

Denne rapport
tilhører



L&U DOK.SENTER

L.NR. 20084180001

KODE Well 31/3-1 nr.36

Returneres etter bruk

REPORT NO.

IFE/KR/F-83/094

REPORT TITLE

USE OF TRITIATED WATER AS A DRILLING
MUD TRACER IN WELL 31/3-1 IN THE NORTH
SEA.

CLIENT

STATOIL

Den norske stats oljeselskap.



Institute for energy technology

KJELLER		HALDEN	AVAILABILITY
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TELEX	76361 energ n	76335 energ n	
REPORT TYPE	REPORT NO.		DATE
	IFE/KR/F-83/094		16.12.1983
	REPORT TITLE		DATE OF LAST REV.
	USE OF TRITIATED WATER AS A DRILLING MUD TRACER IN WELL 31/3-1 IN THE NORTH SEA.		REV. NO.
	CLIENT		NUMBER OF PAGES
STATOIL			
Den norske stats oljeselskap.			
CLIENT REF.		NUMBER OF ISSUES	
SUMMARY			DISTRIBUTION
<p>Useful experience is achieved as to operation and establishment of the tracer method on board the rig. Improvements are done concerning stabilization of the tracer concentration level in the mud system, and a method for correction of leakage of cushion water into samples withdrawn by formation tester equipment is introduced.</p> <p>The concentration of the ions seems to have a nearly linear relationship for R values ranging between about 0.5 and 1 in the flushed zone near the borehole wall. For R values approaching zero, i.e. in the invaded zone, the concentration of most ions have a tendency to increase.</p> <p>In conclusion, the results of the present experiment seem to confirm that the tracer method may be used to achieve reliable analysis of the concentration of different ions in formation water based on samples from formation tester equipment. In addition, the curves of the tracer diagrams seem to give useful information on sorption and desorption processes in the reservoir near the borehole.</p>			
KEYWORDS			
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REPORT NO.:

S - 438/83

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SCOPE OF THE WORK :

To use tritiated water as a drilling mud tracer to improve the analysis of formation water in connection with FMT and production tests.

FIELD WORK :

The experimental part of the work was performed on the rig Deepsea Bergen during August 1983.

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1. INTRODUCTION

The results of this report are based on a method described earlier /1/, /2/, /3/.

The primary scope of the present work was to determine the fraction of mud filtrate in formation water withdrawn from 31/3-1 by drill stem test (DST). During drilling through the reservoir it was decided, however, that DST should not be performed.

Water samples were taken from various depths of the reservoir by "formation multi-tester" (FMT)-equipment. The results presented in this report are therefore mainly dealing with the chemical and radiochemical analysis of FMT samples, and how the tracer method may contribute to more reliable analysis of the formation water samples.

In order to verify the applicability of the tracer method, DST and FMT measurements should be performed in the same well. In that case the size and the variation of the parameters used to calculate the real concentration of different ions in formation water can be established.

The present experiment has given useful experience as to performance and establishment of the various operational steps of the tracer method on board the rig. In addition, the satisfactory results of radiation safety of rig personnel achieved in the first experiment was confirmed, as no tritium was found in urine samples from any persons attached to the mud processing plant on board Deepsea Bergen (including personnel from IFE).

2. SUMMARY OF THEORY OF THE TRACER METHOD

The tracer method is based on the assumption that a certain fraction (α_1) of ion Y in mud filtrate is sorbed in the mud cake and/or in the reservoir during drilling. During stay in the reservoir another fraction (α_2) of ion Y in mud filtrate and formation water is sorbed in the reservoir materials.

The total fraction of ion Y that is not sorbed is defined by :

$$(1-\alpha_1) \cdot (1-\alpha_2) = (1-\alpha_Y), \text{ or } \theta_1 \cdot \theta_2 = \theta_Y$$

Based on these assumptions, the following equation has been

derived /2/ :

$$C_{YSM} = (\theta_1 \cdot \theta_2 \cdot C_{YMW} - \theta_2 \cdot C_{YFW}) \cdot R + \theta_2 \cdot C_{YFW} \quad (1)$$

where

C_{YSM} = the concentration of ion Y in DST or FMT water samples
 C_{YMW} = the average concentration of ion Y in drilling mud filtrate
 C_{YFW} = the average concentration of ion Y in pure formation water.

R = the fraction of tritium in a DST or FMT sample, i.e., C_{TSM}/C_{TMM}

From this equation we find that C_{YSM} limits $\theta_2 \cdot C_{YFW}$ when R limits zero, and that C_{YSM} limits $\theta_1 \cdot \theta_2 \cdot C_{YMW}$ when R limits 1.

With reference to this equation the state of experience in using the tracer method shall be briefly summarized :

Suggesting that the mud filtrate ion Y takes part in no chemical or physico-chemical reactions during invasion and stay in the reservoir, and that the mud filtrate in the reservoir has no effect on the formation water and the reservoir materials, the parameters θ_1 and θ_2 in the equation are both equal to 1, i.e.:

$$C_{YSM} = (C_{YMW} - C_{YFW}) \cdot R + C_{YFW} \quad (2)$$

This linear curve is indicated by "A" in figure 1.

However, for all mud ions observed so far, the parameter $\theta_Y = \theta_1 \cdot \theta_2$ seems to be different from 1. As examples, ions

such as Na^+ , K^+ , Cl^- , SO_4^{--} and HCO_3^- seem to have θ_Y values less than 1, whereas ions such as Ca^{++} , Mg^{++} , Ba^{++} and Sr^{++} seem to have θ_Y values larger than 1.

θ_Y values larger than 1 indicate that Y-ions from the mud cake and/or the solid reservoir materials have been dissolved in the aqueous phase of the system.

In the case θ_Y is different from 1, it is of interest to observe to what degree the linear theoretical curve defined by equation (1) fits with the experimental curve for different types of ions, as indicated by "B" in figure 1. The experimental curve is determined by means of regression analysis, and is thought to refer to the "flushed zone" near the bore-hole wall.

An increase in the concentration of ions such as Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Ba^{2+} , Sr^{2+} , Cl^- , etc. was observed in DST-water samples from 30/6-6 for R-values approaching zero. This increase is indicated by curve "C", and is mainly thought to refer to the "invaded zone", as indicated in figure 1.

It should be emphasized that θ_Y values different from 1 show that the ion takes part in some kind of chemical or physico-chemical reactions, without saying anything of the type of reactions taking place. In order to achieve further knowledge of these reactions, it is suggested to perform laboratory experiments in a "physical reservoir model" /4/.

3. EXPERIMENTAL

3.1. Preparation of standard tracer solutions

The package with concentrated tritiated water was sent in a closed container with supply ship to the rig (Deepsea Bergen). The tracer was placed in a transport container on the deck, which was used as a "dispensing laboratory" for concentrated tracer solutions during the whole experiment.

All radioactivity and dose units used in this report are listed in table 1.

The content of one glass ampoule with approximately $3.7 \cdot 10^{11}$ Bq of tritium in the form of tritiated water (HTO) was diluted with tap water to 100 ml in a measuring flask. The concentration of this solution, called A, was then approximately $3.7 \cdot 10^9$ Bq/ml.

10 ml of solution A was diluted further to 100 ml in a measuring flask. The concentration of tritium in this solution, called B1, was then approximately $3.7 \cdot 10^8$ Bq/ml. Two more B- solutions were prepared during the experiment, called B2 and B3 respectively.

3.1.1. Calibration of the standard tracer solutions B1, B2 and B3

The standard tracer solutions were calibrated against a secondary tritium standard (LKB-WALLAC 1210-121) as described in section 3.5.

3.2. Injection of tracer into the circulating mud system

3.2.1. Main injection of tracer

In order to obtain a predetermined concentration of tritium in the mud water in a short period of time, the main injection of tracer was performed as described earlier /2/. According to this procedure, the concentration of tritium in the mud water is given by :

$$C_{TMW} = \frac{A}{V} = \frac{C \cdot q \cdot t \cdot n}{V} \quad (3)$$

where

A = total amount of tracer added to the mud system to achieve the predetermined concentration (Bq)

V = total water volume of the circulation mud system (ml)

- C = concentration of tritium in the tracer solution injected (Bq/ml)
- q = injection rate of tracer solution (ml/min).
- t = estimated time of one circulation of mud in the mud system (min)
- n = number of circulation periods.

The total volume of mud at the beginning of the experiment was estimated to be $225 \text{ m}^3 = 2.25 \cdot 10^8 \text{ ml}$, of which 89% was estimated to be water, i.e. $2 \cdot 10^8 \text{ ml (V)}$.

The total amount of tritium to be added to the circulating mud system to achieve an average concentration of about 80 Bq/ml (\bar{C}_{TMW}) is then $1.6 \cdot 10^{10} \text{ Bq (A)}$.

From eq. (3) the tritium concentration of the tracer solution to be injected into the mud system is found to be :

$$C = \frac{A}{q \cdot t \cdot n} \text{ Bq/ml} \quad (4)$$

If the tracer injection rate is 100 ml/min (q), the mud circulation time 90 min (t) and the number of mud circulation periods 3 (n), the concentration of the tracer solution is $5.93 \cdot 10^5 \text{ Bq/ml (C)}$.

The tracer solution was prepared in a plastic tank equipped with a manually operated mixing propeller, an explosion proof metering pump and plastic tubes for transfer of tracer to the mud. The injection was performed in the reconditioning plant just downstream of the shale shaker unit.

Due to errors in calibration of the B1 tracer solution (probably uncorrect volumes of 1 ml pipettes) and some difficulties in estimating the mud water volume, the tracer concentration in the mud leveled off at a value of about 65 Bq/ml.

3.2.2. Supplementary injection of tracer.

In order to maintain the tracer concentration level at about 65 Bq/ml, definite amounts of tracer (from the B2 and B3 solutions) were added to all new mud prepared in slug pits. The amount of tracer was calculated to yield a concentration of 65 Bq/ml in the mud water of the slug pits, i.e., $65 \cdot 10^6$ Bq was added to each m^3 of mud water prepared.

3.2.3. Adjustment of the tracer concentration level.

During the experiment the tracer concentration level in the mud gradually dropped due to seepage of foreign water into the system. In order to compensate for the decrease in tracer concentration, a weak tracer solution was injected into the mud system whenever needed.

If the tracer concentration level in the mud water shall be increased by X_{TMW} Bq/ml, a formula similar to eq. (3) may be used, i.e.:

$$X_{TMW} = \frac{c \cdot q \cdot t \cdot n}{V} \quad (5)$$

where

- c = concentration of tracer solution to be injected (Bq/ml)
- q = injection rate of the tracer solution (ml/min)
- t = estimated time of one mud circulation period (min)
- n = number of circulation periods
- V = total volume of the mud system

When the main injection started, the estimated time of one mud circulation was 90 min. If the maximum injection rate of the pump is 100 ml/min, the total volume of the mud system $2 \cdot 10^8$ ml and the injection of tracer is performed within one mud circulation period ($n = 1$), the concentration of the tracer solution can be calculated :

scintillation fluid. The samples were brought to another place for activity measurement, as described in section 3.5.

3.4. Method for testing of leakage of "cushion water" into FMT - samples

Water samples from the FMT - measurements were handled and distilled in the same way as the mud samples described above. In order to detect any leakage of cushion water into the sample chambers of the FMT-equipment, non-radioactive iodine in the form of sodium iodide was added to the cushion water. This tracer was chosen because the concentration of iodine in cushion water, mud water, and formation water is very low. In addition, the sorption of iodide to solid mud particles is considered to be negligible.

Due to the fact that leakage of cushion water into the FMT-chamber will influence the concentration of ion Y (C_{YSW} mg/l) and the fraction of mud water in the sample (R), corrections have to be made in these figures. The following procedure was used :

The concentrations of iodide in cushion water and in mud water are C_{ICW} (mg/l) and C_{IMW} (mg/l) respectively. If the concentration of iodide in a FMT sample with volume V (l) is found to be C_{ISW} , the volume of cushion water x (l) may be calculated in the following way (the concentration of iodide in pure cushion water (tap water) is neglected in this connection, as it was found to be very low, i.e. 0.002 mg/l):

$$C_{ICW} \cdot x + C_{IMW} \cdot V \cdot R = C_{ISW} \cdot V \quad (8)$$

or

$$x = \frac{(C_{ISW} - C_{IMW} \cdot R) \cdot V}{C_{ICW}} \quad (9)$$

The concentration of tritium in a pure FMT-sample, i.e. the concentration of tritium if no leakage had occurred, is then :

$$C'_{TSW} \cdot (V - x) = C_{TSW} \cdot V \quad (10)$$

or

$$C'_{TSW} = C_{TSW} \cdot \frac{V}{V - x} \quad (11)$$

Consequently, the fraction of mud water in a pure FMT-sample is :

$$R' = \frac{C'_{TSW}}{C_{TMW}} \quad (12)$$

or

$$R' = R \cdot \frac{V}{V - x} = R \cdot f \quad (13)$$

Correspondingly, the concentration of an ion Y in a pure FMT-sample is :

$$C'_{YSW} = C_{YSW} \cdot \frac{V}{V - x} = C_{YSW} \cdot f \quad (14)$$

where f is a correction factor for the effect of leakage of x liter of cushion water into the sampling chamber.

By combining equation (9) and (14) this factor may be expressed in terms of concentration figures (C_{ICW} , C_{ISW} , C_{IMW}) and the parameter R , i.e.:

$$f = \frac{C_{ICW}}{C_{ICW} - C_{ISW} + C_{IMW} \cdot R} \quad (15)$$

3.5. Instruments and activity measurements of tracer. The accuracy of the measurements

Tritium is a radioactive hydrogen isotope emitting beta particles with a maximum energy of 0.018 MeV. The most convenient way of measuring tritium is to use a liquid scintillation counter. When this method is used, a small volume of the sample (1 ml) is mixed with a certain volume of a scintillation liquid (10 ml).

In this mixture, beta particles generate tiny flashes which are registered by a photomultiplier tube and counted by a scaler.

3.5.1. Instrument

A manual liquid scintillation counter of type Aston 1006 was used for the tritium measurements. As this instrument is a two-channel counter, the measured results can be corrected for possible quenching error.

3.5.2. Accuracy and sources of error in the measurement.

The most important sources of error of interest in the performed measurements are as follows :

3.5.2.1 Statistical errors

The detection of radioactivity is based on random processes, which obey statistical laws. Consequently, an absolute true value of a nuclear disintegration rate is not obtainable, i.e. only mean values with a predictable standard deviation can be obtained.

When the tritium content of a sample is measured, a number of beta particles N are registered in a time interval t . The tritium content of the sample is then $k \cdot \frac{N}{t}$, where k is a calibration factor depending on the efficiency of the detector equipment employed. In most practical applications the standard deviation σ of a count rate $\frac{N}{t}$ is $\frac{\sqrt{N}}{t}$, when the rate is caused by random processes. The fractional standard deviation is given by

$$\frac{\sigma}{N/t} = \frac{\sqrt{N}/t}{N/t} = \sqrt{\frac{1}{N}} \quad (16)$$

From this equation we see that the uncertainty due to counting statistics can be reduced by increasing the number of registered beta particles. When N is 10 000, the fractional standard deviation will be 0.01 or 1 %.

When a sample is measured, the gross count rate is determined. From this figure one has to subtract the background count rate, i.e. a count rate caused by other radioactive sources than the sample, e.g. cosmic radiation, natural radioactive elements in the surrounding materials, etc.

If σ_g is the standard deviation of the gross count rate and σ_b the standard deviation of the background, the standard deviation of the net count rate σ_n is

$$\sigma_n = \sqrt{\sigma_g^2 + \sigma_b^2} \quad (17)$$

The fractional standard deviation of the net count rate is then

$$\frac{\sigma_n}{R_n} = \frac{\sqrt{\sigma_g^2 + \sigma_b^2}}{R_g - R_b} \quad (18)$$

where

$$\begin{aligned} R_n &= \text{net count rate} \\ R_g &= \text{gross count rate} \\ R_b &= \text{background count rate} \end{aligned}$$

Equation (18) shows that in order to obtain an accurate measurement, the gross count rate (R_g) should preferably be considerably higher than the background count rate (R_b).

3.5.2.2. Volumetric errors

When liquid scintillation samples are prepared, there may be an error in the sample volume transferred to the measurement vial, where it is mixed with scintillation liquid. The magnitude of this error depends on the equipment used and the skill of the operator. In this work a fixed volume dispenser with disposable tips was used. Based on experience, the standard deviation of the volumetric error for a given dispenser is estimated to be less than one percent.

3.5.2.3. Errors due to chemical quenching

Some of the tiny flashes of the scintillations caused by the beta particles in a liquid scintillation sample may be quenched if certain impurities are present in the sample.

In order to avoid this effect, all samples were distilled, and the measured results were checked for quenching effects by means of the two-channel method. This check rendered no significant figures indicating quenching, and therefore no correction was made for this type of error.

3.5.2.4. Errors caused by photoluminescence

Scintillation cocktails, as well as the materials in the scintillation vials, may be excited by ultraviolet light. The excitation energy is given up as light and this process is called photoluminescence. The light photons emitted in this process is registered by the counter as ordinary beta counts. To avoid this source of error, the samples were kept away from direct daylight and the light from fluorescent lamps. Before the samples were measured, they were kept in the counter for five minutes. This allowed most of the light from the photoluminescence process to fade away. Measurements indicate that the error caused by this process is less than one percent.

3.5.2.5 Errors due to instrument drift

To avoid this type of error, reference samples were counted several times a day, and when necessary, the mud water samples were corrected for instrument drift.

3.5.2.6 Uncertainty in the results caused by inhomogeneous tracer distribution in the mud

Care was taken to add the tritium to the mud in a way that would secure a homogeneous distribution. No effort has been made to separate the effect of inhomogeneous tracer concentra-

tions from other random errors, e.g. those caused by inaccurate sample volumes, counting statistics, etc. However, as the overall standard deviation of the mud samples in a series is in the range 1-4 percent, the error due to inhomogeneous tracer distribution is probably 1 - 3 percent.

When the mud water fraction (R) of the FMT water samples was calculated, mean values of several mud water samples was used. The standard deviation of these mean values will be less than the standard deviation of the samples themselves by a factor \sqrt{Z} where Z is the number of mud water samples used in the calculation of the mean.

4. RESULTS AND DISCUSSION

4.1. The tracer concentration level in the mud system

The concentration of tritium in the mud water in relation to drilling time and depth of the bit is summarized in table 2.

Apart from the results of the first tracer level adjustment performed on 13.8.83, when the level was increased from about 60 Bq/ml to 65 Bq/ml, the tracer concentration level is kept fairly constant all through the experiment.

Based on experience from this experiment, we consider it important to have sufficient time to make accurate calibration measurements of the tracer solution to be injected into the mud system. Further, it is important to estimate the "total volume of mud water (V)" in the circulating mud system as correctly as possible before the tracer injection, as this figure is used to calculate the amount of tracer required to obtain the desired tracer concentration level in the mud.

In this experiment it proved necessary to make small adjustment of the tracer concentration level achieved, as this level had a tendency to decrease by time due to leakage of foreign

water into the mud system. The adjustment (section 3.2.3.) was easy to perform, and the results were satisfactory.

4.2. Analysis of FMT samples

The results of this work are based on chemical analysis and activity measurements of FMT water samples. No production tests (DST) were performed. It may thus be difficult to discuss the results in view of the potential applicability of the tracer method.

However, in this experiment, the possibility of leakage of cushion water into the FMT sample chambers was taken care of, as an iodide tracer was added to the cushion water before the measurements started. The leakage of cushion water proved to be in the order of 2-15 % of the sample volumes.

A general "tracer diagram for ion Y" is shown in figure 1. For all ions reported in the following subsections, the concentration of ion Y in mud water (\bar{C}_{YMW}) is determined as an average (with one standard deviation) of the results of analysis of three samples (123, 125, and 134). These mud samples are spread over the depths where the FMT samples were collected.

The results of the measurements show that C'_{YSW} values are located on or close to a straight line curve. The curve is determined by linear regression calculation, and the "accuracy" of the curve is expressed by the correlation coefficient K.

The concentration of tritium in FMT and mud water samples together with calculated values of R are shown in table 3.

The chemical analysis of the FMT samples were performed by West Lab A/S, Stavanger, and the contents of iodine in cushion water, mud filtrate, etc. were found by neutron activation analysis in the laboratories at Kjeller.

The following FMT samples were analyzed :

FMT 1a, sample from 1 gallon chamber, depth 1574.2 m
FMT 1b, sample from 2 3/4 gallon chamber, depth 1574.2 m
FMT 2a, sample from 1 gallon chamber, depth 1579.5 m
FMT 2b, sample from 2 3/4 gallon chamber, depth 1579.5 m
FMT 3a, sample from 1 gallon chamber, depth 1570 m,
 sample rejected.
FMT 3b, sample from 2 3/4 gallon chamber, depth 1570 m

Chemical analysis of produced water from 30/6-6 shows that the concentration of many ions have a tendency to increase for R values approaching zero (table 4). As no water was produced from 31/3-1, the same percentage of increase will be used in this case to estimate the approximate size of the average concentration of ions in formation water (\bar{C}_{YFW}). Actually, this means that the same θ_2 value will be used as found by analysis of produced water from 30/6-6.

The results presented in this report are corrected for the effect of leakage of cushion water on the concentration of ions in sampled water (C_{YSW}) and on the fraction of mud filtrate (R), as shown in table 5. From this table data are taken for plotting of "tracer diagrams" for the ions in question, i.e. Na, Ca, Mg, Ba, Sr, K, Cl, SO₄ and HCO₃. The diagrams are shown in figure 3 to 11.

4.2.1. Tracer diagram for Na

The tracer diagram for sodium is shown in figure 3.

The correlation coefficient of curve B is found to be 0.81 and the total transmission coefficient (θ_{Na}) 0.9 ± 0.1 . This transmission coefficient is nearly the same as found for 30/6-6, i.e. 0.8.

The increase in the concentration of sodium in produced water from 30/6-6 for R values approaching zero, is about 19 % of the estimated $\theta_2 \cdot \bar{C}_{NaFW}$ value.

If the same percentage of increase is estimated to take place in produced water from 31/3-1, the average concentration of sodium in pure formation water (\bar{C}_{NaFW}) will be about 15700 ppm.

The corresponding figures of θ_1 and θ_2 by these conditions will be about 1 and 0.8 respectively, i.e. during movement into the formation the sodium ions of the mud filtrate are negligibly sorbed ($\theta_1 \approx 1$). During stay in the reservoir, however, about 20 % of sodium in a mixture of mud filtrate and formation water near the borehole is sorbed ($\theta_2 \approx 0.8$). According to the theory the resulting average concentrations of sodium in mud filtrate and formation water in the reservoir (flushed zone) are $\theta_{Na} \cdot \bar{C}_{NaMW}$ and $\theta_2 \cdot \bar{C}_{NaFW}$ respectively.

4.2.2. Tracer diagram for Ca

The tracer diagram for calcium is shown in figure 4.

The correlation coefficient of curve B is 0.95, and the total transmission coefficient (θ_{Ca}) 2.7 ± 0.6 .

The increase in the concentration of calcium in produced water from 30/6-6 for R values approaching zero was roughly 56 % of the estimated value of $\theta_2 \cdot \bar{C}_{CaFW}$. Using the same figure of increase on the extrapolated value of $\theta_2 \cdot \bar{C}_{CaFW}$ in this case (figure 4), the average concentration of calcium in formation water is found to be about 3780 ppm. The corresponding figures of θ_1 and θ_2 are 4.2 og 0.64 respectively.

The results indicate that calcium ions from the mud cake and/or the reservoir materials are desorbed during movement of mud filtrate into the formation ($\theta_1 = 4.2$). During stay in the reservoir about 40 % of calcium ions in a mixture of mud filtrate and formation water seem to be sorbed ($\theta_2 = 0.64$). The resulting average concentrations of calcium in mud filtrate and formation water near the borehole (flushed zone) are then $\theta_{Ca} \cdot \bar{C}_{CaMW}$ and $\theta_2 \cdot \bar{C}_{CaFW}$ respectively.

4.2.3. Tracer diagram for Mg

The tracer diagram for magnesium is shown in figure 5.

The correlation coefficient of curve B is 0.97, and the total transmission coefficient (θ_{Mg}) 3.2 ± 0.3 .

The increase in the concentration of magnesium in produced water from 30/6-6 relative to the extrapolated value of $\theta_2 \cdot \bar{C}_{MgFW}$ seems to be small, i.e. $\theta_2 \approx 1$. The estimated average concentration of magnesium in formation water from 31/3-1 is then about 510 ppm. The corresponding figure of θ_1 is 3.2, i.e. magnesium ions are desorbed during invasion of mud filtrate, whereas the mud filtrate itself seems to have no or little effect on the average concentration of magnesium in formation water ($\theta_2 \approx 1$).

4.2.4. Tracer diagram for Ba

The tracer diagram for barium is shown in figure 6.

The correlation coefficient of curve B is 0.53, and the total transmission coefficient (θ_{Ba}) 0.9 ± 0.2 .

The increase in the concentration of barium in produced water from 30/6-6 for R values approaching zero, relative to the extrapolated figure $\theta_2 \cdot \bar{C}_{BaFW}$, is very high, i.e. more than 2000 % (figure 6). Using this figure, the estimated average concentration of barium in formation water in the reservoir around 31/3-1 is about 150 ppm. The corresponding figures of θ_1 and θ_2 are about 18 and 0.05 respectively.

The results indicate that barium ions from the mud cake and/or the reservoir materials near the borehole are dissolved in mud filtrate moving into the formation ($\theta_1 \approx 18$). During stay in the reservoir, however, most of the barium ions (95 %) seem to be sorbed, which may be explained by the very low θ_2 value (0.05). The resulting effect on the average concentration of barium in mud filtrate and formation water near the borehole

(flushed zone) is then $\theta_{Ba} \cdot \bar{C}_{BaMW}$ (about 2 ppm) and $\theta_2 \cdot \bar{C}_{BaFW}$ (about 8 ppm) respectively, whereas the estimated true average concentration of barium in formation water is about 150 ppm.

4.2.5. Tracer diagram for Sr

The tracer diagram for strontium is shown in figure 7.

The correlation coefficient is 0.99 and the total transmission coefficient (θ_{Sr}) 5.9 ± 0.7 .

The increase in the concentration of strontium in produced water from 30/6-6 for R values approaching zero relative to the extrapolated value of $\theta_2 \cdot \bar{C}_{SrFW}$ is about 27 %. Using this figure, the estimated concentration of Sr in formation water from 31/3-1 is then about 405 ppm. The corresponding values of θ_1 and θ_2 are 7.4 and 0.8 respectively.

As for Ca, Mg and Ba, the results indicate that strontium ions are desorbed in the mud cake and/or the reservoir materials around the borehole ($\theta_1 \approx 7.4$). During stay in the reservoir about 20 % of strontium ions in mud filtrate and formation water is sorbed ($\theta_2 \approx 0.8$).

4.2.6 Tracer diagram for K

The tracer diagram for potassium is shown in figure 8.

The tracer diagram shows that the concentration of FMT 1b is very high compared with the concentration of the other FMT samples, which may be placed along a linear curve with a correlation coefficient 0.96.

If the B-curve indicated in the diagram is based on representative concentration values of potassium, the average concentration of this element in formation water is estimated to be about 5700 ppm. This value is very high compared with that found in produced water from 30/6-6, i.e. about 500 ppm.

If about 500 ppm is the true value in this case, curve A1 must be replaced by A2. This means that curve C2 must decrease by decreasing values of R.

4.2.7. Tracer diagram for Cl

The tracer diagram for chloride is shown in figure 9.

The correlation coefficient for curve B is 0.65 and the total transmission coefficient (θ_{Cl}) 0.9 ± 0.01 .

The increase in the concentration of chloride in produced water from 30/6-6 for R values approaching zero relative to the extrapolated value of $\theta_2 \bar{C}_{ClFW}$ is about 14 %. Using the same percentage of increase, the average concentration of chloride in formation water is found to be about 44600 ppm (figure 9). The corresponding parameters θ_1 and θ_2 are about 1.0 and 0.9 respectively.

4.2.8. Tracer diagram for SO₄

The tracer diagram for sulphate is shown in figure 10. The correlation coefficient for curve B is 0.98, and the total transmission coefficient 0.6 ± 0.04 .

The concentration of sulphate in produced water from 30/6-6 approached zero for decreasing values of R. The same trend is possible in this case, i.e. the average concentration of sulphate in formation water is estimated to be approximately zero, as indicated by curve C in figure 10. The corresponding figures θ_1 and θ_2 will then have the values approximately 0.6 and 1 respectively.

If this estimate is correct or nearly correct, about 40 % of the sulphate ions in mud filtrate moving into the reservoir is sorbed by some chemical reactions in the mud cake and/or in the reservoir close to the borehole wall. Our experience in using ³⁵SO₄ as a tracer for SO₄ in different soil/water systems (the Acidic Rain Fallout Project) confirms that the value of θ_2 must be close to 1.

4.2.9 The tracer diagram for HCO_3

The tracer diagram for hydrogen carbonate is shown in figure 11.

The tracer diagram shows that the concentration of HCO_3 of the FMT 3b sample is very high compared with the other ones, which may be placed along a linear curve with a correlation coefficient of 0.81.

Based on curve B in figure 11 the average concentration of HCO_3 in formation water ($\bar{C}_{\text{HCO}_3\text{FW}}$) is estimated to be about 300 ppm. The corresponding values of θ_1 and θ_2 will then be about 0.5 and 1.7 respectively. Consequently, the total transmission coefficient (θ_{HCO_3}) is equal to about 0.8.

4.3. Radiation safety of personnel

Urine samples of 12 persons (including 3 from IFE) who had contact with the mud processing plant during the experiment, have been analyzed for the contents of tritium by the Radiation Protection Department of IFE. No tritium was found in any of the urine samples.

A special report concerning the results of the urine tests has been prepared and sent to the Medical Office in Statoil.

5. CONCLUSIONS

The results of this work give basis for the following conclusions :

5.1. A stable tracer concentration level in the circulating mud system can be achieved and maintained by means of simple procedures for main injection of tracer, supplementary injections of tracer into slug pits, and adjustment of the tracer level by periodic injections into the circulating mud.

5.2. A stable tracer method is developed and used in this work to make corrections for leakage of cushion water into samples collected by formation tester equipment. Leakages in the range of 2 to about 15 % were observed in this case.

5.3. As formation water was not produced in 31/3-1 it was found useful to make comparisons with the results obtained from 30/6-6, in order to make estimates of the average concentration of ion Y in formation water (\bar{C}_{YFW}).

The estimates are based on the assumption that θ_2 for 31/3-1 is approximately the same as that found by analysis of produced water from 30/6-6. This assumption certainly has to be verified by analysis of water samples from formation tester equipment (RFT, FMT, etc.) and DST measurement performed in the same well.

5.4. The tracer diagram of an ion Y is defined by three characteristic curves :

Curve A which shows the relation between C'_{YSW} and R' in case ion Y and other components of the mud filtrate have no chemical influence on the system around the borehole. The curve is a linear function of R and refers to both the "flushed zone" and the "invaded zone" as indicated in figure 1.

Curve B which shows the relation between C'_{YSW} and R' in case ion Y and other components of the mud filtrate have a chemical effect on the system. The curve seems to be linear or approximately linear for R values ranging between about 0.5 and 1, and refers to the flushed zone near the borehole wall.

Curve C which shows the relation between C'_{YSW} and R' for R values approaching zero. The curve is not linear and refers most probably to the invaded zone only.

5.5. Evaluation of the parameters θ_1 and θ_2 (and θ_Y) seems to yield meaningful information on sorption and desorption processes in the system.

5.6. The approximate linearity of the B curve observed in this work indicates that the tracer method described can be used to determine the average concentration of an ion Y in formation water (\bar{C}_{YFW}) based on samples from formation tester equipment (RFT, FMT, etc.), without having recourse to the more expensive DST water samples.

6. REFERENCES

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- /2/ DAHL, J.B. AND TOLLAN, O.: Use of tritiated water as a drilling mud tracer in well 30/6-6 in the North Sea.
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- /3/ DAHL, J.B., MICHELSEN, O.B., RAMBÆK, J.P.: Bruk av gammakamera-teknikk ved studier av flerfasestrømning i porøst materiale.
Institutt for energiteknikk, IFE/KR/F-83/062, Progress report, oktober 1983.
- /4/ INSTITUTE FOR ENERGY TECHNOLOGY, KJELLER : Utvikling av fysisk reservoarmodell for undersøkelse av migrasjon og omsetning av boreslamfiltrat, kompletteringsvæske, etc. i reservoaret rundt borehull ved hjelp av nukleære tracer-metoder. Prosjektforslag, desember 1983.

Table 1: Activity and dose units

Dimensions	Symbols (old units)	Symbols (SI units)	Expressed in SI units or derived units	Connection between old and new units
Activity	curie (Ci)	becquerel (Bq)	1 Bq = 1 disintegration \cdot sec ⁻¹	1 Ci = 3.7 \cdot 10 ¹⁰ Bq
Exposure	roentgen (R)	No name	coulomb/kg (C \cdot kg ⁻¹)	1 R = 2.58 \cdot 10 ⁻⁴ C \cdot kg ⁻¹
Absorbed dose	rad	gray (Gy)	joule/kg (J \cdot kg ⁻¹)	1 rad = 0.01 Gy
Dose equivalent	rem	sievert (Sv)	joule/kg (J \cdot kg ⁻¹)	1 rem = 0.01 Sv

1 Ci corresponds to 37 GBq (gigabecquerel) where: m (milli) = 10⁻³ G (giga) = 10⁹
 1 mCi " " 37 MBq (megabecquerel) μ (micro) = 10⁻⁶ M (mega) = 10⁶
 1 μ Ci " " 37 kBq (kilobecquerel) n (nano) = 10⁻⁹ k (kilo) = 10³
 1 nCi " " 37 Bq (becquerel)

Table 2. Tritium concentration in mud water samples.

Sample No.	Sampling time		Bit depth at sample time - m	Tritium concentration Bq/ml	Remarks and day averages of tritium conc. Bq/ml
	Date	hour			
3	11.8	1233	1327	10.2	
4	"	1247	1329	14.3	
5	"	1300	1332	19.6	
6	"	1315	1336	21.4	
7	"	1333	1338	22.3	
8	"	1345	1340	25.6	
9	"	1402	1340	31.1	
10	"	1415	1340	26.2	
11	"	1436	1340	40.5	
12	"	1451	1340	42.3	
13	"	1506	1341	40.0	
14	"	1521	1345	50.5	
15	"	1536	1346	51.7	
16	"	1606	1351	63.7	
17	"	1630	1351	66.2	
18	"	1700	1351	68.9	
19	12.8.	0130	1351	65.5	
20	"	0230	1351	63.2	
21	"	0330	1357	62.0	
22	"	0430	1360	63.2	
23	"	0530	1365	63.7	
24	"	0630	1366	63.0	
25	"	1500	1366	62.5	
26	"	1600	1366	59.8	
27	12.8.	1736	1370	58.7	
28	"	1833	1371	59.3	$\bar{X} = 61.9$
29	"	1845	1372	58.8	$\sigma = 2.3$
30	13.8.	0140	1372	60.9	
31	"	0205	1372	62.2	
32	"	0300	1374	62.4	
33	"	0340	1375	59.1	
34	"	0530	1379	61.2	
35	"	0705	1380	68.7	
36	"	0735	1386	67.0	

Sample No.	Sampling time		Bit depth at sample time - m	Tritium concentration Bq/ml	Remarks and day averages of tritium conc. Bq/ml
	Date	hour			
37	13.8.	0760	1386	65.3	
38	"	0850	1388	64.7	
39	"	1000	1391	63.7	
40	"	1005	1391	63.8	
41	"	2010	1391	67.5	
42	"	2110	1393	67.0	
43	"	2210	1397	65.3	$\bar{X} = 64.3$
44	"	2300	1398	65.3	$\sigma = 2.7$
45	14.8	0000	1401	65.8	
46	"	0100	1403	65.4	
47	"	0200	1405	65.3	
48	"	0300	1406	65.3	
49	"	0400	1406	64.8	
50	"	0500	1406	65.1	
51	"	1100	1407	64.6	
52	"	1155	1407	65.5	
53	"	1300	1408	64.2	
54	"	1400	1412	65.0	
55	"	1500	1414	65.4	
56	"	1600	1416	65.0	
57	"	1700	1417	63.3	
58	"	1800	1418.5	63.8	
59	"	1900	1420	63.1	
60	"	2000	1422	64.0	
61	"	2100	1424	64.4	$\bar{X} = 64.6$
62	"	2145	1424	62.7	$\sigma = 0.9$
63	15.8.	0500	1425	62.6	
64	"	0600	1427	63.7	
65	"	0700	1431	63.5	
66	"	0920	1436	63.4	
67	"	1000	1438	63.3	
68	"	1100	1440	63.1	
69	"	1300		64.0	
70	"	1700		-	

Sample No.	Sampling time		Bit depth at sample time - m	Tritium concentration Bq/ml	Remarks and day averages of tritium conc. Bq/ml
	Date	hour			
71	15.8.	1905		64.6	
72	"	1924	1443	63.1	
73	"	2030		62.4	
74	"	2125	1445	63.6	
75	"	2210	1446	62.7	$\bar{X} = 63.5$
76	"	2307	1447	65.0	$\sigma = 0.8$
77	16.8.	0040	1451	65.7	
78	"	0200	1454	65.1	
79	"	0300	1458	66.2	
80	"	0400		65.0	
81	"	1050		62.2	
82	"	1235	1465	66.3	
83	"	1300	1467	65.7	
84	"	1400	1781	65.2	
85	"	1515	1474	64.5	
86	"	1600	1478	62.8	$\bar{X} = 64.8$
87	"	1700		62.9	$\sigma = 1.3$
88	17.8.	0100		64.8	
89	"	0200		63.8	
90	"	0300		63.7	
91	"	0900		63.1	
92	"	1900		61.7	
93	"	2000	1481	62.4	
94	"	2100		63.6	
95	"	2200	1486	61.1	$\bar{X} = 62.9$
96	"	2300	1487	62.3	$\sigma = 1.2$
97	18.8.	0000	1488	63.0	
98	"	0215	1493	63.1	
99	"	0315	1495	63.5	
100	"	1107		62.1	
101	"	1200	1500	62.9	
102	"	1300	1504	61.7	
103	"	1415	1509	62.0	

Sample No.	Sampling time		Bit depth at sample time - m	Tritium concentration Bq/ml	Remarks and day averages of tritium conc. Bq/ml	
	Date	hour				
104	18.8.	1500	1511	61.8	$\bar{X} = 62.5$ $\sigma = 0.6$	
105	"	1555	1515	62.3		
106	19.8.	0000		62.1	$\bar{X} = 63.2$ $\sigma = 1.5$	
107	"	0100	1520	62.4		
108	"	0230	1524	62.3		
109	"	0330	1526	-		
110	"	0430	1530	62.3		
111	"	0630	1535	61.8		
112	"	1300		60.4		
113	"	1400	1536	62.7		
114	"	1500	1538	63.5		
115	"	1610	1541	63.7		
116	"	1700	1544	62.7		
117	"	1800	1545	63.9		
118	"	1900	1547	65.4		
119	"	2000	1549	65.5		
120	"	2100	1552	63.8		
121	"	2200		66.0		
122	20.8.	0725	1558	64.0		$\bar{X} = 62.6$ $\sigma = 1.2$
123	"	0830	1564	63.9		
124	"	1000	1571	62.8		
125	"	1730		63.1		
126	"	1830	1577	61.7		
127	"	2000	1587	61.5		
128	"	2100	1591	60.9		
129	21.8.	0440	1592	62.7	$\bar{X} = 62.2$	
130	"	0500	1594	62.0		
131	"	0530	1596	62.8		
132	"	0640	1599	62.2		
133	"	0800	1603	61.0		
134	"	2020	1613	63.0		
135	"	2100	1619	62.5		
136	"	2200	1630	-		
137	"	2300	1640	61.5		

Sample No.	Sampling time		Bit depth at sample time - m	Tritium concentration Bq/ml	Remarks and day averages of tritium conc. Bq/ml
	Date	hour			
138	21.8.	2355	1647	62.2	$\sigma = 0.6$
139	22.8.	0100	1648	62.4	
140	"	0200	1653	64.5	
141	"	0300	1662	66.4	
142	"	0400	1672	63.5	
143	"	0500	1677	63.9	
144	"	0600	1683	65.4	
145	"	0700	1689	64.8	
146	"	0800	1695	62.2	
147	"	0900	1999	64.1	
148	"	1000	1700	65.4	
149	"	1100	1712	65.8	
150	"	1200	1715	65.3	
151	"	1925	1720	63.2	
152	"	2000	1728	62.4	
153	"	2100	1736	62.8	
154	"	-	-	-	$\bar{X} = 64.1$
155	"	2300	1755	63.4	$\sigma = 1.3$
156	"	-	-	-	
157	23.8.	0045	1764	63.3	
158	"	-	-	-	
159	"	0300	1778	62.8	
160	"	-	-	-	
161	"	0500	1789	63.5	
163	"	0700	1802	62.9	
164	"	0800	1807	-	
165	"	0900	1811	63.8	
166	"	1000	1816	62.3	
167	"	1100	1820	65.2	
168	"	1200	1826	-	
169	"	1300	1831	66.1	
170	"	1400	1835	65.8	$\bar{X} = 64.1$
171	"	1600		66.0	$\sigma = 1.4$
172	24.8	2330		66.2	$\bar{X} = 65.3$
173	"	2400		64.3	$\sigma = 1.3$

Table 3. Concentration of tritium in FMT samples and in mud water.
 Calculated values of the mud fraction R.

Sample identification	Depth of sample m.	FMT-samples		Mud water		Mud water fraction in FMT-samples	
		Tritium conc. Bq/ml	St. dev. %	Tritium conc. Bq/ml	St. dev. %	R	St. dev. %
FMT 1 a	1574.2	27.6	1.8	61.8	0.5	0.447	2
FMT 1 b	"	36.9	1.8	61.8	0.5	0.597	2
FMT 2 a	1579.5	32.8	1.8	61.8	0.5	0.531	2
FMT 2 b	"	47.8	1.8	61.8	0.5	0.773	2
FMT 3 a	1570	21.8	1.8	62.3	0.5	0.350	2
FMT 3 b	"	56.8	1.8	62.3	0.5	0.912	2

* Best estimate of the average tritium concentration in the mud water in the 24 hours after drilling through the zones where the FMT-samples were taken.

Table 4: Ion analysis of produced formation water/mud water from 30/6-6 sampled at 0015, 0100 and 0600 hours. Start of production at 2345 hours the day before. (Source : Statoil)

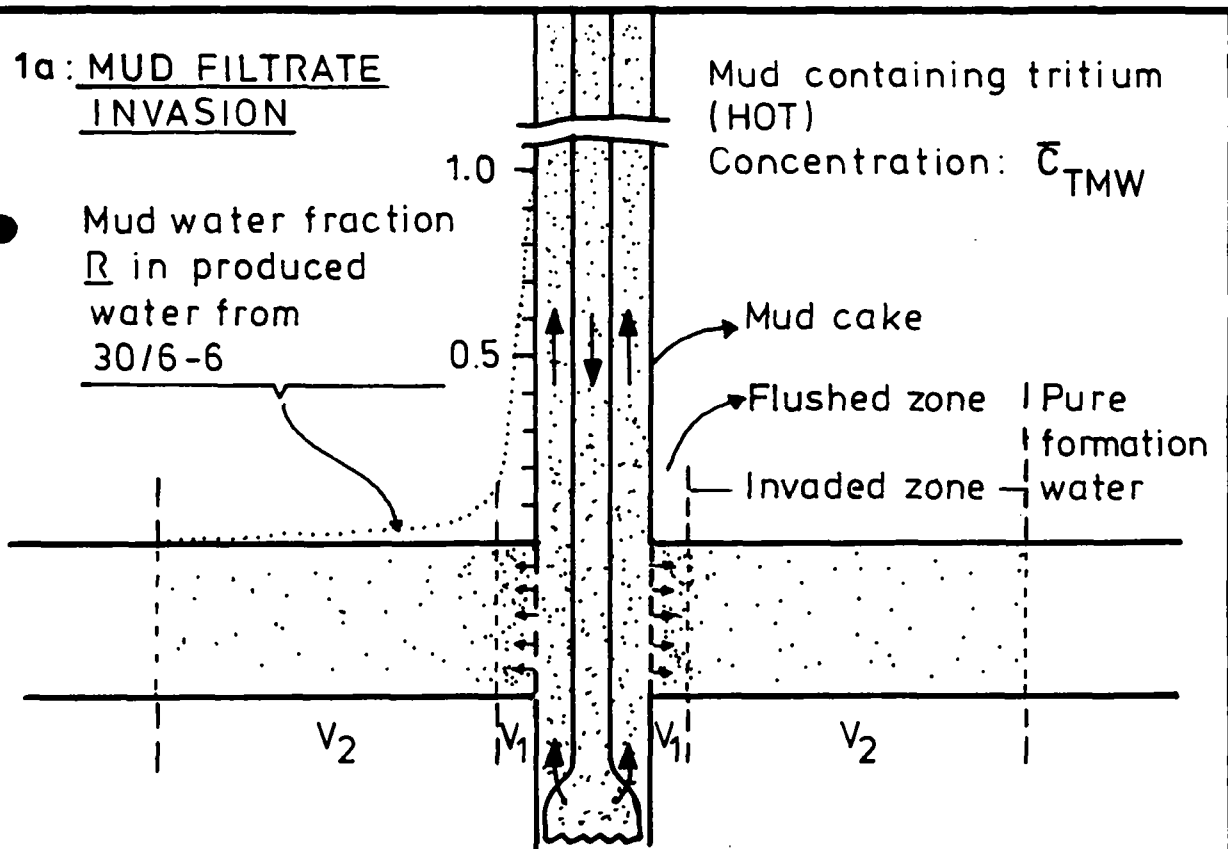
Sample	hr 0600	hr 0100	hr 0015
Density at 20°C, g/cm ³	1.0281	1.0275	1.0288
pH at 20°C	7.9	8.5	8.0
Total dissolved solid, %	4.33	4.31	4.19
Conductivity at 20°C mmho/cm	56.50	55.5	55.5
TOC; ppm	6	9	12
ION	Concentration (ppm)		
Na ⁺	14784	13430	13219
K ⁺	486	438	428
Mg ²⁺	1556	1538	1458
Ca ²⁺	1252	779	764
Ba ²⁺	232	140	19.4
Sr ²⁺	179	170	150
Fe ⁿ⁺	22.6	2.2	2.2
Li ⁺	13.8	13.6	13.4
Zn ²⁺	1.6	14.1	10.7
Cr ⁿ⁺	0.1	0.1	0.1
Si	40.7	33.1	33.4
Mn	0.10	0.15	0.16
Cl ⁻	24104	23174	22259
SO ²⁻	4.5	113.7	45.7
HCO ₃ ⁻	691	759.9	968.8
CO ₃	0	63.1	0
OH ⁻	0	0	0
Sum ion %	4.34	4.07	3.94
TOL	43366	40668	39383
$R = C_{TSW} / \bar{C}_{TMW}$	0.0025	0.0301	0.0702

Table 5. Correction for leakage of cushion water into
FMT samples

R', C' _{YSW}	FMT FMT 1a 1574.2 m	FMT 1b 1574.2 m	FMT 2a 1579.5 m	FMT 2b 1579.5 m	FMT 3b 1570 m
Sample volume V liter	2.15	6.10	3.70	6.70	1.50
C _{ISW} ppm	6.64	5.20	5.96	3.76	1.60
C _{IMW} ppm	0.60	0.60	0.60	0.60	0.60
C _{ICW} ppm	43.9	43.9	44.9	44.9	47.9
R	0.447	0.597	0.531	0.773	0.912
Leakage volume x liter	0.312	0.673	0.465	0.492	0.033
Correction factor J	1.170	1.124	1.144	1.079	1.022
R'	0.52	0.67	0.61	0.83	0.93
C' _{YSW} for : ppm					
Na	9945	10397	8866	8362	7410
Ca	1264	1135	1121	788	373
Mg	275	241	233	159	90
Ba	3.3	2.9	5.5	4.1	1.1
Sr	165	118	132	80	35
K	4897	8430	6223	6733	6663
Cl	34059	35912	33708	33708	30476
SO ₄	702	1012	801	1511	1942
HCO ₃	662	725	634	748	1140

FIG 1a: MUD FILTRATE
INVASION

- Mud water fraction R in produced water from 30/6-6

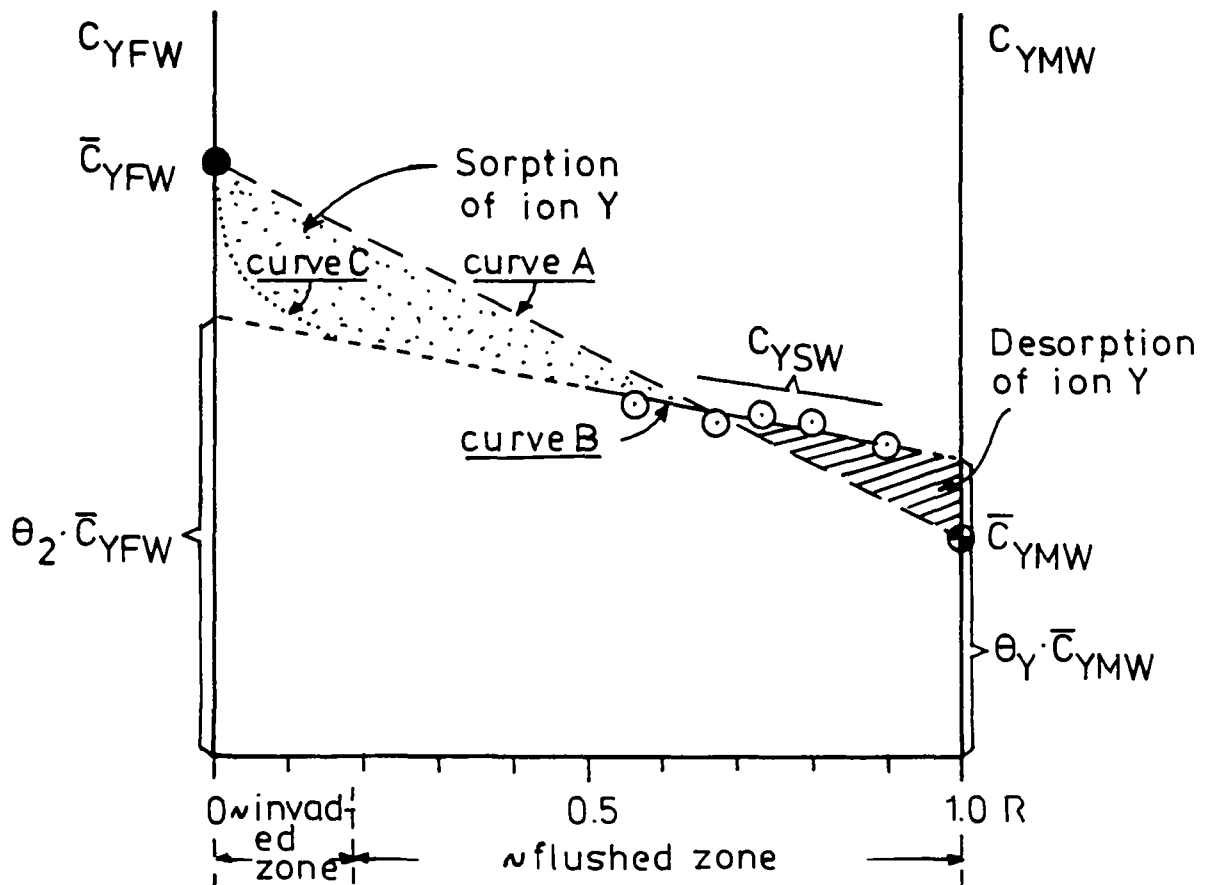


- $$\frac{V_1}{(V_1 + V_2)} < 0.1$$

 V_1 contains about 60% mud water

} 30/6-6

FIG 1b: TRACER DIAGRAM FOR ION Y



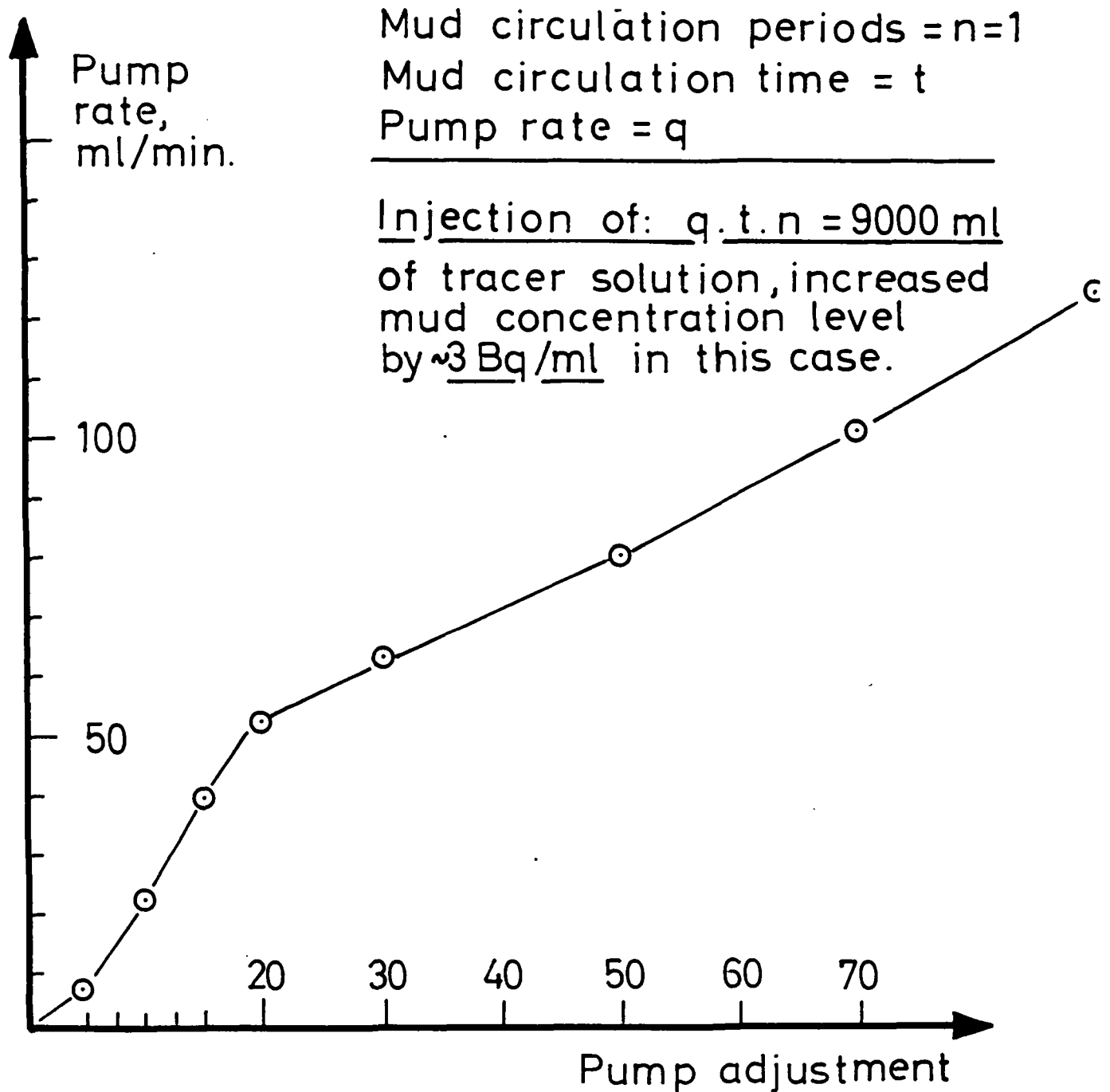


FIG 2: DIAGRAM FOR ADJUSTMENT
OF TRACER CONCENTRATION
LEVEL IN THE MUD

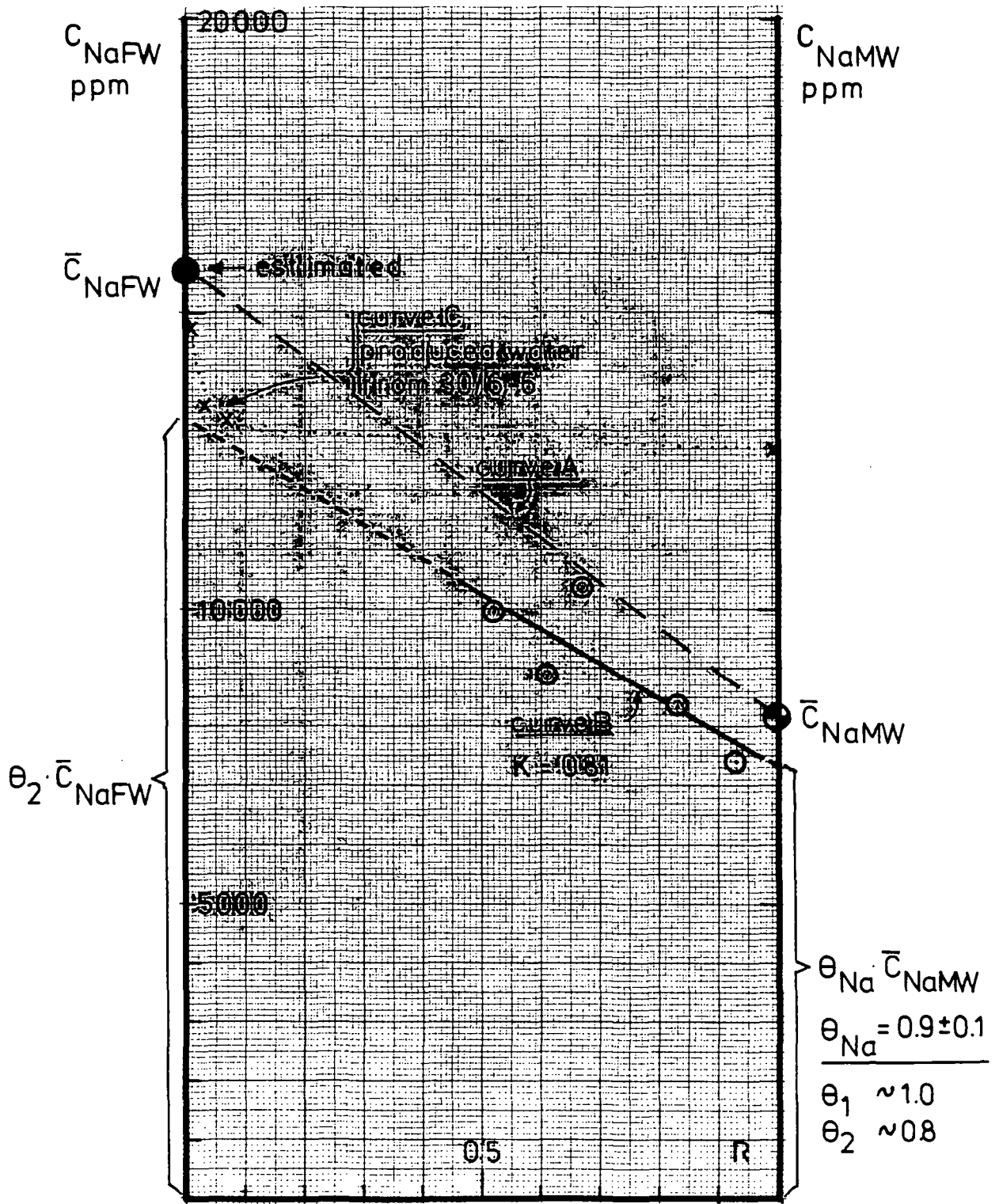


FIG 3: TRACER DIAGRAM FOR SODIUM

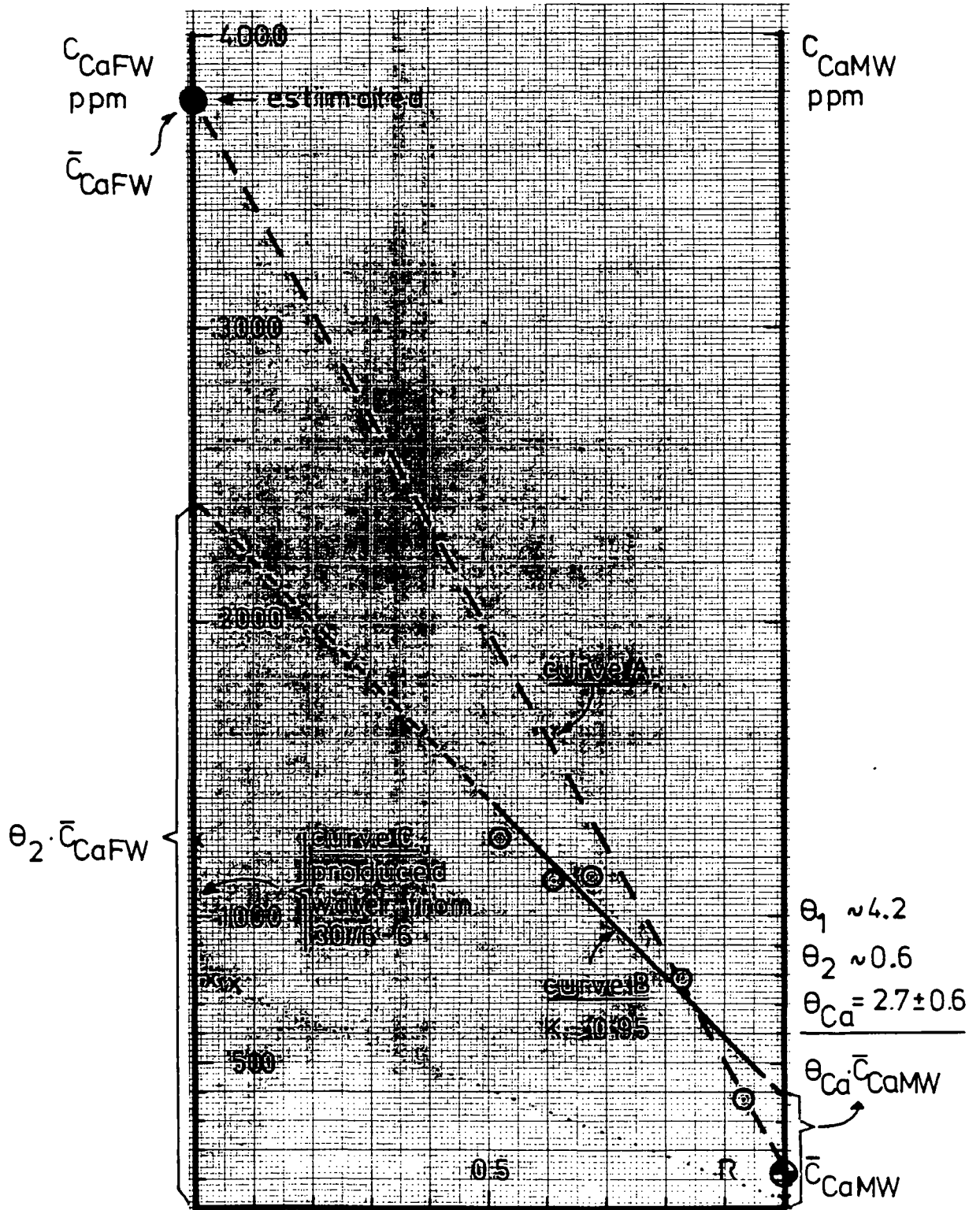


FIG 4: TRACER DIAGRAM FOR CALCIUM

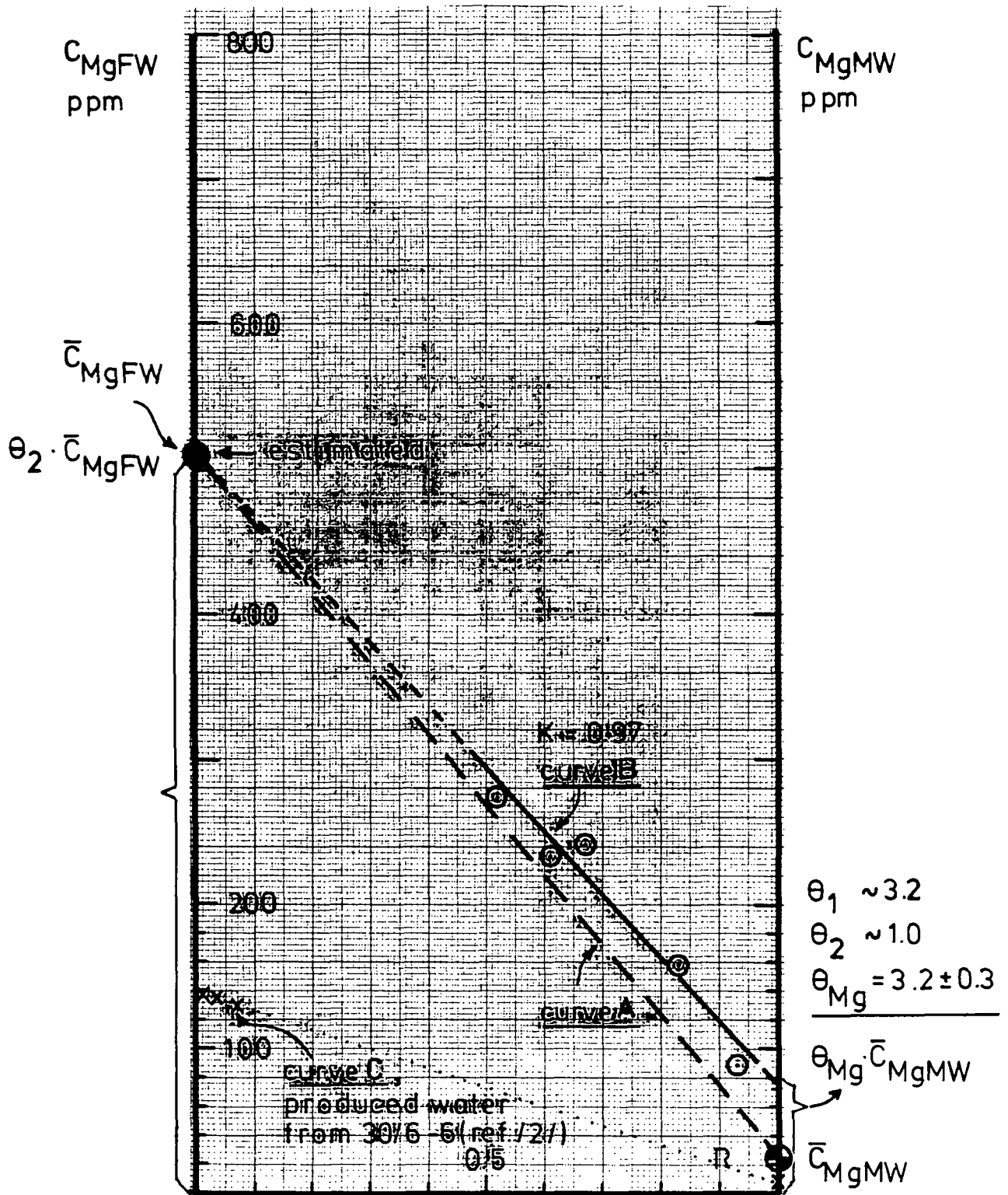


FIG 5: TRACER DIAGRAM FOR MAGNESIUM

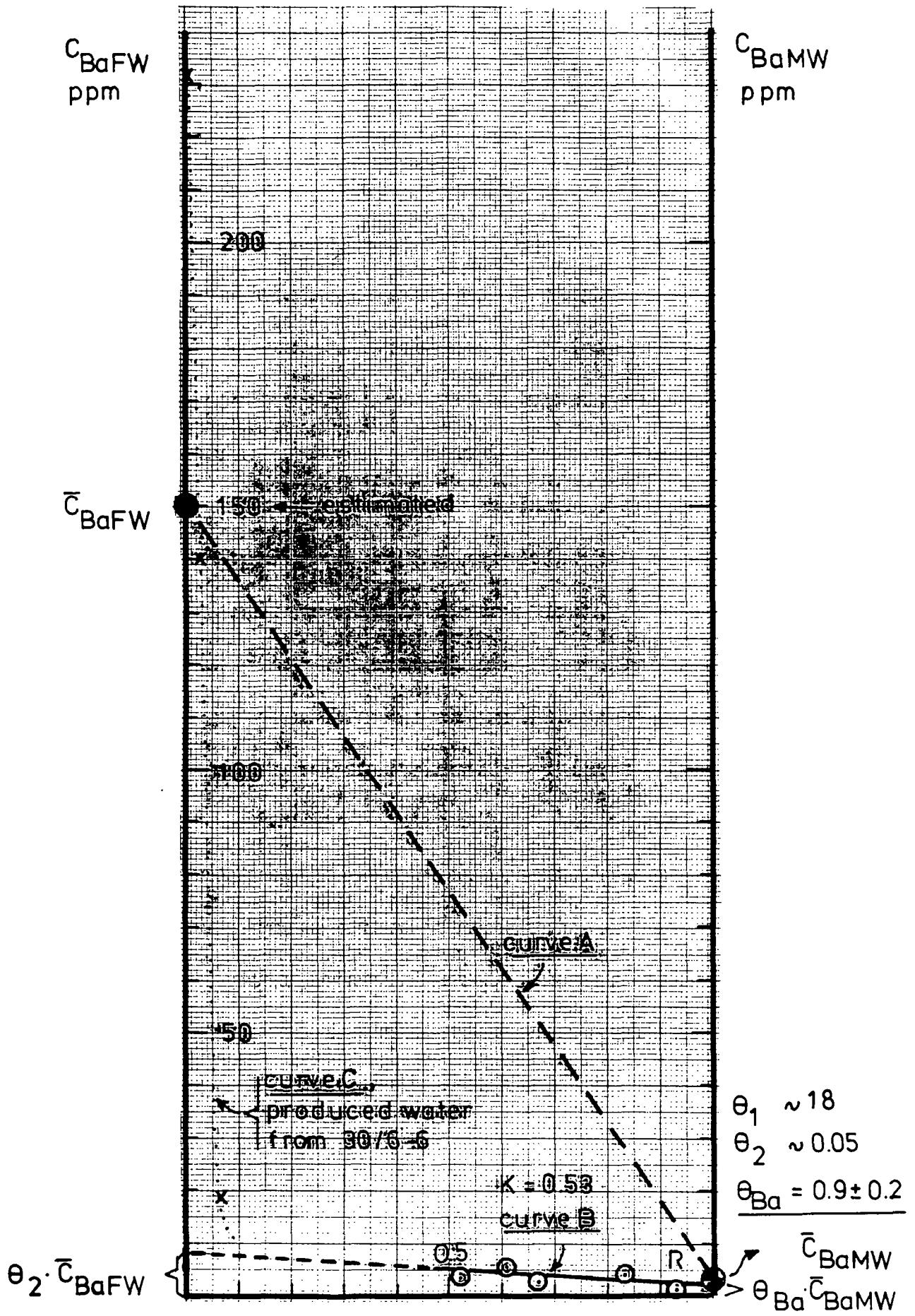


FIG 6: TRACER DIAGRAM FOR BARIUM

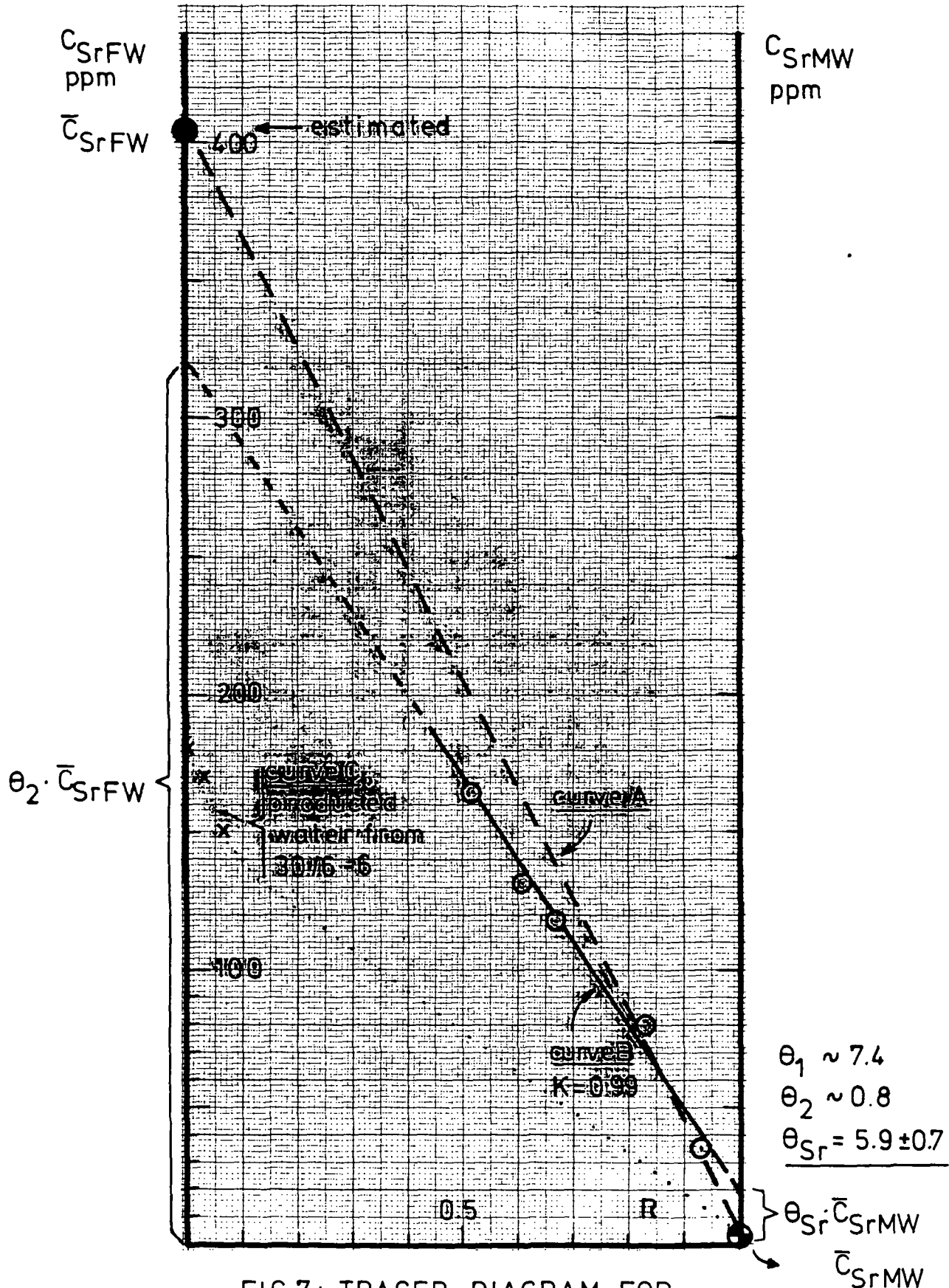


FIG 7: TRACER DIAGRAM FOR STRONTIUM

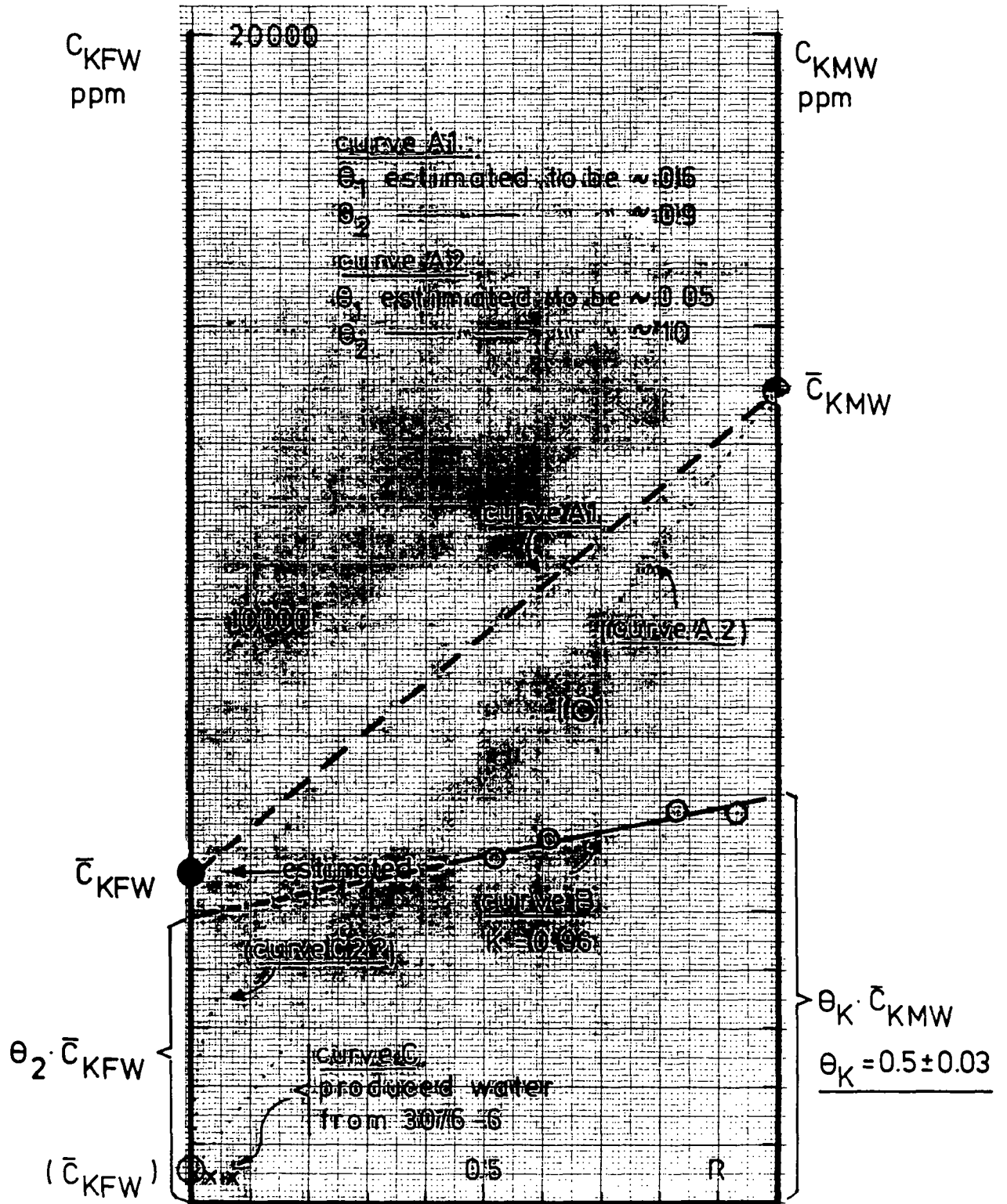


FIG8: TRACER DIAGRAM FOR KALIUM

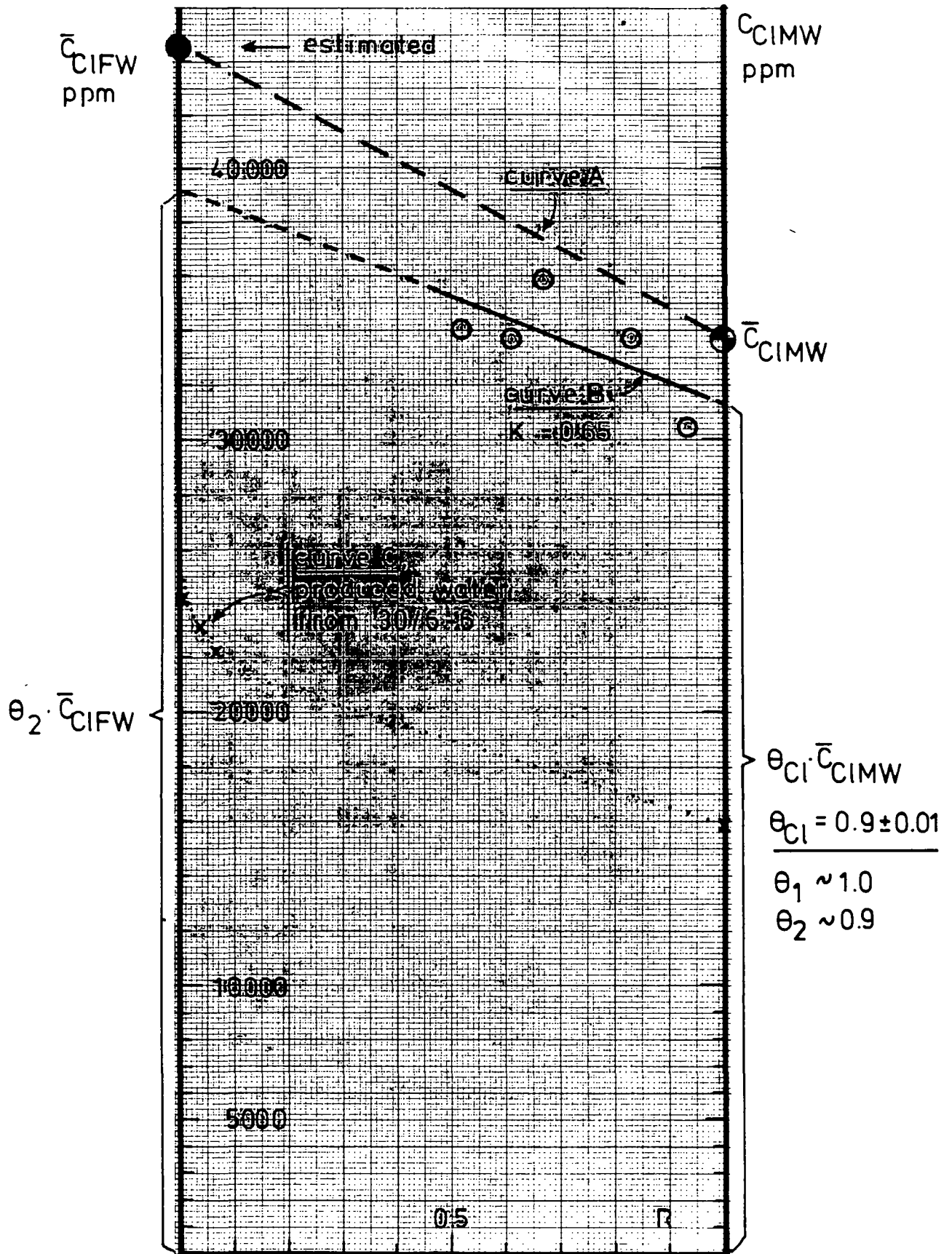


FIG 9: TRACER DIAGRAM FOR CHLORIDE

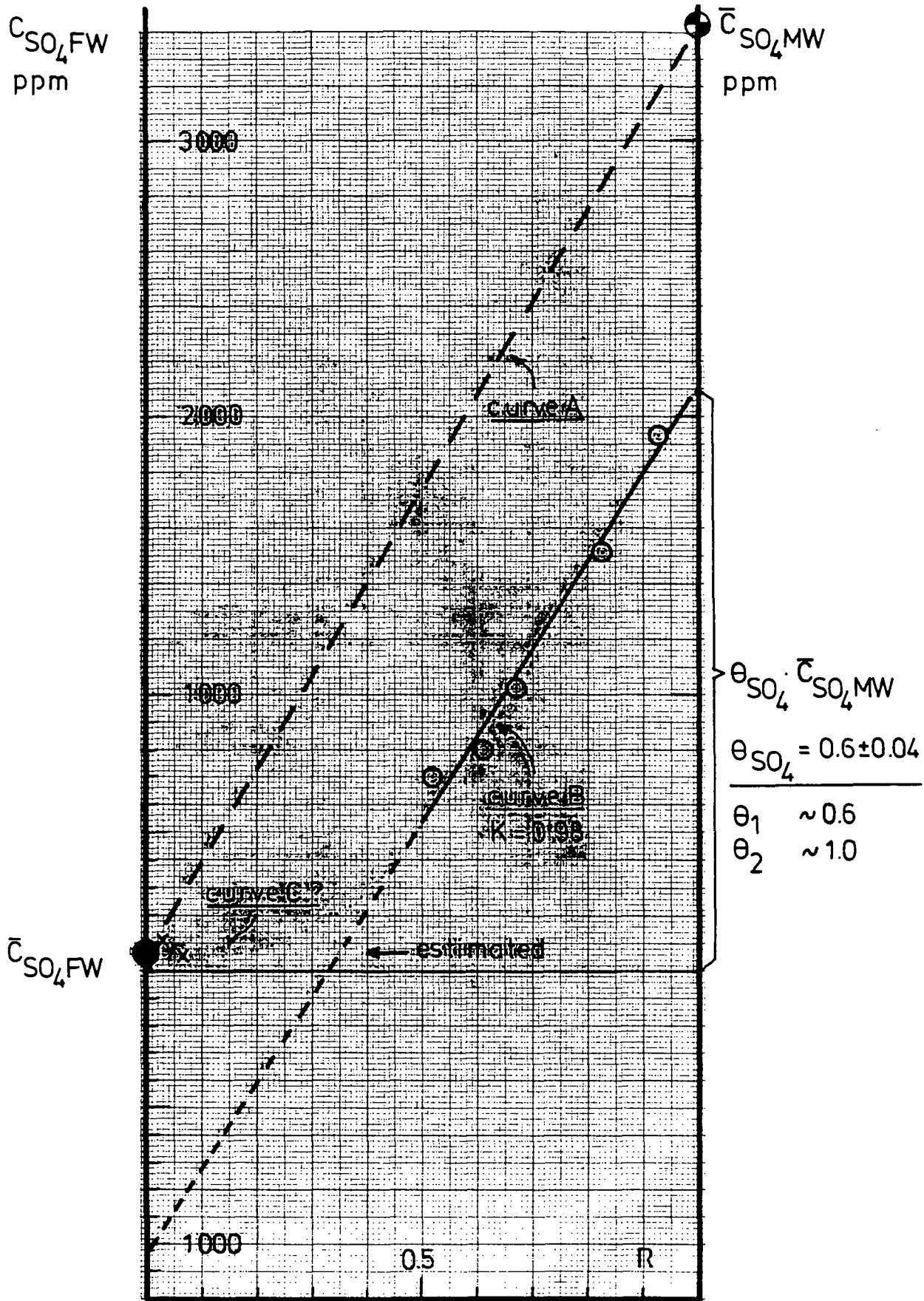


FIG 10: TRACER DIAGRAM FOR SULPHATE

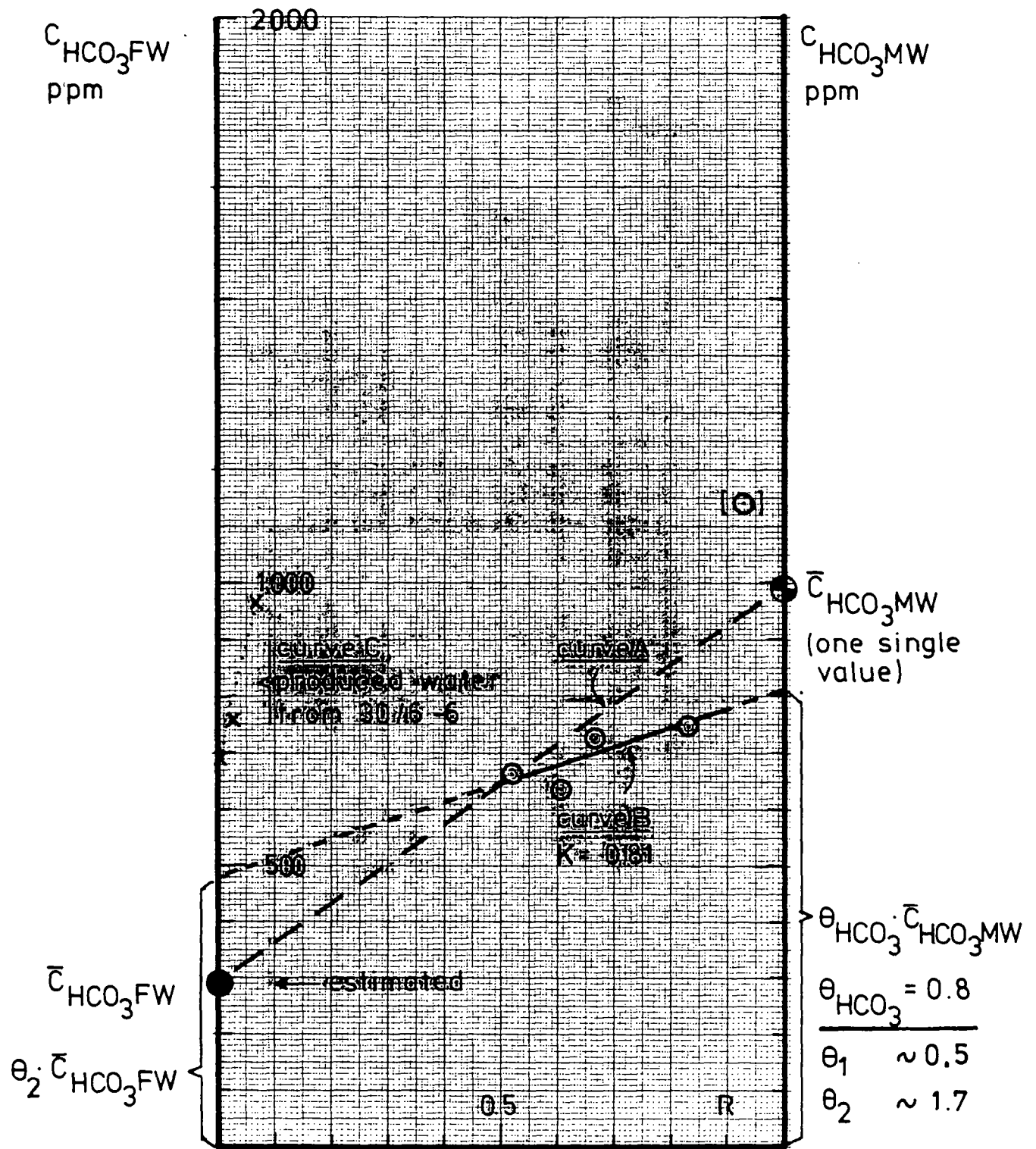


FIG 11: TRACER DIAGRAM FOR HYDROGEN CARBONATE