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DEVELOPMENT AND TRIAL OF MULTIPHASE FLOW METERS FOR OIL, WATER AND GAS IN PIPELINES

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ABSTRACT

The CSIRO has developed two meters for the measurement of the flow of multiphase fluids in oil well pipelines. The gamma-ray multiphase flow meter (MFM) is based on single and dual energy gamma-ray transmission, and the microwave/gamma-ray MFM is based on microwave and gamma-ray transmission. Both have been trialed at the oil field facilities on Thevenard Island where they were installed on an 140 mm bore pipeline carrying the full flow from each of seven wells and approximately eleven commingled well streams. Measurements were made over a wide range of water cuts (25-96 %) and flow rates of liquids (6600-33000 BPD).

For the gamma-ray MFM mounted on the vertical upflow (downflow) pipeline, the flow rates were determined to 4.0 (3.3) % relative for liquids, 7.5 (6.1) % for oil, 4.5 (4.5) % for water and 7.9 (7.7) % for gas. Water cut was determined to 3.6 (3.7) % relative. For the microwave/ gamma-ray MFM mounted on the vertical upflow (downflow) pipeline, water cut was determined to 3.3 (5.4)% and oil and water flow rates to 5.5 (6.6) % and 5.9 (5.6) %.

1. INTRODUCTION

The CSIRO Division of Mineral and Process Engineering is involved in the development, trials and commercialisation of gamma-ray and microwave techniques for the measurement of the flow of multiphase fluids in oil well pipelines. The main criteria for these developments has been that the multiphase meter be compact and mounted directly on the production pipeline; the meter be non-intrusive and hence not obstructing flow; the measurement not require an homogenised flow; the technique be applicable to the majority of flow regimes; and the meter determines the flow rate of each component to within 5-10% relative.

Use of such a meter should lead to

a) the replacement of the need for test separators, initially in non-critical applications and later, after the MFM technology has been proved to be dependable, on most new offshore platforms,

b) the reduction in the cost of subsea piping because the outputs of two or more wells can be commingled and flow through a single flowline from satellite platform to central facility,

c) the reduction in capital costs of new platforms because the heavy and bulky test separator can be replaced by the light and compact MFM,

d) better reservoir management, production allocation, and optimisation of total oil production over the field lifetime.

Various organisations are developing multiphase flow meters for oil, water and gas in pipelines [1-8]. Most of these techniques have been tested on laboratory loops; some have had limited testing on production pipelines, none covering all the flow conditions occurring in pipelines from oil wells.

This paper describes results of trials of two multiphase flow meters, one based on gamma-ray transmission, and the other on microwave and gamma-ray transmission. The trials were undertaken from September to December 1993 at WAPET's oil production facilities on Thevenard Island. The current status of development of the MFMs is discussed.

2. GAMMA-RAY AND MICROWAVE/GAMMA-RAY MFMs

There are two main components in the determination of the flow rates of oil, water and gas [4,5]: determination of water cut (WC) and determination of flow rates of liquids and gas. In the gamma-ray MFM, water cut is determined by dual energy gamma-ray transmission (DUET). In the microwave/gamma-ray MFM, water cut is determined either by microwave phase shift and gamma-ray transmission or by microwave phase shift and attenuation. The flow rates of liquids and gas are determined from measurements of mass per unit area of liquids across a diameter of the pipeline by single energy gamma-ray transmission, cross-correlation of the outputs of two gamma-ray transmission gauges to determine flow velocity, and measurements of the operating pressure and temperature in the pipeline. These measurements are combined with models of flow regime to determine liquids and gas flow, and oil and water flow are respectively determined by multiplying liquids flow by (1-WC) and by WC.

The gamma-ray multiphase flow meter consists of two non-intrusive gamma-ray transmission gauges mounted about a pipeline (Figure 1). One of these gauges depends on measurement of the transmitted intensity of 662 keV gamma-rays (^{137}Cs) through the pipeline. The other depends on measurement of the transmitted intensities of 59.5 and 662 keV gamma-rays respectively from ^{241}Am and ^{137}Cs. The scintillation detectors are housed in flameproof enclosures, and electrical pulses from the detectors were routed via armoured cable to processing electronics and computer located in the plant room. The transmitted intensities of gamma-rays were determined every five milliseconds. This data was then grouped into approximately 17 second blocks for processing. The flows of liquids, gas, oil and water, and the water cut, were continuously displayed graphically on the MFM computer.

The microwave and gamma-ray technique has been described previously [8]. A schematic of the prototype microwave/gamma-ray MFM used in the Thevenard Island trial is shown in Figure 2. The MFM comprised the two gamma-ray transmission gauges with a single microwave transmission gauge mounted between them.

The microwave transmitter and receiver sensors of the microwave gauge were mounted in a pipeline crosspiece so that they were diametrically opposite and flush with the internal bore of the pipeline. These non-intrusive sensors were designed to comply with oil industry standards for integrity and safe operation. All the microwave circuitry associated with the MFM was housed in a flameproof enclosure mounted on the pipeline adjacent to the microwave gauge. The transmission of microwave signals between the sensors and this enclosure was via microwave cable enclosed in flameproof conduit. In routine operation, the phase shift and attenuation of an

~2.3 GHz microwave signal, transmitted across the diameter of the pipeline, was determined at approximately 30 ms intervals. This data was then grouped into ~14 s blocks for processing. The gauge electronics was housed in a flameproof enclosure located adjacent to the pipeline. The operation of both microwave gauge, and all data logging, was controlled by a plant room computer that was linked to the field enclosures via a armoured communications cable.

3. THEVENARD ISLAND TRIAL

West Australian Petroleum Pty. Ltd. (WAPET) produces oil from the Saladin, Yammaderry and Cowle oil fields near Thevenard Island, North West Shelf, Western Australia (Figure 3). At the time of the trial, eight oil wells were in operation, three on the Island and five offshore. The offshore wells produce from small platforms, and single or commingled flows are carried via pipelines on the sea bed to Thevenard Island. The processing facilities for all wells are on the Island.

3.1 MFMs and test pipeline

Two gamma-ray MFMs were used in each of the three phases of the trial. These were mounted on a 'test pipeline' joining the test manifold to the test separator (Figure 4), the density gauges being on steel spool pieces and the DUET gauges on glass reinforced epoxy (GRE) spool pieces. Individual streams from each well, and commingled streams from two or three wells, were routed through the test pipeline.

One of the gamma-ray MFMs was installed on the vertical (upflow) pipeline for the whole trial (position C, Figure 4). The other was moved to a different position on the test pipeline after completion of each phase of the trial. In Phase 1, the second gamma-ray MFM was mounted on the horizontal pipeline with a long straight length of pipe (12.4 metres) upstream of it (position B). In Phase 2, it was mounted on the vertical downflow pipeline (position D). In Phase 3, it was mounted on the horizontal pipeline about 1.4 metres downstream of a 90^0 bend (position A). The two gauges were spaced about 1100 mm apart on spool pieces of 139.8 mm bore.

The microwave gauge was installed in a cross piece of the spool piece on which the gamma-ray density gauge was mounted, between the two gamma-ray gauges of one of the gamma-ray MFMs. It was mounted on the horizontal (Position B) pipeline for Phase 1 of the trial, on the vertical downflow pipeline for Phase 2, and on the vertical upflow pipeline for Phase 3.

3.2 Test conditions during trial

The test separator on Thevenard Island is a horizontal type with an internal diameter of 2.7 metres and length 9.5 metres, and operates at a pressure of about 10 atmospheres. The single phase outputs from the separator are monitored by conventional turbine meters for oil and water, and orifice plates for gas.

The range and mean of test conditions during the periods in which the MFM measurements were made during Phase 2 of the trial are detailed in Table 1. These are typical of the whole trial. The ranges of flow rates for liquids, oil, water and gas were large.

During the trial, WAPET became aware that the test separator was overestimating the flow rates of oil. The separator was opened up late in December 1993, and holes found in its oil bucket from failure of repair work done in June 1993. Water was leaking through these holes into the oil bucket. Production accounting routines indicate that the leak rate increased with time. Using an 'oil decline' method, WAPET estimated the leakage rates during the trial based on production data obtained prior to June 1993 and after fixing the separator in 1994. CSIRO used in its calculations a simplification of this method, assuming that, over the short period of each Phase of the trial, the leak rate was constant and equal to the mean of the WAPET oil decline predictions for the various wells. The average corrections corresponding to the times of Phases 1, 2 and 3 of the trial were to subtract respectively 543, 1036 and 1128 BPD from the oil flow rates measured by the separator, and to add the same BPD to the water flow rates.

In each of the three phases of the trial, measurements with the gamma-ray and microwave/ gamma-ray MFMs were made on all single well flows except for Saladin 7 during Phase 3. Some pairs of wells chosen for commingling were different between each phase depending on availability at the time of measurement. Measurements on Saladin 2 well flow during Phases 1 and 2 were discarded since during this period the water flow of this well was far too low to be measured accurately by the separator water meter. During Phase 1 of the trial, measurements were made on each single well stream at normal operating pressure in the pipeline, and at one or two higher pressures. The aim was to cover a greater range of operating conditions. In practice, the maximum change in flow rate achieved was relatively small. For Phases 2 and 3 of the trial, Saladin wells 4, 5 and 6 were each measured at two pressures, whilst the other single wells were measured only at the normal operating pressure.

The microwave/gamma-ray MFM data for Saladin 4 and Saladin 7 wells during Phase 1, and Saladin 2 well during Phase 3 were discarded due to insufficient data being available as a result of gauge malfunction during data logging. Data from one commingled stream (Cowle 2/Saladin 6) was also excluded from the Phase 3 data as inadequate mixing of the component wells resulted in unacceptable errors for the microwave/gamma-ray MFM.

3.3 Setting up the gamma-ray MFM

The procedures for off-line calibration of the gamma-ray MFM were refined between the first and second phases of the trial. This change would be expected to lead to more accurate results for determination of flows and water cut during Phases 2 and 3 compared with Phase 1. In particular, the determinations based on off-line calibration of the MFM would be very considerably improved and, to a lesser extent, determinations based on the on-line calibration.

Some of the count rates measured with the DUET gauges during Phase 1 of the trial were considerably higher than desirable for accurate measurement. This did not effect the liquids or gas flow measurements much, but directly affected the water cut determination and, via this, determinations of the oil and water flow rates. For Phases 2 and 3, the count rates were reduced by use of a smaller diameter collimator than that used in Phase 1.

4. PROCESSING OF RESULTS

The outputs of the MFM and separator output meters were processed by comparing the mean readings of each averaged over a period of 60 minutes. The determinations of liquids and gas flow rates for both gamma-ray and microwave/gamma-ray MFMs were based on the gamma-ray transmission measurements.

4.1 Gamma-ray MFM

There are four ways in which the results of the gamma-ray MFM were compared with those of the separator output meters:

a) The MFM was calibrated off-line based on measurements on static samples of oil, well water and gas, and models of the flow in the pipeline. The standard deviation between the flow rates predicted by the MFM and by the separator output meter was calculated.

b) Least squares regression was used to obtain the best fits, separately for water cut and for liquids flow rate, comparing the MFM predictions in a) above with the corresponding separator output meter results. The r.m.s. differences so determined by this 'one variable fitting' do not include linear offsets in calibration caused by either or both the MFM and the separator.

c) Water cut was determined as in b) above (i.e., one variable fitting), but liquids flow rate was determined by least squares regression using the predicted MFM flow and the additional (linear) parameter of pressure. This is called 1-2 variable fitting.

d) Both water cut and liquids flow rate were determined by least squares regression, each with two parameters, one being the MFM result from a). This is called 2-2 variable fitting.

When a second variable measured by the MFM is included (c and d above) in the least squares regression, not only is compensation made for linear offsets as in b) but also for any linear error in the MFM or separator which depends on the second variable. In general, the larger the number of MFM measured variables incorporated into the least squares regression, the more the chance that there will be a better correction for separator errors and hence a lower r.m.s. difference between the results of the MFM and the separator. However, this does not make the calibration of the MFM more accurate; in practice it incorporates into the MFM calibration the errors of the separator.

The results given in Sections 5-7 are expressed as the ratio of r.m.s. difference to the mean of the flow rates or of the water cuts of all multiphase mixtures measured. For simplicity, this ratio in the rest of this paper is called the relative error, even though the ratio includes not only errors of the MFM but also those of the separator and separator output meters. For the determinations of oil and water flow rates, the MFM flow rates were the product of the MFM determinations of liquids flow rate and the oil or water cut.

4.2 Microwave/gamma-ray MFM

The error in the microwave/gamma-ray MFM predicted water cut was determined by direct correlation of the MFM data with the separator data. Consequently, the r.m.s. errors determined include the errors of the separator output meters, however, they do not include offsets in the estimation of the water cut due to either or both the MFM and the separator.

The r.m.s. errors were calculated using conventional linear least squares fitting and using non-linear fitting based on optimisation of the correlation using neural net fitting techniques.

5. LIQUIDS AND GAS FLOW RATES

5.1 Mass per unit area and velocity

Figure 5 shows the results of the determinations of mass per unit area (g cm^{-2}) of fluids in the gamma-ray beam versus time, for three different flows. The higher mass per unit area regions are slugs which are interspersed with lower mass per unit area regions of film. The top two plots of mass per unit area versus time for the onshore wells are very different to the bottom two plots which show two 17 second records of the commingled flow from two offshore wells. The former have approximately regular slugging with several slugs in the 17 second periods; the latter shows part of a very long slug (second from bottom) and part of a very long film (bottom). The latter flow was piped for more than a kilometre along the sea bed prior to surfacing at Thevenard Island. Long slugs build up in the seabed pipeline, and these are interspersed by long periods of film. The pattern of slug and film, seen on plots over much longer periods than 17 seconds, is very irregular.

Velocity is determined by cross-correlation of the two gauge outputs of transmitted intensities of ^{137}Cs gamma-rays which gives the time displacement, and the distance between the two gauges on the pipeline. Velocities are determined each 17 seconds. The range of velocities for flows from different individual and commingled wells was 4.4 to 23 metres per second.

5.2 Liquids and gas flow rates

The flow rate of liquids versus time for three streams are shown in Figure 6. The upper plot is for a well on Thevenard Island; the middle plot for commingled flows of two wells also on Thevenard Island; and the bottom plot for the commingled flows of two wells from an offshore platform. The upper and middle plots show reasonably constant flow over a 60 minute period, each point corresponding to one 17 seconds interval. The bottom plot shows the very large changes in flow rates which are more typical of the flow from offshore wells, due to the terrain slugging in the long pipeline along the sea bed.

The plots of the one-two variable fitting results of liquids and gas flow rates in the vertical upflow pipeline for the Phase 2 trial are shown in Figure 7. The plot for the liquids shows a very good correlation, with a relative error of 3.7%. The plot for gas flow has fewer data points because of lack of suitable orifice plates for the higher flows of gas. The relative error is 7.1%. These relative errors include errors both MFM and separator errors.

The relative errors for all MFM measurements of liquids and gas flows, based 2 variable fitting, are detailed in Table 2. The results of liquids flow in the vertical upflow pipeline average 4.0% over the three Phases of the trial. The results for the vertical downflow pipe is 3.3% (Phase 2), and for the two positions on the horizontal pipe worse at 5.3 and 6.2%. The one variable fitted results (not shown) for the vertical upflow pipeline are only slightly worse than those for the 2 variable fitting. The off-line calibration (not shown) is significantly worse, due to a linear offset in either or both the separator and the MFM. The results for one variable fitting in the vertical downflow pipeline are somewhat worse than for the two variable fitting, but the off-line calibration is considerably worse. The one variable fitting results for the horizontal pipeline are much worse than for the two variable fitting, probably because of the lack of a good flow model for flows in the horizontal pipe.

The relative errors for the gas flows are given in Table 2. The ratios average 7.4%. There are relatively few experimental points, due to lack of suitable orifice plates to measure the higher gas flows from commingled streams.

6. WATER CUT

6.1 DUET gauge

Figure 8 shows a plot of water cut, determined in the vertical upflow pipeline by the gamma-ray MFM, and water cut determined by the separator (Phase 2). The relative error is 3.7% for the very wide range of water cuts of 25-96%.

The relative error for all MFM measurements of water cut, averaged over a period of one hour per measurement, are detailed in Table 2. For the vertical upflow stream, one variable fitting is used; for the horizontal and vertical down flow streams, two variable fitting. The results of water cut in the vertical upflow pipeline average 3.6% over the three Phases of the trial, with the relative error increasing with time probably due to the increase with time of the leak rate of water to the oil bucket in the separator. The relative error for the vertical downflow pipe is 3.7% (Phase 2), and for the two positions on the horizontal pipe at 6.6 and 2.7%. The high value of 6.6% is due to the very high count rates in the DUET gauge in Phase 1 of the trial. The count rates were reduced before the start of Phase 2 of the trial.

6.2 Microwave/gamma-ray gauges

An example of the trial data for a 14 s logging period on a commingled well flow (Saladin 6 + Saladin 7 + Yammaderry 2) is shown in Figure 9. The phase shift and attenuation data was determined by the microwave gauge and the liquids thickness was determined by the gamma-ray gauge (Figure 2). Due to the physical separation of the microwave and gamma-ray gauges on the pipeline there is a time lag of approximately 50-250 ms (depending on the flow velocity) between the data from these gauges. However, this delay is too small to be obvious in Figure 9. The data in Figure 9 indicates that there is a correlation between the phase shift, attenuation and gamma-ray data, with a very similar response to the thickness variation of the fluid flow due to the passage of slugs. This result also indicates that, as expected, there is little variation in the water cut over the 14 s period shown.

The data from the ~14 s blocks of data was averaged over the total logging period (~1 hour) for each well (or well mixture) to enable a comparison to be made with the separator data for the corresponding period.

The % relative errors (ratio of the r.m.s. difference to the mean) in the determination of the water cut by the microwave/gamma-ray MFM are shown in Table 3. In Table 3, separate errors are given for calculation of the water cut based on either linear or non-linear fitting of the microwave data. The non-linear fit, based on optimisation of the correlation using artificial neural net fitting techniques, is the more accurate, with errors typically less than half those obtained using a linear fit. The best results for the determination of the water cut were obtained when the MFM was installed on the vertical upflow position. A plot of the microwave and gamma-ray predicted water cut for Phase 3 (vertical upflow), using the non-linear fit in Table 3, is shown in Figure 10.

7. OIL AND WATER FLOW RATES

7.1 Gamma-ray MFM

The oil and water flow rates determined, in the vertical upflow pipeline, in Phase 2 of the trial, are shown in Figure 11 (1-2 variables fitting). The flow rates determined by the MFM closely correlate with those of the separator. The flow rates for oil are determined to about 7.3% (Table 2), and water to about 4.7%. These averages exclude the results for the horizontal pipeline in Phase 1, which were the worst affected by the too high count rates (Section 3.3). For the vertical upflow pipeline, the results (not shown) of the one parameter fits for oil and for water are slightly worse than for the 1-2 parameter fits, while the results for the off-line calibration are significantly worse because of a linear offset error due to the MFM or separator, or both.

7.2 Microwave/gamma-ray MFM

The calculation of liquids flow rate, from liquids thickness and flow velocity, was performed by the same method as used in the gamma-ray MFM. The calculated flow rates for oil, water and gas during Phases 1, 2 and 3 of the Thevenard Island trial are given in Tables 4-6. The liquids flow rate has been calculated from the liquids mass per unit area, determined by gamma-ray transmission, and the flow velocity determined by cross-correlation of the outputs of the two gamma-ray transmission gauges. The oil and water flow rates have been determined from the product of the liquids flow rate and the respective oil and water cuts (using the non-linear fitting results in Table 3).

The results in Tables 4-6 indicate that over all three phases of the trial the microwave/gamma-ray MFM determined the oil and water flow rates, of the Thevenard Island wells and well mixtures, with errors of 6.8 % and 6.8 % relative respectively. The best results were obtained when the MFM was installed on either the vertical upflow or downflow positions. However, acceptable measurement accuracy was obtained for horizontal, vertical upflow and vertical downflow installations.

8. SUMMARY AND COMMENTS: GAMMA-RAY MFM

8.1 Accuracy

The gamma-ray MFM has now been proved in two trials on oil production pipelines: on the Vicksburg offshore oil platform [4-6] and on Thevenard Island. The flow rates of liquids for the two trials were very different; and the total range over which the MFM has now been proved is 1,400 to 33,400 BPD. Water cuts have ranged in the two trials from 17 to 96%. For the Thevenard Island trial, the flow rates were determined in the vertical upflow (downflow) pipeline to 4.0 (3.3) % relative for liquids, 7.5 (6.1) % for oil, 4.5 (4.5) % for water and 7.9 (7.7) % for gas. Water cut was determined to 3.6 (3.7) % relative. These relative errors include errors not only due to the MFM but also due to the separator and its output meters.

The results for the vertical downflow, and horizontal flows, are roughly the same as for the vertical upflows, but depended on the use of 2-2 variable fitting.

8.2 Calibration

The mounting of the MFM on a vertical pipeline is preferred because the models for describing the flow regime in vertical pipelines are much simpler and better understood than those for horizontal pipes. The results of the present trial show that a simple one parameter calibration determines flow rates with sufficient accuracy for many practical applications. This is possible because the basic principles, including the mathematical equations, of gamma-ray transmission in liquids and gases are very well understood. There is a reasonable possibility that off-line calibration on static samples of oil, well water and gas will give sufficient accuracy. This has not been definitely established mainly because of the uncertainty of the absolute accuracy of the test separator.

8.3 Operating envelope

The operating envelope of a multiphase flow meter is the region in which the MFM determines the flow rates and water cut with acceptable accuracy for the application. Wolff [9] has defined one important parameter of the operating envelope of the MFM as the area on the two phase map of gas and liquid flow rates where the MFM measures flow rates with sufficient accuracy; the gas flow rate in this case is the gas volume flow rate at the pipeline operating pressure. The complete operating envelope of the gamma-ray MFM on this two phase map has not yet been established due to lack of sufficiently different flow conditions in the Vicksburg platform and Thevenard Island trials. However, the results of the trials on the Vicksburg platform (74 mm bore pipe) and on Thevenard Island (140 mm bore pipe) can be used to show at least some of the operating envelope covered by it (Figure 12).

Based on current experience with the gamma-ray MFM, gas volume fractions (GVFs) up to 0.9 should not limit the accuracy of the MFM determinations. We do not have any experience with GVFs above 0.9 and hence cannot make any predictions other than that there is a better chance of accurate measurement if the flow regime is not a misty annular flow. The limitation at very high GVFs is inaccuracies in determination of water cut by the DUET gauge; there is insufficient mass per unit area (g cm^{-2}) liquids in the gamma-ray beam. [The microwave/gamma-ray gauge can determine water cuts at much lower mass per unit areas of liquids; its main limitation being at high water mass per unit areas where the high absorption of microwaves prevents accurate measurement of transmitted microwave intensity.] The determination of liquids and gas flow rates is not a problem because the single energy gamma-ray transmission measures mass per unit area very sensitively; and since the determination of velocity by cross-correlation is also based on two single energy gamma-ray transmission measurements.

8.4 Pipe bores

The gamma-ray MFM can operate over a wide range of pipe bores, with limitation at small and very large pipe bores. With small pipe bores, less than approximately 75 mm but depending on the GVF, there is insufficient mass per unit area of liquids in the gamma-ray beam for the accurate determination of water cut. At very large pipe bores, larger than about 300 mm, insufficient ^{241}Am gamma-rays will penetrate the very large mass per unit areas of liquids in the pipe (assuming the pipe is full of liquids with no gas) and hence the intensity of gamma-rays cannot be accurately measured. The liquids and gas flow rates can be determined accurately over a much wider range of pipe bores than possible for water cut.

9. SUMMARY AND COMMENTS: MICROWAVE/GAMMA-RAY MFM

A prototype microwave/gamma-ray MFM has been developed and successfully trialed at the Thevenard Island oil production facility for in-pipe measurement of oil, water and gas flow rates on production pipelines. The microwave/gamma-ray MFM determined the oil and water flow rates with errors of 6.8 and 6.8 % relative respectively for the wide range of wells and flow conditions during the trial period. The technique has been demonstrated to have acceptable accuracy for reservoir management purposes and the gauge design has been proven to be reliable in an industrial environment.

The water (or oil) cut and liquids thickness can be directly determined from a measurement of both microwave phase shift and attenuation [8]. However, compared to the microwave/gamma-ray transmission technique this approach was previously limited by the accuracy of the microwave attenuation measurement. As a result of developments during the Thevenard Island trial of the microwave/gamma-ray MFM, significant advances were made in the accuracy of the on-line determination of both microwave phase shift and attenuation. These developments led to a reassessment of a microwave MFM based on a simultaneous measurement of microwave attenuation and phase shift. In this technique, a transmission measurement of microwave attenuation and phase shift by a single microwave sensor is sufficient to determine water (or oil) cut and liquids thickness, and the cross-correlation of the output of two such sensors is used to determine flow velocity. The oil, water and gas flow rates are then determined from combining liquids thickness, water cut, pressure and temperature data in an appropriate flow model.

A preliminary assessment of the viability of the technique was based on a calculation of the water cut for the Thevenard Island Phase 3 data from microwave attenuation and phase shift measurements alone. A non-linear correlation of the measured attenuation and phase shift data with the separator water cut, using an artificial neural net fitting technique, gave a 3.2 % relative error in the predicted water cut for the Thevenard Island data. This error was comparable to that obtained by the microwave/gamma-ray MFM (Table 3). This result confirmed the viability of the technique for determination of water cut. However, a trial of a prototype microwave MFM is required to establish the accuracy of this technique for the direct determination of the flow rate of oil, water and gas in production pipelines.

A schematic of the prototype microwave MFM spool piece that is presently under development is shown in **Figure** 13. The microwave MFM is comprised of two independently operated microwave sensors mounted in pipeline crosspieces. The two microwave sensors are aligned so that they measure over the same transmission path and are flush with the internal bore of the pipeline. The attenuation and phase shift of a microwave signal transmitted across the diameter of the pipe at each sensor is used to determine the liquids thickness and the volume fractions of oil, water and gas in the measurement path. The fluids flow velocity is determined from the cross correlation of the outputs from each microwave sensor. Measurements of oil, water and gas volume fractions and the flow velocity are then combined using an appropriate flow model to determine the flow rate of each component.

10. 1994 TRIAL

Trials of both the gamma-ray and microwave MFMs will be undertaken on the West Kingfish platform in the Bass Strait operated by ESSO Australia. There are 24 oil wells flowing to this platform with a wide range of flow conditions and water cuts. The facility to increase gas lift and thereby gas volume fractions will allow further definition of the operating envelope of the MFM. The 1994 trial is scheduled to commence late in September, and last for about four months.

The gamma-ray MFM to be trialed is an advanced prototype, equivalent to a commercial prototype. The aim of the trial is to demonstrate the accuracy of the gamma-ray MFM equipment in long-term operation, and to assess further the calibration techniques based on off-line measurements on static samples. The gamma-ray MFM outputs of flow rates of liquids, oil, water and gas, and water cut, will be routed to the ESSO computer in the platform control room.

The aim of the trial of the microwave MFM is to assess the accuracy of on-line determination of oil, water and gas flow rates over a range of wells and flow conditions.

11. CONCLUSION

The gamma-ray MFM has now been demonstrated in trials on the Vicksburg offshore oil platform and at the oil production facilities on Thevenard Island. Flow rates and water cut are determined to an accuracy sufficient to meet the oil industry's requirments for optimisation of oil production over the whole field life. The hardware and software of the MFM have been demonstrated to be reliable under field conditions, giving continuous and instantaneous display of water cut and flow rates. An advanced prototype, equivalent to the commercial prototype, of the gamma-ray MFM will be trialed at the West Kingfish offshore oil platform late in 1994.

A prototype microwave and gamma-ray MFM has been developed and successfully trialed at the Thevenard Island oil production facility for in-pipe measurement of oil, water and gas flow rates on production pipelines. The microwave and gamma-ray MFM determined the oil and water flow rates with errors of 6.8 and 6.8% relative respectively for the wide range of wells and flow conditions during the trial period. The technique has been demonstrated to have acceptable accuracy for reservoir management purposes and the gauge design has been proven to be reliable in an industrial environment. A microwave only MFM is presently being developed and an industrial prototype gauge will undergo a platform trial in late 1994.

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8. Ashton, S.L., Cutmore, N.G., Roach, G.J., Watt, J.S. and Zastawny, H.W. - Development and trial of microwave techniques for measurement of multiphase flow of oil, water and gas. SPE 1994 Asea Pacific Oil and Gas Conference, Melbourne, 7-10 November, 1994.

9. Wolff C.J.M. - Required operating envelope of multiphase flow meters for oil well production measurement. The North Sea Flow Metering Workshop, Bergen, Norway, October 26-28, 1993.

Table 1. Range and mean of flow parameters at times corresponding to MFM measurements.

PARAMETER	RANGE	MEAN	UNITS
Liquids	7233-32346	18,278	BPD
Oil	445-16020	8,095	BPD
Water	3715-20630	10,184	BPD
Gas	1423-4494	3,074	MSCF/D*
Water cut	25.4-95.6	58.2	%
Gas to oil ratio	379-2960	749	SCF/Barrel
Pressure	1123-1595	1,219	kPa
Temperature	24-78	60	°C
Velocity	4.4-19	11.3	m s^{-1}

*thousand standard cubic feet per day

Table 2. Relative errors (r.m.s. difference σ/mean) for flow rates and water cuts determined by the gamma-ray MFM. The r.m.s. difference is the combined errors of the MFM and the separator.

Phase	MFM	σ/mean (%)				
		Liquids	Water cut	Oil	Water	Gas
1	Vertical ↑	4.0	3.1	6.9	5.2	8.0
	Horiz.(B)	5.3*	6.6*	10.4*	9.2*	7.5
2	Vertical ↑	3.7	3.7	7.1	3.7	7.1
	Vertical ↓	3.3	3.7	6.1	4.5	7.7
3	Vertical ↑	4.4	4.1	8.4	4.5	8.6
	Horiz.(A)	6.2	2.7	8.1	5.6	5.7

* too high count rates

Table 3. Results of the water cut determined by the microwave/gamma-ray MFM for Phases 1, 2, and 3 of the Thevenard Island trial.

TRIAL	% RELATIVE ERROR IN WATER CUT*	
	Non-linear fitting	Linear fitting
Phase 1 (horizontal B)	5.2	10.5
Phase 2 (vertical downflow)	5.4	12.2
Phase 3 (vertical upflow)	3.3	9.2

*ratio of the r.m.s. difference to the mean (%)

Table 4. Phase 1: % relative error for microwave/gamma-ray MFM mounted in the horizontal position.

PARAMETER	HORIZONTAL (Position B)	
	% Relative Error	Correlation Coefficient
Liquids Flow	3.2	0.993
Oil Flow	8.4	0.994
Water Flow	9.0	0.973

Table 5. Phase 2: % relative error for microwave/gamma-ray MFM mounted in the vertical downflow position.

PARAMETER	VERTICAL DOWNFLOW (Position D)	
	% Relative Error	Correlation Coefficient
Liquids Flow	3.2	0.997
Oil Flow	6.6	0.994
Water Flow	5.6	0.992

Table 6. Phase 3: % relative error for microwave/gamma-ray MFM mounted in the vertical upflow position.

PARAMETER	VERTICAL UPFLOW (Position C)	
	% Relative Error	Correlation Coefficient
Liquids Flow	4.1	0.991
Oil Flow	5.5	0.993
Water flow	5.9	0.982

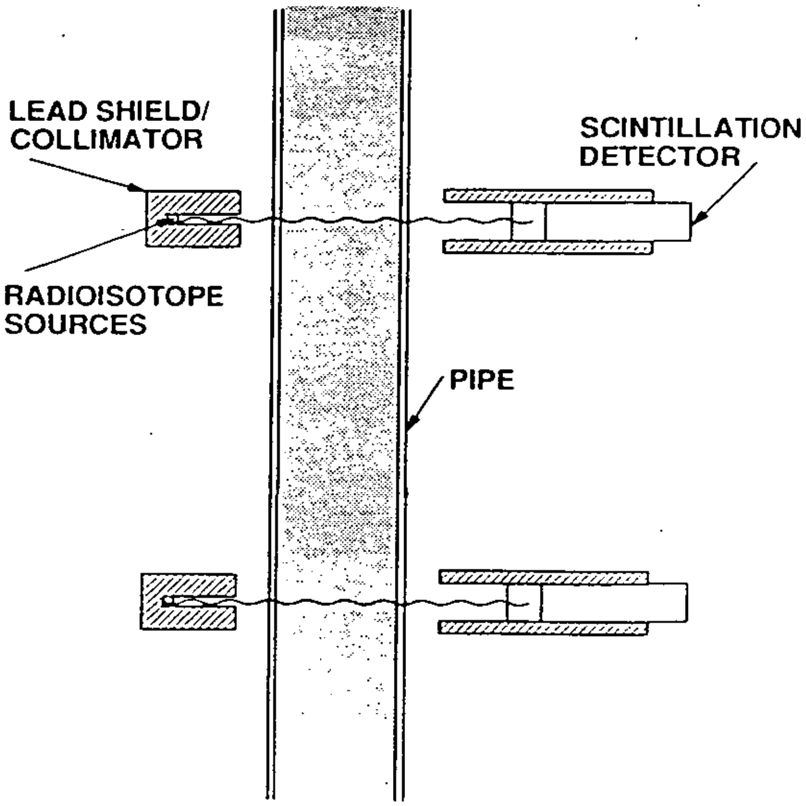

Fig. 1. Schematic of the gamma-ray MFM.

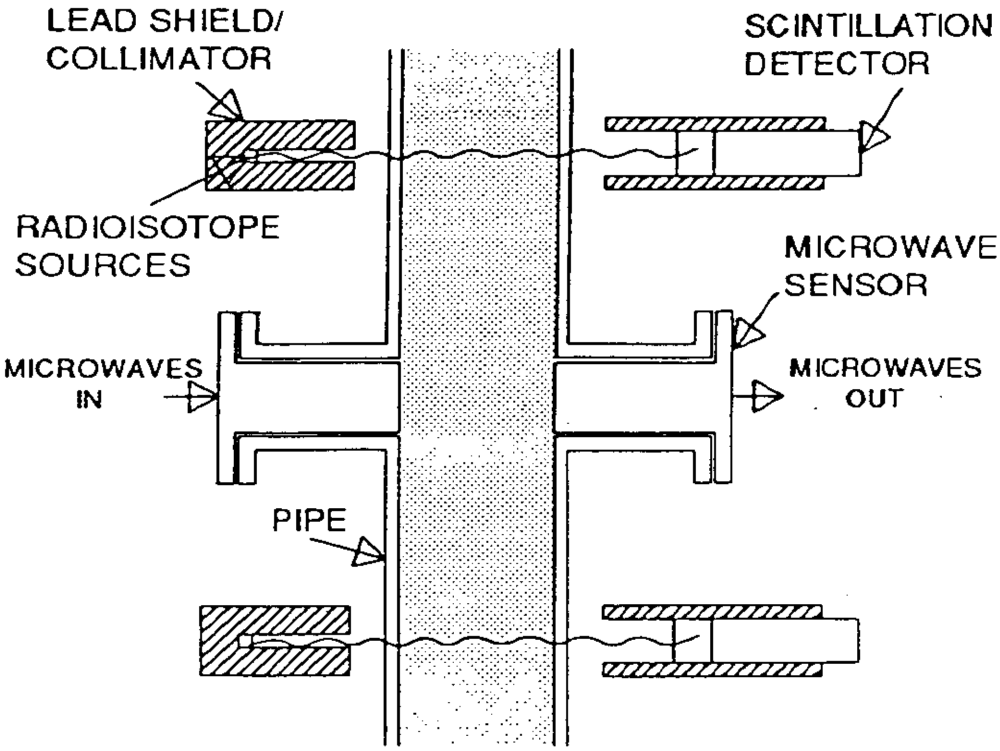

Fig. 2. Schematic of the prototype microwave/gamma-ray MFM used in the trial on Thevenard Island.

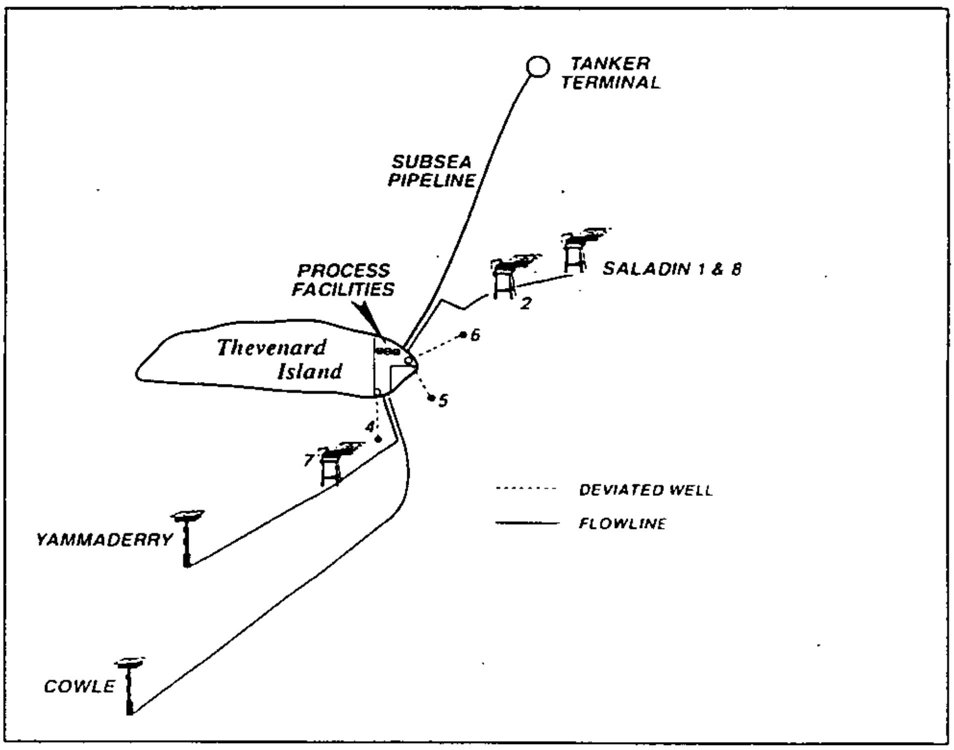

Fig 3. Schematic showing the Saladin, Yammaderry and Cowle facilities near Thevenard Island.

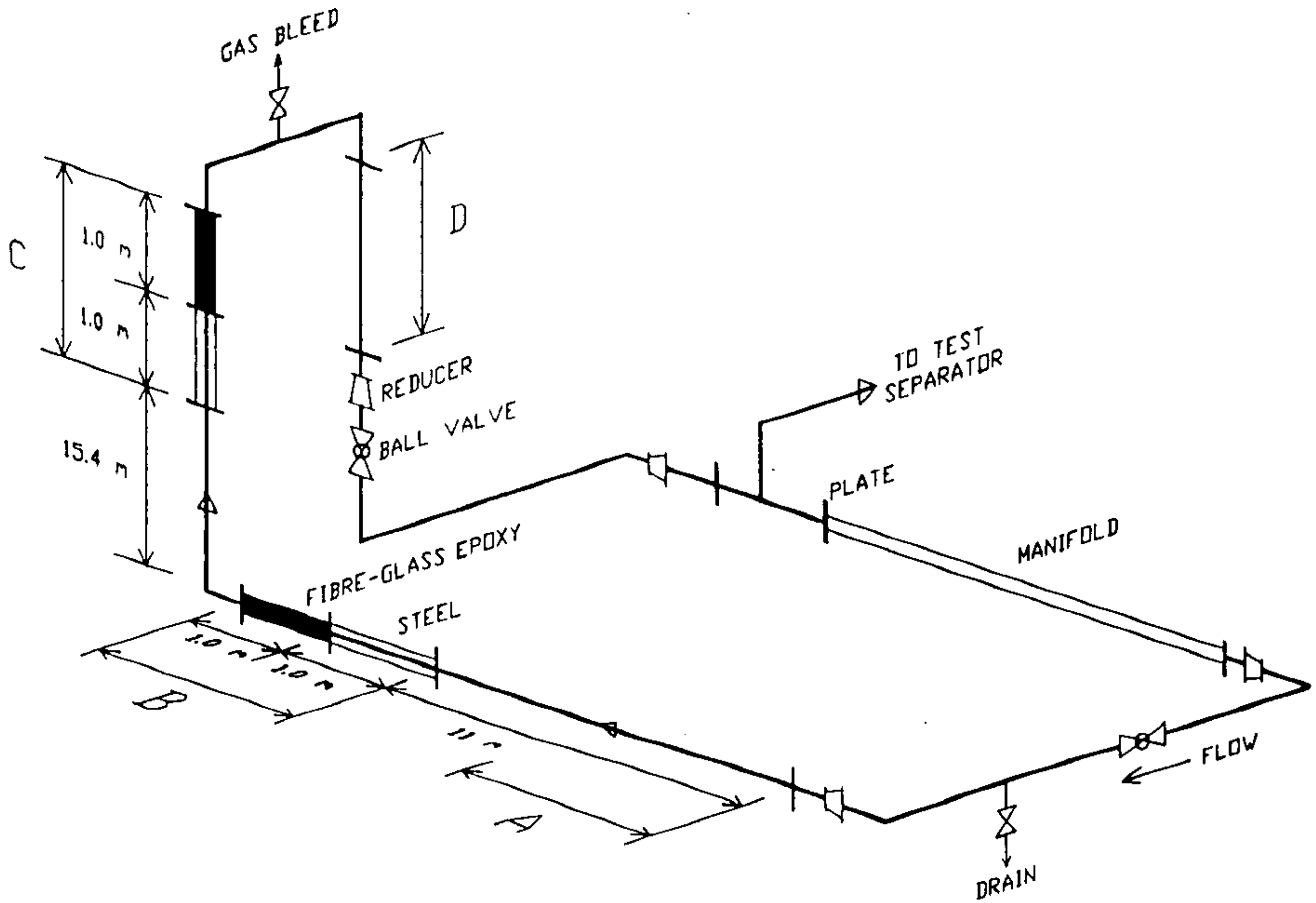

Fig. 4. Schematic of the test pipeline at Thevenard Island. A, B, C, and D are the positions at which the two-gamma-ray multiphase flow meters were mounted during the trial, with one MFM always in position C.

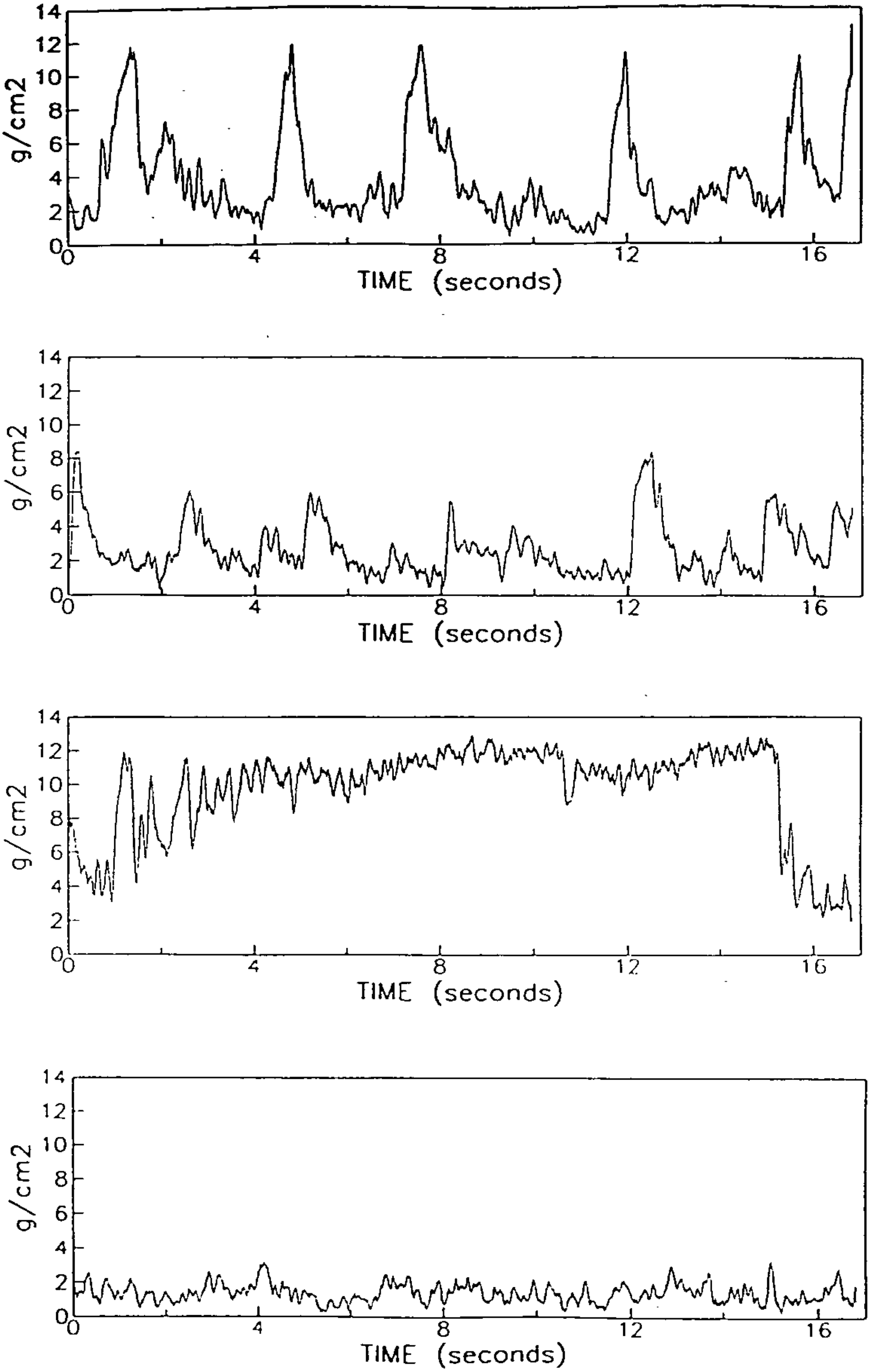

Fig. 5. Mass per unit area (g cm^{-2}) of fluids versus time for the flow of the Saladin 4 well (top), for the commingled flow of the Saladin 4 and 5 wells (second from top), and for the commingled flow of the Saladin 7 and Yammaderry 2 wells (bottom two).

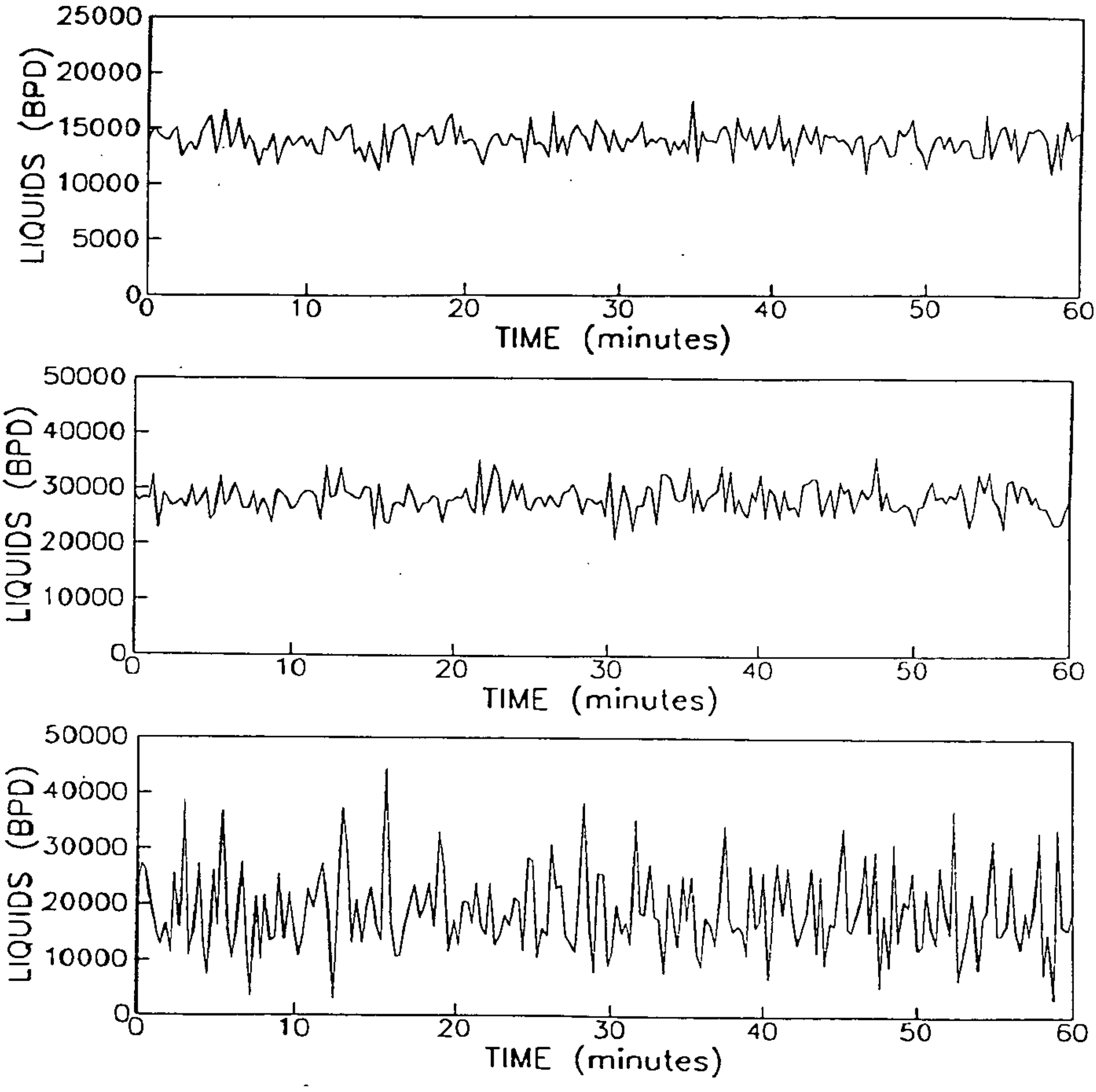

Fig. 6. The flow rate of liquids versus time for the flow from the Saladin 4 well (top), for the commingled flows of the Saladin 4 and 6 wells, and for the commingled flows of the Saladin 7 and Yammaderry 2 wells.

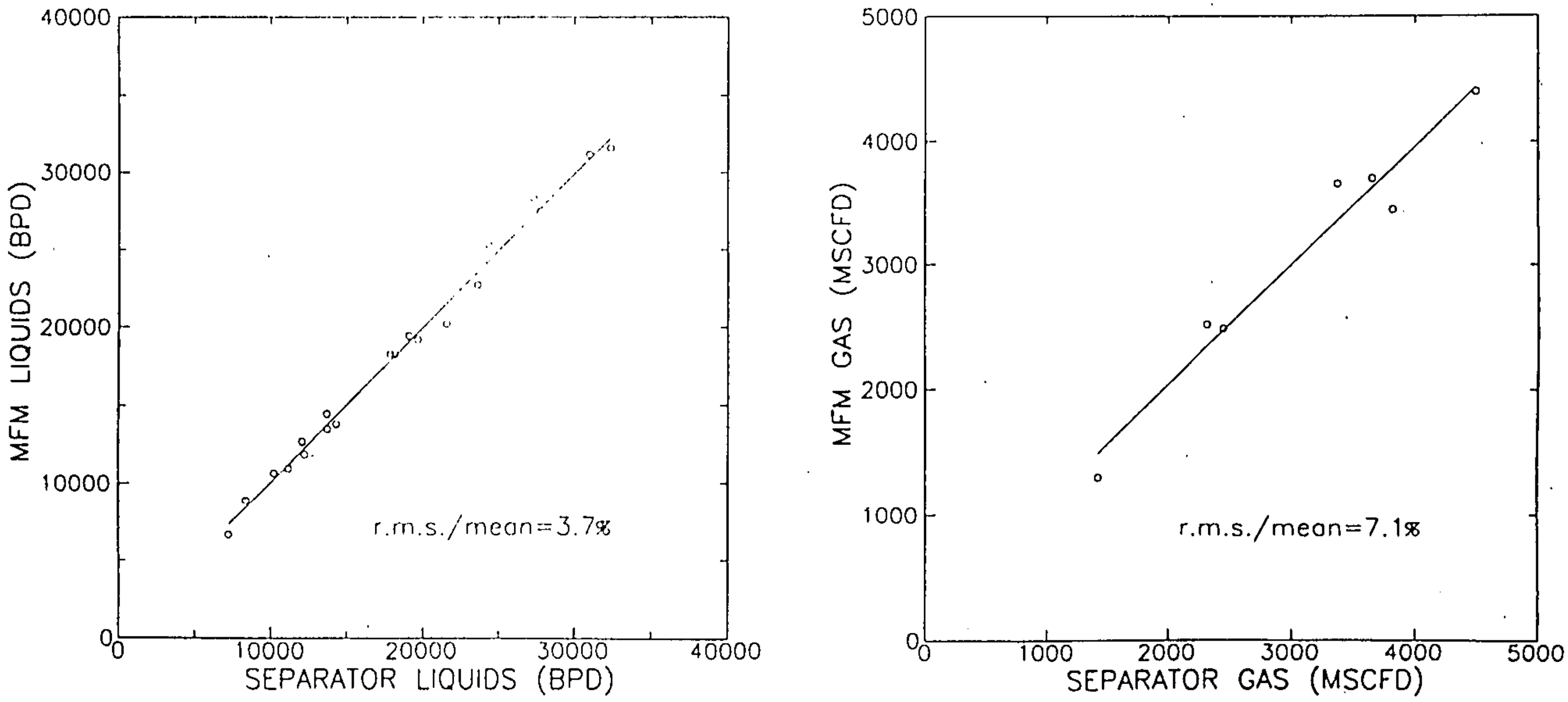

Fig.7. Liquids and gas flows for the gamma-ray MFM mounted about the vertical upflow pipeline: Phase 2 of the trial.

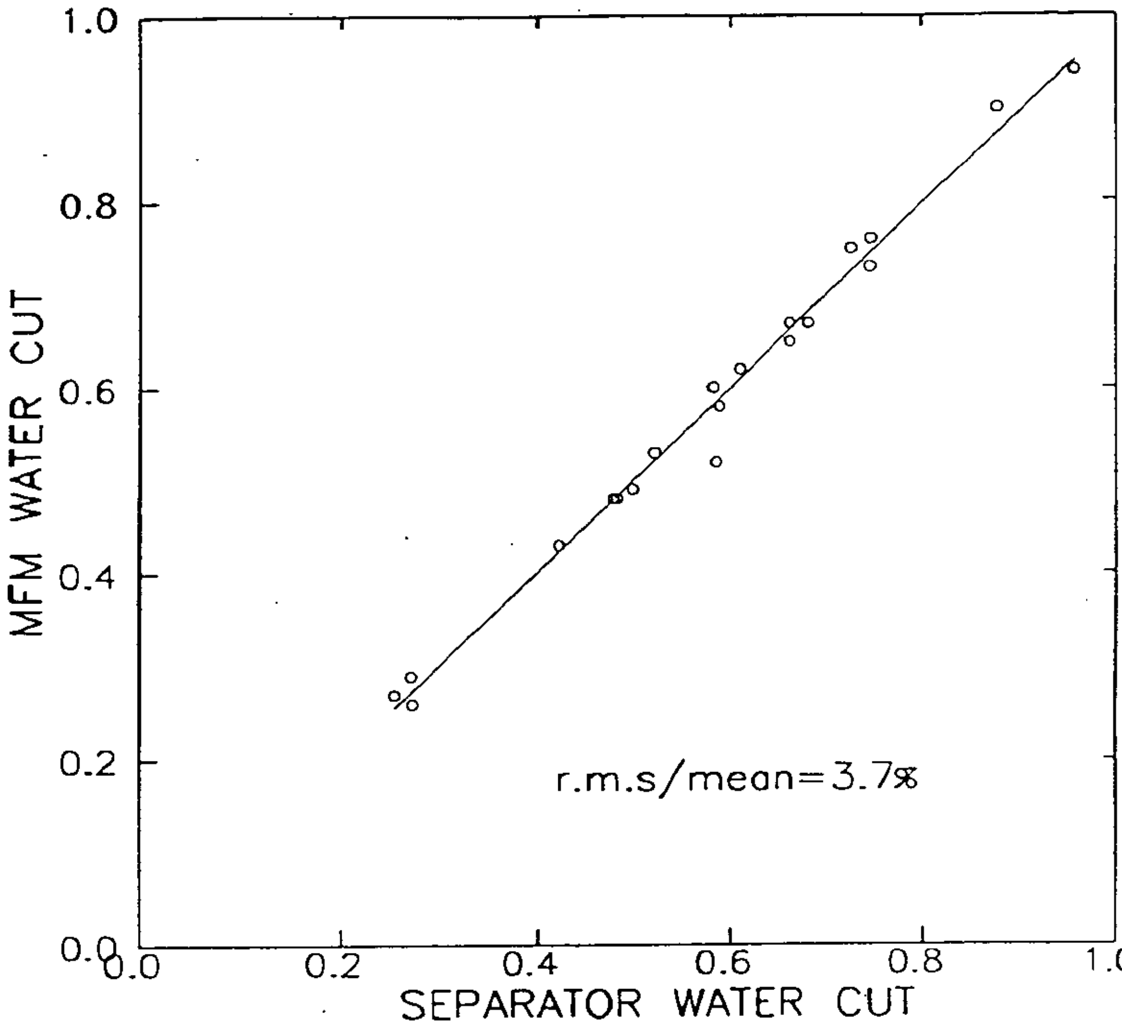

Fig. 8. Water cut for the gamma-ray MFM mounted about the vertical upflow pipeline: Phase 2 of the trial.

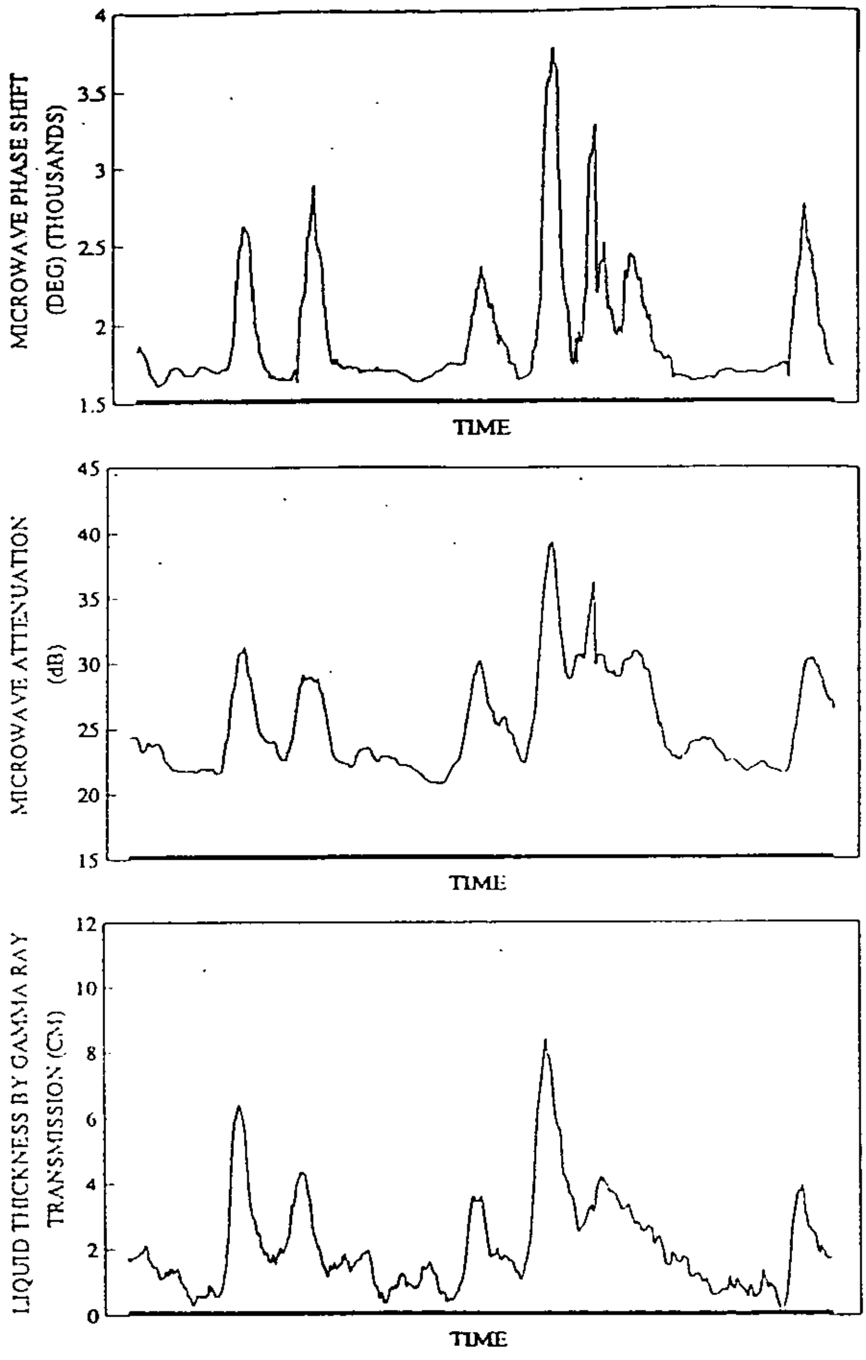

Fig. 9. Plot of microwave/gamma-ray MFM data for an ~14 s logging period of a commingled (Saladin 6+Saladin 7+Yammaderry 2) well flow during the Thevenard Island trial. The phase shift and attenuation data were measured by the microwave gauge of the MFM and liquids thickness by the gamma-ray gauge of the MFM.

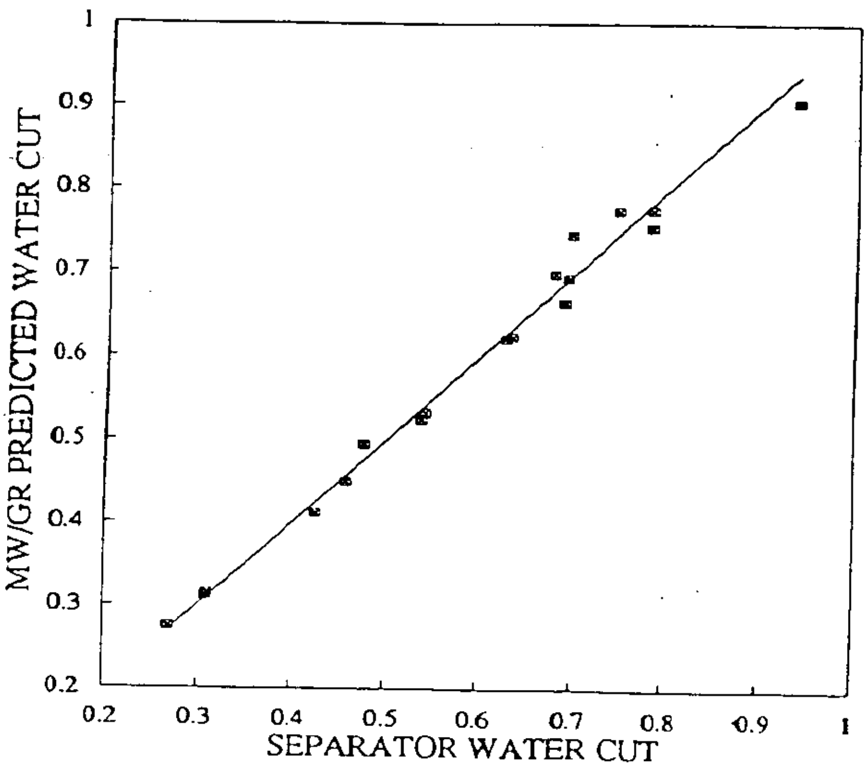

Fig. 10. Plot of the microwave/gamma-ray MFM predicted water cut versus the separator water cut during Phase 3 of the Thevenard Island trial.

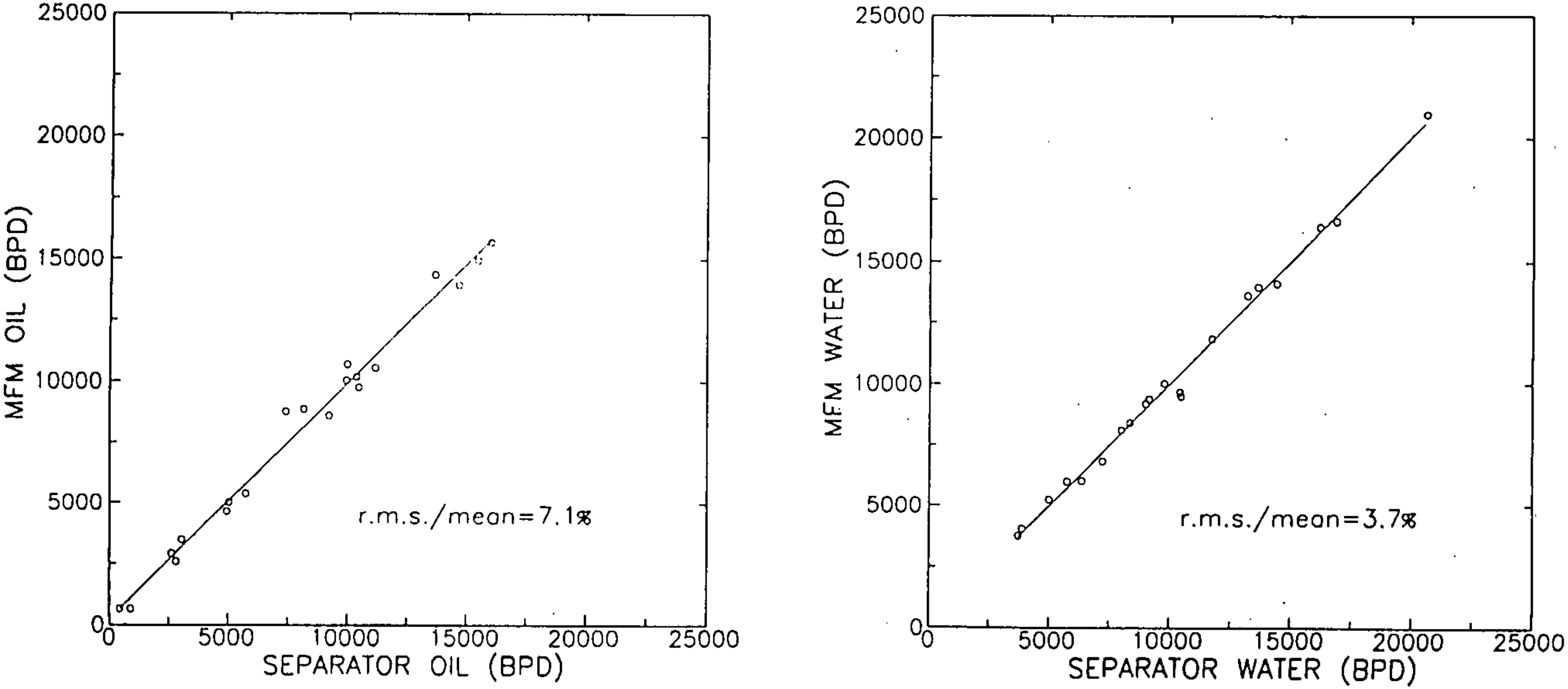

Fig. 11. Oil and water flows for the gamma-ray MFM mounted about the vertical upflow pipeline: Phase 2 of the trial.

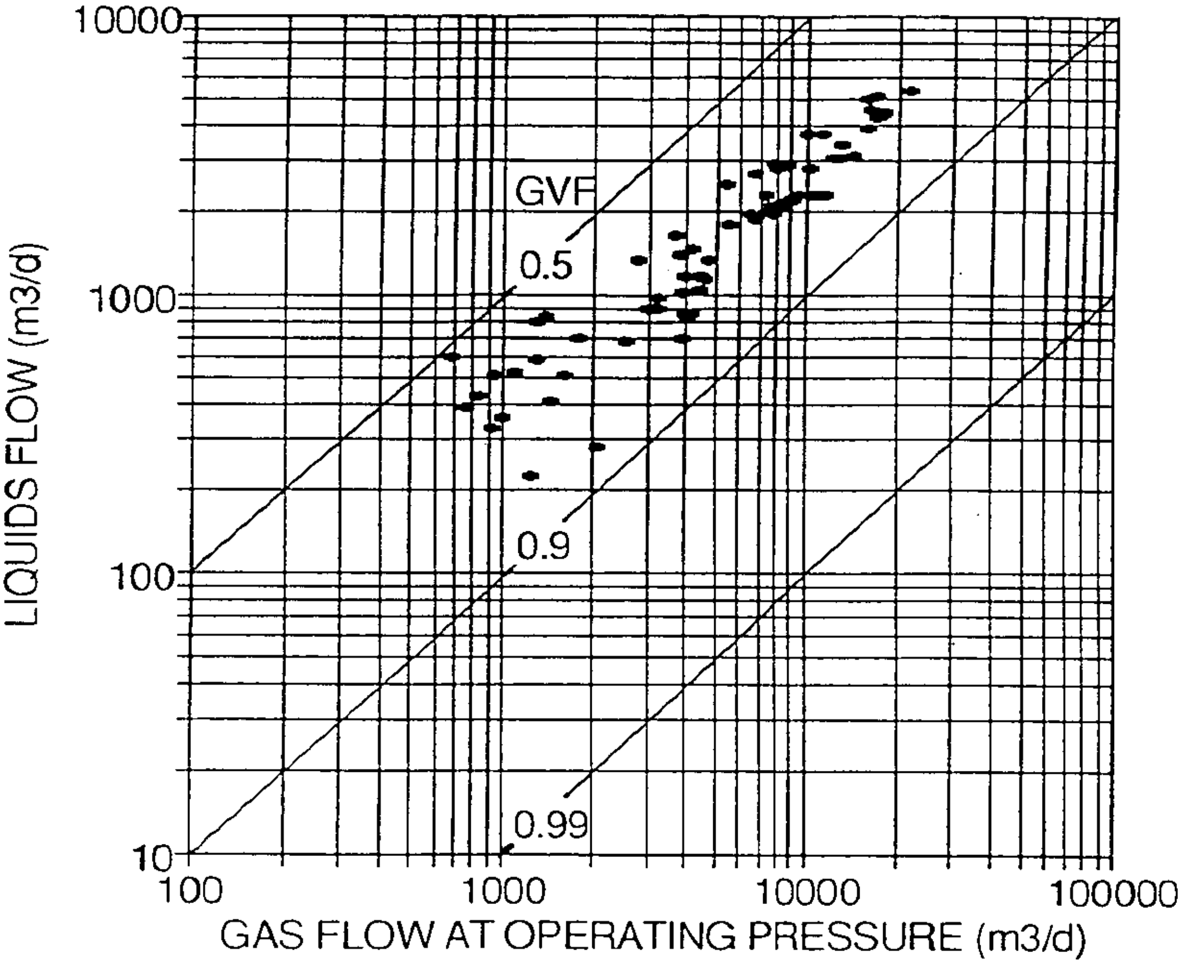

Fig. 12. Flow rates of liquids and gas (at operating pressure in pipeline) during the Vicksburg platform and Thevenard Island trials.

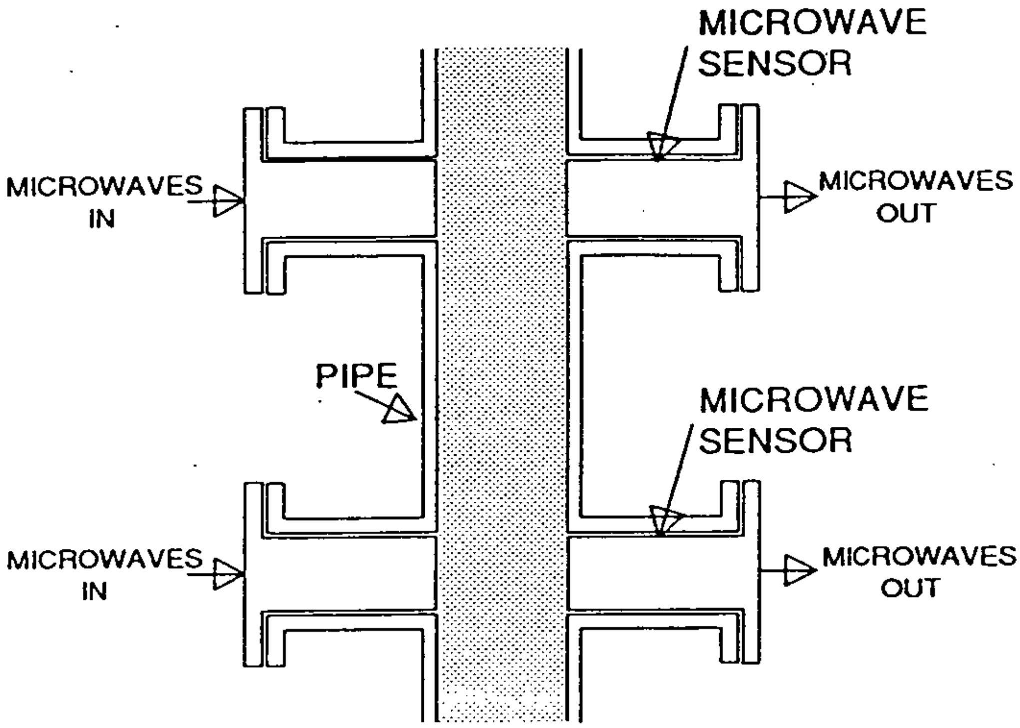

Fig. 13. Schematic of the prototype microwave MFM to be used in the West Kingfish platform trial.