1974/12
COPY3

Restricted until after publication.
Manuscript submitted for publication
to: APEA 1974

DEPARTMENT OF MINERALS AND ENERGY

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

Record 1974/12

LABORATORY STUDIES OF GAS DISPLACEMENT FROM SANDSTONE RESERVOIRS HAVING STRONG WATER DRIVE

by

B.A. McKay

Record 1974/12

LABORATORY STUDIES OF GAS DISPLACEMENT FROM SANDSTONE RESERVOIRS HAVING STRONG WATER DRIVE

by

B.A. McKay

Laboratory Studies of Gas Displacement from Sandstone Reservoirs having Strong Water Drive

by

B.A. McKay

Bureau of Mineral Resources
CANBERRA

ABSTRACT

Investigations by the Petroleum Technology Section of the Bureau of Mineral Resources have shown that a substantial residual gas saturation is trapped behind the flood front in gas-producing reservoirs having a strong water-drive; the volume of gas trapped may be as high as 44 percent of pore space, and lies within the same range as residual oil saturation in a flooded out oil reservoir.

Core samples from gas productive reservoirs in three Australian sedimentary basins have been subjected to laboratory tests to measure this effect. The tests comprised capillary pressure measurements, water-flooding by dynamic-displacement and imbibition at ambient and elevated temperatures, and repeat gas recovery measurements in core samples exhibiting variations in irreducible water saturation.

The results show a loose correlation between porosity and residual gas behind the flood front in these samples. Temperature appears to have little effect on the residual gas saturation. Gas recovery, however, is strongly dependent on the irreducible water saturation established prior to flooding.

INTRODUCTION

In the early history of natural gas development, it was assumed by most technologists that recovery from natural gas reservoirs would generally be very high, largely because of the mobility of gas. This was supported by certain displacement phenomena such as the ease with which gas channelling occurred in oil reservoirs and the generally low equilibrium saturation at which gas flowed during gas-oil or gas-water relative permeability tests. It was therefore believed that when gas was the produced and/or displaced phase (as in a water drive), recovery to gas would be very high.

Investigations since 1952 have shown that high recovery from a natural gas reservoir does not generally prevail, particularly when the gas is in communication with a major aquifer. It has been shown, both in laboratory and field tests, that the volume of residual gas remaining behind in a flooded reservoir is substantial, and may equal or exceed the total volume of gas recovered. On the other hand, in gas reservoirs producing by expansion drive only, the recovery at depletion may approach 70 to 80 percent of pore volume (up to 90 percent of gas in place).

In Australia, notably in the Northwest Shelf and in the offshore Gippsland Basin, large gas reservoirs are in communication with extensive aquifers. The laboratory work described in this paper was carried out to study the gas recovery/residual gas saturation characteristics of six of these reservoirs by total water displacement.

The tests, which were carried out on selected core samples, can be grouped as follows:

- Gas recovery tests from core samples at ambient and elevated temperatures.
- The effect of variation in initial (interstitial) water saturation on gas recovery.
- Drainage-imbibition capillary pressure tests.
- Comparison of residual gas and residual oil saturations at floodout.

The results of the tests enable a general appraisal of gas recovery characteristics to be made under complete water displacement, considering such diverse reservoir parameters as porosity, permeability, interstitial water saturation, and temperature. A comparison can also be drawn between residual oil and residual gas saturation in similar types of reservoir rock at floodout conditions.

DISCUSSION OF LABORATORY METHODS

A. Core preparation

Core samples were selected from six gas reservoirs: the Barracouta and Marlin fields in the Gippsland Basin, the North Rankin, Goodwyn, and Angel fields in the Dampier Sub-basin; and the Walyering field in the Perth Basin.

Twenty-five test plugs, 1⅛ inches in diameter, were drilled parallel to bedding planes from these core samples. The plugs were trimmed to approximately 1 inch in length, then extracted and dried. After cooling, porosity and permeability to nitrogen were measured, whereupon each plug was saturated with distilled water.

The plugs were then prepared for gas recovery tests by flushing them to irreducible water saturation with humidified nitrogen; this was carried out in a Hassler cell (Fig. 1). To obtain maximum gas contact with the sample pore systems, the flushing was carried out against a back pressure. Irreducible water saturation values were obtained in each case from the results of mercury injection capillary pressure tests of adjacent ¾-inch plugs at an injection pressure of 1000 psig.

B. Gas recovery tests

Displacement by water imbibition at ambient temperature

Gas recovery testing was conducted by placing a core sample (at irreducible water saturation) in contact with water at its base (Fig. 2). Water rising into the sample pore system under the influence of capillary suction displaced gas in the pores to a residual saturation.

Geffen et al. (1952) demonstrated the reliability of the imbibition process for complete water flushing of natural core samples. This was confirmed in our tests by using a comparison dynamic displacement flooding process on four of the plugs. These plugs were waterflooded at an injection rate of 10 ml/h to residual gas saturation after establishing similar irreducible water in the manner already described.

The gas recoveries and residual gas saturations obtained by imbibition for the 25 plugs are shown in Table 1. Table 2 presents a comparison between the imbibition and dynamic displacement methods of waterflooding on four of the samples while Figure 3 depicts gas displacement by the water imbibition process in a core sample from the Goodwyn reservoir.

Displacement by water imbibition at elevated temperature

The effect of temperature on the recovery efficiency of gas under water drive was studied in another series of tests. These were carried out by water imbibition at a stabilized temperature of 75°C, using the four samples as prepared for dynamic displacement tests. The results are shown in Table 2 in conjunction with displacement at ambient temperature.

The effect of variation in initial water saturation on the gas recovery

Four core plugs were selected for these tests, one each from the Marlin, Goodwyn, North Rankin, and Angel gas reservoirs. The samples were dried and saturated with distilled water, then flushed with humidified nitrogen to an initial water saturation of 40 percent of pore volume. Each of the four plugs was then tested for gas recovery at this water saturation, using the imbibition displacement process. Subsequently, the plugs were dried and again prepared for separate gas recovery tests using initial water saturations of 30, 20 and 10 percent of pore volume; the final test was carried out on a dry core. The results are shown in Table 3 and for the Goodwyn sample only in Figure 4.

Drainage - imbibition capillary pressures

The initial preparation of samples for gas recovery tests included capillary pressure measurements for determination of interstitial water saturations. As already mentioned, this was done for all the samples adjacent to those included in Table 1 by using the mercury injection method.

By extending these tests to include both injection and withdrawal (drainage and imbibition), it is possible to define the characteristics so far measured by water imbibition or dynamic water displacement. That is, in addition to determining irreducible water saturation by mercury injection, hydrocarbon recovery and residual hydrocarbon saturations can be measured by mercury withdrawal. These factors are shown in the diagram in Figure 5.

Capillary pressure tests can also define the effects of a variable initial water saturation on the recovery/residual hydrocarbon saturation. This was demonstrated on three $\frac{3}{4}$-inch diameter plugs cut adjacent to the Goodwyn sample referred to in Table 2. Using different final injection pressures for each plug, three values of initial water saturation were established (45, 28, and 13 percent of pore volume); the recovery and residual hydrocarbon saturations were then determined in each case by capillary withdrawal. The results of these tests are also shown in Figure 5.

Comparison of residual gas and residual oil saturation at floodout

Three of the samples used in the gas recovery tests in Table 3 (Marlin, Goodwyn, and Angel reservoirs) were subjected to oil recovery/residual oil saturation measurements, in order to directly compare residual oil and gas saturations at floodout in similar types of sample material.

The plugs were dried, saturated with distilled water, and then flushed in a Hassler cell with a refined viscous mineral oil to establish irreducible water saturation. The mineral oil was displaced by a light refined oil (Soltrol-C core test fluid).

A waterflood was carried out on each of the three plugs at a pumping rate of 10 ml/h; the total oil recovery and residual oil saturation were measured at floodout conditions and the results of these tests are shown in Figure 6.

DISCUSSION OF LABORATORY RESULTS

Gas recovery tests

Flooding by water imbibition

The results of the tests listed in Table 1 show gas recoveries in the range 37 to 60 percent of pore volume, with gas saturations varying from 44 to 24 percent of pore volume remaining at floodout. In general, the amount of gas displaced by water from the samples considerably exceeds the gas remaining in the reservoir; this is particularly noticeable where high porosities (> 20 percent) are present. Conversely, when lower porosities are encountered, the ratio of recovered to residual gas approaches or exceeds one.

This suggests a relation between porosity and recovery characteristics; a plot of residual gas saturation against porosity was therefore made (Fig.7). This plot shows increasing residual gas saturation with decreasing porosity, although divergence from this relation is apparent in some samples. No obvious relation exists between permeability and gas saturation.

These characteristics have also been examined by other investigators (Chierici et al., 1963; Katz et al., 1966); data derived by Katz et al. are also shown in Figure 7.

Flooding by dynamic displacement

Dynamic displacement has generally been a standard laboratory technique for waterflooding of core samples. In particular this method expresses the characteristics of water injection (secondary recovery) into a permeable medium where oil is the displaced phase. However, in the case of large reservoirs where movement of the water-table is comparatively slow, displacement is dominantly controlled by capillarity, and water advance is probably equal to or less than the natural imbibition rate. Therefore, laboratory imbibition displacement should adequately define the flooding characteristics in reservoirs of the latter type.

In the case of gas reservoirs, however, it seems to be immaterial which displacement technique is used. Crowell et al. (1966) have suggested that gas recovery by water displacement is essentially insensitive to flooding over a broad range of rates. The results in Table 2, showing dynamic displacement (at 10 ml/h) and imbibition flooding characteristics in the same sample, also confirm this. Although minor variations in irreducible water saturation occurred within each group of tests, the recovery characteristics at floodout for each plug were essentially the same by either technique.

During dynamic displacement flooding, it is interesting to note that significant two-phase (gas-liquid) flow from the effluent rarely occurred after flooding water reached the outflow face. Apparently, in this type of displacement the flood front is extremely short, and transition from irreducible water saturation before the front to final water and residual gas saturation behind the front is abrupt. Although not as obvious, this condition would also be expected to prevail during water imbibition into a gas reservoir.

Imbibition at elevated temperatures

The ambient conditions in which most laboratory core testing is carried out do not take into account all the factors which may have an influence on hydrocarbon production under reservoir conditions. Certain of these, (such as wetting properties) may be difficult to interpret and duplicate. The effects of other parameters such as temperature and pressure can often be closely simulated in the laboratory, with direct application to the reservoir.

Table 2 presents gas recoveries by water displacement at ambient and elevated temperatures. With one exception, the four test samples indicate that temperature does not affect the recovery characteristics within the range studied.

The one exception (Marlin), which is a highly permeable core sample, indicated a lower gas recovery at simulated reservoir temperatures than that measured under ambient conditions. This could be attributed to a lower interfacial tension at increased temperature, which in this particular sample resulted in reduced water saturation and a greater residual gas. A further study of this effect with additional equipment for flooding by dynamic displacement would be warranted.

Geffen et al. (1952) and Chierici et al. (1963) studied both the factors of temperature and pressure on gas recovery in laboratory samples and in field conditions under the influence of water drive. They concluded that neither factor appears to alter the gas saturation characteristics, and that recovery can generally be simulated in simple laboratory displacement tests on small core samples at ambient temperature and pressure.

Gas recovery with a variable initial water saturation

Various gas recovery tests in the Petroleum Technology Laboratory have shown that, with a reduction in initial water saturation, a nearly corresponding increase in gas recovery occurred, with only minor changes in residual gas saturation. Data in Table 3 present additional confirmation of this effect over a measured range of irreducible water saturations between 0 and 40 percent of pore volume. In each of the samples tested, the greatest increase in residual gas saturation occurred when irreducible water was less than 20 percent of pore volume.

Crowell et al (1966) have also reported on this, but with a more constant increase in residual gas saturation with decreasing irreducible water. They have also suggested that in waterflooded gas reservoirs the irreducible water occupies the finest-size pore spaces, residual gas the intermediate, and the flooding water the coarsest pores. In practice, the interstitial (irreducible) water occupies a position in all the pore samples but only coats the walls of the coarse and intermediate pores, while completely saturating the finer pores.

Tests we have carried out have shown that the residual gas volume remained essentially constant (Table 3) when the samples were waterflooded at the three initial water saturations of 40, 30, and 20 percent of pore volume. In effect, the residual gas in these tests is 'locked' within the same intermediate pore system, while the increased production of gas and saturation by flooding water is at the expense of the (decreasing) irreducible water in the coarse pores.

As irreducible water decreases below 20 percent saturation, the residual gas increases to a maximum value which occurs when a dry core is water-flooded. This suggests a movement of the residual gas from the intermediate to the finer pores, where less of the pore space is contacted by the flooding water under the prevailing capillary pressure conditions.

Drainage - imbibition capillary pressure curves

In this series of tests, a range of irreducible water saturations between 13.4 and 44.4 percent of pore volume was established by mercury injection. The subsequent withdrawal (or imbibition) curve shows recovery characteristics similar to those measured by water displacement (Goodwyn, Table 2). However, mercury withdrawal does indicate a trend towards lower residual gas at higher initial water saturations than those shown in Table 2.

The mercury injection method of determining these capillary relationships is extremely simple, and in the case of clean homogeneous sands such as the sample tested, the recovery results appear to correlate reasonably well with those of other techniques.

Unfortunately, mercury injection-withdrawal test results are not always reliable; differences in residual gas saturations of the order of 20 percent of pore volume have been experienced between the mercury withdrawal and the standard water displacement method in some instances. The reason may be differences in wetting, for, particularly when clays are present in a sample, mercury may no longer represent a non-wetting fluid. Where clays are present, it would therefore be advisable to use drainage-imbibition data determined by mercury injection with some caution.

Residual oil and gas saturation at floodout

Waterflood displacement tests (Fig. 6) showed similar residual hydrocarbon saturations when either oil or gas was used as the saturating (non-wetting) phase. However, a marked difference between the oil and gas displacement characteristics at water breakthrough was shown in the same sample. The displacement of oil by water was generally characterized by significant production of oil after water breakthrough. As noted previously, gas production essentially ceases when the floodfront reaches the sample outlet face.

Crowell et al (1966) have observed that production of trapped gas into the flooding water can occur by diffusion, after the passage of the floodfront. However, most investigators agree that this effect is essentially a laboratory phenomenon which may be recognized in particular from an imbibition displacement curve. It is generally conceded that diffusion probably does not play a significant role in gas production by water drive under reservoir conditions.

CONCLUSIONS

The foregoing tests have demonstrated that a complete water drive mechanism does not necessarily result in the efficient displacement of gas from a reservoir.

The tests have also demonstrated that -

(1) Residual gas saturation at floodout shows a general relation to porosity, but none to permeability.

(2) Temperature does not alter the recovery characteristics of a natural gas reservoir producing by water drive.

(3) The recovery characteristics of a gas reservoir under water drive can be determined equally well by water imbibition or by dynamic displacement; drainage imbibition capillary pressure tests can also be used for this purpose but with less reliable results.

(4) The initial (irreducible) water saturation has greater control over gas recovery than over residual gas saturation at floodout.

(5) At floodout, residual saturations are similar when either oil or gas is the initial saturating medium.

(6) The foregoing studies lead to a consideration for improving the recovery of certain large gas reservoirs producing under water drive, by increasing the gas withdrawal rate. This may convert a 100 percent water drive to a partial water drive, thereby retarding pressure maintenance and water advance while enhancing gas expansion within the reservoir.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Director, Bureau of Mineral Resources, Geology & Geophysics, Canberra. The author wishes to thank B.O.C. of Australia, Esso Exploration and Production Australia Inc., and Hematite Petroleum Pty Ltd for permission to use samples for this project. Acknowledgement is also given for the technical assistance of I. Donald, Petroleum Technology Section, Bureau of Mineral Resources.

REFERENCES:

Chierici, G.L., G.M. Ciucci and G. Long, 1963 - Experimental research on gas saturation behind the water front in gas reservoirs subjected to water drive. Proc. Sixth World Petrol. Cong., pp. 483-98.

Crowell, D.C., G.W. Dean, and A.G. Loomis, 1966 - Efficiency of gas displacement from a water-drive reservoir. U.S. Bur. Mines Bull., Rep. Invest. 6735

Geffen, T.M., D.R. Parrish, G.W. Haynes and R.A. Morse, 1952 - Efficiency of gas displacement from porous media by liquid flooding. Trans. AIME, V. 195 pp. 29-38.

Katz, D.L., M.W. Legatski, M.R. Tek, L. Gorring, and R.L. Nielsen, 1966 - How water displaces gas from porous media. Oil Gas J. 64(2), pp. 55-60.

Table 1

Gas recovery characteristics by water displacement

Field	Sample	Permeability to nitrogen (md.)	Porosity (% bulk volume)	Sample fluid saturation (% pore volume)			Lithology
				Irreducible water	Gas recovery	Residual gas	
Barracouta	1	212	23.6	21.2	53.0	25.8	Sst; f.gr. slty carb, mic.
	2	527	30.9	13.8	60.5	25.7	as above.
	3	1146	29.9	17.6	57.9	24.5	Sst; f.gr. slty
	4	412	27.3	15.5	53.9	30.6	Sst; f.gr. slty carb., arg.
Marlin	1	5400	21.6	20.3	54.3	25.4	Sst; c.gr. to v.c gr.
	2	5600	19.7	21.1	54.4	24.5	Sst; m.gr. to v.c.gr.
	3	105	9.2	18.9	37.2	43.9	Sst; v.f.gr. to v.c.gr.
North Rankin	1	1050	23.8	12.0	49.0	39.0	Sst; m.gr. to c.gr.
	2	476	21.5	12.8	52.7	34.5	Sst; m.gr. to v. c.gr.
	3	757	19.3	15.0	48.0	37.0	Sst; m.gr. to c. gr. sl. pyr.
	4	187	25.7	21.7	49.0	29.3	Sst; v.f.gr. slt
	5	724	15.7	15.0	45.5	39.5	Sst; m.gr. slty
	6	445	14.8	20.7	51.5	27.8	Congl.
Goodwyn	1	239	24.9	10.5	54.0	35.5	Sst; f.gr. to m.gr.
	2	43	21.8	12.8	55.2	32.0	Sst; f.gr. to m. gr. slty
	3	18	20.1	25.7	46.8	27.5	Sst; f.gr. to m. gr. sl. carb.
	4	140	22.0	16.0	49.4	34.6	Sst; m.gr. to c. gr.
	5	2700	22.5	16.0	47.9	34.1	Sst; v.c.gr.
Angel	1	198	19.6	12.0	49.0	39.0	Sst; m.gr. glauc
	2	397	19.1	15.8	48.2	36.0	Sst; m.gr. to c. gr. glauc.
	3	235	13.7	19.5	50.0	30.5	Sst; f.gr. to v.c gr. glauc.
	4	370	18.4	19.4	47.2	33.4	Sst; m.gr. to c.gr glauc.
	5	359	15.8	23.8	46.0	30.2	Sst; f.gr. to m. gr. glauc.
Walyering	1	7.1	11.3	20.2	37.8	42.0	Sst; f.gr. to c.gr.
	2	1.0	12.0	32.0	43.1	24.9	Sst; f.gr. to m. gr.

Table 2

Flooding characteristics at ambient and elevated temperatures

Field	Sample	Permeability to nitrogen (md)	Porosity (% bulk volume)	Sample fluid saturation (% pore volume)								
				Water imbibition (ambient temp.)			Dynamic displacement (ambient temp.)			Water imbibition (elevated temp - 75°C)		
				Irreducible water	Gas recovery	Residual gas	Irreducible water	Gas recovery	Residual gas	Irreducible water	Gas recovery	Residual gas
Marlin	2	5600	19.7	21.1	54.4	24.5	20.0	52.9	27.7	20.8	41.8	37.4
North Rankin	3	757	19.3	15.0	48.0	37.0	14.7	49.2	36.1	14.7	49.0	36.3
Goodwyn	2	43	21.8	12.8	55.2	32.0	13.7	56.3	30.0	10.8	55.1	34.1
Angel	2	397	19.1	15.8	48.2	36.0	14.7	47.0	38.3	16.3	48.5	35.2

Table 3

Flooding characteristics with variable initial water saturation

Field	Sample	Approximate initial water saturation (% pore volume)													
		40			30			20			10			(Dry core)	
		Recovery characteristics – % pore volume													
		Initial water saturation	Gas recovery	Residual gas	Initial water saturation	Gas recovery	Residual gas	Initial water saturation	Gas recovery	Residual gas	Initial water saturation	Gas recovery	Residual gas	Gas recovery	Residual gas
Marlin	1	40.6	36.8	22.6	28.4	45.5	26.1	20.3	54.3	25.4	3.1	65.5	30.4	66.7	32.3
North Rankin	1	36.0	32.7	31.3	30.2	38.9	30.1	19.7	47.0	33.3	10.9	50.8	38.3	54.2	45.8
Goodwyn	1	40.1	29.2	30.7	32.4	36.8	30.8	17.9	49.4	32.7	10.5	54.0	35.5	65.0	35.0
Angel	1	39.1	25.0	35.9	30.5	35.9	33.6	19.4	45.7	34.9	12.0	49.0	39.0	56.6	43.4

Figure 1: Apparatus for flushing core samples to irreducible water saturation.

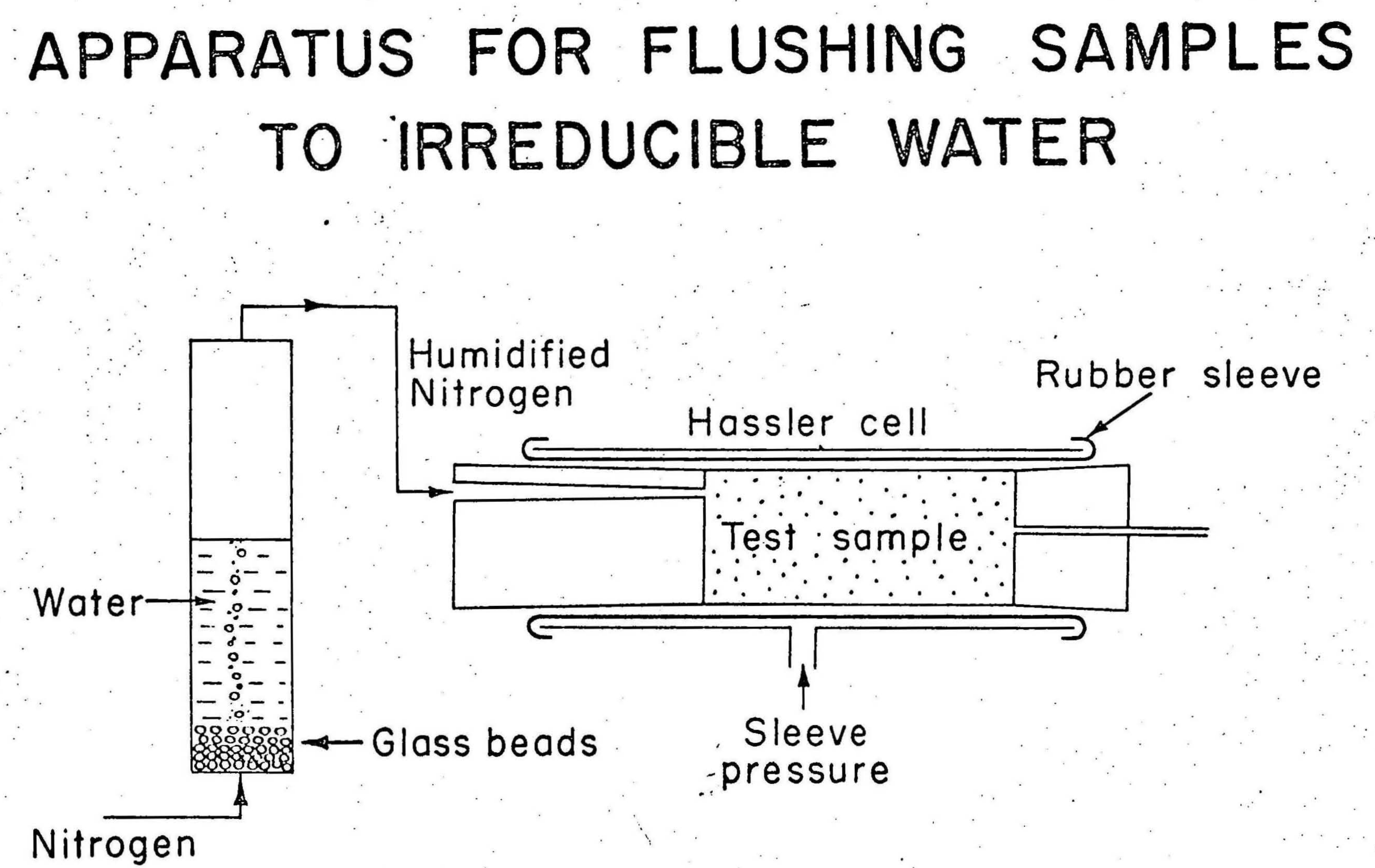
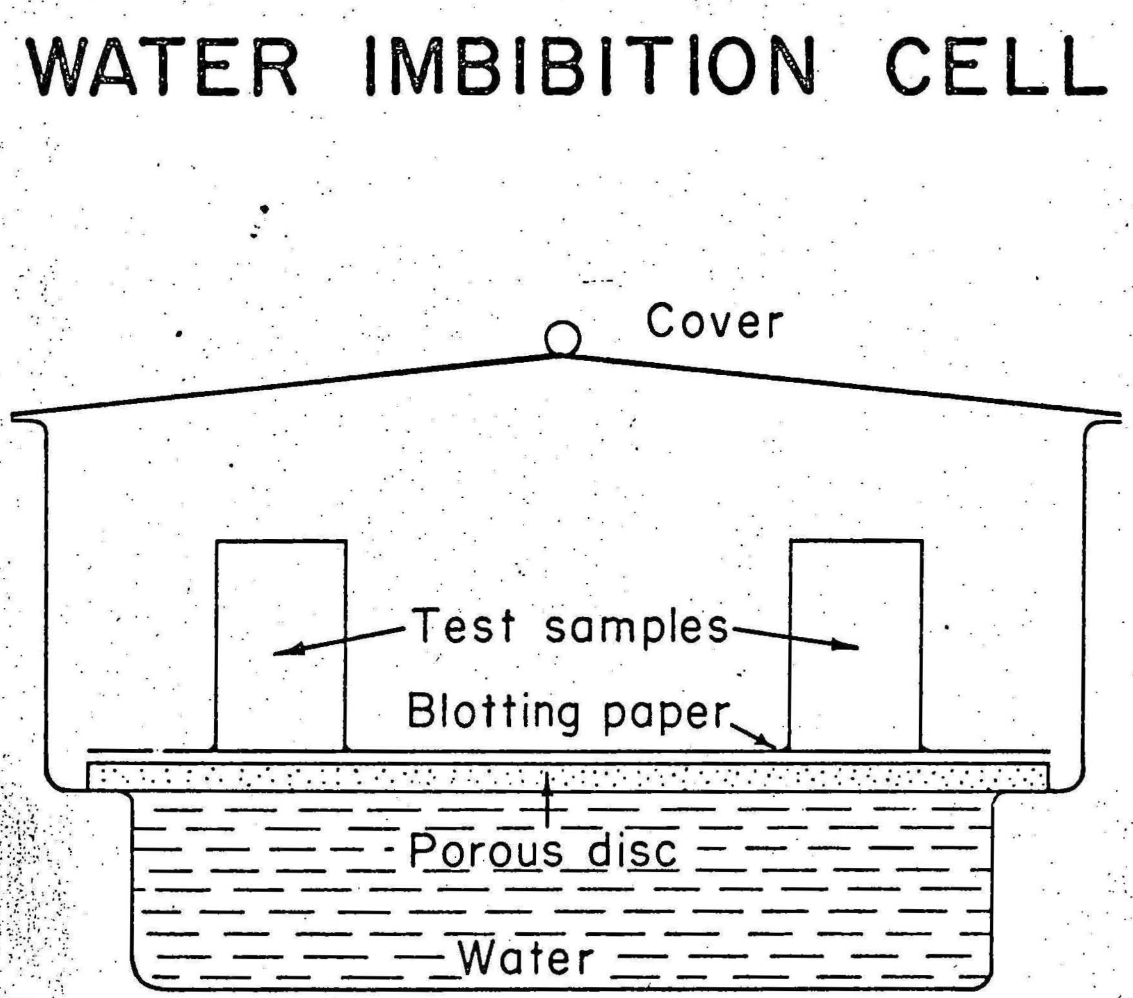


Figure 2: Cell for determining gas recovery by water imbibition.



[redacted]Fig[redacted]3: [redacted]Wat[redacted]mbi[redacted]icn [redacted]t d[redacted] - Goodwyn[redacted]core sample.[redacted]

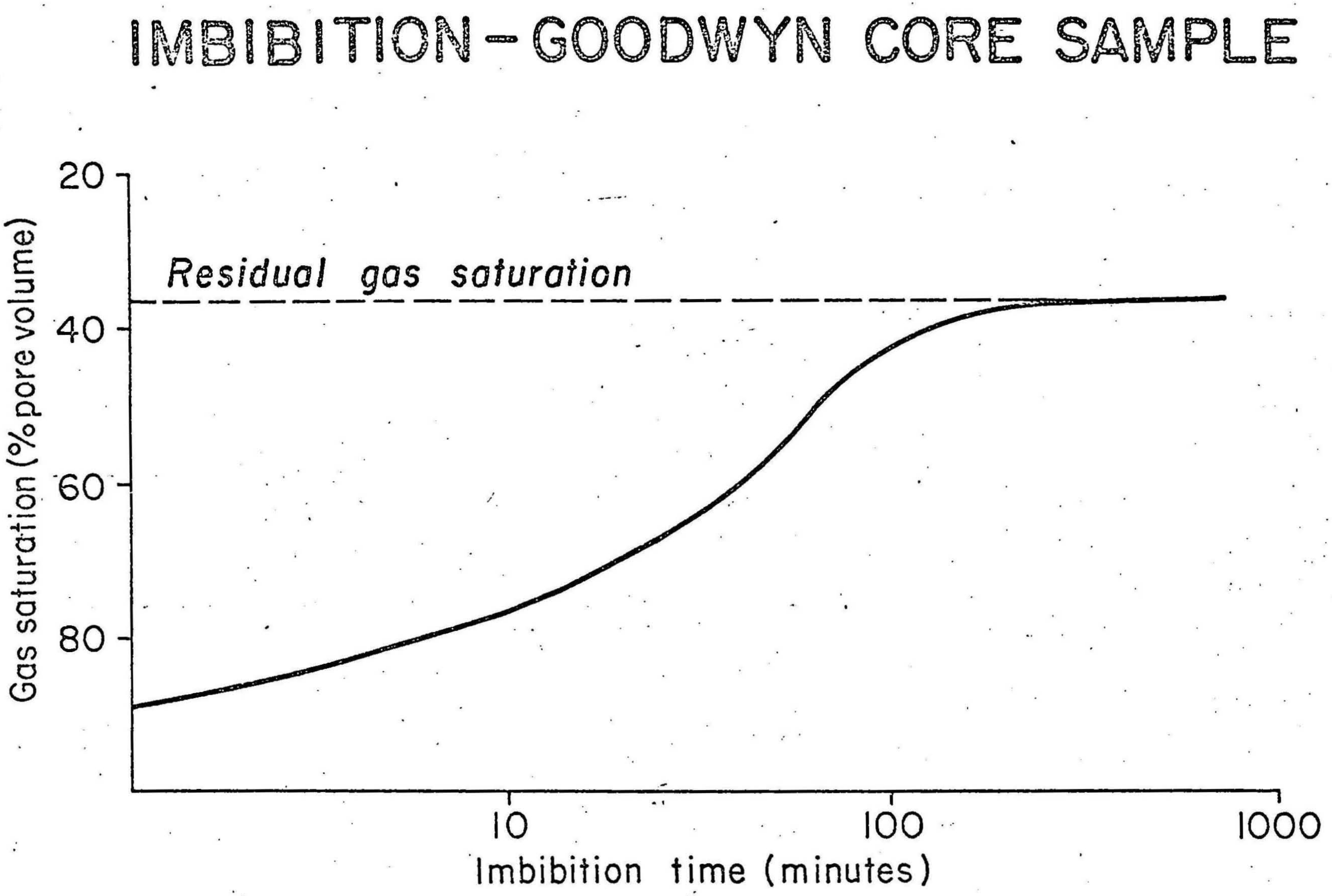


Figure 4: The effect of a variation in the initial water saturation on the gas recovery and residual gas saturation - imbibition flooding, Goodwyn core sample.

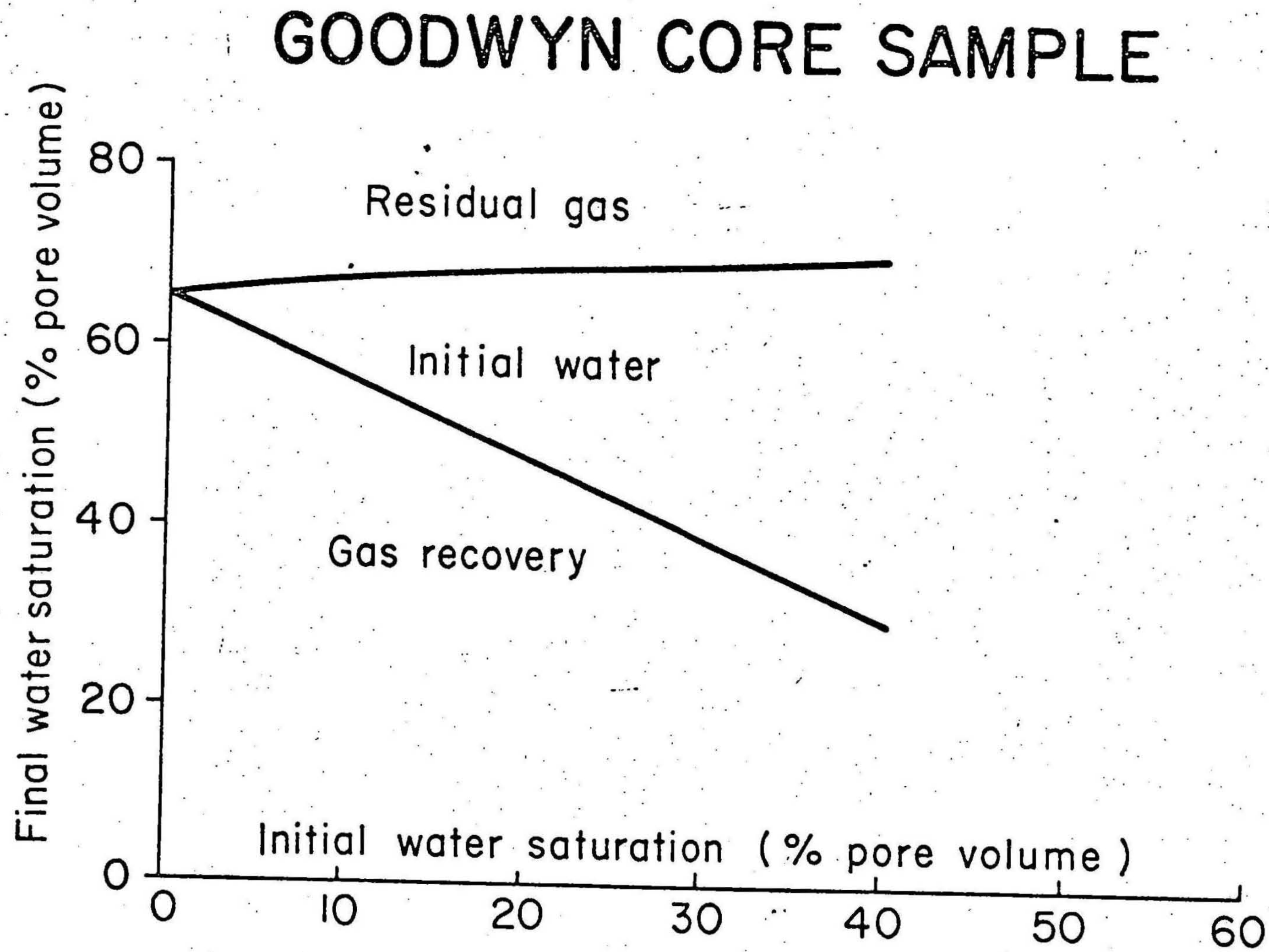


Figure 5: Drainage-imbibition capillary pressure tests by mercury injection-Goodwyn core sample

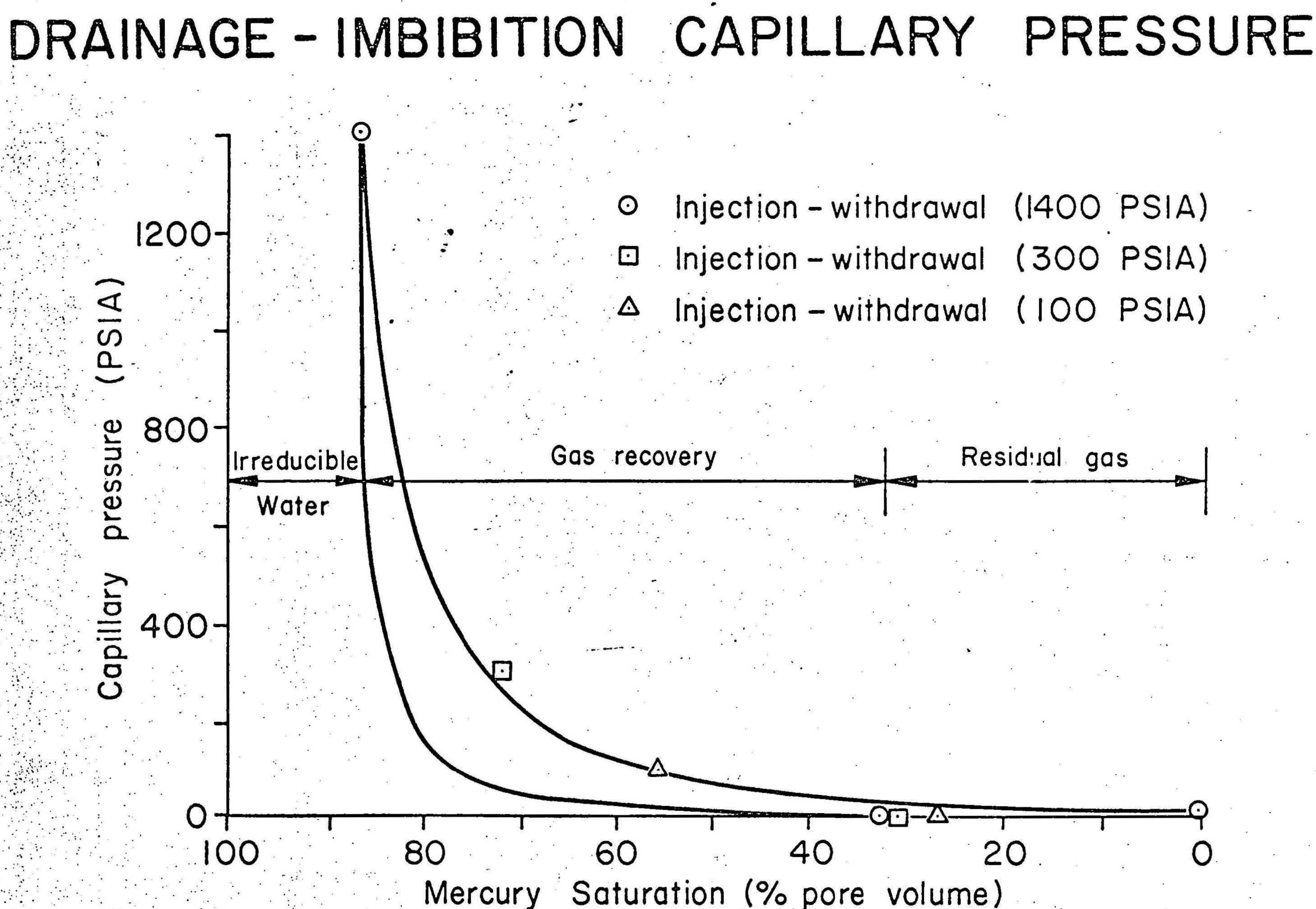
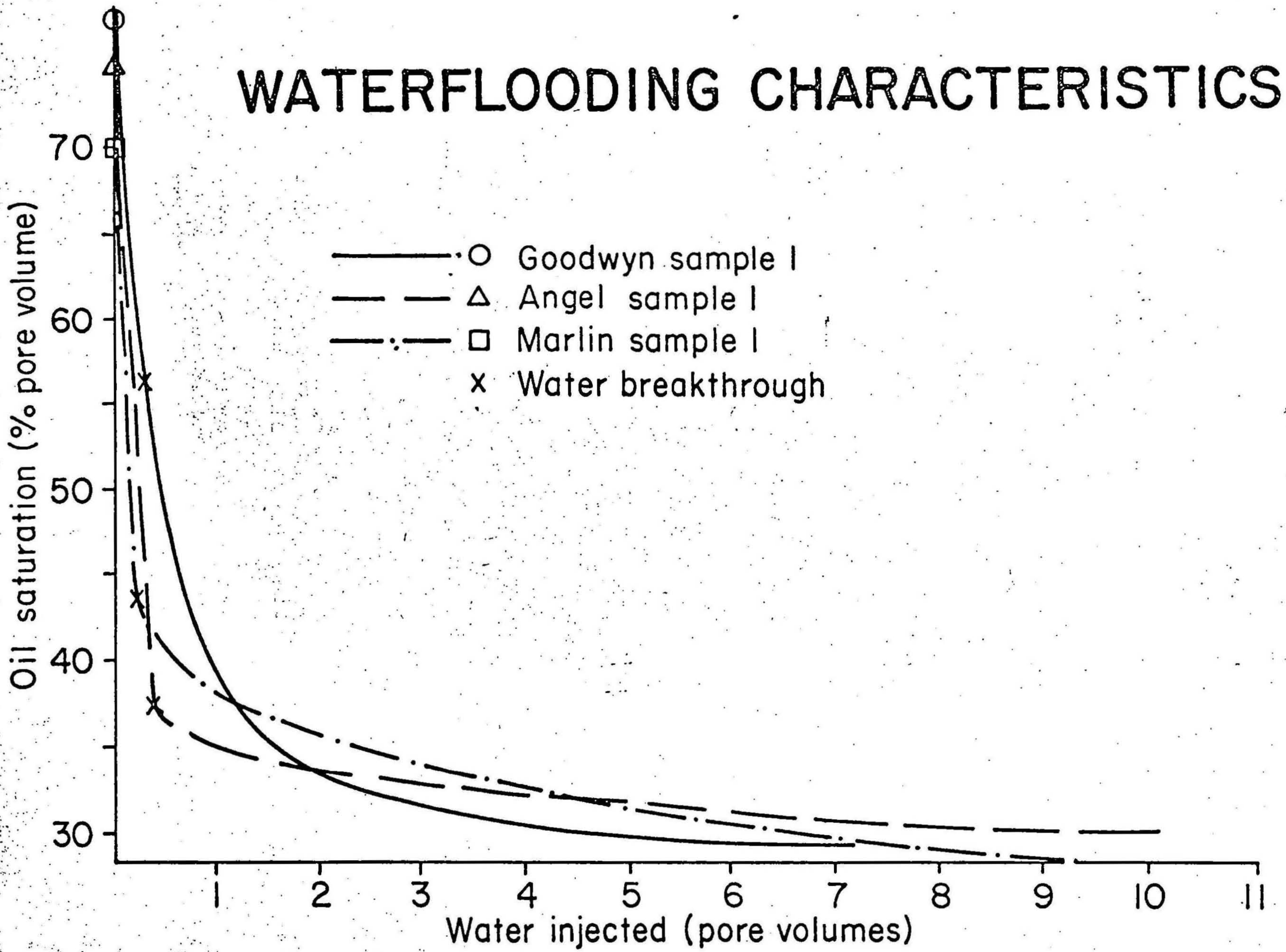


Figure 6: Oil saturation characteristics after waterflooding samples from the Goodwyn, Angel, and Marlin reservoirs.



[redacted]Fig[redacted] 7: [redacted]elationship between porosity and residual gas saturation after waterflooding various gas productive sandstones.