - C was +0.039 per cent v/v water with 95 per cent confidence limits of the mean of $\pm$0.044 per cent v/v water, ie the difference was not significant. The magnitude of the difference correlated with neither crude oil flowrate nor nominal water content. All the profile tests gave overall means with an 'A' ISO Sampling System Rating (see notation) except, that is, for test J/K which returned a 'C' rating.

Although the change in tank levels occurring during a test might have given rise to a change in flowrate, and hence injected water content, no conclusive evidence of this was observed. The profiles were determined at the start of each test where higher exporting tank levels and lower receiving tank levels could possibly have given a slightly higher than the test mean value of oil flowrate through the pumps. This would have effectively

diluted the injected water content and hence S would be less than C. Because the opposite was observed, it would suggest that although the mean difference was not significantly different, there could be a systematic element in the difference. It should be noted that the discrepancy in the case of test J/K was much larger than the expected $\pm$0.10 per cent v/v water. This could be explained by the water content varying while the profile samples were being taken.

5 TRANSIENT STUDIES

As a further examination of mixing characteristics, water transients of 1-, 2-, and 10-minute duration were injected into the oil flow. The 'Aquasyst' capacitance cell in the external-loop was used to monitor their passage through the sampling station. A summary of the transient tests is given in Table 3 while Table 5 gives a summary of the transient tests results. It must be noted that all the times were taken from the chart recording of the tests and include an element of subjective measurement of first detection and 95 per cent full magnitude times. The values given in the table are the mean values for the 1-, 5-, and 10-minute transients injected at each test condition. Although the three transients varied in length, the shape of their leading and trailing edges on the chart recorder were indistinguishable from each other at each test condition.

One surprising result of the tests was how little distortion the transients experienced in transit from injection point to sampling station. The transients were generated with a square waveform by a rapid opening and closing of the water injection lines and were shown to be so by the square waveform traces of the water injection meters on the chart recorder. The capacitance cell showed the transients were received at the sampling station with only a slight distortion of this square waveform as shown by the times of the leading slope in Table 5. A measure of the received waveform can be given by the fact that approximately 75 per cent of the peak had registered in half the time required for 95 per cent to register.

It could also be seen that there was surprisingly little slip between the water and oil phases as exemplified by the correspondence of calculated and measured time delays which would confirm that the water was well mixed with the crude oil. It would be expected that the measured time delay would exceed the calculated time delay as a finite time would be required to pass through the external-loop to the capacitance cell. This was seen to be so in the majority of tests, though the uncertainty in determining exact measured times from the chart recording and exact calculated times from the hold up volumes and flowrate could account for tests M-S, conducted on the mixed crude, indicating that the water actually arrived ahead of the calculated time.

It was difficult to assess the slip between water and oil components as injection of a given percentage of water was expected to increase the overall mainline flowrate by a similar percentage, ie the injection of water transients into the mainline was accompanied by corresponding mainline velocity transients to accommodate the extra fluid.

6 EXTERNAL-LOOP SAMPLING RATE STUDIES

Previous work in the NEL test facility had shown that samples obtained from the NEL design of external-loop scoop probe, ie the internally chamfered, forward-facing scoop, was least affected by water droplet size or varying sampling flowrates from 10-100 per cent of mainline velocity, ie 10-200 per

cent isokinetic sampling flowrates. Further, these laboratory tests had also shown that the NEL design of probe was relatively unaffected by being turned 30° upwards, or 30° downwards to the axis of the pipe. It would appear, therefore, that this design of scoop in addition to being little affected by sampling flowrate was also little affected by swirl angles of up to ±30°.

Field studies of the effect of external-loop flowrate on sampling accuracy were undertaken on an external-loop fitted with a NEL design of sampling probe. The fluid resistance through the external-loop and the capacity of the external-loop pump were such that external-loop flow of up to a maximum of only 80 per cent isokinetic were possible with the mainline flows used in the tests.

Tests were performed at several external-loop sampling rates using the valve in the external-loop to control the external-loop flow. Samples were taken from the External-loop grab sampler and from the centre probe of the Profiler at three separate instants for each sampling rate. In some tests, samples were also taken at the same time from the In-the-line grab sampler and from the wall tapping.

The results of the tests are given in Table 2 which, for each test and each sampling, gives C, the water content calculated from the oil and water flowrates, and S the sampled water contents from the External-loop cell sampler, the In-the-line sampler, the Profiler and the wall tapping.

Examination of the External-loop sampler results in Table 2 shows an outlier in the data for the 8 per cent isokinetic sampling flowrate for test J. This was due to a surge in background water during the course of the sampling. Although not thought to be significant it has nevertheless been neglected in the analysis below.

Two methods were available with which to compare the results of the External-loop sampler when used at each sampling flowrate; firstly, comparison could be made with C the calculated water content and secondly, comparison could be made with the water content measured at the centre probe of the Profiler. The results of both comparisons are given below.

6.1 Comparison with Calculated Water Contents

It must be noted that the measurement uncertainties associated with the calculated water content could be comparatively large at ±0.10 per cent v/v water and the difference between the calculated and sampled water contents was significant only if it exceeded ±0.10 per cent v/v water.

On this basis, the seven tests which showed significant differences between the calculated water content and the sampled water content from the External-loop cell sampler did not indicate that the difference was due to a change in sampling rate because the differences occurred at high as well as low percentage isokinetic sampling flowrates.

6.2 Comparison with Profiler Measurements

The uncertainties associated with the sampled water contents were less than those for the injected water contents, particularly as three samples were taken at each percentage isokinetic sampling flowrate. Statistical analysis showed these to be ±0.02 per cent v/v water and that any two sampled measurements were significantly different only if the difference exceeded ±0.03 per cent v/v water.

A comparison could, therefore, be made between the External-loop sampler and the other sampling methods with comparatively less uncertainty than a comparison with the calculated water contents. Only the samples obtained from the centre probe of the Profiler were used for this purpose as those obtained from the In-the-line grab sampler and the wall tapping could be subject to errors as described in Section 7 below.

When the External-loop sampler and Profiler results were compared, 15 of the 27 tests gave significant differences but no correlation between these differences and percentage isokinetic sampling flowrate could be found. There was, therefore, no evidence to suggest that sub-isokinetic sampling flowrate effected sampler accuracy. This conclusion was also confirmed by previous exploratory work by BP at the sampling station[10].

7 COMPARISON OF SAMPLING METHODS

The field tests provide an opportunity to compare the results of the in-the-line grab sampler, the External-loop grab cell sampler, the Profiler, the wall tapping and the capacitance cell mounted in the External-loop.

7.1 Comparison of Sampling Methods with Constant Water Content

Accepting the conclusion of Section 6, that the sampling flowrate did not effect the External-loop cell sampler, then the results of the sampling flowrate tests given in Table 2 can be used to compare the two grab samplers, the Profiler and the wall tapping. No quantitative measurements were taken from the capacitance cell as for the purpose of these tests it was only used as a water content monitor. Nevertheless, the output from the capacitance cell was found to qualitatively reflect the calculated and sampled water content measurements in a stable and responsive manner.

Excluding the 8 per cent isokinetic sampling flowrate in test J for the reasons given in Section 6, the mean of the differences between the calculated and sampled water contents shown in Table 2 is expressed as shown in part A of Table 6. The mean values for the External-loop cell sampler, the In-the-line sampler, the Profiler and the wall tapping were +0.09, +0.02, +0.06 and +0.74 per cent v/v water respectively. It can be seen that all four methods overestimate the water content which corresponds with the findings of Section 4.3.2. Again no correlation between this difference and the crude oil flowrate or nominal water content could be discerned.

Part A of Table 6 also shows the confidence levels to which these means could be quoted to 95 per cent confidence. This shows that the readings from all four methods except the In-the-line sampler were considered to be significantly different from the calculated water contents. The table also shows that the degree of scatter associated with the In-the-line sampler is greater than that associated with either the External-loop cell sampler or the Profiler but that the wall tapping had, by far, the largest degree of scatter of any method.

An alternative to using the calculated water contents was to use the Profiler water contents for comparison. Use of the Profiler, which had the NEL design of scoop tube, was vindicated both from the findings of the laboratory work which showed it to be the best method of obtaining a representative sample from the main line and also in that all measurements involved in the comparison were based on the Karl Fischer titration and any systematic error from this source was therefore eliminated.

The comparison with the Profiler results is shown in part B of Table 6 which shows that the External-loop cell sampler, the In-the-line sampler and the wall tapping differed on average from the Profiler results by +0.03, -0.02 and +0.70 per cent v/v water respectively. The table also gives the 95 per cent confidence limits to which these means could be quoted and these show that the External-loop cell sampler and the wall tapping were significantly different from the Profiler whereas the In-the-line sampler was not. This statement must be qualified by drawing attention to the fact that the larger scatter exhibited by the In-the-line sampler was largely responsible for no significant difference being found in its case.

The results showed that the wall tapping grossly overestimated the water content though this was most likely due to its very unfavourable geometry. In contrast, point 6, the bottom-facing probe on the Profiler, which also sampled from near the pipe wall and at right angles to the flow was seen to give reasonable results.

The results also showed that the External-loop cell sampler tended to overestimate and the In-the-line sampler tended to underestimate the water content compared to the Profiler. The results also show that the scatter associated with the In-the-line sampler was twice as large as that associated with the External-loop sampler.

Another method of comparing the sampling methods was to compare the ISO Sampling System Rating (see notation). These ratings are given for each sampling method in Table 2 and can be summarised in the table below in which the total number of tests falling in each rating category is given for each of the four sampling methods:

Sampling method	External-loop	In-the-line	Profiler	Wall tapping
Rating 'A'	13	8	16	0
Rating 'B'	5	3	3	0
Rating 'C'	3	2	1	0
Rating 'D'	0	0	1	6
Total tests	21	13	21	6

7.2 Comparison of Sampling Methods with Water Content Transients

The main objective of the transient tests was to assess the response of the different sampling methods to water transients. To achieve this end the two grab samplers and the Profiler were operated while water transients were injected into the oil flow at each test condition. Use of the Profiler in these tests was for academic interest only as the spot samples obtained by the Profiler at two-minute intervals were not intended to form part of a sampling system as in the case of the two grab samplers. Transients of one minute, then five minutes and, in some cases, ten minutes duration were injected into the flow at each test condition. Test S, in which 18 one-minute transients were injected into the line was a special case which was performed to give a comparison with the NEL computer simulation work.

As described previously, Table 3 gives a summary of the individual transients, while Table 7 gives a comparison of the sampling methods in the transient conditions prevailing over the duration of each test. For each test given in Table 7 the transient water, over and above the background water, which was measured by each sampling method is expressed as a percentage of the total amount of water injected evaluated from a knowledge

of injected water flowrates and injection time. The mean of these percentages for the External-loop sampler, the In-the-line sampler and the Profiler, was calculated with allowance for the different numbers of samples taken in each test. This showed that 98, 99 and 84 per cent of the injected transient water was recovered by the External-loop sampler, In-the-line sampler and Profiler respectively. The large uncertainties associated with the measurement of the injected water content makes it difficult to give any statement about the absolute uncertainty to be expected with each sampling method except that, as expected, the Profiler gave a substantially different reading because of the relatively long two-minute interval between successive samples. This difficulty with the accuracy of the Profiler method in transient conditions also removed the possibility of comparing its results with results of the External-loop and In-the-line samplers as above.

Only in test R was the wall tapping used and this, like the Profiler, also had the disadvantage of a long two-minute period between samples but nevertheless, at 173 per cent recovered transient it exceeded the maximum deviation recorded by any of the other methods confirming the conclusion in Section 7.1 that, in this particular case, it was a most inaccurate method of obtaining a sample.

7.3 Field and Laboratory Comparisons

After the completion of the field tests the In-the-line grab sampler was shipped to the NEL and installed horizontally in the NEL water-in-kerosine sampling facility. When the facility was operated on closed loop at a nominal 5 per cent v/v water content the sampler was found to underestimate the water content on average by -0.25 and -0.22 per cent v/v water in two separate tests. The uncertainty in measuring the calculated water content in the test facility was $\pm$0.01 per cent v/v water and the 95 per cent confidence limits of the mean of the two tests was $\pm$0.04 per cent v/v water which made the sampled water content significantly different from the calculated water content. The laboratory results of -0.25 and -0.22 per cent v/v water were also significantly different from the field result of -0.02 per cent v/v water though it must be remembered that the field water content seldom rose above 2.5 per cent v/v water. It was also noted that between 200 and 400 grabs were required to obtain a representative sample in the laboratory facility, but that 40 grabs in the field appeared to be sufficient to obtain a representative sample.

The discrepancy in measured water content and the longer time taken to obtain a representative sample would indicate that the water-in-kerosine laboratory facility provides a more demanding sampling environment than in the field where the water does not usually experience rapid separation from the oil.

8 CONCLUSIONS AND RECOMMENDATIONS

The main findings of the work conducted at the refinery were:

a The mixing of background and injected water was well within the ISO 3171 specifications showing that the method of water injection and the simple crossover manifold used in the tests provided sufficient mixing even at the low flow velocities used. No correlation between mixing efficiency and flow velocity or crude type was found over the range of variables studied.

b Transients of water were found to experience relatively little distortion or slip even after passage through long pipes, bends and valves.

c Uncertainties of up to ±0.10 per cent v/v water were associated with the measurement of the calculated injected water content. This was mainly due to tank dips being used to measure the total volume transferred during a test and an insertion flowmeter to indicate any change of the flowrate during a test. The ISO 3171 recommended limits of ±2 per cent on crude oil and injected water volumes may not be sufficient to give confident comparisons between injected and sampled water contents.

d External-loop flowrate did not effect the sampling accuracy of an External-loop cell sampler when used over a range of 6 to 79 per cent of the isokinetic sampling rate.

e In steady-state conditions, the In-the-line and the External-loop cell samplers overestimated water content on average by +0.02 and +0.09 per cent v/v water respectively compared to the calculated injected water. Because of the large uncertainties involved in the measurement of the calculated water content (see g below), only the cell sampler was considered to have a significant difference. Compared to the Profiler, the In-the-line sampler underestimated on average by -0.02 per cent v/v water and the cell sampler overestimated on average by 0.03 per cent v/v water. Again, the cell sampler result was considered to be significantly different. A wall tapping gave samples that overestimated by 0.74 per cent v/v water.

f In sampling water transients, on average the External-loop cell sampler recovered 98 per cent and the In-the-line sampler 99 per cent of the water in the transients. By contrast, the spot samples obtained from the Profiler recovered 84 per cent and the wall tapping 173 per cent of the water in the transients.

g The In-the-line grab sampler was found to underestimate the water content by 0.02 per cent v/v water in the field, but to underestimate the water content by 0.25 per cent v/v water and to have a longer delay in producing a representative sample in the NEL laboratory facility. Both the larger underestimation and the longer delay in obtaining a representative sample indicate that the NEL water-in-kerosine test facility is more demanding than normal field conditions.

ACKNOWLEDGEMENT

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TABLE 1

SUMMARY OF TESTS PERFORMED AT THE BP ROTTERDAM REFINERY

Test	Date	From tank	To tank	Tank dips min.	Oil type	Vis. cSt	Pipe config.	Flow vel. m/s	Per cent v/v water			Ext-loop per cent isokin. flowrate	Time of transients min.	No. pro-files
									Back. B	Inj. I	Calc. C			
A	19/11/85	T109	T101	253	Statfiord	6.5	direct	0.89	0.43	1.82	2.25	8, 17, 31, 63	continuous	3
B	19/11/85	T109	T101	253	Statfiord	6.5	direct	0.89	0.43	1.82	2.25	36	5, 10	
C	19/11/85	T109	T101	146	Statfiord	6.5	direct	1.46	0.43	1.07	1.50	9, 16, 36, 49	continuous	3
D	19/11/85	T109	T101	146	Statfiord	6.5	direct	1.46	0.43	1.07	1.50	20	1, 5, 10	
E	19/11/85	T109	T101	47	Statfiord	6.5	direct	2.06	0.43	0.69	1.12	10, 19, 34	continuous	3
F	19/11/85	T109	T101	47	Statfiord	6.5	direct	2.06	0.43	0.69	1.12	38	5	
G	20/11/85	T101	T109	118	Statfiord	6.5	jetty	1.43	0.61	0.91	1.52	37	1, 5, 10	3
H	16/02/86	T110	T104	138	Iran. heavy	30.0	direct	0.89	0.15	2.32	2.47	11, 20, 38, 79	continuous	10
I	16/02/86	T110	T104	138	Iran. heavy	30.0	direct	0.89	0.15	2.32	2.47	37	1, 5	
J	16/02/86	T110	T104	117	Iran. heavy	30.0	direct	1.63	0.15	1.23	1.38	8, 20, 47	continuous	10
K	16/02/86	T110	T104	117	Iran. heavy	30.0	direct	1.63	0.15	1.23	1.38	40	1, 5, 10	
L	02/09/86	T104	T107	120	Mixed	7.0	direct	0.89	0.24	2.29	2.53	15, 34, 56	continuous	10
M	02/09/86	T104	T107	120	Mixed	7.0	direct	0.89	0.24	2.29	2.53	56	1, 5	
N	02/09/86	T104	T107	100	Mixed	7.0	direct	1.20	0.24	1.73	1.97	9, 21, 41	continuous	10
O	02/09/86	T104	T107	100	Mixed	7.0	direct	1.20	0.24	1.73	1.97	41	1, 5	
P	02/09/86	T104	T107	67	Mixed	7.0	direct	2.01	0.23	0.86	1.09	6, 13, 24	continuous	3
Q	02/09/86	T104	T107	67	Mixed	7.0	direct	2.01	0.23	0.86	1.09	24	1, 5	
R	03/09/86	T107	T104	151	Mixed	6.8	jetty	1.17	0.81	1.28	2.10	30	1, 1, 5	10
S	03/09/86	T107	T104	126	Mixed	6.8	direct	1.37	0.67	1.28	1.95	29	18 x 1	

TABLE 2

SUMMARY OF SAMPLING FLOWRATE TESTS

Test	Date	Oil Type	Vis. cSt	Flow vel. m/s	Per cent isokin. flowrate	Per cent v/v water				
						Calculated C	Ext-loop sampler	In-the-line sampler	Profiler	Wall tap
A	19/11/85	Statfiord	6.5	0.89	8	2.25	2.42 B		2.34 A	
A	19/11/85	Statfiord	6.5	0.89	17	2.25	2.35 A		2.34 B	
A	19/11/85	Statfiord	6.5	0.89	31	2.25	2.54 C		2.50 C	
A	19/11/85	Statfiord	6.5	0.89	63	2.25	2.55 C		2.46 B	
C	19/11/85	Statfiord	6.5	1.46	9	1.50	1.52 A		1.53 A	
C	19/11/85	Statfiord	6.5	1.46	16	1.50	1.54 A		1.56 A	
C	19/11/85	Statfiord	6.5	1.46	36	1.50	1.55 A		1.55 A	
C	19/11/85	Statfiord	6.5	1.46	49	1.50	1.54 A		1.57 A	
E	19/11/85	Statfiord	6.5	2.06	10	1.12	1.14 (A)		1.18 (B)	
E	19/11/85	Statfiord	6.5	2.06	19	1.12	1.17 (A)		1.17 (A)	
E	19/11/85	Statfiord	6.5	2.06	34	1.12	1.17 (A)		1.15 (A)	
H	16/02/86	Iran. heavy	30.0	0.89	11	2.47	2.47 A	2.34 B	2.49 A	
H	16/02/86	Iran. heavy	30.0	0.89	20	2.47	2.50 A	2.37 A	2.52 A	
H	16/02/86	Iran. heavy	30.0	0.89	38	2.47	2.49 A	2.49 A	2.50 A	
H	16/02/86	Iran. heavy	30.0	0.89	79	2.47	2.51 A	2.54 A	2.49 A	
J	16/02/86	Iran. heavy	30.0	1.63	8	1.38	1.58 C	1.56 C	1.67 D	
J	16/02/86	Iran. heavy	30.0	1.63	20	1.38	1.40 A	1.38 A	1.41 A	
J	16/02/86	Iran. heavy	30.0	1.63	47	1.38	1.40 A	1.36 A	1.41 A	
L	02/09/86	Mixed	7.0	0.89	15	2.53	2.72 B	2.80 C	2.58 A	4.05 D
L	02/09/86	Mixed	7.0	0.89	34	2.53	2.73 B	2.62 A	2.63 A	3.23 D
L	02/09/86	Mixed	7.0	0.89	56	2.53	2.75 B	2.71 B	2.70 B	3.32 D
N	02/09/86	Mixed	7.0	1.20	9	1.97	2.01 A	1.95 A	1.95 A	3.81 D
N	02/09/86	Mixed	7.0	1.20	21	1.97	2.05 A	2.05 A	1.97 A	2.30 D
N	02/09/86	Mixed	7.0	1.20	41	1.97	2.07 B	2.10 B	2.00 A	2.32 D
P	02/09/86	Mixed	7.0	2.01	6	1.09	1.14 (A)	0.96 (C)	1.10 (A)	1.65 (D)
P	02/09/86	Mixed	7.0	2.01	13	1.09	1.14 (A)	0.98 (C)	1.10 (A)	1.38 (D)
P	02/09/86	Mixed	7.0	2.01	24	1.09	1.16 (B)	1.02 (B)	1.12 (A)	1.40 (D)

All figures in per cent v/v water - letters denote ISO ratings, those in brackets are where I ≤ 1.0 per cent.

TABLE 3

SUMMARY OF WATER CONTENT TRANSIENT TESTS

Test	Date	Oil Type	Vis. cSt	Flow vel. m/s	Pipe config.	Transient duration min.	Per cent of actual transient sampled		
							Ext-loop	In-the-line	Profiler
B	19/11/85	Statfiord	6.5	0.89	direct	5	105	96	85
B	19/11/85	Statfiord	6.5	0.89	direct	10	108	95	105
D	19/11/85	Statfiord	6.5	1.46	direct	1	102	106	113
D	19/11/85	Statfiord	6.5	1.46	direct	5	100	94	87
D	19/11/85	Statfiord	6.5	1.46	direct	10	105	97	109
F	19/11/85	Statfiord	6.5	2.06	direct	5	109	114	84
G	20/11/85	Statfiord	6.5	1.43	jetty	1	87	96	83
G	20/11/85	Statfiord	6.5	1.43	jetty	5	97	87	88
G	20/11/85	Statfiord	6.5	1.43	jetty	10	104	90	104
I	16/02/86	Iran. heavy	30.0	0.89	direct	1	103	125	20
I	16/02/86	Iran. heavy	30.0	0.89	direct	5	99	101	83
K	16/02/86	Iran. heavy	30.0	1.46	direct	1	104	112	12
K	16/02/86	Iran. heavy	30.0	1.46	direct	5	101	98	85
K	16/02/86	Iran. heavy	30.0	1.46	direct	10	102	100	104
M	02/09/86	Mixed	7.0	0.89	direct	1	117	220	23
M	02/09/86	Mixed	7.0	0.89	direct	5	104	95	89
O	02/09/86	Mixed	7.0	1.20	direct	1	106	250	11
O	02/09/86	Mixed	7.0	1.20	direct	5	105	97	84
Q	02/09/86	Mixed	7.0	2.01	direct	1	104	263	11
Q	02/09/86	Mixed	7.0	2.01	direct	5	103	116	82
R	03/09/86	Mixed	6.8	1.17	jetty	1	52	52	85
R	03/09/86	Mixed	6.8	1.17	jetty	1	59	59	85
R	03/09/86	Mixed	6.8	1.17	jetty	5	96	90	100

TABLE 4

RESULTS OF PROFILE MEASUREMENTS BETWEEN TESTS H AND I

	Top		Centre			Bottom	Mean	95 per cent conf. lim.	Per cent conf. lim.
	1	2	3	4	5	(6)	(a)	(b)	(c)
	2.47	2.46	2.49	2.47	2.50	(2.48)	2.48	0.05	2.00
	2.50	2.48	2.49	2.50	2.50	(2.49)	2.49	0.02	0.80
	2.48	2.50	2.49	2.50	2.50	(2.51)	2.49	0.02	1.10
	2.50	2.47	2.49	2.50	2.50	(2.49)	2.49	0.04	1.50
	2.49	2.50	2.50	2.51	2.52	(2.50)	2.50	0.03	1.10
	2.49	2.49	2.50	2.50	2.51	(2.50)	2.50	0.02	0.80
	2.51	2.51	2.52	2.53	2.52	(2.51)	2.52	0.02	0.80
	2.52	2.53	2.52	2.56	2.53	(2.51)	2.53	0.05	1.80
	2.53	2.50	2.52	2.51	2.53	(2.51)	2.52	0.04	1.40
	2.52	2.50	2.50	2.49	2.53	(2.50)	2.51	0.05	1.80
Mean	2.50	2.49	2.50	2.51	2.51	(2.50)	Overall mean = 2.50		
95 per cent conf. lim.	0.04	0.05	0.03	0.05	0.03	(0.02)	Scatter = 0.40 per cent		
Per cent conf. lim.	1.70	1.80	1.20	2.20	1.20	(1.10)	Calc. water = 2.47		

(a) = Mean of all figures in column or row.
(b) = 95 per cent confidence limits or degree of scatter of figures in column or row (with Student's 't' adjustment).
(c) = 95 per cent confidence limits as per cent of mean.

TABLE 5

SUMMARY OF WATER TRANSIENT TIMES

Test	Flowrate m/s	External-loop flowrate l/s	Calc. delay s	Measured delay s	Diff. s	Leading slope s
B	0.89	0.52	37	45	8	45
D	1.46	0.48	38	35	7	30
F	2.06	1.29	16	23	7	20
G	1.43	0.89	236	245	9	30
I	0.89	0.53	37	45	8	50
K	1.63	1.06	20	25	5	25
M	0.89	0.92	37	35	-2	25
O	1.20	0.92	27	28	1	25
Q	2.01	0.89	16	17	1	16
R	1.17	0.65	324	295	-29	50
S	1.37	0.65	24	25	1	20

Calc. delay = Calculated time delay between injection point and arrival at sampling station based on flow-rate and volume of passage between injection and sampling points.

Measured delay = Measured time delay between start of injection and the first detection of the transient by the capacitance probe.

Diff. = Difference, measured - calculated time delay.

Leading slope = Time transient takes to increase from 0-95 per cent of full magnitude on the capacitance cell readout.

TABLE 6

COMPARISON OF SAMPLERS WITH CONSTANT WATER CONTENT

	External-loop	In-the-line	Profiler	Wall tapping
A Differences between Sampled and Calculated water contents expressed as per cent v/v water				
Mean of (S - C) values	+0.087	+0.017	+0.062	+0.743
±95 per cent confidence limits of the mean	0.035	0.066	0.027	0.435
±95 per cent scatter of (S - C) values	0.177	0.255	0.134	1.305
B Differences between Profile and other Sampled water contents expressed as per cent v/v water				
Mean of (S - Profile) values	+0.025	-0.020	0.000	+0.701
±95 per cent confidence limits of the mean	0.020	0.058	0.000	0.439
±95 per cent scatter of (S - Profile) values	0.101	0.225	0.000	1.317

Mean = Mean of all the (Sampled - Calculated) or (Sampled - Profile) water content readings given in Table 2.

±95 per cent confidence limits of the mean = the confidence level to which the mean value can be read.

$$= \frac{\sigma \times t}{\sqrt{\text{No Samples}}}$$

where

σ = σ value of the data about the mean
t = Student's 't' value for the appropriate number of data
No. Samples = Number of samples used to derive the mean.

±95 per cent scatter of (Sampled - Calculated) (Sampled - Profile) values = the ±scatter from the mean within which 95 per cent of the data lie

$= \sigma \times t.$

T A B L E 7

COMPARISON OF SAMPLERS WITH WATER CONTENT TRANSIENTS

Test	No. samples	Background water	Calculated water	External-loop sampler		In-the-line sampler		Profiler spot sampler		Wall tapping spot sampler	
		B	C	Mean	% Trans.	Mean	% Trans.	Mean	% Trans.	Mean	% Trans.
B	15	0.430	1.339	1.409	108	1.298	95	1.335	100		
D	18	0.430	0.904	0.914	102	0.892	97	0.877	94		
F	6	0.430	0.719	0.720	100	0.760	114	0.678	86		
G	23	0.611	0.927	0.927	100	0.893	89	0.918	97		
I	12	0.150	0.731	0.734	101	0.762	105	0.572	73		
K	22	0.150	0.597	0.599	100	0.592	99	0.565	93		
M	13	0.235	0.812	0.800	98	0.854	107	0.632	69		
O	13	0.235	0.625	0.647	106	0.712	122	0.518	73		
Q	11	0.235	0.470	0.482	105	0.564	140	0.398	69		
R	22	0.820*	1.025	0.985	80	0.977	76	0.995	85	1.175	173
S	46	0.665*	0.924	0.909	94	0.914	96	0.867	78		

Background, Calculated and Mean Sampler water contents expressed at per cent v/v water.
No. samples = Number of samples taken during the test.
Background water = Average background water-in-oil flow.
* = Background water changed during test.
Calculated water = Background water plus Injected water.
Mean = Mean water content of samples collected.
% Trans. = Amount of injected transient water recovered by sampler expressed as a percentage of injected water only in transient, ie background water not included in calculations.

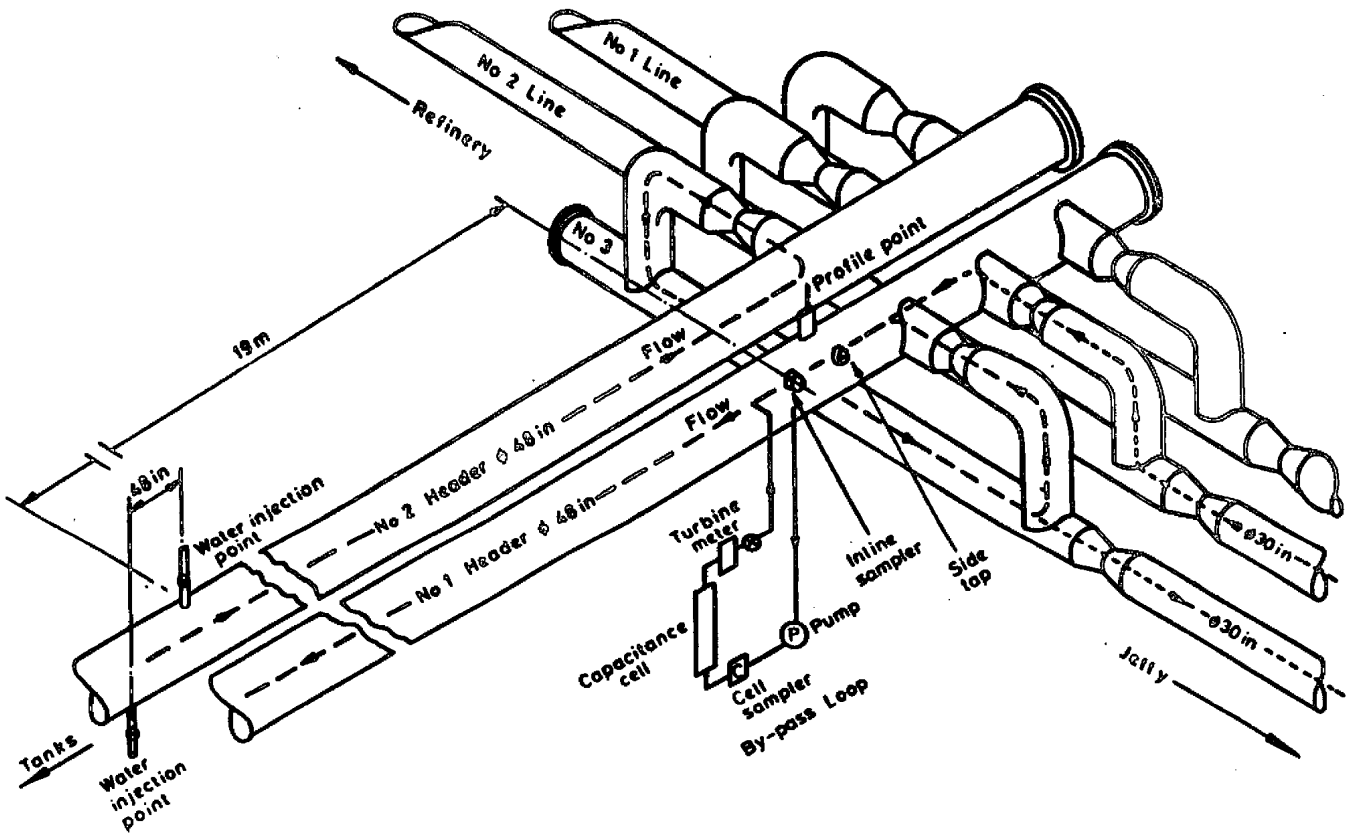

Fig 1 Schematic of Rotterdam Sampling Facility

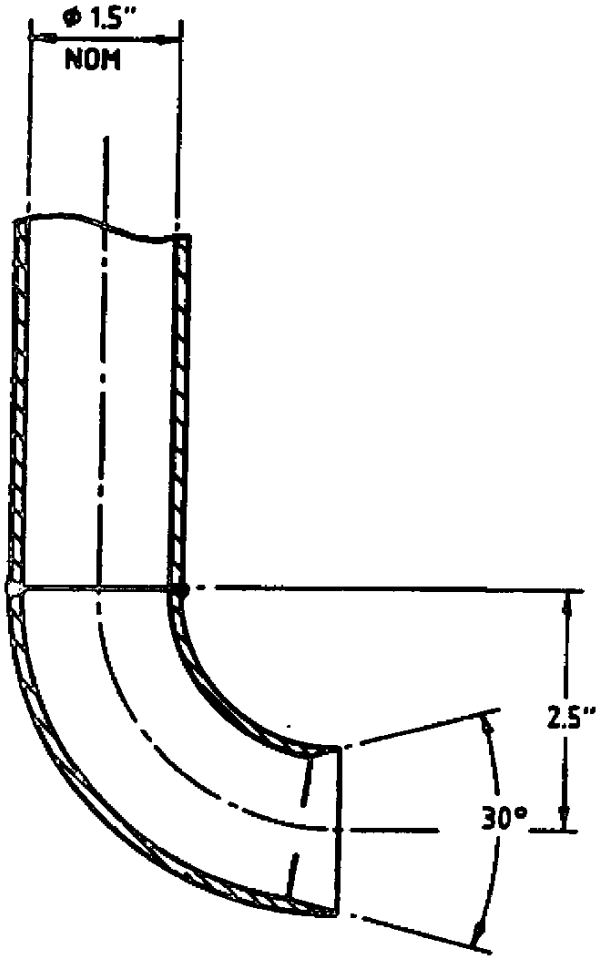

Fig 2 External-Loop Scoop Probe