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STATOIL

L&U DOK. SENTER

L. NR. 20085200016

KODE Well 31/2-13 nr 19

Returneres etter bruk

GRADERINGEN GJELDER TIL _____

January 1985

RKER.85.027

HIGH RATE GAS FLOW TESTS ON ROCK SAMPLES FROM
WELL 31/2-13 (TROLL), NORWAY

by

L.J.T.M. Kempers

Sponsor: Norske Shell



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KONINKLIJKE/SHELL EXPLORATIE EN PRODUKTIE LABORATORIUM

RIJSWIJK, THE NETHERLANDS

(Shell Research B.V.)

EP-62398

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SUMMARY

To investigate migration of formation fines and subsequent plugging near perforations in the Troll field, high rate gas flow tests have been performed on samples from well 31/2-13. The samples appeared to be contaminated with oil from the drilling mud, which hindered the interpretation of the test results. If the test conditions are considered representative of the in-situ conditions or are considered as a worst case, then it is concluded that fines production in well 31/2-13 is not probable below a gas velocity of 0.025 m/s which is estimated to correspond to a production rate 40 m³/s (120 MMscf/d). No permeability damage was detected in the tests so that plugging of pores has not occurred on a large scale.

KEYWORDS

Permeability damage, formation damage, formation fines, fines migration, plugging of pores, core flood tests.

HIGH RATE GAS FLOW TESTS ON ROCK SAMPLES FROM
WELL 31/2-13 (TROLL), NORWAY

1. INTRODUCTION

High rate gas flow tests on samples from well 31/2-13 (Troll field) have been performed to determine possible permeability damage due to fines migration and subsequent plugging near perforations.

The initial motive for proposing tests of this type was that the production rate of the tested wells in the Troll field (13, 17 and 20 m³/s (40, 50 and 60 MMscf/d)) was less than what was expected considering the high permeabilities (5 - 10 Darcy). After a successful production test of well 31/2-12 (production rate 40 m³/s (120 MMscf/d)), it was still felt useful to perform gas flow tests on samples in order to anticipate any future permeability damage due to fines plugging. The possible erosion of the well facilities due to fines production was another motive for high rate gas flow tests.

2. LITERATURE

The limited literature available on fines migration is first briefly reviewed. An introductory paper on the mechanism of fines migration through porous media is ref. 1 by Muecke. In this paper it is concluded that most formation fines are not only clays but also quartz, other minerals and amorphous material. Muecke reports that not only is mechanical bridging of fines at pore restrictions important but also particle wettability and the relative amounts of two or more immiscible fluids flowing through the pores. Gabriel et al. (ref. 2) extend this with the conclusion from an experimental investigation that the flow of a chemically incompatible fluid results in the total loss of permeability and this does not depend on fluid velocity, while the flow of a chemically compatible, wetting fluid results in severe permeability loss when the fluid velocity exceeds a critical value. A mathematical description of particle transport through sandstones is given by Donaldson et al. (ref. 3). Gruesbeck et al. (ref. 4) describe local laws of deposition and entrainment of fines in the formation.

3. DESCRIPTION OF THE TESTS

To simulate the gas flow through the reservoir a uniform flow of gas was passed through cylindrical rock samples (diameter 2.5 cm, length variable between 3.7 and 8.4 cm). The samples were taken from core material of well 31/2-13. A few scouting tests were performed on samples from well 31/2-6 to test the equipment and the procedure.

3.1 Simulating in-situ conditions

The in-situ conditions were simulated as closely as possible regarding effective stress, gas velocity near a perforation, gas density, viscosity and humidity. Temperature and pore pressure were also taken into consideration, but it was not possible to give all the quantities involved their in-situ values. In-situ conditions representative of the Troll field are:

- temperature T: 60°C
- reservoir pressure: 16 MPa
- pore pressure near well p_0 : 15 MPa
- porosity (well 13): 0.35
- water depth: 340 m
- reservoir depth: 1500 m BSL

The test conditions, which are discussed below, were:

- gas: nitrogen
- temperature: 20°C
- pore pressure: 9 MPa
- effective stress: 10 MPa (hydrostatic)
- gas humidity: saturated

Appendix A discusses the selection of the most important quantities.

Gas velocities

Throughout this report "gas velocity" means: Darcy velocity, i.e. the actual velocity times the porosity. It is equal to the flow rate through the sample divided by the cross-sectional area of the sample.

The gas velocity was taken as the estimated maximum gas velocity in the formation near a perforation corresponding to a production rate of 33 m³/s (100 MMscf/d). The maximum gas velocity is estimated as the production rate per perforation divided by the internal surface of a perforation. With 1000 perforations per well, perforation length 0.17 m and perforation diameter

0.02 m it follows that the estimated maximum gas velocity is 2.0 cm/s at in-situ conditions. Appendix B gives details of the calculation.

Flowing gas

Nitrogen was used in the tests as the flowing gas instead of the reservoir gas since it can be delivered safely at high flow rates in the laboratory.

Pore pressure and temperature

The pore pressure p_0 was taken as 9 MPa and the temperature T as 20°C. At 9 MPa and 20°C, the density of the reservoir gas (mainly CH₄) and the density of nitrogen are calculated to be equal (about 110 kg/m³). The in-situ dynamic viscosity is $1.9 \cdot 10^{-5} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$ and the nitrogen dynamic viscosity at 9 MPa and 20°C is $2.2 \cdot 10^{-5} \text{ kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$. The calculations of density and viscosity are to be found in Appendix B.

Another pore pressure-temperature combination may also give equal density and may give a better dynamic viscosity correspondence. However, at temperatures below 20°C the nitrogen dynamic viscosity is almost constant while at temperatures above 20°C it increases the nitrogen dynamic viscosity (see Appendix B). Only at a much lower pore pressure (1.6 MPa) are the dynamic viscosities equal but this low pore pressure was considered as undesirable.

In-situ stresses

The samples were pressurised hydrostatically. The confining pressure S was 19 MPa, resulting in an effective stress σ on the rock matrix of 10 MPa ($\sigma = S - p_0$). The value of the vertical in-situ effective stress σ_V is estimated as 15 MPa and the value of the horizontal in-situ effective stress σ_H as 7.5 MPa (with the help of ref. 5). The effective stress value of 10 MPa was chosen because it is equal to the average in-situ effective stress $= \frac{1}{3} (\sigma_V + 2 \cdot \sigma_H)$.

Humidity

Because humidity is considered an important parameter in the mechanism of fines migration (ref. 3), the nitrogen gas was saturated with water to simulate in-situ conditions.

3.2 Test equipment

The experimental set-up was as follows (see Fig. 1). The nitrogen is humidified and filtered before it enters the sample, which is contained in a pressure vessel. In the pressure vessel filters are placed at both ends of diameter 100-160 μm). The effluent gas is filtered to collect any produced fines or other minerals (filter: Millipore, pore diameter 0.45 μm). The flow rate is measured with a rotameter (range: 400 to 3300 cc/s). The pressure drop across the sample, Δp_{sample} , is measured to detect permeability damage. The pressure drop across the filter, Δp_{filter} , is measured to determine any blockage of the filter by minerals or liquid. In addition the pressure of the inflowing gas p_{in} , and the gas pressure on the downstream side of the flow meter p_{out} , are measured. The pressure vessel and filter are equipped with bypass valves.

3.3 Core handling

The reservoir rock of block 31/2 is very friable so that handling of the core samples needs special attention. The core material was frozen to allow drilling of the samples, which was done in Norway before the samples were sent to KSEPL. The samples were transferred to KSEPL in hollow plastic cylinders packed in CO_2 -iceblocks. At KSEPL the samples were stored at -25°C for 5 weeks until the start of the tests. In spite of careful handling one sample (sample depth 1781.5 m) was found to be badly damaged because of the friable nature of the sample. Every sample was installed in the pressure vessel at least 18 hours before the start of the test.

3.4 Test procedure

Each test consisted of a sequence of seven flushes at increasing flow rates in order to investigate the dependence of the onset of any permeability damage on the gas velocity. During a flush the flow rate was kept constant, because flow rate fluctuations may have a significant effect on the construction and destruction of fines bridges at pore restrictions (ref. 4). The gas velocities used were about 1, 2.5, 3.5, 5, 6, 7.5 and 8 cm/s. The length of a flush was taken as 100 pore volumes, as is indicated in a similar test (ref. 2). In one test the length of a flush was 200 pore volumes and in another 2000 pore volumes.

After each test the filter was removed and analysed. In addition, in most tests the filter was also replaced after the first, second or third flush when Δp_{filter} had increased to 0.02 MPa or more, in order to have a better insight into the dependence of the composition of the produced material on the gas velocity. The mineralogical composition of the deposition on the filter was analysed with XRD (x-ray diffraction). The chemical composition of the deposition on some filters was analysed with XRF (x-ray fluorescence). During the scouting tests, one filter was viewed with SEM (scanning electron microscope) to investigate the sizes and shapes of the minerals.

Before a new sample was placed in the pressure vessel the equipment was flushed with nitrogen to remove any particles left in the equipment.

3.5 Preparation for the tests

Calibration

The equipment was first calibrated without a sample in the pressure vessel. In addition the nitrogen gas was filtered and the filter was analysed with XRD, to investigate the presence of fines or other minerals in the nitrogen supply system or in the filter itself. No minerals were found.

Scouting experiments

A few scouting tests were performed on three-year old samples from well 31/2-6. These scouting tests showed that

- clay particles can be collected and identified with the available facilities,
- the accuracy of the measurement of the pressure drop across the sample and the flow rate is sufficient to establish a relationship between pressure drop and gas velocity and to detect a permeability decrease of 5%.

4. RESULTS

The most striking of the results is the deposition of oil on the filters (see Table 2). Apparently, the samples were contaminated with the drilling mud which is oil-based. One tested sample (test 1.3) showed the presence of excessive oil and the test was stopped. The depth of this sample (1803.5 m AH)

is below the gas-oil contact at 1790 m AH. For this reason the remaining three samples from the oil-bearing zone have not been tested. In addition, one successful test (test 1.1) is not considered as representative because of the presence of a lot of water and some oil. During this test the flowmeter became contaminated with water and oil.

4.1 Production of fines

For each test the results of the XRD, XRF and colour analyses of the deposition on the filter are given in table 1A. (The results of the scouting tests on samples from well 31/2-6 are given in Table 1B). Table 1A also gives the value of the gas velocity, v_{filter} , and the number of pore volumes from the start of the test, n_{filter} , at which Δp_{filter} increased to 0.02 MPa. Table 2 summarizes and interprets the results shown in Table 1A.

According to Table 2 no fines or other minerals were produced at a gas velocity below 2.5 cm/s in tests 1.2, 1.4 and 1.5. From this result it is concluded that production of fines or other minerals is not probable at a gas velocity below 2.5 cm/s if the test conditions are considered representative of the in-situ conditions.

The presence of the oil from the drilling mud hinders the interpretation of the tests and leads to doubts as to whether the test conditions are representative of in-situ conditions. According to ref. 1, two-phase flow may result in considerable fines movement due to localised pressure disturbances caused by fluid interfaces travelling through the pores. On the other hand, according to ref. 1, particles that are wet by both fluids locate at the interface between the fluids and their movement appears to be confined to that interface. When one of the wetting fluids is immobile it confines the movement of the particles. However, if the fines in the samples from well 31/2-13 are not wet by the oil, the first mechanism, fines movement by pressure disturbances, is probably more important than the second mechanism, confinement of fines movement by the immobile oil. Then it follows that the tests performed are a worst case: less fines are produced at the same gas flow rate in samples without oil.

4.2 Permeability damage

The measurement of Δp_{sample} and the flow rate, from which the gas velocity, v , has been calculated, show that in all tests Δp_{sample} did not increase at constant flow rate. This means that no permeability damage has been detected. From this result it is concluded that plugging of pores has not occurred on a large scale. It is difficult to translate this conclusion to the reservoir because of the small length of the samples.

The measurement of the pressure drop and the flow rate makes it also possible to establish a relationship for each sample between the pressure drop across the sample and the gas velocity. Fig. 2 gives a typical recording of Δp_{sample} and of the flow rate ϕ (and also of Δp_{filter} and p_{in}). The measured values are fitted best by a parabola:

$$\Delta p_{\text{sample}} = Av^2 + Bv + C,$$

where A, B and C are constants.

From a comparison of this equation with the Forchheimer equation (ref. 6):

$$\Delta p_{\text{sample}} = \frac{\mu L}{k}v + \beta \rho L v^2,$$

with μ the dynamic viscosity, L the sample length, k the permeability and ρ the density, the permeability and the so-called β -factor can be calculated, while C should be zero. Table 3A shows that the calculated k -values and β -factors range from 0.5 to 1.8 Darcy and from 1.10^6 to 3.10^6m^{-1} respectively. (The results of the scouting tests on sample from well 31/2-6 are shown in Table 3B). The calculated C -values are not exactly zero. The small systematic deviation from zero is probably due to the calibration inaccuracy of the flow meter in the low flow regime. It causes an inaccuracy of 10% at maximum in the values of the permeability and β -factor.

5. CONCLUSIONS

1. Interpretation of the results of the high rate gas flow tests is hindered by the presence of oil in the samples.
2. If the tests performed represent the worst case, then fines production in well 31/2-13 is not probable at a gas velocity below 0.025 m/s, which corresponds to a production rate of 40 m³/s (120 MMscf/d).
3. Plugging of pores on a large scale has not been detected at gas velocities between 0.01 and 0.08 m/s.
4. The relationship between the pressure drop across the sample and the gas velocity is described best by the Forchheimer equation. Calculated permeabilities range from 0.5 to 1.8 Darcy and calculated β factors range from 1.10^6 to 3.10^6m^{-1} .

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| Test | Sample depth in reservoir (m) | Filter code | v _{filter} (cm/g) | n _{filter} | Colour of deposition on filter | X-ray diffraction (XRD) (in decreasing order of concentration) | X-ray fluorescence ⁵ (XRF) |
|------------------|-------------------------------|-------------|----------------------------|---------------------|--------------------------------|--|--|
| 1.1 | 1780.8 | 1.1.1.1 | 1 | 40 | yellow | KCl, organic material ³ , quartz, kaolinite (< 0.1 mg) | Fe, Cr, S, Si, Ni, Cu, Al |
| | | 1.1.2 | 3.5 | 190 | light brown | kaolinite (0.2 mg), quartz (trace), gypsum ⁴ (probably) | |
| 1.4 ² | 1781.5 | 1.4 | 6 | 800 | light brown | nothing ⁶ | |
| 1.5 | 1786.17 | 1.5.1 | no pressure increase | | no colour | nothing ⁶ | |
| | | 1.5.2 | no pressure increase | | no colour | nothing ⁶ | |
| | | 1.5.3 | increase ⁷ | 10,000 | brown | very much organic material ³ , gypsum ⁴ , kaolinite (probably) | |
| 1.2 | 1788.5 | 1.2.1 | 2.5 | 100 | light brown | gypsum ⁴ , probably kaolinite (< 0.1 mg), illite, quartz | |
| | | 1.2.2 | 3.5 | 250 | a bit brown | gypsum ⁴ , kaolinite (< 0.1 mg), quartz, halite (probably) | Fe, Cr, Ni, Cl, Si, Ca (smaller quantities than 1.1.2) |
| | 1791.7 | | | | | | |
| | 1793.5 | | | | | | |
| | 1799.6 | | | | | | |
| 1.3 | 1803.5 | 1.3 | <1 | | dark brown | not analysed | |

TABLE 1A: COLOUR, XRD ANALYSIS AND XRF ANALYSIS OF DEPOSITION FROM SAMPLES 31/2-13 (v_{filter} and n_{filter} are respectively velocity and cumulative number of pore volumes at which Δp_{filter} has increased to 0.02 MPa)

1: excessive water, some oil
 2: sample in bad condition
 3: small quantities of organic material cannot be detected because of composition of filter

4: CaCl₂ (from the mud) instead of CaSO₄.2H₂O (gypsum) is not probable but is possible
 5: elements with an atomic number less than 12 not detectable
 6: quantities less than 0.05 mg kaolinite not detectable

| Test vfilter ($\frac{cm}{s}$) | X-ray diffraction (XRD) (in decreasing order of concentration) | X-ray fluorescence ² (XRF) | Energy dispersive X-ray fluorescence attachment (EDAX) | Scanning electron microscope (SEM) |
|------------------------------------|---|---------------------------------------|--|------------------------------------|
| 0.1 ¹ | kaolinite, quartz | | | |
| 0.2 | KCl, NaCl, Mg ₃ Si ₄ O ₁₀ (OH) ₂ (probably) | K, Cl, Fe, Ca, S, Si | salts (mainly gypsum), kaolinite | Ø kaolinite 5-10 µm |
| 0.3 | KCl, NaCl, clay, Mg ₃ Si ₄ O ₁₀ (OH) ₂ (probably) | K, Cl, Fe, Cr, S, Cu, Ca, Si | | Ø illite 10-20 µm |
| 0.4 | KCl, NaCl, Mg ₃ Si ₄ O ₁₀ (OH) ₂ (probably) | K, Cl, Fe, Cr, S, Cu, Ca, Si | | |

TABLE 1B: CHEMICAL ANALYSIS OF DEPOSITION FROM SAMPLES 31/2-6 (SCOUTING TESTS)
(vfilter and nfilter are respectively velocity and cumulative number of pore volumes at which Δpfilter has increased to 0.02 MPa)

1: nitrogen not humidified

2: elements with an atomic number less than 12 cannot be detected.

| Sample depth (metres AH) | Deposition on filter | Gas velocity at which deposition is produced (cm/s) |
|-----------------------------|---|---|
| 1780.8 | water, oil, KCl, quartz, kaolinite (<0.1 mg) | 1 |
| | kaolinite (0.2 mg), quartz, gypsum (probably) | 3.5 |
| 1781.5 | oil (a little) | 6 |
| 1786.17 | oil, gypsum, kaolinite (probably) | 7 |
| 1788.5 | oil, gypsum, kaolinite (<0.1 mg), illite, quartz | 2.5 |
| | gypsum, kaolinite (<0.1 mg), quartz, halite | 3.5 |
| 1803.5 | excessive oil (not analysed) | 2.5 |

TABLE 2: INTERPRETATION OF DATA GIVEN IN TABLE 1A

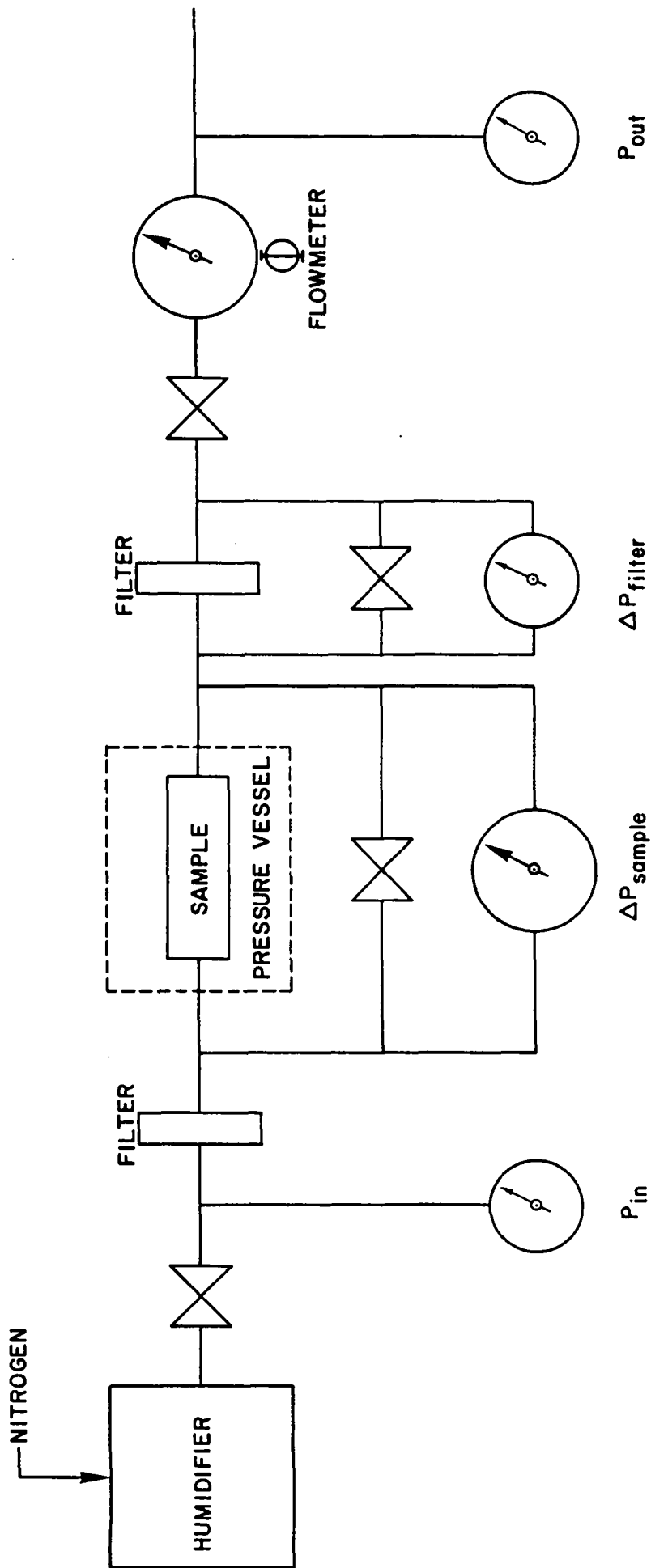
| Test | Sample depth AH (m) | Sample length (mm) | Number pore volumes per flush | k (D) | β (m ⁻¹) | C (MPa) |
|------------------|------------------------|-----------------------|-------------------------------|----------|-------------------------------|------------|
| 1.1 | 1780.8 | 84 | 100 | 0.5 | 1.10 ⁶ | -0.021 |
| 1.4 ² | 1781.5 | 37 ¹ | 200 | 1.8 | 1.10 ⁶ | -0.009 |
| 1.5 | 1786.17 | 42 | 2000 | 1.1 | 2.10 ⁶ | -0.006 |
| 1.2 | 1788.5 | 72 | 100 | 0.5 | 3.10 ⁶ | -0.017 |
| not tested | 1791.7 | 45 | | | | |
| | 1793.5 | 83 | | | | |
| | 1799.6 | 68 | | | | |
| 1.3 | 1803.5 | 59 | - | - | - | - |

TABLE 3A: MEASURED PERMEABILITY AND β -FACTOR OF SAMPLES FROM WELL 31/2-13

| | | | | | | |
|------------------|--|----|-----|-----|-------------------|--------|
| 0.1 ³ | | | | | | |
| 0.2 | | 79 | 100 | 1.1 | 5.10 ⁶ | -0.007 |
| 0.3 | | 87 | 100 | 0.7 | 6.10 ⁶ | -0.013 |
| 0.4 | | 86 | - | - | - | - |

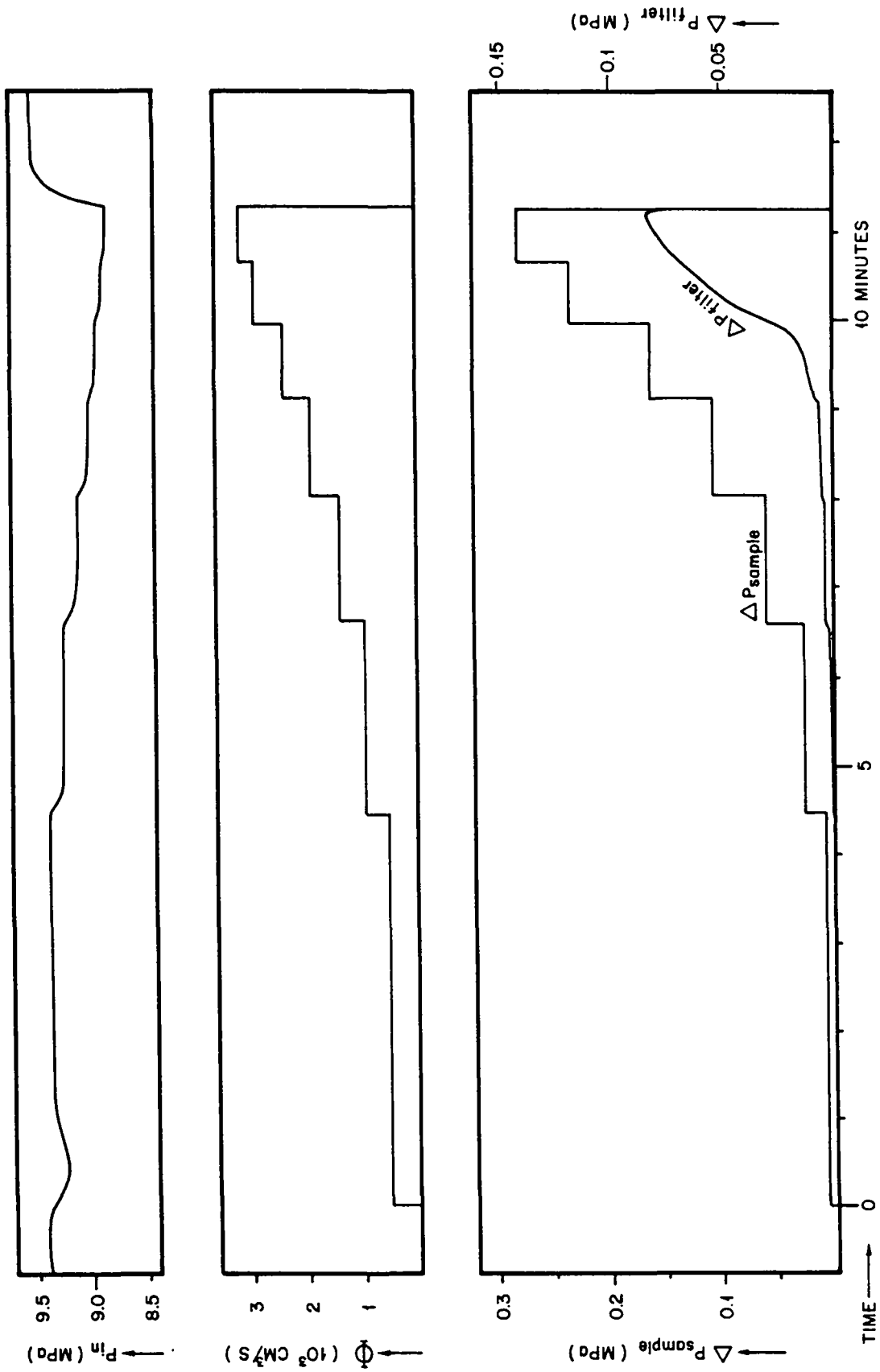
TABLE 3B: MEASURED PERMEABILITY AND β -FACTOR OF SAMPLES FROM WELL 31/2-6

- 1: sample in bad condition (loose sand)
- 2: test repeated: k and β change by less than 10%
- 3: nitrogen not humidified



EXPERIMENTAL SET-UP

Fig. 1



MEASURED QUANTITIES AS A FUNCTION OF TIME IN TEST 1.4

APPENDIX ADIMENSIONAL ANALYSIS

Many quantities play a role in the mechanism of fines migration. This makes it difficult to simulate in-situ conditions in the tests when nitrogen gas is used instead of the reservoir gas. With dimensional analysis the number of independent quantities can be diminished. In addition, dimensional analysis may make it easier to select the most important parameter.

In the following, only mechanical parameters are considered. Temperature T, humidity and wettability of the fines play a role as well. The quantities considered are:

- porosity ϕ
- permeability k
- pore diameter D
- fine diameter d
- number of fines per volume n
- weight density of fine ρ_0
- minimum force for dissociation of a fine from the rock matrix F_c
- volume of rock V
- gravitational constant g
- mean gas velocity u
- gas density ρ
- gas kinematic viscosity ν
- gas pressure p_0
- velocity gradient (in non-uniform flow) $\frac{u}{L}$

A dimensional analysis gives the following set of independent parameters (although there is a complex relation between p_0 , T, ρ , ν and there may be a relation between ϕ , k, D):

- porosity ϕ
- Reynolds number $\frac{D \cdot u}{\nu}$
- diameter ratio $\frac{d}{D}$
- density ratio ρ/ρ_0
- ratio k/D^2
- Froude number $\frac{u}{\sqrt{gd}}$
- drag coefficient $C_D = F_c \left(\frac{1}{2} \rho u^2 \cdot \frac{1}{4} d^2 \right)^{-1}$

- number of fines nV
- volume ratio D^3/V
- pressure coefficient $C_p = p_0 / \frac{1}{2} \rho u^2$
- dimensionless velocity gradient $\frac{D}{L}$

If original rock samples are used, then ϕ , k , D , d , n , F_C keep their in-situ values so that the parameters porosity ϕ , diameter ratio $\frac{d}{D}$ and ratio k/D^2 do not change. The Reynolds number, which determines the flow condition, is considered as the most important parameter, together with the drag coefficient C_D , which determines the dissociation of fines from the rock matrix. From this it follows that the quantities $\frac{u}{v}$ and $\frac{1}{2} \rho u^2$ should have in-situ values.

The number of fines, nV , which determines the number of fines available for pore plugging, is considered as the next important parameter. It is not possible to give this parameter its in-situ value unless fines are injected into the inflowing gas. This also applies to the volume ratio D^3/V .

The Froude number may influence the movement of fines through the pores and is also considered as an important parameter. From this it follows that u , ρ and v should have in-situ values.

If the pressure coefficient C_p is taken into consideration, then p_0 should have its in-situ value. Because of the relation between p_0 , T , ρ and v , this is not usually possible.

Finally the parameter $\frac{D}{L}$ is considered. It was decided to generate a uniform flow for practical reasons, so that this parameter is zero in the tests.

APPENDIX B

CALCULATIONS

B.1. GAS VELOCITY

The calculation of the gas velocity is as follows. Given the production rate of 33 m³/s per well and 1000 perforations per well, the production rate per perforation is 0.033 m³/s (at standard conditions: 0°C and atmospheric pressure). In section B.2. the gas density is calculated to be 1.1.10² kg/m³ at reservoir conditions and 0.71 kg/m³ at standard conditions. From this it follows that a production rate of 0.033 m³/s at standard conditions corresponds to 2.2 . 10⁻⁴ m³/s at reservoir conditions.

The internal surface area of a cylindrical perforation with diameter 0.02 m and length 0.17 m is 0.011 m². The production rate per perforation at reservoir conditions divided by the internal surface area of a perforation is then calculated to be 0.020 m/s.

B.2. DENSITY

The density ρ can be calculated from the equation of state

$$\frac{p V}{nRT} = 1 + n \frac{B}{V}$$

with p: pressure

V: volume

n: number of moles

R: gas constant

T: absolute temperature

B: second virial coefficient,

together with the relation

$$n = \frac{pV}{M}$$

with M: molar mass.

(The relationships of this section are taken from ref. 7.) The coefficient B is a function of temperature according to:

$$\frac{B}{V} = 0.430 - 0.866 \frac{T_c}{T} - 0.694 \left(\frac{T_c}{T}\right)^2 \quad \text{if } 0.55 < \frac{T}{T_c} < 6$$

with T_c : critical temperature

V_c : critical molar volume.

For both methane and nitrogen,

$$\frac{p_c V_c}{R T_c} = 0.29$$

with p_c : critical pressure.

When these relations are applied to the data for methane,

CH: $p_c = 4.58$ MPa reservoir: $p = 15$ MPa
 $T_c = 190.7$ K $T = 333$ K
 $M = 0.016$ kg/mol

it follows that $B = 2.9 \cdot 10^{-5}$ and hence in the reservoir $\rho = 1.1 \cdot 10^2$ kg/m³.

Applying the same relation to the data for nitrogen:

N₂: $p_c = 3.35$ MPa test conditions: $p = 9$ MPa
 $T_c = 126.2$ K $T = 293$ K
 $M = 0.028$ kg/mol

gives $B = 6.6 \cdot 10^{-6}$ and hence under the test conditions $\rho = 1.1 \cdot 10^2$ kg/m³.

Note that the term $n \frac{B}{V}$ is small enough to be neglected so that nitrogen is effectively considered here as an ideal gas with an equation of state

$$\frac{p V}{nRT} = 1.$$

B.3. VISCOSITY

The viscosity of CH₄ and N₂ as a function of pressure and temperature can be read from graph 1.3-1 in ref. 8. The dynamic viscosity μ is given as the reduced viscosity μ/μ_c where μ_c is the critical dynamic viscosity. Values of μ_c can be found in Table B-1 of ref. 8:

$$\text{CH}_4: \mu_c = 15.9 \cdot 10^{-6} \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$$

$$\text{N}_2 : \mu_c = 18.0 \cdot 10^{-6} \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$$

From the graph it can be seen that in a temperature range 250 to 375 K and a pressure range 6 to 30 MPa the dynamic viscosity of nitrogen is almost unaffected by the temperature.