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FLOATING PRODUCTION AND STORAGE SYSTEMS -MEASUREMENT IN THE NEW ERA

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FLOATING PRODUCTION AND STORAGE SYSTEMS - MEASUREMENT IN THE NEW ERA

by

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SUMMARY

The paper considers the implications for oil measurement posed by the introduction of floating production and storage systems which are becoming increasingly common in the offshore environment.

The requirements of the measurement systems installed on floating storage vessels are described and uncertainty analyses are carried out for various tank gauge based systems. It is shown that provided specific operating procedures are adopted the uncertainties achieved by tank gauging systems can match those of meter systems.

A number of potential improvements are proposed and various practical considerations to ensure optimum measurement performance are highlighted.

1 INTRODUCTION

At the beginning of 1995 there were at least thirty projects, either existing or planned involving the use of floating production or storage systems in the UK sector of the North Sea. These projects differ in detail but broadly they can be categorised into four different types as follows:

a) SWOPS (single well operation/production) type vessel (fig 1)

The vessel is totally self-contained. It connects to a subsea wellhead, performs production, separation and storage functions, disconnects and transports the cargo to the discharge location using its own propulsion system.

b) FPSO (floating production/storage) (fig 2)

Similar to SWOPS but the vessel is permanently connected to the subsea wellhead. The propulsion system is normally limited to positional needs only. The cargo is discharged to a shuttle tanker.

c) FSU (floating storage) (fig 3)

The vessel provides storage facilities only. It may require a propulsion ability for positioning. The cargo is again discharged to a shuttle tanker.

d) Barge or Subsea Tank (fig 4)

The barge is moored to a buoy and provides a storage capability only. Again a shuttle tanker is employed. No subsea tanks are in use in the UK sector at present.

In each of these cases there will be a requirement to measure the crude oil to satisfy fiscal, allocation or custody transfer purposes.

Fiscal measurement requirements can in some cases be satisfied by installing a metering system and sampling equipment on the production platform, but where no suitable fixed installation exists, this option is obviously not available. In this case the solution must almost inevitably be provided on the floating storage unit.

In many installations of this kind the key point of reference for custody transfer is at discharge from the storage vessel.The measurement requirements for custody transfer are somewhat more flexible than those for fiscal purposes in that commercially acceptable compromises can be introduced. For example where the transfer of crude oil to a tanker involves a change of ownership the two parties concerned may agree to base the commercial transaction on the outturn figures of the tanker at discharge. Whilst this compromise may save the seller a significant investment in sophisticated measuring systems on board the storage vessel it obviously means that he is totally dependent on discharge measurements over which he has no control and which he has no means of validating. There is therefore a significant incentive to install suitable measurement equipment and to develop compatible operating procedures on the storage vessel to satisfy custody transfer needs.

We therefore have a situation where high quality measurement on board the storage vessel may be an essential requirement for fiscal purposes and a very desirable option for custody transfer purposes.

2 MEASUREMENT OPTIONS

In the ideal world crude oil discharges from the storage vessel would be measured by a metering system designed for the purpose. Unfortunately the costs of such equipment are very high and may not be considered justifiable unless fiscal requirements dictate. Furthermore in some situations, operational problems can arise where high viscosity crude oils need to be maintained at a high temperature to suit the operating characteristics of the meters. There is therefore a significant incentive to avoid the use of metering systems and to base the measurements on tank gauges and other shipboard instrumentation. However such an approach will only be feasible for custody transfer purposes if acceptable measurement uncertainties can be achieved, and for fiscal purposes if uncertainties comparable with those achieved by metering are attainable. In practice it has always been argued that measurement by tank instrumentation cannot consistently achieve the levels of uncertainty produced by metering systems, and as a consequence, meters are still required for fiscal measurement. The remainder of this paper examines the use of tank instrumentation as an alternative to metering on storage vessels, comparing the measurement uncertainties and the relevant operational issues involved.

3 COMPARISON OF MEASUREMENT UNCERTAINTIES

3.1 Metering Systems

Uncertainty analyses of metering systems designed to fiscal standards generally produce an overall figure in the range +/-0.2 to 0.25%. Although this is a theoretical figure, experience indicates that similar results are achieved in practice provided the system is operated and maintained in accordance with established procedures.

Whilst there are obviously constraints imposed on the operation and maintenance of such systems when used on offshore installations and storage vessels, and whilst such constraints could increase the measurement uncertainties, the range of figures given above provide a realistic basis for comparison with figures derived for tank gauge systems.

In this comparison the quantities involved are gross measurements of oil expressed in standard volume. In other words the assessment of water quantity is not included since it is assumed that the same figure derived from a properly installed pipeline sampling system on the storage vessel can be used in both cases.

3.2 Measurement by Tank Gauge Systems

3.2.1 Factors affecting uncertainty

The standard volume of oil contained within a storage tank is calculated as:

$V = h.A.vcf$

where

V = standard volume of oil

h = level of oil within the tank

A = cross-sectional area of tank

vcf = volume correction factor to correct measured volume to standard volume

The main factors affecting each of these variables need to be considered in order to arrive at an overall uncertainty on the standard volume figure. As far as the oil level is concerned the main factors are:

a) the characteristics of the gauge by which level is determined.

b) the motion of the fluid within the tank.

The fluid will move from pitching and rolling of the storage vessel. Such movements will result in the need for trim and list corrections which are included in the tank calibration tables. The motion of the vessel may also produce surface waves or ripples.

The cross-sectional area is reflected in the tank calibration figures. It is not a single figure but is a composite of all areas from the lowest liquid level of the tank to the surface of the oil. It includes corrections for deadwood within the tank. The factor which dominates the uncertainty of the cross-sectional area is the method by which the calibration has been determined. The calibration may be determined from drawings, or individual tanks may be physically calibrated. The resultant uncertainties are very different. Temperature, and its calculated influence on the tank dimensions between calibration and use will play a minor role in the uncertainty.

The volume correction factor will have an uncertainty which is characteristic of the oil being stored. The use of the standard tables produces this oil specific uncertainty. Temperature plays the dominant part in the determination of volume correction factor and, therefore, dominates the uncertainty. Oil density plays a relatively minor role.

In many operations the determination of the quantity of oil transferred from a tank requires two sets of measurements, one prior to and one on completion of the transfer. When the tank is empty on completion of the transfer a different uncertainty will result from that which arises when the tank is part full on completion.

During the transfer a small quantity of oil may be retained as clingage on the tank walls. This will produce a small systematic overstatement of all transfer quantities.

All of these factors are considered in more detail below.

3.2.2 Tank Contents Level

Many storage vessel systems employ radar gauges; these are ullaging devices with a claimed uncertainty of +/-1mm. Although this figure may be achievable under ideal conditions, it is considered that a figure of +/-3mm is more realistic in practice. This will be used for the base uncertainty calculations when the liquid surface is stationary.

Liquid surface movements can arise as ripples or waves. These might occur due to wave action of the sea during a transfer operation. Such movements will increase the uncertainty in the level measurement.

A second type of liquid movement will arise from the fact that the tanks do not retain the same orientation to the horizontal during a transfer. Such changes occur slowly and result in the need for trim and list corrections, which are a normal part of transfer operations. Corrections for trim and list variations are included within all marine tank calibration tables. They may need to be determined when wave conditions are quite severe which leads to uncertainty in the readings and an increase in the overall measurement uncertainty whenever conditions are adverse. Although the effect of trim and list is to vary the liquid level it is simpler to consider this under calibration considerations, rather than here under level factors.

Surface movements in the form of waves or ripples, arising from tank movement, must be considered as contributing to liquid level uncertainty. The radar gauge electronics may be dampened to provide either an instantaneous reading at low damping, or an effective average of several readings at high damping. The manufacturers claim that the latter will allow for the level to be measured with waves or ripples with minimal increase in uncertainty. Such a claim could be optimistic and a figure of +/-10mm is considered to be realistic under adverse weather conditions when surface waves are present on the oil. It will be seen below that even this conservative estimate does not have a huge influence on the overall transfer uncertainty.

If we assume nominal tank dimensions of 17.5 x 32 x 25m high, the volume of an individual tank is 14000 cubic metres. An uncertainty of 3mm in level is equivalent to an uncertainty of 1.7 cubic metres or 0.01% of total tank volume. This is relatively insignificant in percentage terms when the tank is full. Even when the more conservative figure of 10mm is taken, for the situation in rough weather conditions, the uncertainty on a full tank is only 0.04%. As the level drops these uncertainties become more significant percentages of the volume. The procedures adopted during transfers will influence the overall significance of level measurement and will be considered later.

3.2.3 Tank Calibration

Most marine tankers are not calibrated physically and tank volume tables are determined from the manufacturer's dimensions. These pseudo calibrations are compared with metered oil quantities on most occasions that the tanker is loaded at a crude oil terminal. The average of 10 load ratios allows an average ratio known as the vessel experience factor to be established. This factor is effectively a calibration ratio for the complete tanker. Part cargoes are specifically excluded from the experience factor determination.

Experience indicates that the pseudo calibrations referred to above overestimate cargo quantities by about 0.2%(see ref 1). However the variability which arises with uncalibrated vessels is a key factor in this paper. A database has been maintained over a period of eight years tracing voyage measurements from bill of lading to outturn. The paper referenced above was based upon this data . The database covers some 4000 voyages per year. Load data allows average load ratios to be determined for all vessels which have 10 or more voyages in a given year. Fig 5 shows the distribution of such average ratios from a large sample of voyages in 1993.

This histogram shows that at the 95% confidence level the ratio varies from below 0.996 to about 1.006, representing a range of +/-0.5%. If dimensional checks were conducted during the construction of a storage vessel it is possible that some improvement in the uncertainty could be achieved, but a figure of +/-0.3% for the uncertainty of volume tables for uncalibrated complete vessels is considered to be a minimum value. This value has been assumed in all analysis from this point.

If we assume that the storage vessel contains 10 tanks, each individual tank will have an uncertainty of +/-0.3%$*\sqrt{10}$. The individual tank uncertainty will be above that of the whole vessel (on a percentage basis) owing to randomisation effects. This figure of +/-1.0% is a realistic assessment of the likely individual tank uncertainties which will apply all the way up the tank for each volume/level figure.

Claims for the volume uncertainty of an individual calibrated tank range between +/-0.1 and 0.3%. In the past calibration was undertaken using tapes, a process which is now regarded as expensive, dangerous and less accurate than the optical techniques now available. Whilst these latest methods may be able to achieve uncertainties at the lower end of the range, a figure of +/-0.3% will nevertheless be used for this analysis.

Marine tankers are not calibrated because the use of vessel experience factors can limit the significance of any bias in the ship's tables. However where a storage vessel is used as the basis of measurement, experience factors will not be available and a physical calibration is to be recommended.

Tank volume tables are calculated at a specific temperature and a small correction is needed to account for changes in wall temperature from the calibration temperature. The correction itself is small and any uncertainty arising from temperature measurement or the correction calculation is below 0.1%.

3.2.4 Trim and List Corrections

Tank volume tables, whether derived from drawings or from calibration, always include corrections for trim and list. In a storage vessel the orientation of the vessel to the horizontal will change as the tanks are emptied during a transfer. Trim and list corrections will be an essential part of the calculation process. Unfortunately the determination of trim and list on the open sea is not easy. These figures must be taken prior to the start of the transfer and, if the tanks are not completely emptied, after the transfer has finished. The calculation of uncertainty requires a knowledge of the gauge positions within the tanks as well as information on the methods of trim and list measurement. In the circumstances the best compromise is to consider how an error in, for example, the trim reading affects the liquid level which is measured. A pessimistic assumption of a 20mm error produces a figure of 0.1% of actual volume. This is considered to be a realistic assessment of the additional uncertainty arising from trim and list readings on the open sea.

3.2.5 Volume Correction Factor

Temperature is by far the most important factor in determining the vcf uncertainty. Although the measurement device used plays a small part in this, the dominant factor by far is the existence of temperature gradients within the oil. The gradients may exist both vertically and horizontally and although temperature is normally measured at three levels within the tank, this does not overcome all the problems of vertical gradients and none of the problems of horizontal gradients.

It is generally considered that measuring temperature in one vertical line will give a temperature reading with an uncertainty of +/-1 degC. Such a variation is the equivalent of 0.1% in the vcf tables at a density around 820kg/m3. The uncertainty of each temperature measurement device is well below 1 degC and may be considered to be included in the overall figure of 0.1% on volume.

Density has a very small influence. A change below 0.01% on volume would occur for a 10 kg/m3 variation in density and may be ignored compared with the temperature effect.

The tables themselves, which are used for crude oil vcf determinations, have an inherent uncertainty. In the range 0 to 30 degC a figure of +/-0.05% is quoted in the API Manual of Petroleum Measurement Standards, Chapter 11.1.

3.3 Overall Uncertainty of Tank Measurements

Having considered the individual contributions to a single set of measurements leading to a standard volume uncertainty, it is necessary to put all these together to give an overall figure. First the individual figures must be characterised as random or systematic.

The figures derived above may be summarised as follows:

		% uncertainty full tank	nature
Level measurement	calm	0.01	random
Level measurement	rough	0.04	random
Tank tables	ship drawings	1.0	systematic
Tank tables	calibration	0.3	systematic
Trim/list reading		0.1	random
vcf temperature		0.1	random
vcf tables		0.05	systematic

Other factors are insignificant compared with these in the determination of a single tank standard volume figure.

The overall systematic uncertainty from these figures is:

for an uncalibrated tank	1.05%
for a calibrated tank	0.35%

The overall random uncertainty derived from quadrature addition is:

calm conditions	0.10%
rough conditions	0.15%

It is assumed that under calm conditions no uncertainty in trim and list will arise.

The figures relate to the percentage uncertainty in standard volume determination on a full single tank. **It is clear that overwhelmingly the most significant factor lies in tank calibration.**

With small fractions of tank filled with oil, the level measurement becomes much more significant. In this case the uncertainty of the level measurement is inversely proportional to the percentage of the tank that is filled. When a tank is 10% full of oil the level uncertainties are:

calm conditions	0.1%
rough conditions	0.4%

These lead to overall random uncertainties for a single volume measurement with around 10% of the tank full as:

calm conditions	0.14%
rough conditions	0.42%

The figures derived above may be used to determine the uncertainty of a transfer from the storage vessel, as described in the next section.

The key message from this section is, however, that the storage vessel should be calibrated if systematic biases are to be avoided. Experience shows that it is unlikely to be possible to determine the equivalent of a vessel experience factor for a storage vessel against the vessels which are loaded since the range of tanker load ratios is too wide.

3.4 Transfer Uncertainties

The figures for measurement uncertainties in a single tank may be used as the basis for determining the overall uncertainty of a transfer from a storage vessel. In fact transfer uncertainties have been calculated for a number of different conditions as follows:

Best case - transfer of a large quantity of oil by completely emptying several tanks under calm conditions. Assume a cargo of 112000 cubic metres is transferred by completely emptying 8 tanks of the storage vessel. The overall uncertainties of the transfer would be:

Systematic

Uncalibrated tanks	$1.0/\sqrt{8} + 0.05\% = 0.4\%$
Calibrated tanks	$0.3/\sqrt{8} + 0.05\% = 0.16\%$

Random (calm sea)	$0.1/\sqrt{8}\% = 0.04\%$

Overall

Uncalibrated tanks	0.44%
Calibrated tanks	0.20%

The randomisation of the tank calibrations between tanks arises because, although the bias is systematic within each tank, these biases are random between tanks. No such randomisation occurs with the vcf table bias, since the oil is identical in all tanks.

Worst case - transfer of part of a single tank under rough sea conditions. For the transfer of 90% of a single tank the uncertainties would be:

Systematic

Uncalibrated tanks	1.05%
Calibrated tanks	0.35%

Random (rough sea)	0.17%

Overall	
Uncalibrated tanks	1.22%
Calibrated tanks	0.52%

Intermediate case - consider a transfer of 56000 cubic metres derived by completely emptying 3 tanks and 50% emptying 2 further tanks under rough conditions.

Overall Uncertainties	
Uncalibrated tanks	0.57%
Calibrated tanks	0.25%

Other cases may be determined by following similar procedures.

A number of important conclusions can be drawn from these figures:

a) calibration of the tanks is the biggest influence in minimising systematic errors.
b) tanks should be fully emptied wherever possible.
c) the largest possible transfers drawn from as many tanks as possible will minimise uncertainty.
d) the influence of sea state is not as important as the above factors.

In fact it may be concluded from this analysis that provided large volumes are transferred from a number of calibrated tanks which are completely emptied, then overall uncertainties close to those achieved by metering can be achieved even in rough sea conditions.

4 OPERATING EXPERIENCE

Detailed information comparing the measurement of transfers from storage vessels by metering and tank gauge systems is not readily available. However a limited analysis has been carried out on data derived from twenty consecutive transfers from one installation. The results are shown as differences between metered and tank gauge figures expressed as a percentage of the metered figures. These results are presented as a frequency distribution in fig 6. This distribution is seen to have a Gaussian form (indicating that random effects dominate), producing a standard deviation of 0.13%. However it is also apparent that there is a systematic difference between the two sets of measurements, averaging -0.18%.

The systematic difference is consistent with the data shown in fig 5 which indicates that uncalibrated vessels tend to produce an overestimation of cargo quantities averaging about 0.2%. In this case the vessel was not calibrated so the difference should not be seen as surprising.

The standard deviation of 0.13% represents the combined random variations of the metering and tank gauging figures. Without a detailed analysis it is not possible to assign specific levels of uncertainty to either method but the results are not inconsistent with the figures or conclusions derived in the preceding sections.

5 POTENTIAL DEVELOPMENTS AND IMPROVEMENTS

The analyses presented above show the major contributors to the uncertainty of measurement by storage vessel tank gauge systems. Whilst calibration of the tanks offers the greatest improvement, there are nevertheless a number of areas where smaller but worthwhile improvements could be achieved. Two of these are considered below.

> **Temperature measurement** - the uncertainty of vcf determination is mainly influenced by the uncertainties of temperature measurement in the vessel's tanks. Improvements in this area can be achieved by increasing the number and changing the distribution of temperature probes in the tanks. Potentially this could improve the random uncertainty on a single tank volume by 0.04% and on a typical transfer quantity by 0.02%.
>
> **Level measurement** - errors in level measurement contribute less to the overall uncertainty than temperature errors. Even so the additional uncertainty arising in rough sea conditions could be reduced through improvements in this area. For example the use of a second tank gauge in each tank (although expensive) would provide independent verification of measured volumes. Furthermore if the gauges were correctly located, much more confidence could be placed in the trim and list figures through the extra information available. If this approach was not considered feasible then improvements in trim and list measurement in rough sea conditions should be considered.

6 PRACTICAL CONSIDERATIONS

To perform successfully, any measurement system must be correctly designed, installed and maintained. The tank gauging systems discussed in this paper are no exception to this; indeed it is apparent that the complete vessel must be regarded as a measurement device and the various components designed accordingly. A number of practical considerations based on experience and good measurement practice are highlighted below.

> a) It is important that it should be possible to isolate tanks completely and securely from one another. Where appropriate therefore, bottom lines should be fitted from the outset with double block and bleed valves so that isolation can be monitored.
>
> b) Where problems of clingage of oil on the tank walls occur, a systematic overstatement of the transfer quantities will result. This problem is overcome in marine tankers by the use of crude oil washing. The need for the appropriate equipment on the storage vessel could be determined at the design stage from a knowledge of the characteristics of the oil.
>
> c) It is normal practice to de-bottom the tanks to remove free water before the start of any transfer. This water is generally collected in a separate tank and the residual oil allowed to separate before the clean water is discharged. This water

plays no part in the transfer from storage vessel to tanker and is therefore not measured as part of the custody transfer. However, the suspended water which is transferred with the cargo must be accounted for . This is normally achieved by analysing samples drawn by an automatic sampler mounted in the storage vessel transfer line. As far as the comparisons in this paper are concerned, this method of water determination is equally applicable to metering and tank gauge systems, so the uncertainties involved are the same for both methods.

d) The operational requirements for metering and tank gauge systems are to some extent contradictory. To prevent air being drawn through a metering system (a process which will produce measurement errors) it is normal practice to leave 1-2 metres of oil in each storage tank. The remaining oil may then be collected in a single tank from which the transfer is completed. By contrast the optimum procedure for tank gauging is to empty the storage tanks completely so that measurements in partially empty tanks are avoided. As noted above such additional measurements increase the uncertainty of the volume determination; indeed experience confirms that radar gauges can give unreliable results at low liquid levels in storage vessels. However where tanks are emptied completely, procedures must be introduced to ensure that the ship's bottom lines are in the same state before and after a transfer.

One consequence of these arguments is that where metering and tank gauge figures for the same transfers are compared, the procedures which must be adopted for the metering system are likely to increase the uncertainty of the tank gauge measurements.

e) Procedures for monitoring metering systems are well established. Control charts are employed on many offshore installations and sophisticated statistical techniques are also available. The marine tanker industry has developed basic monitoring procedures for loadings and discharges, but as noted above such basic procedures are unlikely to be applicable to storage vessel transfers. Nevertheless monitoring is essential to give the earliest possible warning of problems and more advanced methods should accordingly be considered.

7 CONCLUSIONS

An uncertainty analysis indicates that storage vessel tank gauge systems are capable of achieving uncertainties similar to those of metering systems. The limited practical data available tends to support this.

A number of improvements in both the design and operating procedures of tank gauge based systems are proposed. These together with the practical points which are highlighted will ensure that such systems are able to achieve optimum performance.

References

1 Institute of Petroleum, Committee PLM4. "Shipping Survey Shows Continuing Loss Reduction". Petroleum review, December 1990, pages 627-631.

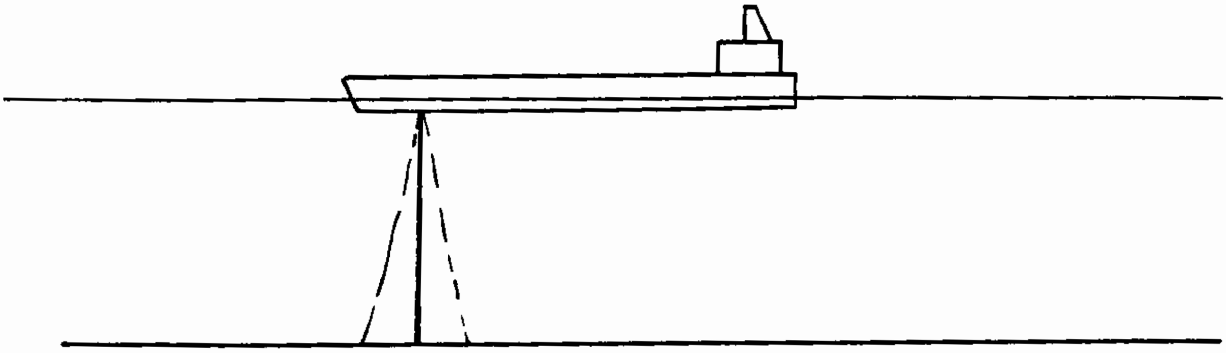

Fig 1 SWOPS Vessel

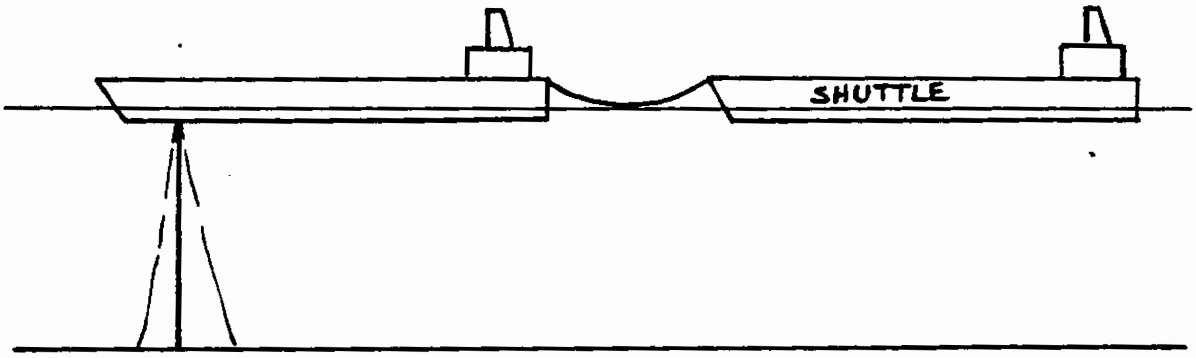

Fig 2 Floating Production and Storage

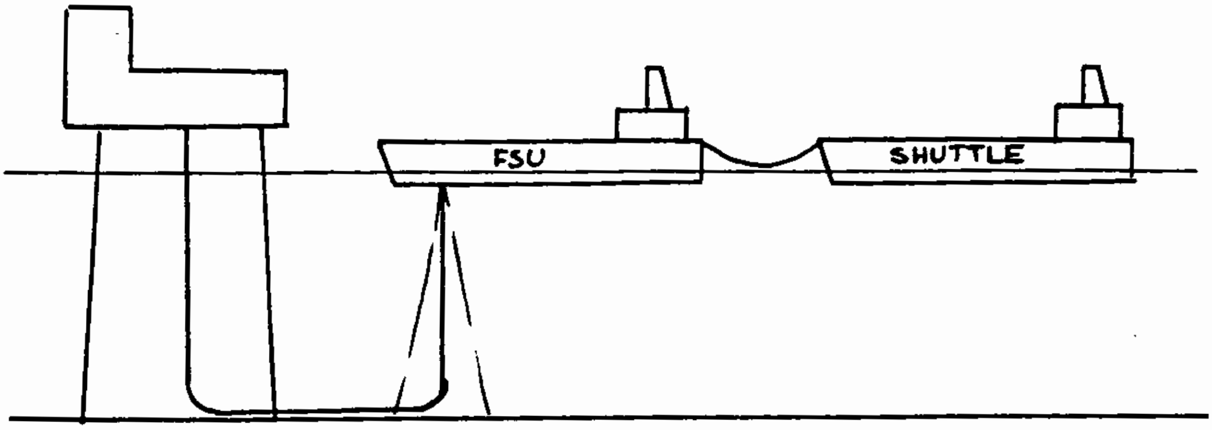

Fig 3 Floating Storage

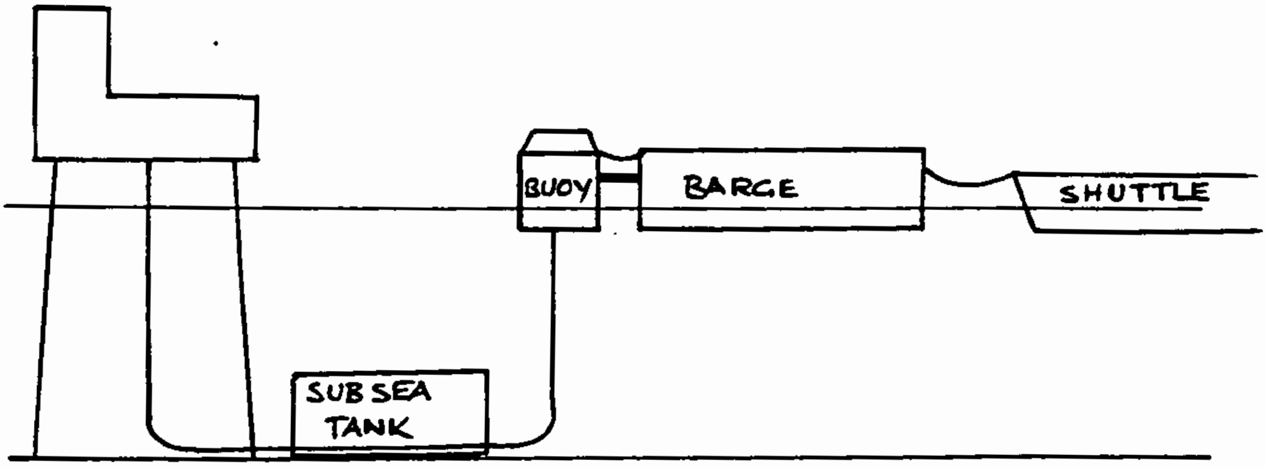

Fig 4 Barge / Subsea Tank

Fig 5 Vessel VEF Values

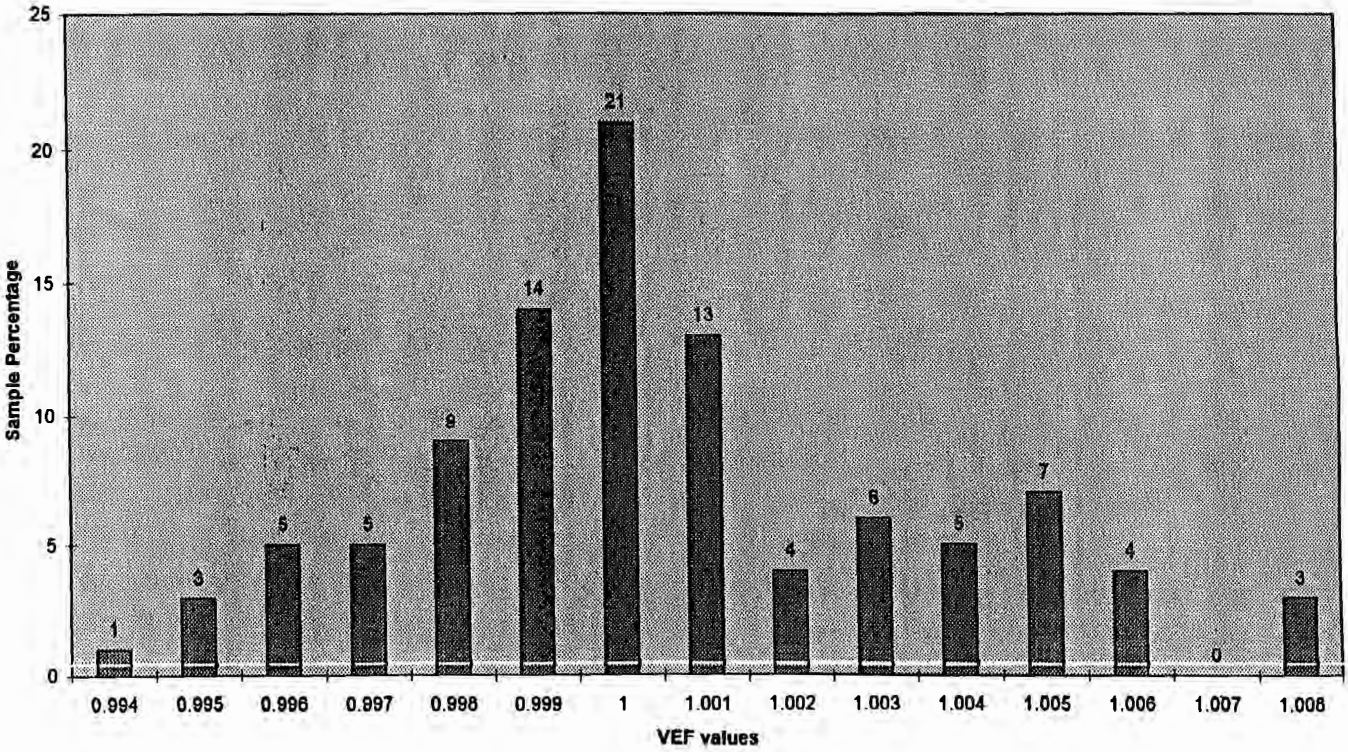

Fig 6 Meter/Tank Gauge Differences