Sample ID
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2000-19

ADVANCED ROCK PROPERTIES STUDY

For

CANADIAN NATURAL RESOURCES LTD.

AMOCO A4 POINTED MTN A-55
CHEVRON ET AL LIARD M25
PAN AM A2 POINTED MTN K-45

2001-08-28 52132-01-1037

Core Laboratories

Core Lab
PETROLEUM SERVICES

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August 28, 2001

Canadian Natural Resources Ltd.
#2000, 425 – 1st Street S.W.
Calgary, Alberta, T2P 3L8

Attention: Ms. Cassandra Lai

Subject: Advanced Rock Properties Study
AMOCO A4 POINTED MTN A-55, CHEVRON ET AL LIARD M25, PAN AM A2 POINTED MTN K-45
File Number: 52132-01-1037

Dear Ms. Lai:

Core Laboratories is pleased to present the final results of the following study performed on core samples from the subject wells:

- Permeability to humidified methane on fractured samples under reservoir conditions
- Pore volume compressibility

We appreciate the opportunity to be of service to *Canadian Natural Resources Ltd.* Should you have any questions or if we may be of further assistance, please do not hesitate to contact us.

Sincerely,

CORE LABORATORIES CANADA LTD.

Chris Pan, Ph.D.
Supervisor,
Advanced Rock Properties

CP/sb

TABLE OF CONTENTS

PROGRAM PARTICIPANTS

Laboratory Measurements

Mike McSwiney

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Report Preparation and Review

Chris Pan, Ph.D.

Lyle Melin, P. Eng.

EXECUTIVE SUMMARY

An Advanced Rock Properties study was conducted on small plug samples of 38.1 mm in diameter from three wells, i.e., AMOCO A4 POINTED MTN. A-55, CHEVRON ET AL LIARD M25, and PAN AM A2 POINTED MTN K-45, representing the Nahanni formation. The objectives of the study are i) to measure the effective permeability to gas on fractured samples under reservoir conditions and the change of permeability with increasing net overburden pressure and ii) to measure pore volume compressibility. A summary of test results is given below.

- The effective permeability to gas at initial water saturation of the fractured samples ranged from 26.2 mD (K-45H) to 31,286 mD (M-25V) at reservoir conditions. The sample with a vertical fracture, M-25V, has a much higher permeability than that with a horizontal fracture, i.e., sample K-45H.
- The decrease in effective permeability to gas is not significant with the increase in net overburden pressure as the reservoir is depleted.
- The pore volume compressibility of sample A-55 decreased from $7.56*10^{-7}$ (1/kPa) at the current reservoir pressure of 26.7 MPa to $3.33*10^{-7}$ (1/kPa) at a reservoir pressure of 1.44 MPa.

RESULTS AND DISCUSSION

At the request of Canadian Natural Resources Ltd., Core Laboratories Canada Ltd. has completed an Advanced Rock Properties study on three small plug samples drilled from cores of the AMOCO A4 POINTED MTN. A-55, CHEVRON ET AL LIARD M25, and PAN AM A2 POINTED MTN K-45 wells. The samples represent the Nahanni formation of the Liard and Pointed Mountain fields of Northwest Territories. The tests included i) measurement of the effective permeability to gas on fractured samples under reservoir conditions and the change of permeability with increasing net overburden pressure and ii) measurement of pore volume compressibility (PVC). The results are summarised in Tables 2.1 and 2.2.

Three 38.1-mm diameter small plugs were drilled using tap water, one each from the aforementioned wells. Two of the samples, K-45H and M-25V, were drilled from their respective whole sections with fractures. Sample K-45H was from the PAN AM A2 POINTED MTN K-45 well, containing a low angle fracture, i.e., near horizontal fracture. Sample M-25V was from the CHEVRON ET AL LIARD M25 well, containing a high angle fracture, i.e., near vertical fracture. The fracture in sample K-45H was discontinuous and intact after drilling. Whereas, the fracture in sample M-25V was open and the sample was broken up in two separate pieces after drilling. One sample, A-55, was from the AMOCO A4 POINTED MTN. A-55 well, containing small vuggs. All of the samples are dolomite with anhydrate nodules of varying sizes. The properties of the samples and tests conducted are listed in the following table.

Sample No.	**Depth,** meter	**Porosity (ambient),** fraction	**Porosity (NOB),** fraction	**Test**
K-45H	3086.25	0.028	0.018	K_g at S_{wi}
M-25V	3456.30	0.033	0.025	K_g at S_{wi}
A-55	3144.93	0.045	0.032	PVC

Simulated formation brine (129,836 mg/L, Total Dissolved Solids [TDS]) was used to saturate the samples for testing. The composition of the brine was derived from an analysis of brine from the PAN AM POINTED MTN A-3 well.

The effective permeability tests on two fractured samples were conducted at reservoir temperature of 152 °C, reservoir net overburden pressure of 43,010 kPa for sample K-45H, and 51,400 kPa for sample M-25V and pore pressure of 20,800 kPa. The pore volume compressibility test was conducted at room temperature and varying pore pressures.

Effective Permeability to Gas at Initial Water Saturation

After toluene and methanol cleaning, the two fractured samples were vacuum saturated with the simulated formation brine. One sample was loaded in a hydrostatic coreholder and stressed to reservoir net overburden pressure and pore pressure slowly. The sample was heated in an oven to reservoir temperature of 152 °C. At least twenty (10) pore volumes of humidified methane was flowed through the sample at high enough flow rate to remove the brine in the fracture or until the pressure drop across the sample stabilized. Permeability to humidified methane was then measured and calculated based on Darcy's law. The back pressure (pore pressure) of the sample was reduced to simulate field depletion process and the permeability was measured again at this decreased pore pressure. A total of seven measurements were made at seven decreasing pore pressures, including the one of the current reservoir pressure of 26,800 kPa. The same test was repeated for the other sample.

Sample K-45H had an effective permeability to gas of 26.2 mD at the current reservoir pressure of 26,800 kPa. As the pressure was depleted to 8,000 kPa, while maintaining the total confining pressure constant, the effective permeability to gas reduced to 21.9 mD. Sample M-25V had an effective permeability to gas of 31,280 mD at the current reservoir pressure of 26,800 kPa. As the pressure was depleted to 8,000 kPa, while maintaining the total confining pressure constant, the effective permeability to gas reduced to 30,776 mD. Both samples did not show much decrease in permeability with increasing net overburden pressure, indicating the competency of the rock against stress. It is known that the permeability of a fracture is proportional to the third power of its aperture. The results indicate that the fracture in each sample did not close much with increasing confining stress. The reason for the significant difference in the permeability of these two samples lies with the nature of the fractures within each sample. The high angle fracture in sample M-25V had a larger hydraulic aperture than that in sample K-45H. Both fractures were very tough against stresses. One can plot the change of effective permeability with net overburden stress to develop a correlation between them for the formation rock.

The results of the effective permeability measurements on two fractured samples are summarized in Table 2.1 and the complete results can be found in Section 5.

FILE: 52132-01-1037

COMPANY: CNRL
WELL: Various
LOCATION: Various

FORMATION: Nahanni
FIELD: Various
TERRITORY: Northwest Territories

Table 2.1: SUMMARY OF GAS PERMEABILITY RESULTS

SAMPLE	DEPTH, meters	NOB CONDITION POROSITY, fraction	NOB CONDITION AIR PERMEABILITY, mD	RESERVOIR PRESSURE kPa	GAS PERMEABILITY at Swi mD	DEAN STARK INITIAL WATER SATURATION (Swi), fraction Vp
Well: Pan Am A2 Pointed Mtn. K-45				26800 (Current Res. Pressure)	26.2	
K-45H	3086.25	0.018	n/a	22000	25.4	
				20000	25.1	
Formation: Nahanni				18000	24.9	
Field: Pointed Mtn.				16000	24.7	
				12000	23.8	
				8000	21.9	0.186
Well: Chevron et al Liard M-25						
M-25V	3456.30	0.025	n/a	26800 (Current Res. Pressure)	31280	
				22000	31152	
Formation: Nahanni				20000	31152	
Field: Liard				18000	31152	
				16000	31026	
				12000	30900	
				8000	30776	0.135

Test Conditions

Pore Pressure, kPa: 26,800 Temperature, °C: 152

Reservoir NOB Pressure, kPa: 43010 (K-45H) , 51400 (M-25V)

		FILE:	52132-01-1037
COMPANY:	Canadian Natural Resources	FORMATION:	Nahanni
WELL:	Amoco A4 Pointed Mtn. A-55	FIELD:	Pointed Mtn.
LOCATION:	n/a	PROVINCE:	Northwest Territories

Table 2.2: SUMMARY OF LIQUID PORE VOLUME COMPRESSIBILTY

1.5 inch Sample Diameter

SAMPLE	DEPTH, meter	POROSITY, fraction	PERMEABILITY TO AIR, millidarcies	AMBIENT PORE VOLUME (cm^3)	Reservoir NOB 34.5 MPa PORE VOLUME (cm^3)	Reservoir NOB 41.4 MPa PORE VOLUME (cm^3)	Reservoir NOB 48.3 MPa PORE VOLUME (cm^3)	Reservoir NOB 55.2 MPa PORE VOLUME (cm^3)	Reservoir NOB 62.1 MPa PORE VOLUME (cm^3)
A-55	3144.9	0.036	n/a	2.297	2.034	2.020	2.011	2.002	2.001
		Reservoir Pore Pressure (MPa) =			36.60	29.70	22.80	15.90	9.02

Reservoir Pore Pressure = 26.7 Mpa

Reservoir Net Overburden Pressure = 44.44 Mpa

CHRONOLOGICAL SEQUENCE OF EVENTS

Sample and Fluids Preparation

1. Three small (3) plugs from the AMOCO A4 POINTED MTN. A-55, CHEVRON ET AL LIARD M25, and PAN AM A2 POINTED MTN K-45 wells were received from the Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada at Core Laboratories Canada Ltd. for testing.

2. All samples were cleaned with toluene, methanol and oven dried at 85° C for a period of twenty-four (24) hours.

3. Petrophysical properties of porosity and grain density were measured at ambient conditions.

4. A simulated formation brine (129,836 mg/L total dissolved solids [TDS]) was prepared based on a compositional analysis of water from the Pan Am. Pointed Mtn. A-3.

5. All three samples were selected for testing.

Effective Permeability to Gas at Initial Water Saturation

6. The samples were saturated 100% with simulated formation brine and then de-saturated using humidified methane to water saturation in hydrostatic coreholders at reservoir conditions.

7. Humidified nitrogen gas was flowed through the sample, and the effective permeability to humidified methane gas was measured at Swi.

8. The net overburden pressure was increased by decreasing the pore pressure and the measurement was repeated for several different net overburden pressures.

9. Following testing, the sample was placed in Dean Stark extractors to determine residual fluid saturation.

10. All the data are presented in graphical and tabulated format in the section 5.

Liquid Pore Volume Compressibility

11. Sample A-55 was loaded into a coreholder and saturated to 100% of its pore volume with simulated formation brine.

12. The overburden and pore pressures were raised simultaneously. To commence the test, a small specific volume of brine was withdrawn from the sample to simulate pressure depletion in the reservoir. During this process the pore pressure was allowed to stabilize while maintaining the overburden pressure constant. The procedure was repeated for a number of effective overburden pressures until maximum possible depletion was achieved.

13. Data are presented in tabular and graphical formate, and include a table of rock compressibility at each equilibrium pressure.

ADVANCED ROCK PROPERTIES PROCEDURES

Net Overburden Pressure

Tests performed under overburden conditions are loaded under hydrostatic conditions in the laboratory. Because laboratory loading is hydrostatic, more strain results than under typical reservoir loading conditions. In order to obtain a hydrostatic net confining pressure that is equivalent to the reservoir loading conditions, the following formula is used:

NOB Hydrostatic =

$$\left[\frac{1}{3}+\frac{2}{3}\left(\frac{\mu}{1-\mu}\right)\right] * \left[\,(Depth * \text{Pressure}\,Gradient\,) - \text{Re}servoir\ \text{Pr}\,essure\,\right]$$

Where:

μ	= Poisson's Ratio (Assumed to be 0.26 for Sandstones) (Assumed to be 0.35 for Carbonates)
Depth	= Reservoir True Vertical Depth, meters
Pressure Gradient	= 22.62 kPa/meter (1.0 psi/ft)
Reservoir Pressure	= kPa

Pore Volume Compressibility

Prior to testing, the core sample is cleaned, dried and encapsulated in heat shrinkable plastic tubing. The sample porosity is measured and it is evacuated and saturated with simulated formation brine.

The core is loaded into a hydrostatic coreholder and the overburden and pore pressure are raised simultaneously to 70 000 kPa. Care is taken to ensure that the differential pressure between overburden and pore pressure remains within 1,380 kPa to avoid compression hysteresis. A small specific volume of brine is withdrawn from the sample, simulating pressure depletion. The internal pressure is allowed to stabilize while the overburden pressure is maintained. This procedure is repeated for several pressure differentials covering the desired range of effective overburden pressures.

Instantaneous compressibility at each stabilized pressure, c_j, is calculated by:

$$c_j = -1/Vp_i \times (dVp/dp)_j$$

Where:

Vp_i = pore volume at maximum pore pressure (minimum effective overburden pressure)

$(dVp/dp)_j$ = the tangent to a plot of pore volume as a function of effective overburden pressure at the corresponding pressure, p_j.

Data are presented in tabular and graphical form and includes a table of rock compressibility at each equilibrium pressure and a graphical data set of pore volume compressibility, pore volume reduction and fractional reduction.

SIMULATED FORMATION BRINE COMPOSITION

CONSTITUENT	CONCENTRATION, mg/L
Sodium Chloride (NaCl)	101 125
Calcium Chloride ($CaCl_2+2H_2O$)	34 249
Sodium Bicarbonate ($NaHCO_3$)	275
Magnesium Chloride ($MgCl_2+6H_2O$)	4 350
Sodium Sulphate (Na_2SO_4)	543

The brine composition was prepared from the following analysis:

COMPANY: Canadian Natural Resources Ltd.
WELL: Pan Am. Pointed Mtn, A-3
PROVINCE: Northwest Territories
FORMATION: Nahanni

CONSTITUENT	CONCENTRATION, mg/L
Sodium	40 031
Calcium	9 337
Magnesium	520
Chloride	79 400
Bicarbonates	200
Sulfates	367

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RESERVOIR CONDITION GAS PERMEABILITY ON FRACTURED SAMPLES

SAMPLE	DEPTH, meters	NOB CONDITION POROSITY, fraction	NOB CONDITION AIR PERMEABILITY, mD	RESERVOIR PRESSURE kPa	GAS PERMEABILITY at Swi mD	DEAN STARK INITIAL WATER SATURATION (Swi), fraction Vp
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				22000	31152	
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COMPANY:	Canadian Natural Resources	FORMATION:	Nahanni
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LOCATION:	n/a	PROVINCE:	Northwest Territories

SUMMARY OF LIQUID PORE VOLUME COMPRESSIBILTY

1.5 inch Sample Diameter

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			Reservoir Pore Pressure (MPa) =		36.60	29.70	22.80	15.90	9.02

Reservoir Pore Pressure = 26.7 Mpa

Reservoir Net Overburden Pressure = 44.44 Mpa

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COMPANY:	CNRL	FORMATION:	Nahanni
WELL:	Amoco A-4 Pointed Mtn. A-55	FIELD:	Pointed Mtn.
LOCATION:		PROVINCE:	Northwest Territories

PORE VOLUME COMPRESSIBILITY

Sample:	A-55	Ambient Condition Air Permeability, mD:	
Depth, meters:	3144.93	Ambient Condition Porosity, fraction:	0.036

RESERVOIR NET OVERBURDEN PRESSURE, kPa	PORE VOLUME, cm^3	BULK VOLUME*, cm^3	POROSITY*, fraction	COMPRESSIBILITY, pv/pv/kPa x 10E-6 (1)	(2)
2000	2.297	64.15	0.036	-	-
10000	2.211	64.06	0.035	5.933	3.669
19900	2.137	63.99	0.033	4.051	2.505
29900	2.088	63.94	0.033	2.735	1.692
39900	2.056	63.90	0.032	1.833	1.134
49800	2.034	63.88	0.032	1.222	0.756
59800	2.020	63.87	0.032	0.812	0.502
69700	2.011	63.86	0.031	0.538	0.333
79700	2.005	63.85	0.031	0.356	0.220
89700	2.001	63.85	0.031	0.236	0.146
99600	1.998	63.85	0.031	0.156	0.096

Res. NOB kPa	Reservoir Pressure kPa	
44440	26700	(Present Value)
49800	21340	(Possible Future Values during Depletion/Production of the Reservoir)
59800	11340	(Possible Future Values during Depletion/Production of the Reservoir)
69700	1440	(Possible Future Values during Depletion/Production of the Reservoir)
79700	n/a	
89700	n/a	
99600	n/a	

* Assumes constant grain volume.

(1) Measured in laboratory under hydrostatic loading conditions.

(2) Uniaxial loading conditions, transformed from hydrostatic data using an average translation factor of 0.6185 as per Teeuw, Dirk: "Prediction of Formation Compaction from Laboratory Compressibility Data." Trans., AIME (1971) 251, 263-271

PORE VOLUME COMPRESSIBILITY

COMPANY:	CNRL	FILE:	52132-01-1037
WELL:	Amoco A-4 Pointed Mtn. A-55	FORMATION:	Nahanni
Sample:	A-55	Ambient Condition Air Permeability, mD:	
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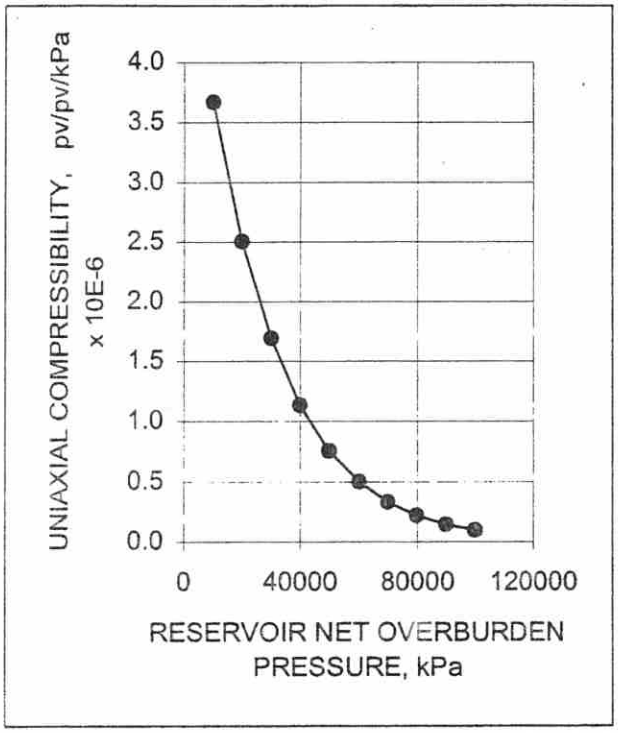

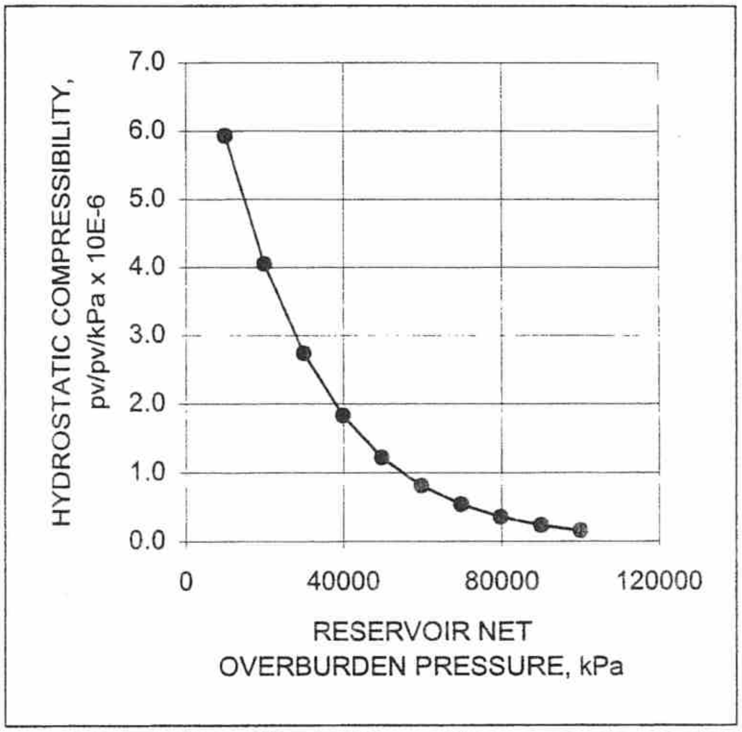

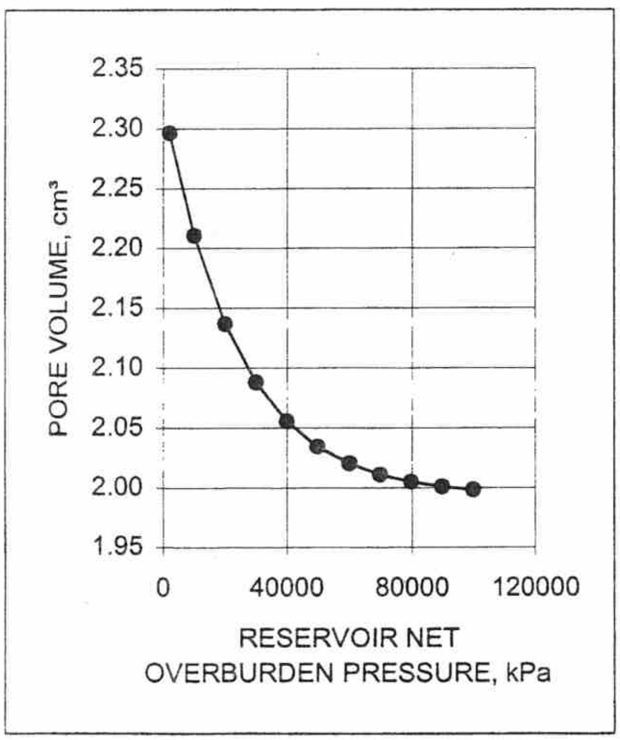

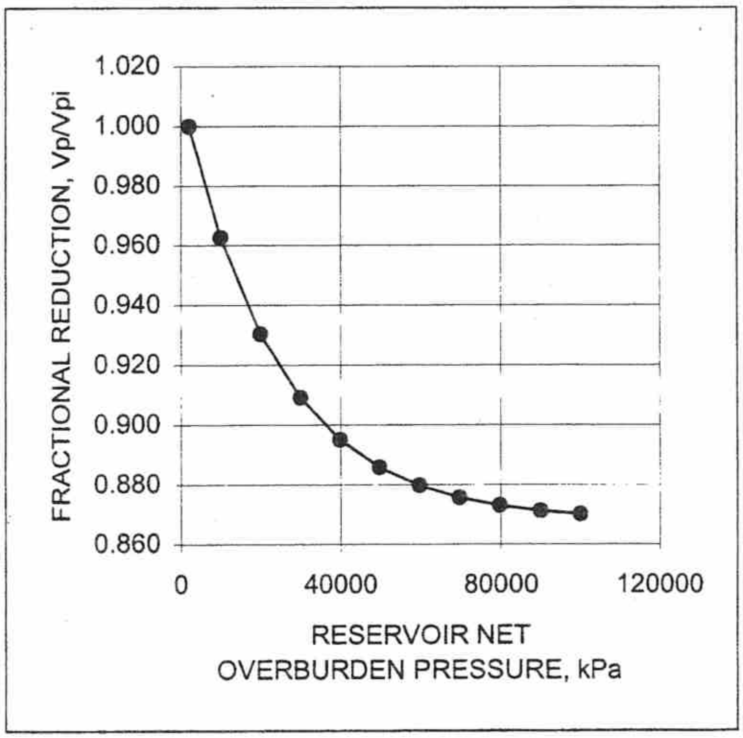

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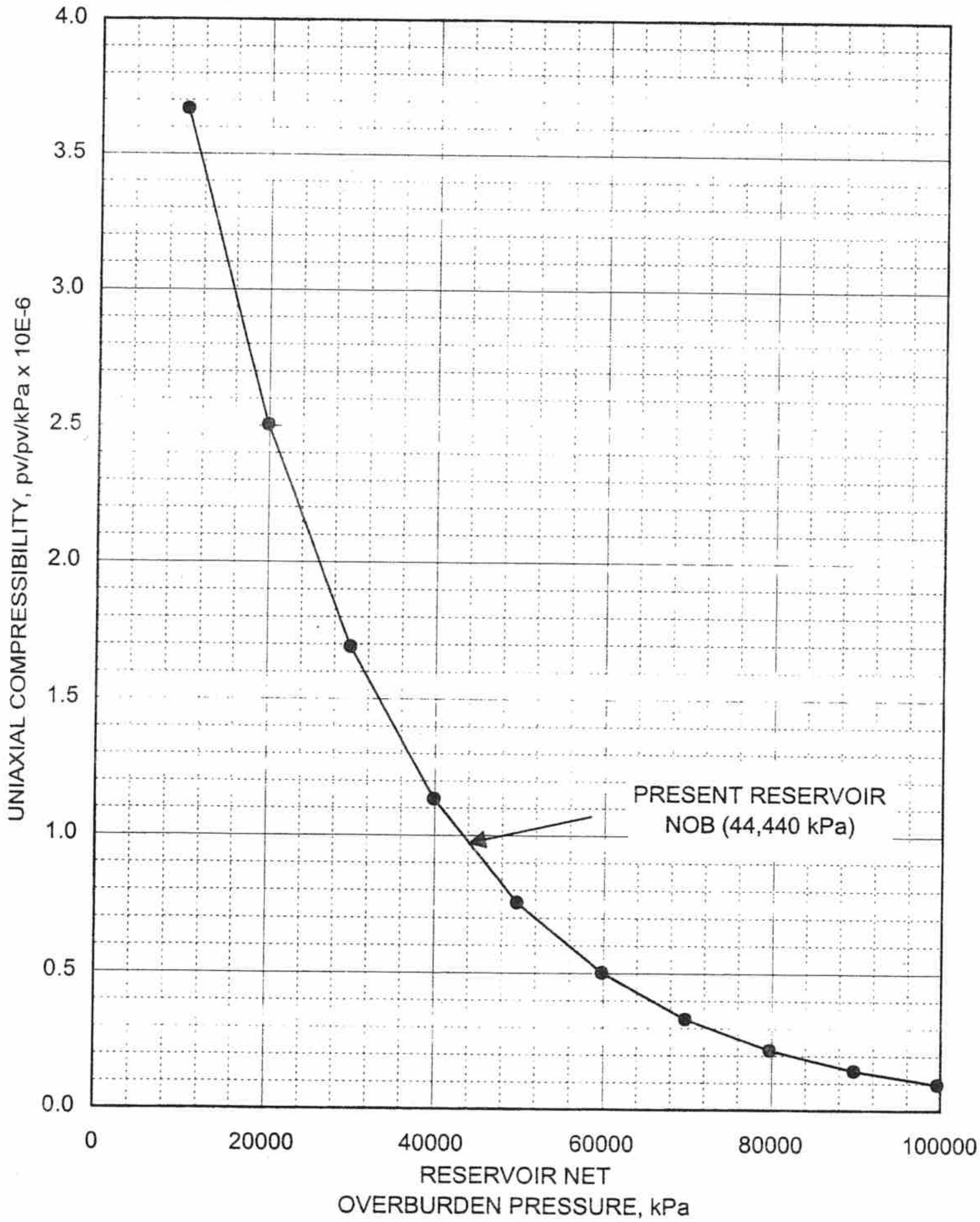

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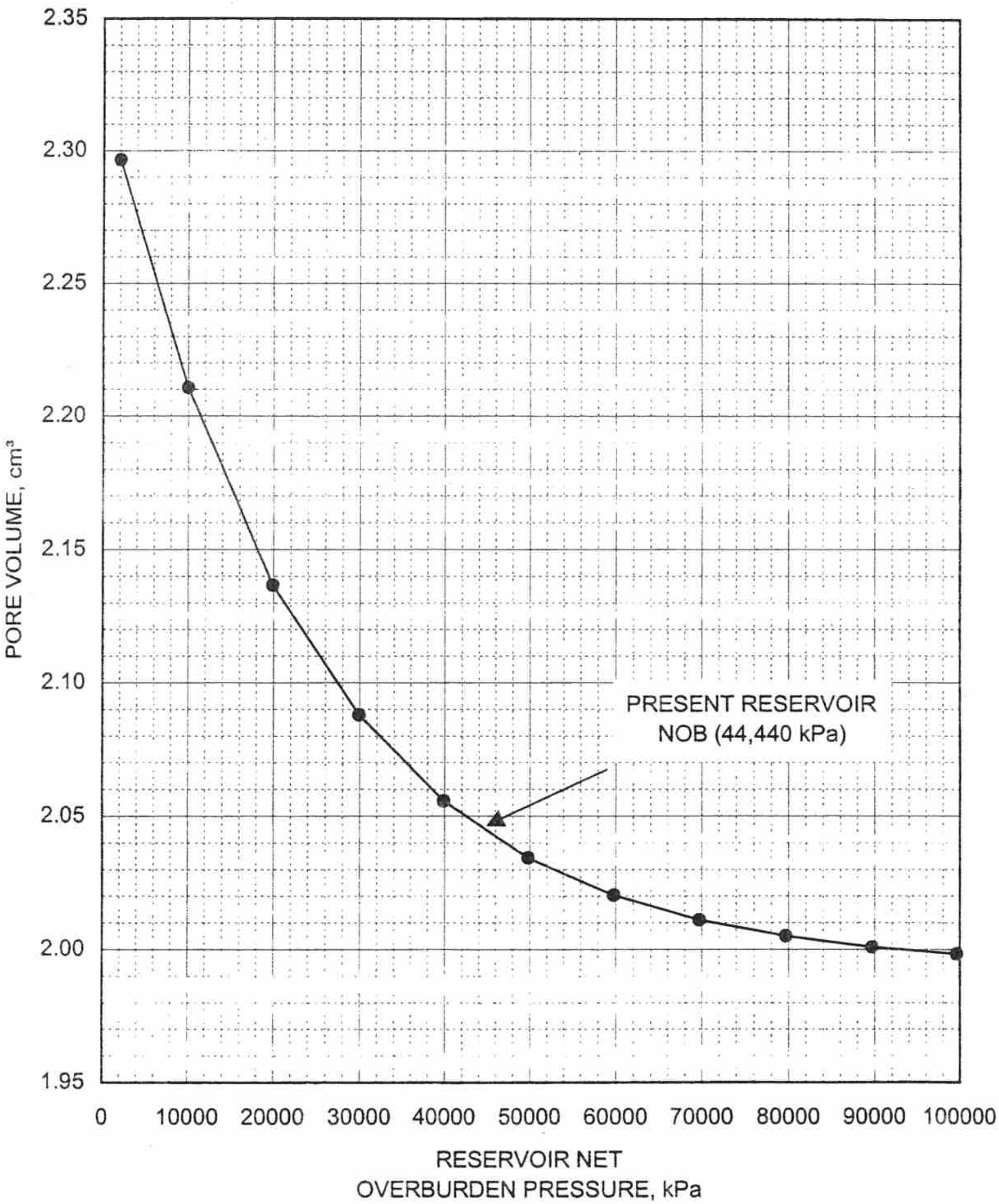

PERMIT TO PRACTICE
CORE LABORATORIES CANADA LTD.
Signature Lyle Martin
Date Aug 29, 2001
PERMIT NUMBER: P 3607
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