IN-SITU SATURATION DISTRIBUTIONS: THE KEY TO UNDERSTANDING CORE ANALYSIS

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ABSTRACT

In order to ensure accurate interpretation of core flood experiments, in-situ saturation measurements are considered to be essential. This paper provides a review of in-situ saturation measurement methods based on ionising radiation and incorporates gamma attenuation, X-ray attenuation and gamma emission. These techniques are routinely employed during reservoir and ambient condition core floods to determine the in-situ saturation distributions of up to three mobile phases. The measurement techniques are described, together with their relative strengths, weaknesses and accuracies thus enabling selection of the optimum technique for a particular application.

Examples of in-situ saturation measurements from studies of wettability and gravity drainage are presented to illustrate the value of this capability. Without this knowledge, core scale artefacts can lead to significant errors when interpreting experimental data. The ability to determine in-situ saturation measurements during gravity drainage enables oil and brine permeabilities to be derived. This capability is attractive since it enables key data to be generated in a flow regime which is representative of the reservoir.

INTRODUCTION

During coreflooding experiments it is common practice to monitor fluid inventories so that mean saturations within the core can be determined. However, it is known that significant spatial variation of fluid saturations can occur because of, for example: gravity override, viscous instabilities, capillary retention and rock heterogeneities. Consequently, the ability to measure in-situ saturations during coreflooding experiments is highly desirable so that an improved understanding of the flow processes and accurate interpretation of the results can be made.

A number of different methods of measuring in-situ saturations have been reported in the literature and a comprehensive summary is given in Reference 1. The only operational techniques which have been reported for three phase measurements involve ionising radiation which is the focus of this paper. Three dimensional data can be generated using tomographic methods but this is beyond the scope of this paper.

DESCRIPTION OF IN-SITU SATURATION MEASUREMENT TECHNIQUES

Gamma Attenuation

This technique involves a gamma source and detector which are located on opposite sides of a core and fluid saturations are determined by measuring the attenuation of the gamma radiation. The method for calculating saturations is described in Appendix 1. This method has been used by AEA for pipe flow measurements for more than

thirty years and has been used by British Petroleum for low pressure core flooding studies since 1985 [2]. AEA routinely uses the technique for two phase, in-situ saturation measurements and is currently extending these techniques to three phase, reservoir condition measurements.

Gamma sources emit discrete energies and do not suffer from artefacts which can be caused by distributed energy sources such as X-rays. The selection of the source isotope depends on the attenuation of the system under study. Americium-241 which emits 59.6 KeV gamma photon is commonly used for two phase measurements. Three phase gamma attenuation measurements require two discrete source energies (see Appendix 1) and the effect of using different energies has been assessed. Photon energy *A* was fixed at 59.6 KeV and the optimum photon energy *B* was found to be about 200 KeV and was independent of sodium iodide (NaI) dopant concentration. The nearest suitable isotope appears to be cesium-137 which emits gamma photons with energies of 511 and 662 KeV and has a half-life of 30.2 years. The minor loss of accuracy resulting from using the higher energy photon can be easily compensated by using NaI as a dopant in the brine.

A variety of gamma detectors are available but an array of discrete detectors is the only system which appears to be suitable for coreflooding experiments. Scintillation detectors linked to a photomultiplier tube are generally used since they give high counting efficiency, have adequate energy resolution and have been used in a variety of widths from 4 mm [2] to 75 mm [3]. Germanium detectors have excellent energy resolution but generally low counting efficiency so are not usually used.

X-Ray Attenuation

A number of laboratories now used X-ray attenuation to determine in-situ saturation data [4]. The principle is the same as gamma attenuation: an X-ray source and detector are located on opposite sides of a core and fluid saturations are determined by measuring the attenuation of the X-rays (see Appendix 1).

X-ray sources up to 225 KeV are commonly available but higher energy source can be obtained at an increased cost and decreased manoeuverability. The X-ray source is not mono-energetic and artefacts can be caused since the spectrum of energies can be changed by material surrounding the core ('beam-hardening'). Current developments in X-ray technology are working towards a mono-energetic source [5].

Several X-ray detectors are available including: image intensifiers, photodiode line arrays, xenon gas detectors and scintillation detectors. Image intensifiers can record two-dimensional data with a spatial resolution of 0.5 mm. Conventional systems typically involve 768 by 512 pixels with an 8 bit resolution of incident X-ray intensity, but such systems are not considered to be sufficiently accurate for quantitative core flooding experiments. AEA has been involved with the development of an Area Array Camera involving 1024 by 20 pixels and a resolution of 16 bits which gives sufficient precision. Photodiode line arrays are available with 1536 detectors at a pitch of 0.45 mm. These arrays are linear across the entire length and have a 12 bit resolution. Both xenon gas and scintillation detectors are used by medical or industrial X-ray computer tomograph (CT) systems. With such systems three dimensional data with a spatial resolution of about 0.5 mm can be achieved.

Gamma Emission

The gamma emission technique [6] involves labelling the hydrocarbon and aqueous phases with gamma emitting tracers and has been used routinely by AEA for more

than twelve years. Ferrocene is an organometallic molecule which can be synthesised from radioactive iron-59. It is used to label the hydrocarbon phase and is insoluble in water. Iron-59 emits gamma photons with energies of 1099 and 1292 KeV and has a half-life of 44.6 days. Potassium cobalticyanide is a salt which can be synthesised from radioactive cobalt-58. It is used to label the aqueous phase and is insoluble in oil. Cobalt-58 emits gamma photons with energies of 511 and 810 KeV and has a half-life of 70.8 days.

The same detectors are used for gamma attenuation and emission and this provides a degree of robustness since either method can be used interchangeably.

The intensity of emitted radiation from each tracer must be calibrated at a known saturation; it is usual to calibrate the aqueous tracer under fully saturated conditions and the oleic tracer at connate water conditions. Experimental saturations can then be calculated from the calibration values, thus:

$$S = \frac{I}{I_c} S_c \qquad 1$$

Since iron-59 and cobalt-58 emit gamma photons with different energies, the tracers can be used simultaneously if the photon intensity is detected with a multichannel analyser. A suite of computer programmes has been developed by AEA to deconvolute these measurements and provide the three phase saturation information.

Selection Of Measurement Technique

Many factors can be considered when selecting which technique to use for a particular application. The resolution of saturation, space and time are discussed in relation to each technique below. The compatibility of any dopants or tracers with the rock and fluid under investigation should be assessed prior to a test. Potential problems include adsorbtion on the rock surface, degredation or precipitation and their occurrence will be system specific. Care must be taken to ensure the dopants and tracers do not have a significant influence on the phase behaviour of the fluids. Conversely, the phase behaviour may influence the linear attenuation coefficients (attenuation technique) or the specific activities (emission technique) of the fluids. If these variations are significant then additional calibration measurements may be required.

Safety considerations are an important factor when selecting which technique to use. The low energy sealed sources used for gamma attenuation are relatively easy to handle and shield. High intensity X-ray sources can produce lethal doses but have the advantage that they can be switched off. The gamma emitting fluids used in the emission technique require the most stringent safety procedures because of their high energy and potential for contamination.

CALCULATION OF ACCURACIES

Intensity Measurement

The 'building block' for all radiation based measurements of in-situ saturation is a determination of photon intensity. In order to compare discrete measurements of intensity, it is necessary to normalise the measurement with respect to measurement duration, background radiation and radioactive decay. The normalised intensity is given by:

$$I = \frac{1}{t_L} (I_T' - I_G') \exp\left[ln2 \frac{t_E}{t_H} \right] \quad 2$$

It may be seen that I is a function of five independent variables and the associated statistical uncertainty can be calculated using standard error analysis [7]. For most practical measurements, this uncertainty is dominated by the uncertainty in total intensity which is given by the square root of the total intensity [8].

Attenuation Accuracies

It may be seen in Appendix 1 that for attenuation measurements fluid saturation is a function of eight independent variables for a three phase system (Equations 1.8, 1.9, 1.10) and a function of three independent variables for a two phase system (Equations 1.11, 1.12). These variables are measured intensities and each has an uncertainty which is discussed in the paragraph above. The statistical uncertainties for both three and two phase systems have been calculated using standard error analysis [7] and example results are given in Figures 1 and 2. The three phase results are for photon energies of 60 and 150 KeV and the two phase results are for 60 KeV. It can be seen that saturation measurements with an accuracy of 1% pore volume (PV) require photon intensities to be determined to an accuracy of 0.004% for a decane/brine/air system (Figure 1) and 0.04% for a decane/brine system (Figure 2). By adding a dopant to the brine (10% NaI), the accuracy of photon intensity measurements can be relaxed to 0.089% and 0.47% respectively. The results in Figures 1 and 2 are applicable to both gamma and X-ray attenuation measurements and are independent of equipment. The presence of a pressure vessel does not alter the results in Figures 1 and 2 but it will reduce the transmitted photon intensities. Ideally, the source intensity should be increased to compensate for the additional attenuation from the core holder but safety considerations may prevent this from being possible. In practice, low attenuation core holders are essential. The accuracy of photon intensity measurements which can be achieved in practice is equipment specific and is related to spatial and temporal resolution.

Using high speed electronics and low attenuation coreholders, gamma photons can be detected at rates up to 25,000 s-1 and the corresponding performance of this system is illustrated in Figures 3 and 4. Figure 1 shows that a saturation accuracy of 1% PV requires a photon intensity accuracy of 0.004% (0% NaI) and 0.089% (10% NaI) for a decane/brine/air system. These accuracies can be achieved for a range of spatial and temporal resolution as illustrated in Figure 3. For example, a spatial resolution of 40 mm^2 requires a measurement time of 417 minutes to give an intensity measurement with an accuracy of 0.004% (0% NaI). This measurement time is unacceptably long and dopants are required; for example, 10% Nal reduces the measurement time to 0.8 minutes for the same saturation and spatial resolutions. The equivalent decane/brine results from Figure 2 are illustrated in Figure 4 and a spatial resolution of 40 mm^2 requires a measurement time of 4.2 minutes to give a saturation accuracy of 1% PV (intensity accuracy of 0.04% with 0% NaI).

AEA have recently commissioned a 'Scanning Platform' which is based on X-ray attenuation using an Area Array Camera. Examples of the spatial and temporal resolutions are compared with gamma attenuation results in Figures 3 and 4. Six measured data point are included which give particular photon intensities corresponding to the gamma attenuation results. Other combinations of spatial and temporal resolution could be employed. It may be seen that for a given spatial

resolution, the temporal resolution is improved by an order of magniture compared to gamma attenuation. This improvement is a result of higher photon intensities and compact detectors.

Gamma Emission Accuracies

The statistical uncertainties for single tracer gamma emission measurements can be calculated from Equation 1 using standard error analysis [7]. Deconvolution of measurements involving two tracers is not amenable to calculation of statistical uncertainties but excellent results can be achieved as discussed below.

The technique was developed so that it was capable of measuring three-phase saturations at reservoir conditions using conventional steel coreholders but has relatively low spatial and temporal resolution. A typical arrangement involves measuring the mean saturation in a 18 mm wide section of a 45 mm diameter cylindrical core. In order to achieve a saturation accuracy of 1% PV for fluids with a 50% saturation, measurement times are about three minutes for a low pressure experiment and twenty minutes for a high pressure experiments involving a conventional steel core holder. This performance can be improved by the use of low attenuation core holders.

EXAMPLES OF IN-SITU SATURATION MEASUREMENTS

Wettability Characteristics

During waterflooding experiments, in-situ saturation measurements not only provide an independent residual oil saturation (ROS) determination, but by improving the understanding of the influence of wettability, it can assist in designing and performing experiments at rates which are representative of the reservoir. Data can be improved by the use of carefully designed wettability pre-studies [9] and the integrated application of in-situ saturation measurements and coreflood simulation.

Figures 5 and 6 and give an example of how wettability can alter the diplacement charateristics and the ROS. Figure 5 illustrates water flooding of a 400 mD water-wet outcrop core sample. A piston like imbibiton process was observed with very little oil production after breakthrough, leaving a ROS of 0.42 after 27 PV of injection. Following ageing in North Sea stock tank oil, the displacement characteritics were altered as illustrated in Figure 6. Following breakthrough there was a continued production of oil with resulting lower ROS of 0.21 after a similar throughput.

1-D Gravity Drainage

A large number of studies of gravity drainage have been conducted by AEA using long, vertical cores and results are presented for a water-wet outcrop sandstone core. The experiment was started with oil at connate water and then waterflooded to residual oil. Gas was injected at constant pressure at the top of the core and fluid was extracted at a constant volume flow rate at the bottom of the core.

Three phase in-situ saturations were determined throughout the experiments using the gamma emission technique and results are shown in Figures 7 and 8. During the early stages of the gas flood, the oil saturation can be seen to increase at certain locations showing the formation of an oil bank which moved down the core. A significant end effect was present in the oil and brine phases and means that the true residual oil saturation to gas was significantly lower than the mean oil saturation. Consequently,

experiments without in-situ saturation measurements could significantly over estimate the residual oil saturation to gas from mass balance results. The consistency of the saturation values is notable and demonstrates the high level of repeatability in the measurements.

These in-situ measurements can be transformed into flow rate information and may be used to calculate oil and water relative permeabilities [10]. Some example results are given in Figure 9. This data constitutes key reservoir engineering information which characterises film flow and is an advance on information available in the literature.

2-D Gravity Drainage in Heterogeneous System

The free drainage of brine in a two-dimensional, heterogeneous, vertical test section has been investigated using gamma attenuation in order to validate numerical simulations of the drainage process in more complex geometries. The porous medium consisted of unconsolidated sand with a central section of consolidated sand. Air was supplied to the top of the test section and brine drained from the bottom. The air/water in-situ saturation distributions were determined throughout the experiment using an array of sources and detectors which traversed the test section. An example of the air saturation at the end of the experiment is given in Figure 10.

CONCLUSIONS

A review of in-situ saturation measurement methods based on ionising radiation has been presented and incorporates gamma attenuation, X-ray attenuation and gamma emission. These techniques are routinely employed during reservoir and ambient condition core floods to determine the in-situ saturation distributions of up to three mobile phases.

The measurement techniques have been described, together with a method of calculating accuracies. The relative strengths and weaknesses of each method are discussed. X-ray attenuation can have a superior resolution of saturation, space and time compared with gamma attenuation but dopants are required for most three-phase applications. The gamma emission technique is the only practical means of determining in-situ saturations during corefloods under extreme conditions where steel pressure vessels are required.

Examples of in-situ saturation measurements from studies of wettability and gravity drainage are presented to illustrate the value of this capability. Without this knowledge, core scale artefacts and capillary end effects can lead to significant errors when interpreting experimental data. The ability to determine in-situ saturation measurements during gravity drainage enables oil and brine permeability data to be derived. This capability is attractive since it enables key data to be generated in a flow regime which is representative of the reservoir.

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NOMENCLATURE

I	normalised photon intensity
x	path length of photon through adsorber
μ	linear attenuation coefficient
ϕ	porosity
S	saturation
s	saturation value during a test
t	time
'	unnormalised data

Subscripts

o	incident
r	rock
T	total
c	calibration
E	elapse
G	background
H	halflife
L	live time
j	phase j = 1, 2 ... n
A, B	energy of incident photons

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APPENDIX 1: CALCULATION OF SATURATION FROM ATTENUATION MEASUREMENTS

The attenuation of ionising radiation is given by [8]:

$$I = I_o exp(-x\mu) \tag{1.1}$$

The linear attenuation coefficient for a rock saturated with "n" phases is:

$$\mu = \mu_r + \phi \sum_{j=1}^{n} (S_j \mu_j) \tag{1.2}$$

hence combining Equations 1.1 and 1.2 and taking logs

$$ln I = ln I_i - x\mu_r - x\phi \sum_{j=1}^{n} (S_j \mu_j) \tag{1.3}$$

$$\text{By definition } 1 = \sum_{j=1}^{n} S_j \tag{1.4}$$

In order to solve Equations 1.3 and 1.4 for saturation, (n - 1) independent measurements are necessary. Since μ is a function of incident energy, these independent measurements can be made at (n - 1) discrete energies. For example, a three phase system requires measurements at two energies (A and B) and Equations 1.3 and 1.4 become:

$$ln I_A = ln I_{iA} - x\mu_{rA} - x\phi(S_1 \mu_{1A} + S_2 \mu_{2A} + S_3 \mu_{3A}) \tag{1.5}$$

$$ln I_B = ln I_{iB} - x\mu_{rB} - x\phi(S_1 \mu_{1B} + S_2 \mu_{2B} + S_3 \mu_{3B}) \tag{1.6}$$

$$1 = S_1 + S_2 + S_3 \tag{1.7}$$

By taking six reference measurements and two test measurements (see Table 1) then it can be shown that:

$$S_1 = \frac{(ln I_{2B} - ln I_{3B})(ln I_A - ln I_{3A}) - (ln I_{2A} - ln I_{3A})(ln I_B - ln I_{3B})}{(ln I_{1A} - ln I_{3A})(ln I_{2B} - ln I_{3B}) - (ln I_{1B} - ln I_{3B})(ln I_{2A} - ln I_{3A})} \tag{1.8}$$

$$S_2 = \frac{-(ln I_{1B} - ln I_{3B})(ln I_A - ln I_{3A}) + (ln I_{1A} - ln I_{3A})(ln I_B - ln I_{3B})}{(ln I_{1A} - ln I_{3A})(ln I_{2B} - ln I_{3B}) - (ln I_{1B} - ln I_{3B})(ln I_{2A} - ln I_{3A})} \tag{1.9}$$

$$S_3 = 1 - S_1 - S_2 \tag{1.10}$$

For a two phase system, two reference measurements and one test measurement are required and:

$$s_1 = \frac{\ln I_A - \ln I_{2A}}{\ln I_{1A} - \ln I_{2A}} \qquad 1.11$$

$$s_2 = 1 - s_1 \qquad 1.12$$

TABLE 1 CALIBRATIONS FOR ATTENUATION MEASUREMENTS

Measurement	S_1	S_2	S_3	I_o	I
Reference	1	0	0	I_{oA}	I_{1A}
	1	0	0	I_{oB}	I_{1B}
	0	1	0	I_{oA}	I_{2A}
	0	1	0	I_{oB}	I_{2B}
	0	0	1	I_{oA}	I_{3A}
	0	0	1	I_{oB}	I_{3B}
Test	s_1	s_2	s_3	I_{oA}	I_A
	s_1	s_2	s_3	I_{oB}	I_B

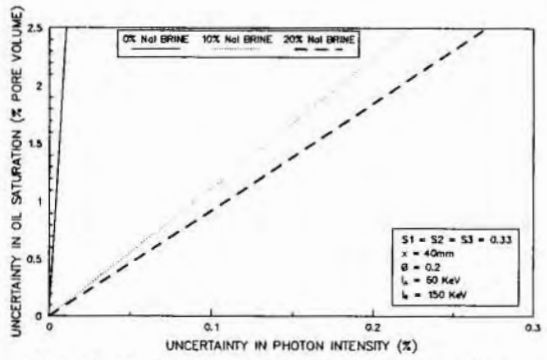

FIG 1: SATURATION RESOLUTION FOR THREE PHASE ATTENUATION

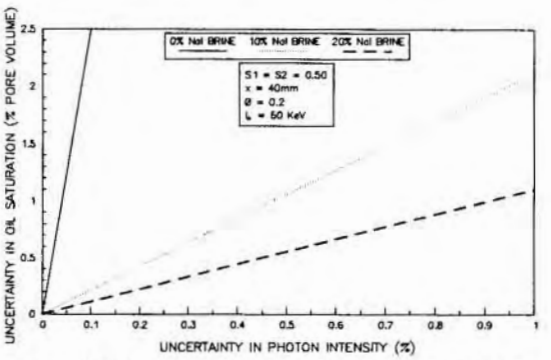

FIG 2: SATURATION RESOLUTION FOR TWO PHASE ATTENUATION

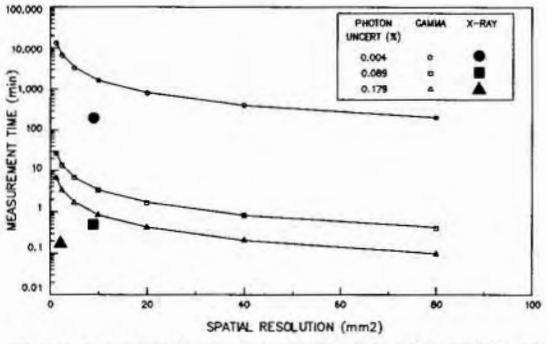

FIG 3: SPATIAL/TEMPORAL RESOLUTION FOR THREE PHASE ATTENUATION

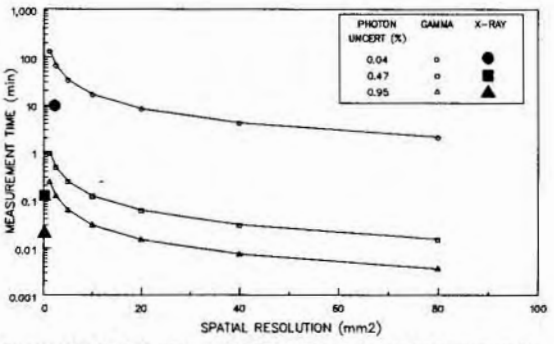

FIG 4: SPATIAL/TEMPORAL RESOLUTION FOR TWO PHASE ATTENUATION

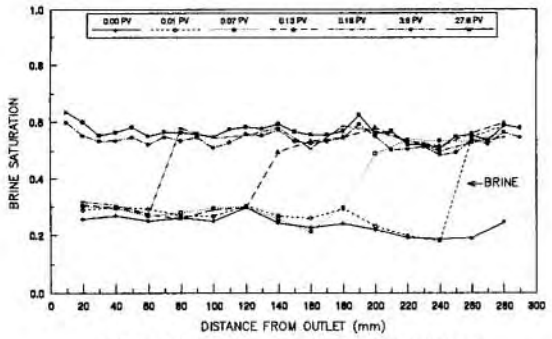

FIG 5: SATURATION PROFILES DURING WATERFLOOD WATER WET CORE

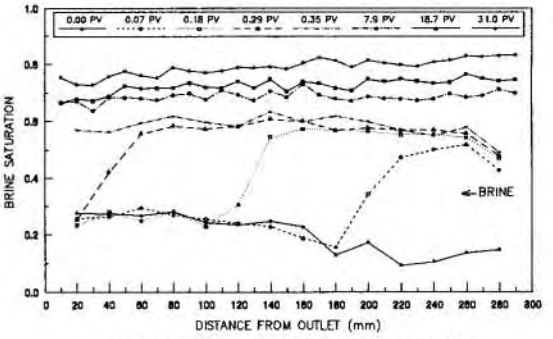

FIG 6: SATURATION PROFILES DURING WATERFLOOD AGED CORE

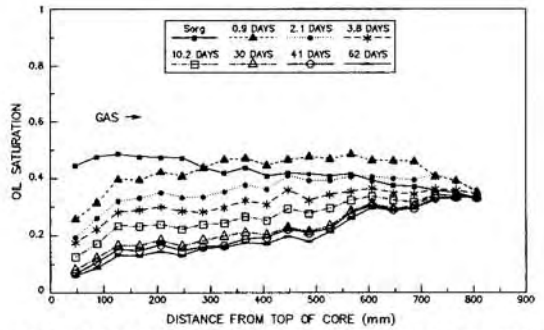

FIG 7: OIL SATURATION DISTRIBUTION DURING TERTIARY GAS INJECTION

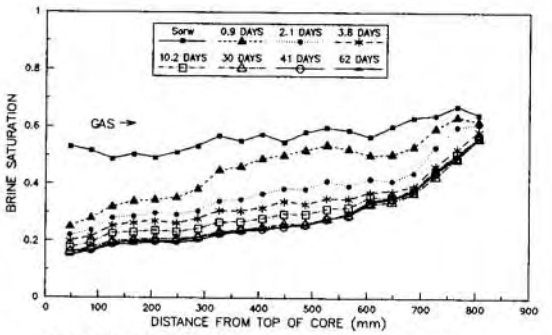

FIG 8: BRINE SATURATION DURING TERTIARY GAS INJECTION

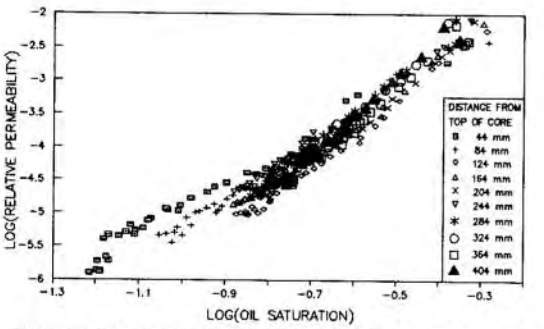

FIG 9: OIL RELATIVE PERMEABILITIES DURING GRAVITY DRAINAGE

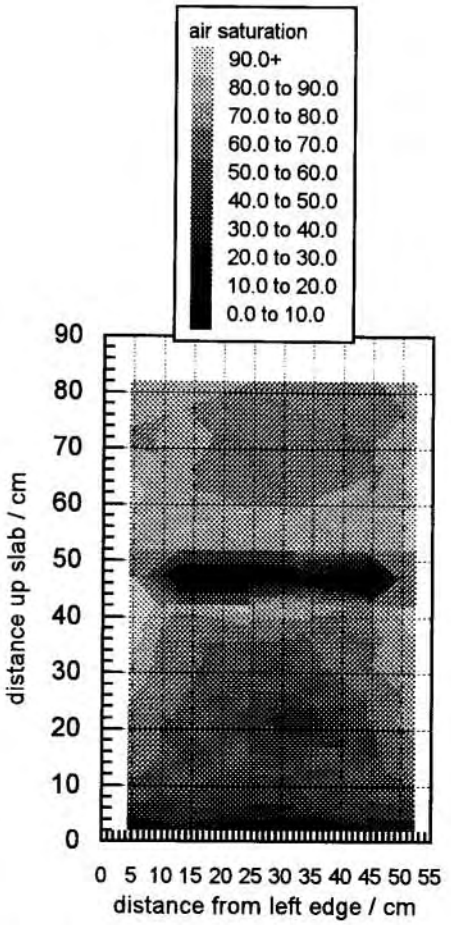

FIG 10 FREE DRAINAGE OF BRINE IN A HETEROGENEOUS 2-D SLAB