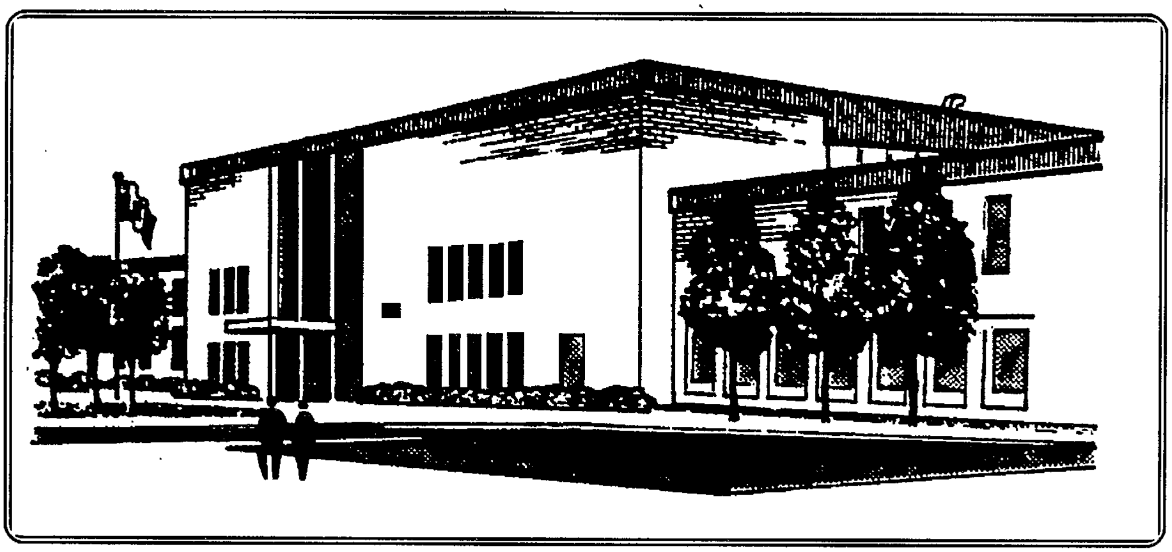
Subsurface Oil Retention In Coarse Sediments Beaches



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Canada

SUBSURFACE OIL RETENTION IN COARSE SEDIMENTS BEACHES

by

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Coastal & Ocean Resources

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The cleanup of oiled coarse sediment beaches during the *EXXON VALDEZ* oil spill proved to be a significant environmental and logistical problem. In that coarse sediment beaches occur extensively along Canada's coastline, the problem is of significant concern to Environment Canada. This project addresses that concern.

Experimental sediment column tests were used to isolate important factors that contribute to oil retention in beaches. Testing included the following procedures: (1) sediment columns were filled with seawater, (2) oil layered onto the water surface and (3) the water level lowered to simulate stranding of oil during a falling tide. Three sediment types were used in the experiment: granules, pebbles and a 50/50 mixture of granules and pebbles. An oil budget was maintained for each experiment and observations made on depth of penetration, oil/sediment colouring and oil layering characteristics.

Two general sediment/oiling conditions were identified:

Impermeable Conditions where a combination of relatively viscous oils and/or low - permeability sediments cause the oil to "plug" the pore space and limit penetration. The result is a thin layer of high concentration oiled surface sediment (>75% saturation, i.e. 75% of the pore-space filled). Emulsions were sufficiently viscous so as not to penetrate granule-sized sediment (<7cm penetration).

Permeable conditions where the combination of relatively fluid oils and/or high-permeability sediments allow the oil to percolate through the sediments. As the oil percolates through the sediments during a falling tide, some oil is retained on the grain surfaces and as capillary fringes on the grain-to-grain contacts. The maximum observed retention was in the order of 30% to 60% saturation (approximately 100 to 200 L of oil per cubic metre of sediment). Volumes of oil retained under permeable conditions have the potential to be high because the penetration is limited only by the depth of the water table. Non-emulsified weathered oil freely penetrated the granules, granule/pebble mix and pebbles with the highest retention in granules and granule/pebble mix (about 110 L/m^3 or ~30% saturation). Pore spaces in the pebble material were sufficiently large to allow penetration of the viscous, emulsified oil with retention values in the range of 235 L/m^3 or ~60% saturation.

Standardized soil colour observations (using a Munsell Soil Color Chart) show promise for visual estimation of sediment oil content; differences in percent saturation as small as 5% were discriminated by colour.

RÉSUMÉ

À la suite de la marée noire de l'EXXON VALDEZ, le nettoyage des plages constitués de matériaux grossiers s'est révélé un problème environnemental et logistique de taille. Comme les plages de ce type sont très abondantes le long des côtes canadiennes, le problème intéresse grandement Environnement Canada. C'est pour aider à le solutionner que ce projet a été entrepris.

Des essais sur colonnes de sédiments ont été effectués afin d'examiner les principaux facteurs en cause dans la rétention du pétrole sur les plages. Ils consistaient : (1) à remplir d'eau de mer des colonnes de sédiments; (2) à déposer le pétrole à la surface de l'eau; (3) à abaisser graduellement le niveau de l'eau de façon à simuler l'«échouage» du pétrole lors de la marée descendante. Ils ont porté sur trois types de sédiments : granules; cailloux et galets; mélange à 50 % des deux premiers types. Pour chaque essai, un bilan du pétrole a été effectué, et la profondeur de pénétration, la coloration des sédiments ainsi que le comportement du pétrole ont été pris en note.

Deux conditions importantes ont été observées :

> Conditions imperméables, lorsque des pétroles relativement visqueux et/ou des sédiments peu perméables causaient l'«obstruction» de l'espace poral, de sorte que la pénétration du pétrole était limitée. Il y avait à la surface une mince couche de sédiments où la concentration du pétrole était élevée (saturation > 75 %; autrement dit, 75 % de l'espace poral était rempli). Les émulsions, trop visqueuses, ne pouvaient pas pénétrer dans les sédiments constitués de granules (pénétration < 7 cm).
>
> Conditions perméables, lorsque le pétrole était relativement fluide et/ou les sédiments, très perméables, de sorte que la percolation du pétrole à travers les sédiments était possible. Une certaine quantité de pétrole était retenue à la surface des grains et dans les franges capillaires entre les grains. La rétention maximale (saturation) était de l'ordre de 30 à 60 % (approximativement 100 à 200 L de pétrole par mètre cube de sédiments). En conditions perméables, les volumes de pétrole retenus peuvent être élevés étant donné que la pénétration est limitée uniquement par la profondeur de la nappe phréatique. Dans les trois types de sédiments étudiés, le pétrole vieilli non émulsionné pénétrait librement, la rétention étant maximale dans les granules et le mélange granules/cailloux et galets (environ 110 L/m^3 ou saturation de ~30 %). Dans le cas des cailloux et galets, l'espace poral était suffisant pour permettre la pénétration du pétrole visqueux émulsionné (rétention de l'ordre de 235 L/m^3 ou saturation de ~60 %).

Pour l'estimation visuelle de la teneur en pétrole des sédiments, le code de couleurs Munsell est apparu une méthode intéressante. Il permettait de discerner des différences du taux de saturation aussi faibles que 5 %.

TABLE OF CONTENTS

LIST OF TABLES AND FIGURES

ACKNOWLEDGMENTS

Funding for this research was provided by (a) the Emergencies Science Division of Environment Canada, Edmonton, Alberta as part of the pollution emergencies R&D program of the River Road Environmental Technology Centre, Ottawa and (b) the Panel for Energy Research and Development (PERD), Ottawa. Mr. Gary Sergy of Environment Canada was the Scientific Authority and provided valuable input throughout the project, particularly during preparation of the final report.

Mr. Blair Humphrey of EnviroEd Inc. provided input during the project with respect to customizing results for input to Environment Canada's SOCS (Stranded Oil in Coarse Sediment) Model.

Paula Jokuty and Zendi Wang of the Emergency Science Division, River Road Environmental Technology Centre, Ottawa provided considerable information on oil properties during the study as well as coordinated geochemical sample analyses and physical properties testing of samples from the study.

1.1 Statement of the Problem

The cleanup of coarse sediment beaches contaminated during the *EXXON VALDEZ* oil spill has proven to be a significant technological and logistical problem. Most of the cleanup effort that occurred within 1990 and 1991 was directed towards the cleaning of coarse sediment beaches, even though this coastal type represented a relatively small proportion of the total coastline oiled (see Bragg *et al* 1990; Owens 1991a & b).

In that coarse sediment beaches are one of the most common coastal types occurring within Canada, the sensitivity of coarse sediment beaches to oiling and cleanup is of significant interest to Environment Canada. In particular, the processes controlling oil retention and penetration in the subsurface of these beaches is poorly understood and, as a result, techniques to mitigate impacts are uncertain.

1.2 Experimental Objectives

The main goal of the project is to experimentally investigate factors controlling subsurface oiling on coarse sediment beaches in order to improve our predictive capabilities for future spills. In particular, the experimental data will be used to refine, and quantify (where possible), relationships used in Environment Canada's SOCS Model (Stranded Oil in Coarse Sediment).

Specific parameters isolated and tested are:

- the effect of oil type on retention and penetration,
- the effect of sediment character on retention and penetration, and
- the effect of submergence/emergence periods on sediment retention.

2.1 Sediment Properties

Grain size, porosity and permeability of sediments were measured as an index of sediment properties.

2.1.1 Grain Size

Three types of sediment were used in the experiments: (1) "#2 Birds Eye", which falls in the granule category and is referred to as **"granules"** (terminology after Folk 1968), (2) "1.5 inch Drain Rock", representing pebble material that passes a 1.5-inch-mesh screen but is retained on a 1-inch-mesh screen (referred to as **"pebbles"**), and (3) a 50/50 mixture (by volume) of the granules and pebbles, referred to as **"granule/pebble mix"**.

The granules were screened from glacial sediments. Size characteristics are summarized in Table 1 and indicate that the material is very well-sorted with over 95% of the material being between 4.75mm and 2.0mm.

Table 1 Granules Size Characteristics

Sieve Size (mm)	% Retained	Cumulative %
4.75	1.6	98.4
2.00	95.8	97.4
1.45	2.1	99.5
0.075	0.2	99.7

The pebble material is a naturally occurring sediment that has been screened from glacial outwash sediment. All of the retained material is between 1.0 inch and 1.5 inch.

The granule/pebble mix was used to simulate a poorly-sorted mixture of pebbles and granules; equal volumes of granules and pebbles were mixed.

2.1.2 Porosity

Some experimental work was conducted on the sediment porosity, particularly on the granules as this material appears to be more sensitive to packing. As such, tests were run to determine how much vibrating was required to reach an "optimal" porosity. An example of a typical curve for the "Birds Eye" sediment is included in Figure 1.

Porosities varied primarily as a function of compaction effort, in this case compaction by vibration. Initial porosities in the tests were up to 49%. However, as indicated in Figure 1, after a 2 to 3 minute vibration period, porosity tended to stabilize.

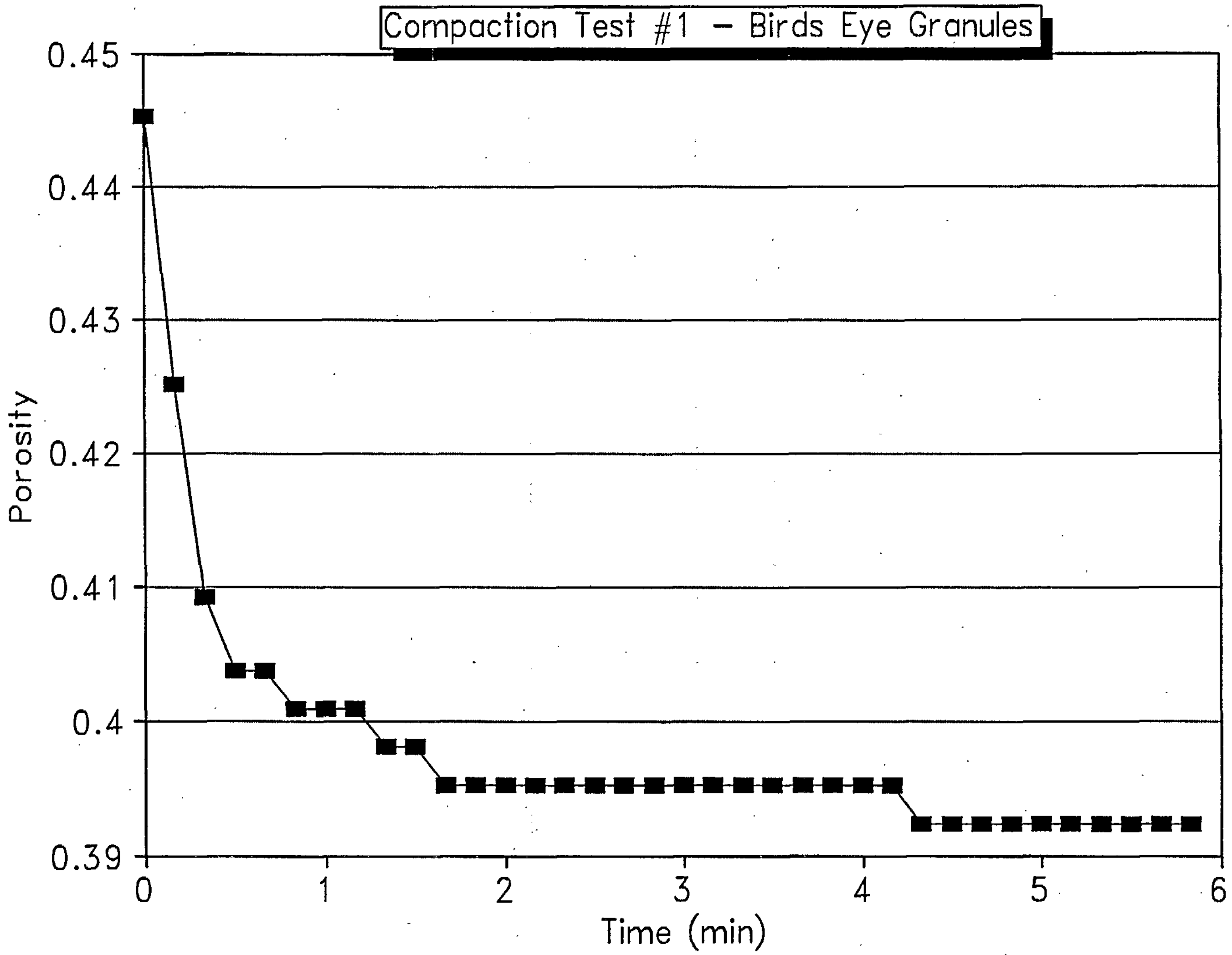


Figure 1. Compaction of granule material by vibration.

Table 2 summarizes porosity, bulk density and mineral density data from the tests; the porosity measurement for the granule sediment was taken as the mean of 5 measurements after 2.5 minutes of vibration.

Table 2 Sediment Properties

Sediment Type	Porosity (%)	Bulk Density (g/cm^3)	Mineral Density (g/cm^3)
Granules	39.4	1.73	2.85
Pebbles	39.4	1.73	2.85

A packing routine was developed to assure "optimum" void space in the sediment columns. This procedure consists of (a) layering about 20 cm of sediment in the column, (b) vibrating this layer for 2 minutes and (c) repeating these operations until the sediment column is filled.

2.1.3 Permeability Tests

It was our original intention to follow the standard ASTM permeability testing procedures to determine permeability (ASTM D2434-68). However, the materials being tested are extremely permeable and under these test procedures are all classified as "free flowing". As such, we designed a custom test to provide an index of permeability for this experiment. For the purposes of the experiment, it is called the "falling-head tube test" (FTT).

The testing apparatus consists of a 1.5m tall, 9.5cm diameter plexiglass tube (Fig. 2). Sediment is loaded into the bottom 38cm of the tube and vibrated to a pre-determined porosity (see Table 2); the sediment is held in place with a screen at the base of the tube. The tube is filled with a fluid to a height of 1.4m. A cap is removed from the base of the tube and the rate of draining noted.

Table 3 Permeability Estimates

SEDIMENT	WATER @ T=20°c, μ=1 cp (cm^3/s)	NON-EMULSIFIED WEATHERED CRUDE @ T=20°C, μ=4.4 cp (est) (cm^3/s)
PEBBLES	Qw = 1268	Qwc approx. 1000 - 1400 (0.79 - 1.1 x Qw)
GRANULES	Qw = 154	Qwc = 22 (0.14 x Qw)
GRANULE/ PEBBLE MIX	Qw = 153	Qwc = 26 (0.17 x Qw)

The index of permeability "Q", is taken as the rate of flow between the 140cm fluid height and the 40cm fluid height (a volume of 7.1L). Sediments that are porous and have high permeabilities have high Q values. Low permeability sediments will have low Q values.

Initial Q values that have been documented are summarized in Table 3. Although the Q-values are a non-standard value of permeability they do provide an important index of permeability differences of the sediment/fluid system.

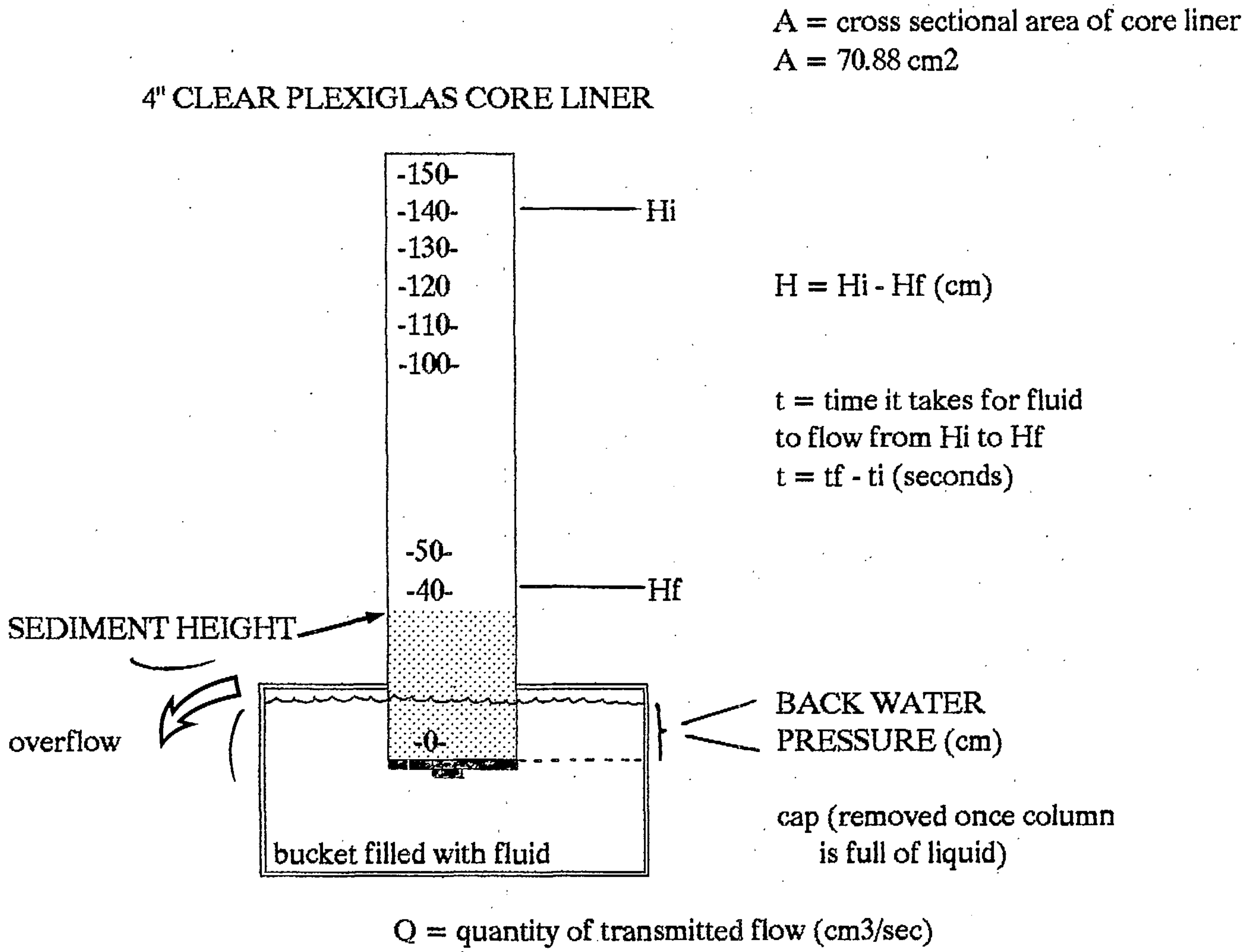


Figure 2. Permeability testing apparatus.

Important observations are:

- the pebble material is nearly an order of magnitude more permeable than the granules,
- the granule/pebble mix assumes the permeability of the finer sediment, in this case the granules; there is no permeability difference between the granules and the granule/pebble mix.
- the weathered crude-oil/pebble system shows that the permeability is not substantially different than that of water.
- the crude-oil/granule system shows a significant reduction in permeability.
- as with the water permeability, there is little difference in the permeability between the granules and granule/pebble mixture.

2.2 Oil Properties

The oil used in the experiments is a light to medium crude oil (supplied from Federated Pipelines). Two derivatives of this oil were used in the experiments: a **weathered** version, where light ends were artificially evaporated and an **emulsified** version where the water was mixed with the weathered oil to form a stable water-in-oil emulsion.

The oil was artificially weathered by bubbling compressed air through a 45 Imperial gallon (205 L) drum of oil. The oil weathering curve is shown in Figure 3. About 20% of the oil (by volume) was weathered. The weathering was discontinued as the oil volume reached equilibrium.

Characteristics of the weathered oil are summarized by the GC/MS plot (Fig. 4; analyses provided by the Environment Canada River Road Environmental Technology Centre.

Viscosities of the fresh, weathered and emulsified oils are shown in Table 4 and plotted in Figure 5. The viscosity of the unweathered crude oil is relatively insensitive to temperature changes whereas the weathered crude oil shows a high sensitivity, especially at temperatures less than 10°C.

Table 4 Federated Sweet Crude Oil Viscosities

Temp (°C)	Fresh Crude Viscosity (cP)	Weathered Crude Viscosity (cP)	Emulsion Viscosity (cP)
0	17.27	67.6	8,400
5	11.09	42.95	5,600
10	7.03	20.93	3,600
15	6.01	14.70	2,600
20	5.28	12.01	-

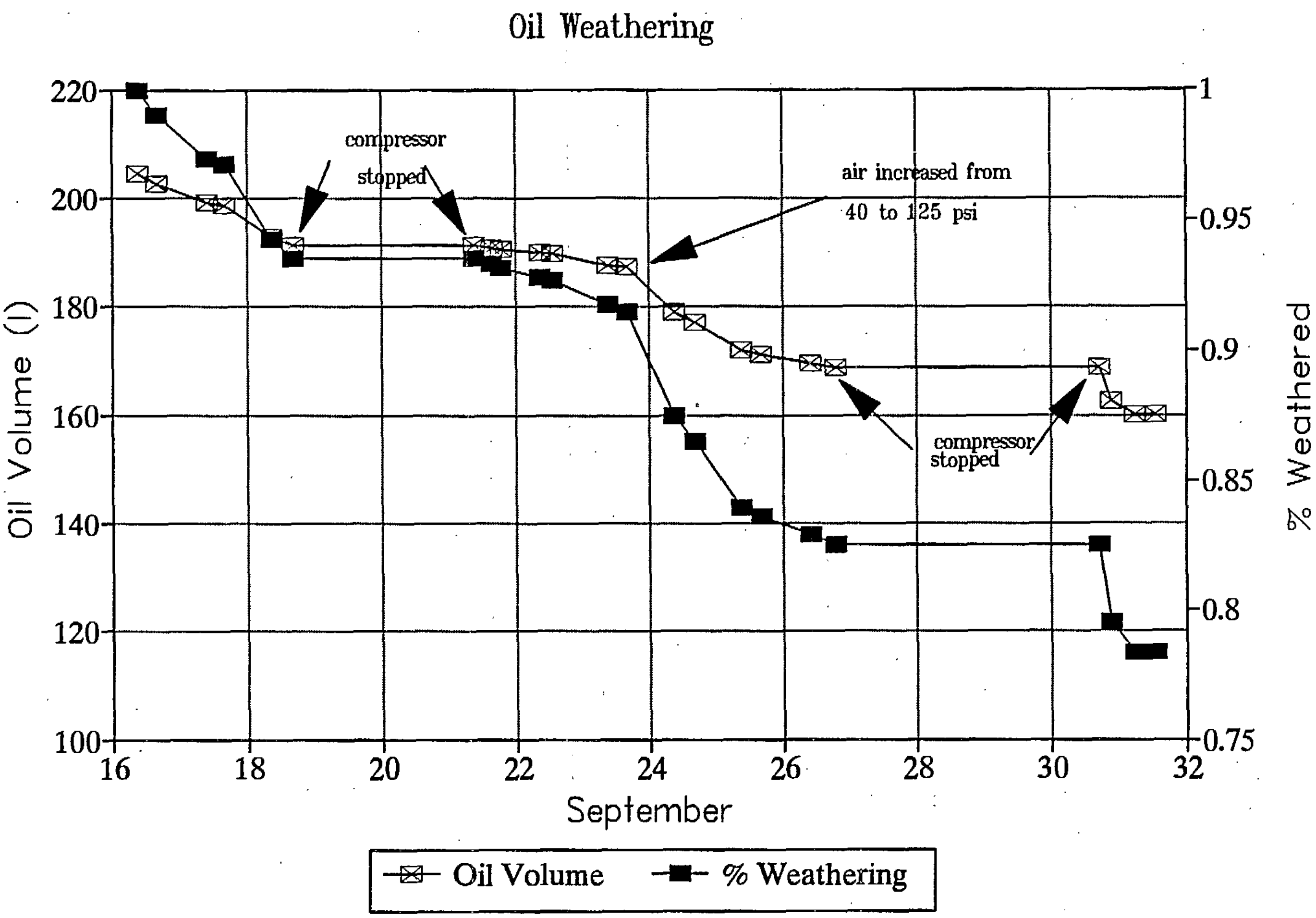


Figure 3. Oil weathering curve for the Federated Sweet Crude.

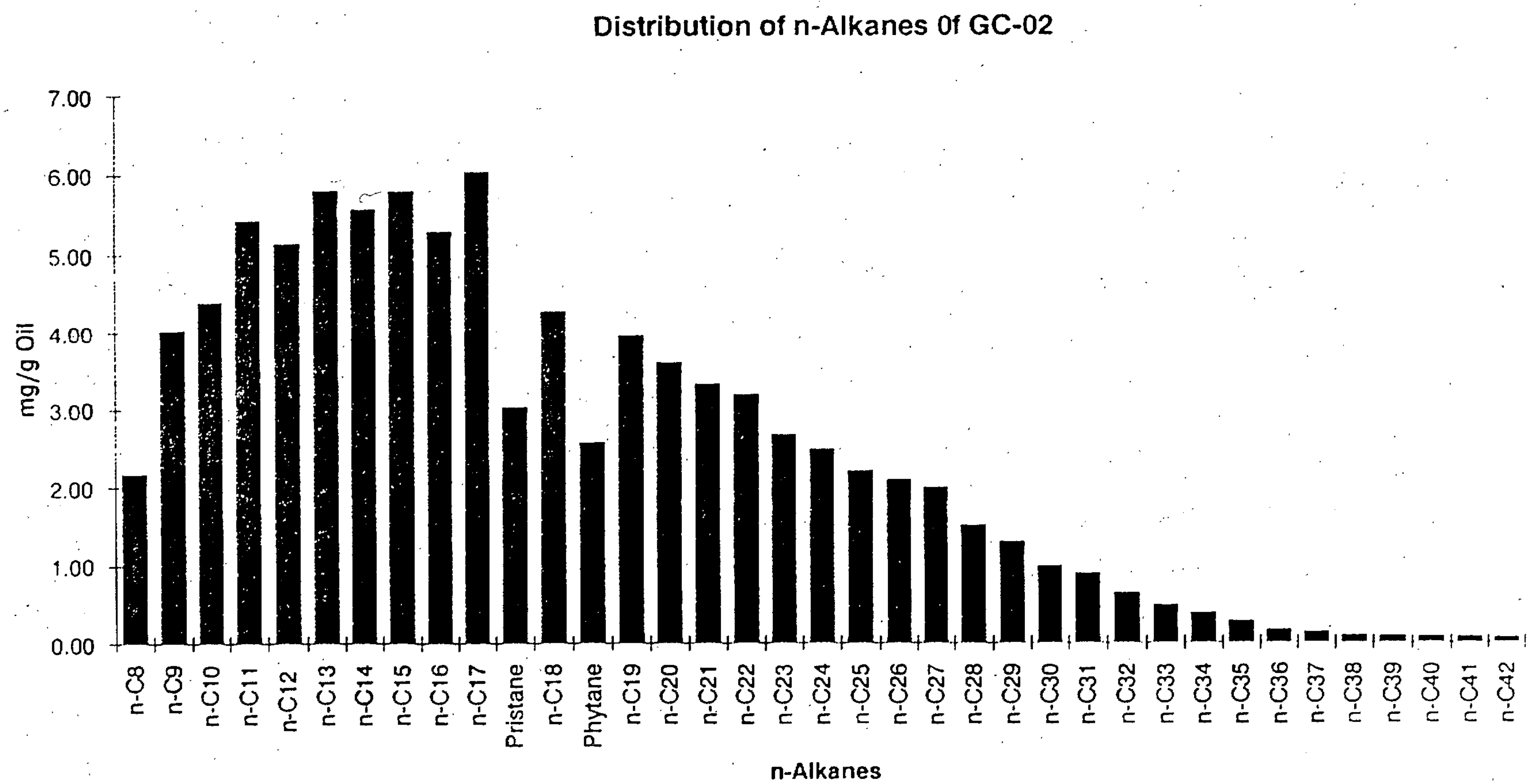


Figure 4. GC/MS plot of the <u>weathered</u> (20% weathered by volume) Federated Sweet Crude Oil (analyses conducted by the River Road Environmental Technology Centre of Environment Canada).

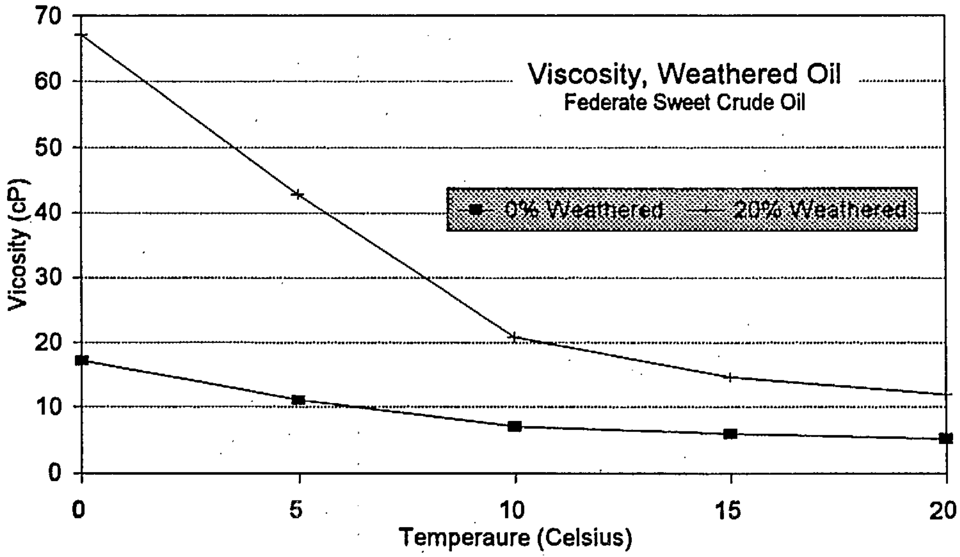


Figure 5a. Viscosities as a function of temperature for weathered and unweathered Federated Sweet Crude Oil.

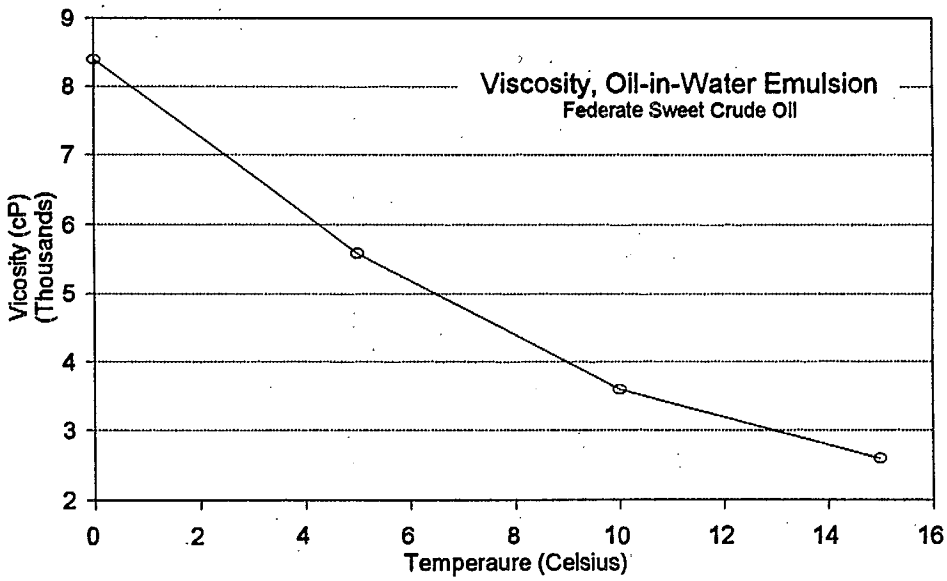


Figure 5b. Viscosities as a function of temperature for a water-in-oil emulsion of Federated Sweet Crude Oil.

Viscosities of the emulsified oil are several orders of magnitude greater than the weathered crude oil and show large changes for small changes in temperature.

2.3 Subsurface Oil Observation Index (SOOI)

Some experimental work has been conducted on defining a Subsurface Oil Observation Index (SOOI). The index provides a means of quantifying field observations of subsurface oil contents. Three avenues were pursued: (1) visual observations, (2) smear tests and (3) colour tests.

2.3.1 SOOI Visual Tests

Weathered crude oil was mixed in varying quantities into 0.5 L samples of the granule sediment to help quantify the index. Based on assumed porosity for the granules of 38%, oil was added to produce 20%, 40%, 60% 80% and 100% saturation of the pore space. Observations were made under natural light (outdoors) at about 14°C. The oil was mixed thoroughly into the sediment in 2L plastic containers.

Dry Sediment: For dry sediments with oil, the most significant observation of this test was that for 20% saturation, almost no free oil percolated out of the sediment after mixing and at 40% a small amount of oil percolated out. The implication is that **the residual capacity of the sediment was about 20% to 30% saturation** (i.e., about 1/5 to 1/3 of the pore space filled). At saturations of 60% and higher, much of the oil readily drained from the sediments.

Frozen, Dry Sediment: The samples were then frozen to simulate a higher viscosity; the soil temperature was -14°C. The more viscous oil was more readily retained in the sediment with less oil draining; this made it much more difficult to distinguish between different saturation levels.

Wet Sediment: 100ml (about 50% of the volume of the pore space) of water was then added to the samples. The addition of water increased the cohesiveness of all samples and had the affect of **apparently** increasing the oil content. Following mixing, water first drained from the sediments, then the oil. At saturations less than 60% the water was relatively clear, at greater than 60% oil saturation, it became difficult to distinguish between the oil and the water.

Except for the observation about the residual oil capacity of the sediments, the observations did not provide any firm guidelines that could be used to distinguish oil contents in the field.

2.3.2 SOOI Smear Tests

During the SOOI Visual Tests, paper plates were used to subsample and photograph the sediments. It was observed that the smear left on the plates provided a very graphic visual indication of the oil content. As a result, smear testing of the sediments was continued for

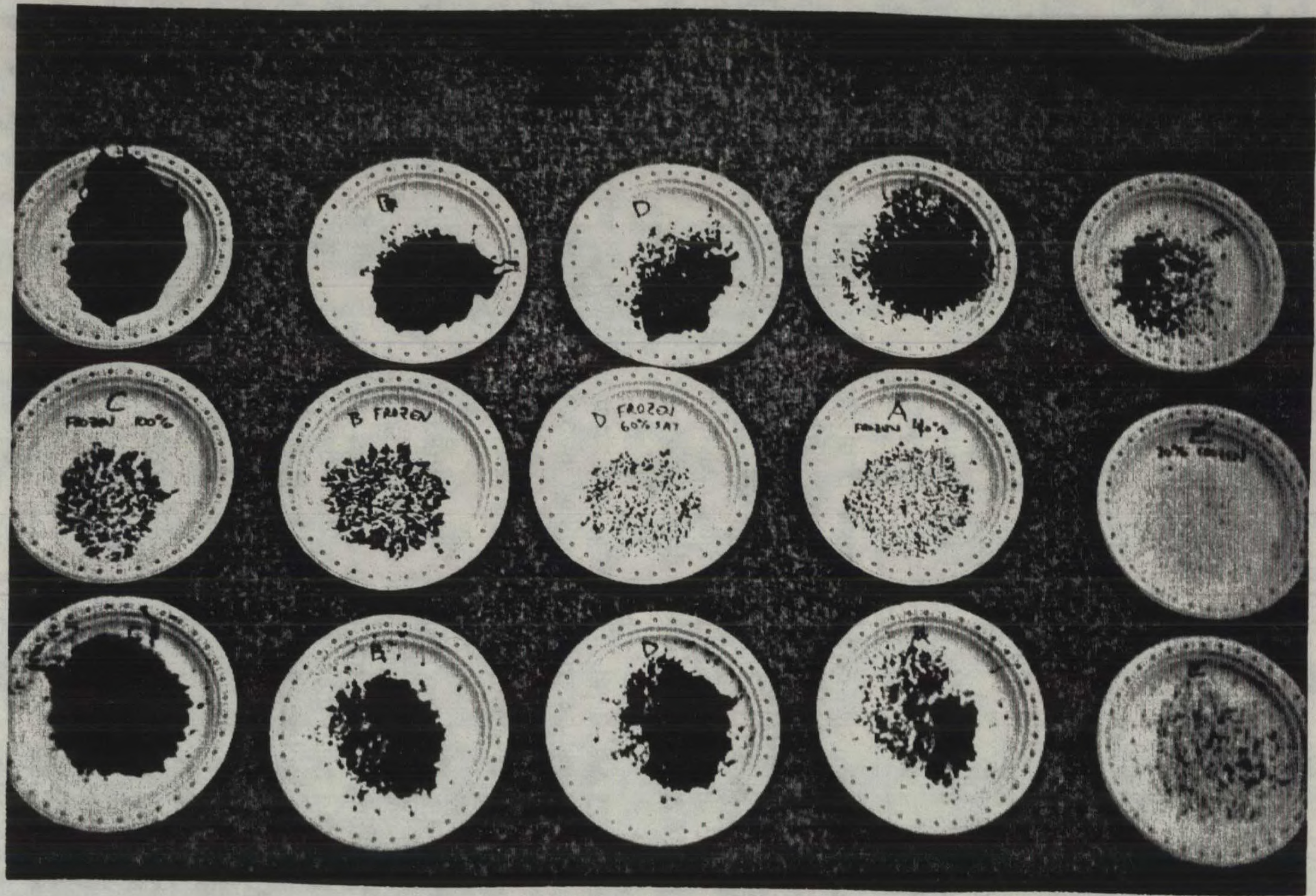


Figure 6. Smear tests on "Chinette" plates (**Bottom Row** - dry sediment 100%, 80%, 60%, 40% 20% saturation; **Middle row** - frozen sediment; **Top row** - wet sediment.)

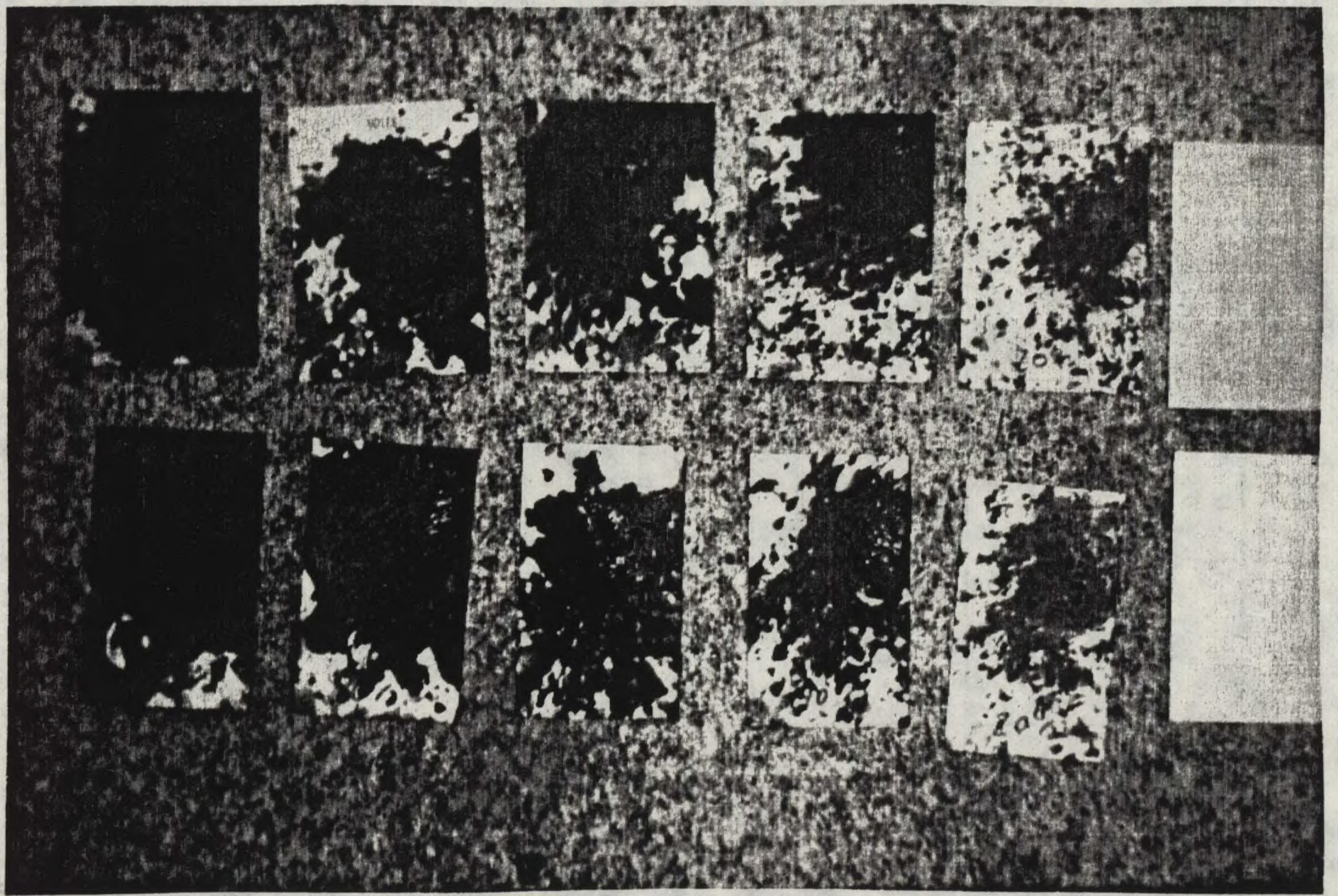


Figure 7. Smear tests on pink telephone message chits (**top row**) and white index cards (**bottom row**).

the dry, frozen and wet sediment/oil mixtures. Smearing was tested on both "Chinette" paper plates (Fig. 6), and index cards and pink phone message chits (Fig. 7; do it right, do it pink).

The smear tests offer a very promising means to quantify observations as the relative smear left by the oiled sediments is directly proportional to oil content. That is:

- the smear darkness was proportional to oil content (Fig. 6, all rows),
- the smear darkness is noticeably lighter for frozen sediments where the oil is much more viscous (Fig. 6, centre row),
- the smear tests for the wet sediments provided a good relative indication of oil contents, but with slightly lighter smears than those for the dry sediment.

2.3.3 SOOI Colour Observations

During the initial column oiling tests, it was observed that the oil film on the sediment surface changed colour and a"fuzzy" appearance overnight. To quantify our colour observations, a Munsell Soil Color chart was used along with visual observations. These standardized colours provide a useful index of oil content Table 5.

Table 5 Relationship of Standardized Colours to Oil Retention for Emulsified and Non-Emulsified Oils

HUE	Light	--->	--->	--->	--->	Dark
COLOUR	dark yellowish brown	dark yellowish brown	dark brown	very dark greyish brown	very dark grey	very dark brown
MUNSELL INDEX	10YR3/6	10YR3/4	10YR3/3	10YR3/2	10YR3/1	10YR2/2
% SATURATION RANGE	57-61*	10.3-14.5	11.4-18.8	23.2-23.3	27.0-28.7	27.8-45.9
AVERAGE % SATURATION (s.d.)	59 (2)	11.8 (1.9)	15.0 (2.2)	23.3 (0.1)	27.9 (0.7)	31.5 (4.7)
SAMPLE SIZE	12	3	7	2	4	16

* oil-in-water emulsion

The test shows sufficient promise to warrant additional testing and some blind testing to establish the validity of the technique.

2.4 Sediment Column Experimental Set-up

Plexiglas columns were used as the primary testing medium for the experiments. Two different sized columns were used: (1) a 1.5m-deep, 0.4m-diameter hexagonal plexiglass column and (2) a 0.6m-deep, 0.2m-diameter hexagonal column (Figure 8). It was originally anticipated that larger columns would be required; however, initial experiments indicated that smaller columns would be appropriate and would considerably reduce the amount of contaminated materials.

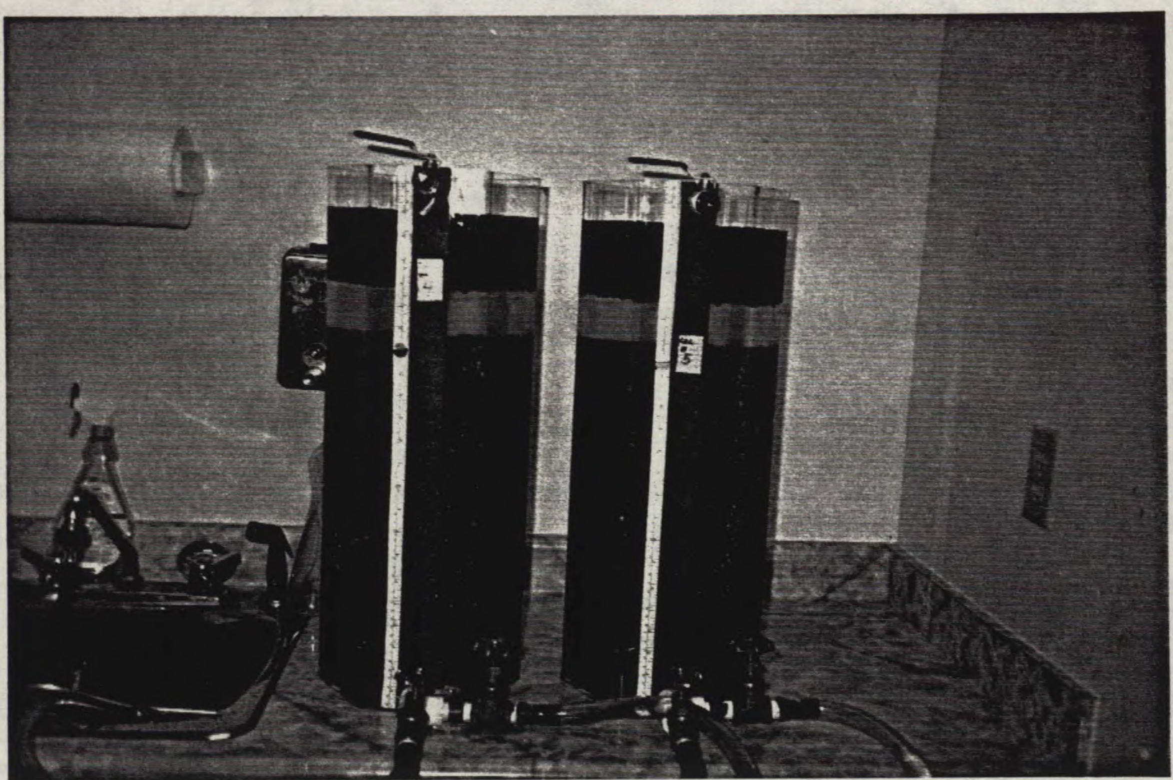


Figure 8. Photograph of the smaller columns used in the experiments (0.6m high and 0.2m in diameter). Columns are filled with sediment, then filled with seawater from a header tank (not shown) through the red valves at the base. Oil (black layer at top) is added to the water surface, then the water level is dropped by opening the valves (blue) at the base.

The following steps were used in most of the experiments:

1. Sediment was loaded into the column in approximately 20cm-thick layers. Each layer was vibrated for 2 minutes to compact to optimum density.

2. The columns were then filled with artificial seawater (30ppt), the amount of infilling noted and the actual porosity computed. The seawater level was then raised an additional 10 cm above the sediment surface.

3. Oil was loaded onto the water surface using a baffle to minimize penetration into the water column.

4. The water level was lowered at approximately 0.5cm/m by opening an outlet valves at the base of the column (Fig. 8), and the thickness of the oil layer (Fig. 9) was observed at approximately 1 minute intervals.

5. After the base of the oil reached 30 or 70cm, depending on the column depth, the column was filled with seawater from the base of the column at about 0.5cm/m until the oil layer was completely above the sediment surface.

6. Steps 4 and 5 were repeated until an equilibrium was reached; that is, no additional oil was retained in the sediments.

7. Once an equilibrium was reached, oil was removed from the water surface and the volume noted.

8. Steps 4 and 5 were repeated until no further oil was removed from the sediments (this step is referred to as the wash cycle).

No water sampling was done during the experiment and as such dissolved oil components are not accounted for in the oil budgets.

2.5 Experimental Observations

The nature of the experiments resulted in a number of visual observations being made of the oil character. These observations included:

- initial thickness of oil layer on the water surface,
- base of oil layer as water level dropped (see Fig. 9),
- top of oil layer as oil passed through the sediment column (Fig. 9),
- colour of unoiled and oiled sediments,
- maximum depth of penetration,
- miscellaneous observations such as presence of bubbles, oil retention character (oil films on grains or residual oil help in grain-to-grain contacts), "piping" that occurs when oil "plugged" the surface sediments.

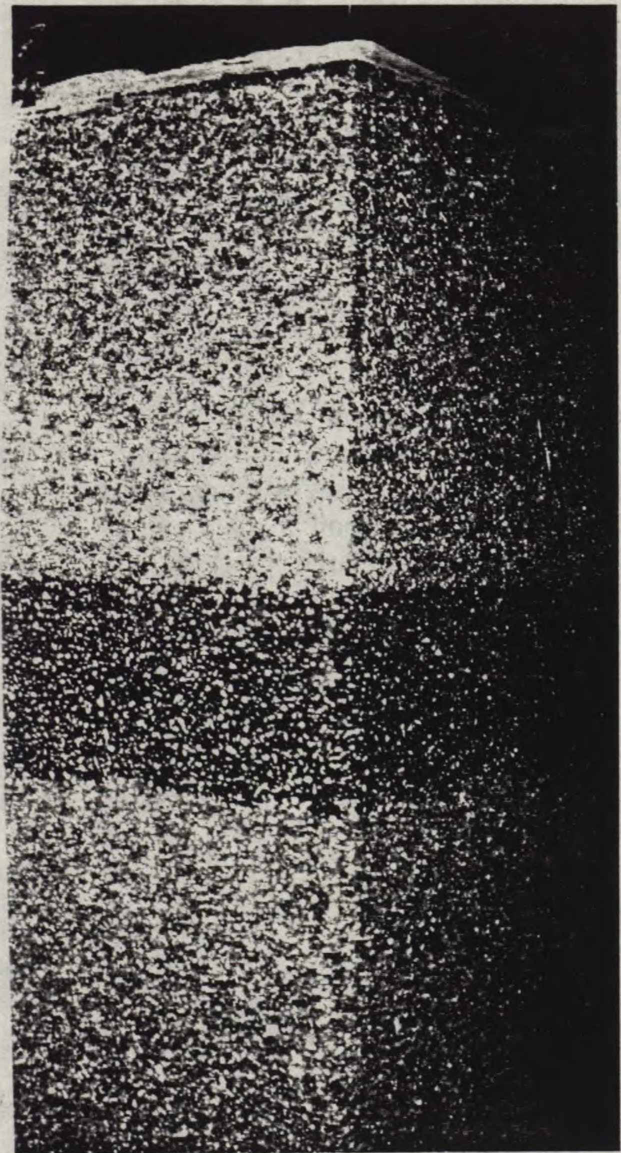


Figure 9a. Photograph of the weathered oil as it passed through the granules (Experiment 1). The top of the oil layer is at 26cm and the base of the oil layer at 38cm.

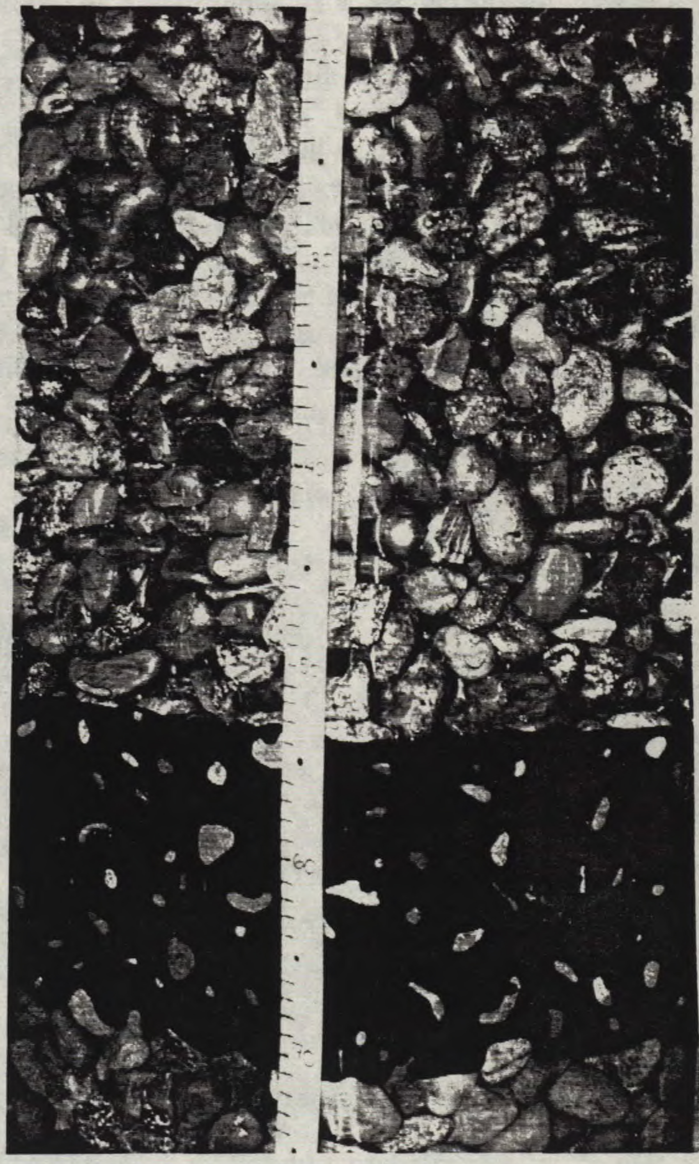


Figure 9b. Photograph of the weathered oil as it passed through the pebbles (Experiment 2). The top of the oil layer is at 53cm and the base of the oil layer at 71cm.

2.6 Experimental Measurements

2.6.1 Oil Budget

An oil budget was kept for each experiment. That is, the amount of oiled recovered from the water surface at the end of the experiment was deducted from the amount of oil that was initially applied to compute the volume of oil retained. The retained volume and porosity values provided an indication of per cent saturation (percentage of void space filled by oil). The volume of dissolved oil was not documented and assumed to sufficiently small to ignore in the oil budget calculations.

2.6.2 Sampling

Samples of oiled sediment were collected from the columns at the completion of the experiment. Samples for GC/MS analysis were placed in baked glass jars and samples for total hydrocarbon analysis were placed in plastic bags. Normally, one set of samples was collected from the smaller columns - a bulk sample for total hydrocarbon analysis and a GC/MS sample. Up to three sets of samples were collected from the larger columns.

Samples were shipped to the River Road Environmental Technology Centre for analysis.

Twenty-five experiments were conducted to evaluate oil retention and penetration characteristics. The experimental design is summarized in Table 6. Experiments 22, 23, 24 and 25 focused on the effect of porosity on oil retention.

Table 6 Summary of Experimental Parameters Tested and Associated Experiments

Sediment Type	Weathered Oil (warm)	Weathered Oil (cold)	Weathered Oil (cool)	Emulsified Oil (cold)	Emulsified Oil (cool)
Granules	1,4,5	-	10,11	16,17	22,23,24,25
Pebbles	2,6,7	-	12,13	-	18,19
Granule & Pebble Mixture	3,8,9	14,15	-	20,21	-

Note: cold <5°C; cool=5-10°C; warm=20-23°C

3.1 General Results

The overall results are summarized in Table 7 along with actual values of measured parameters. Oil concentrations are expressed in terms of litres per cubic metre of sediment as this value appears to provide an intuitive index of the oil concentration; converted values in terms of milligrams oil per kilogram of sediment and barrels of oil per cubic metre of sediment are provided in Appendix C.

The theoretical maximum oil concentration, as expressed in L/m^3, is ten times the porosity value[1]. The volume of oil retained in the sediments used the following volumetric budget:

Vi	Initial Oil Volume (measured)
-Vs	Oil Volume recovered on surface after the experiment (measured)
-Vw	Oil Volume lost in water (assumed small and ignored)
Vr	Volume Retained in Sediment (computed as residual)

[1] **porosity** is the ratio of the volume of voids to the total volume of sediment + voids, expressed in percentages. For example, if the porosity is 35%, then a 1,000L volume (1m^3) would have a void volume of 350L.

Table 7 Experimental Results

Exp. No.	Sediment Type	Crude Oil	Temp. C	Porosity %	Mean Oil Concentration of sediment (litres / cubic metre) tide#1	tide#2	steady state	wash#1	wash#2	wash#3	Oil Volume (L)	Av. Max Oiling Depth (cm)	Max Water Depth (cm)
1	granule	w,NE	20-23	41.00	64.40	n/a	n/a	n/a	n/a	n/a	9.04	65.40	65.40
4	granule	w,NE	20-23	41.05	95.08	95.08	n/a	n/a	n/a	n/a	2.90	30.50	30.50
5	granule	w,NE	20-23	40.98	92.23	95.54	n/a	n/a	n/a	n/a	3.00	31.40	31.40
10	granule	w,NE	4-5	36.27	137.93	144.83	103.45	101.04	99.31	98.10	1.50	14.50	14.50
11	granule	w,NE	4-5	38.86	170.54	178.30	116.28	113.37	111.63	110.27	1.50	12.90	12.90
16	granule	w,EM	1.5-2.5	42.72	410.20	476.14	476.14	475.72	475.72	475.72	1.50	4.83	15.00
17	granule	w,EM	1.5-2.5	42.19	441.65	484.19	484.19	483.97	483.97	483.97	1.50	4.44	15.00
24	granule	w,EM	6-9	40.15	489.32	499.15	499.15	491.41	491.41	491.41	1.50	6.45	15.00
22	granule	w,EM	7-9	39.45	465.62	477.79	477.79	475.70	472.35	469.01	1.50	5.78	15.00
25	granule	w,EM	6-9	37.27	420.25	453.92	453.92	445.66	445.66	445.66	1.50	6.05	15.00
23	granule	w,EM	7-9	31.72	439.47	405.13	405.13	401.42	396.20	393.97	1.50	6.51	15.00
2	pebble	w,NE	20-23	40.00	0.90	n/a	n/a	n/a	n/a	n/a	9.84	70.50	70.50
6	pebble	w,NE	20-23	37.91	0.90	0.90	n/a	n/a	n/a	n/a	1.50	11.20	11.20
7	pebble	w,NE	20-23	38.63	0.90	0.90	n/a	n/a	n/a	n/a	1.50	11.20	11.20
12	pebble	w,NE	4-5	38.89	0.90	0.90	0.90	n/a	n/a	n/a	1.50	11.90	11.90
13	pebble	w,NE	4-5	38.94	0.90	0.90	0.90	n/a	n/a	n/a	1.50	12.20	12.20
18	pebble	w,EM	6-7	40.73	230.84	232.68	232.68	232.68	232.68	232.68	1.50	17.85	20.00
19	pebble	w,EM	6-7	39.63	241.53	241.53	241.53	241.53	241.53	241.53	1.50	16.94	20.00
3	p/g mix	w,NE	20-23	28.00	48.30	n/a	n/a	n/a	n/a	n/a	8.44	72.20	72.20
8	p/g mix	w,NE	20-23	29.28	46.53	46.53	37.23	33.50	31.18	30.25	1.50	21.49	21.49
9	p/g mix	w,NE	20-23	33.73	63.47	63.47	55.00	51.82	49.70	49.06	1.50	23.60	23.60
14	p/g mix	w,NE	2.5-4.5	32.55	108.95	108.95	101.17	101.17	101.17	101.17	1.50	25.70	25.70
15	p/g mix	w,NE	2.5-4.5	33.22	105.77	105.77	94.23	94.23	94.23	94.23	1.50	26.00	26.00
20	p/g mix	w,EM	1-3	29.71	364.94	366.04	366.04	365.99	365.89	365.79	1.50	7.73	20.00
21	p/g mix	w,EM	1-3	31.64	370.58	373.98	373.98	373.93	373.80	373.67	1.50	7.64	20.00

Some problems were experienced with this approach during the experiments that used emulsified oil. The reader will note that several of the experiments ended with the volume of retained oil exceeding the maximum theoretical limit (i.e., exceeding saturation). This difference is attributed to separation of the water-in-oil emulsion during the experiment. As such, Vs (Oil Volume recovered after the experiment) would be erroneously low (because the water fraction of the emulsion was lost), leading to erroneously high Vr values (i.e., the computed residual is then in error). This problem appears to be a result of the separation of the emulsion as it passed through the sediments; small dark bands of "ashphaltines" were commonly observed at the base of the oil layer suggesting separation. It is not known how much separation of the emulsion took place, although it was observed that pores were completely filled (i.e., saturated; see Fig. 10).

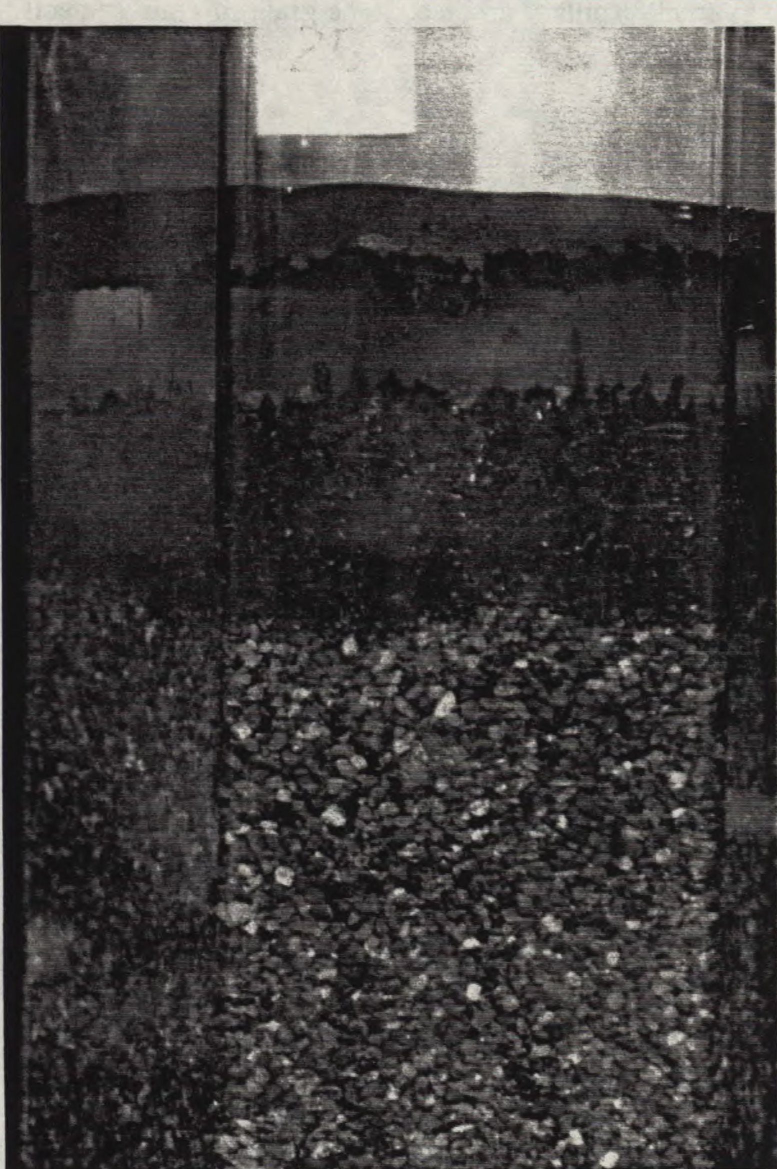


Figure 10. Oil emulsion/granule experiment (#25) showing "emulsion-plugged" surface sediments (penetration 6 cm).

3.2 Weathered Oil

3.2.1 General

The experiments showed lower overall *concentrations* of weathered oil than emulsified oil but that the weathered oil penetrated to greater depths (Table 7). In fact, at no time was the maximum penetration of the weathered oil achieved; the maximum depth of penetration in the experiments was about 70cm and was limited by the water table. Viscosities and stickiness appeared to be the primary control in oil retention. The maximum concentration was 110L/m^3 or 30% saturation (i.e., 30% of the void space was filled).

Results generally showed that the maximum oil retention was achieved during the first pass of the oil through the sediment and that little additional oil was

retained on subsequent passes of the oil layer. The three tidal washes that followed the oiling cycle typically resulted in a reduction of 25% of the initial maximum value; that is, about 25% of the oil was flushed out immediately.

Initial column tests (conducted in a warm laboratory - 20-23°C) suggested that the most oil was retained in the granules, followed by the granule/pebble mix and then by the pebbles. However, subsequent testing during "cool" and "cold" conditions suggested that there is not a significant difference between the granules and the granule/pebble mixture. The pebble sediment had the lowest retention with less than 1% saturation (<1L/m^3).

The observations indicate that only a small percentage of oil is retained as film on the grain surfaces and that most oil is retained as small capillary droplets at the grain-to-grain contacts.

3.2.2 Time Series

The elevations of the top and base of the oil layer were monitored during the experiments. Time series plots of the oil layer (top and base) and oil thickness are developed for each experiment (Appendix A); an example of the time series of the weathered crude oil is provided in Figure 11.

The data are useful for understanding the rate at which oil is removed as the oil passes through the sediment. Figure 11b provides an example:

- as the water level in the column (or beach) dropped, the oil layer thinned as oil was retained in the sediment (Fig. 11b, Hour 0.3 to 1.1).
- when the water level stabilized around 70cm, some water and oil drained through the sediment so the base of the oil was raised and the thickness of the oil layer increased (Fig. 11b, Hours 1.1 to 3.6).
- as the water level rose, the oil layer again thinned as additional oil was "captured" by the sediment (Fig. 11b, Hours 3.8 to 4.8).

These time series data provide an indication of oil retention processes as well as the basis for more sophisticated modelling.

3.3 Water-In-Oil Emulsion

3.3.1 General

As indicated in Table 7, the water-in-oil emulsions had higher oil-in-sediment concentration values than the weathered oil values but generally shallower oil penetration depths. Not only was the viscosity of the oil much greater than that of the weathered crude oil but the "stickiness" was also greater. Large globs of emulsion often adhered to the walls of the columns. These two factors, high viscosity and stickiness, resulted in sediments becoming "plugged" and limiting penetration.

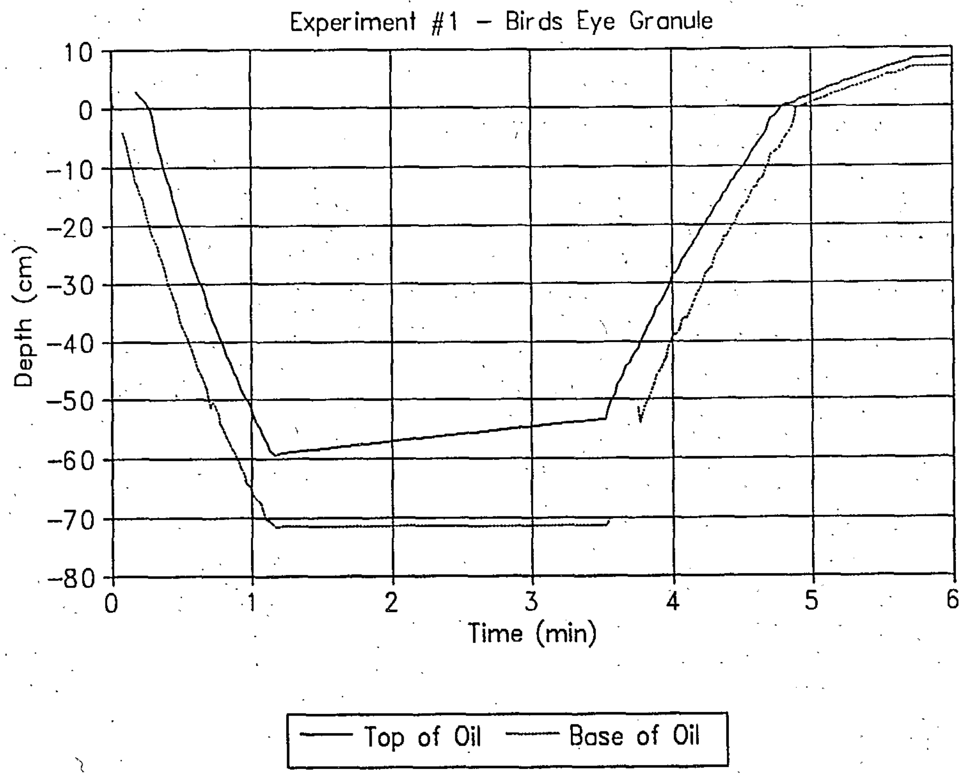


Figure 11a Oil layer limits over one tidal cycle.

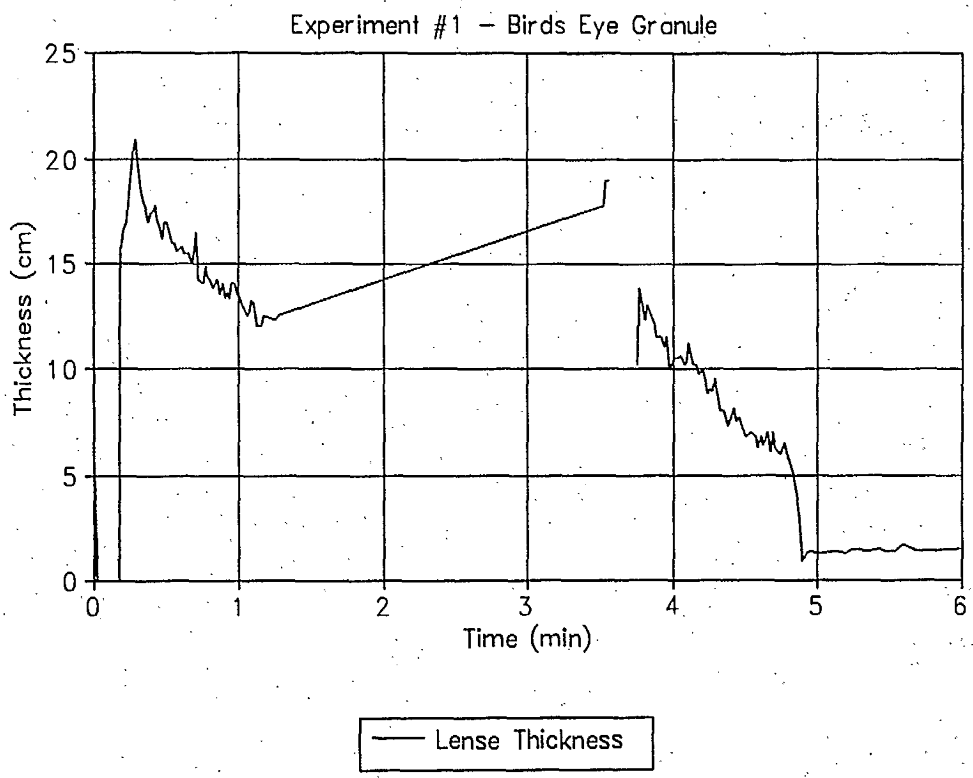


Figure 11b Oil thickness over one tidal cycle.

Saturated or near-saturated conditions (based on visual observations) were achieved on the first pass of the oil through the sediment, except for the pebble where an approximate 50% saturation was achieved on the first pass. Additional amounts of emulsion were retained on the second pass although the exact amount is uncertain in that some separation of the emulsion must have occurred as the oil passed through the sediment (see Section 3.1).

Little change in oil concentration occurred during the wash cycles, indicating that the emulsion, once retained, is very difficult to remove; the maximum reduction of oil during the wash cycle was approximately 1%.

Although the retention values suggest that oil saturation conditions prevailed in the granule sediment, they are not necessarily comparable to the weathered oil experiments as the sediment became plugged and the depth of penetration limited. As such the surface *concentration* of oil was high but the *total volume* of oil was limited. Table 8 provides a simple illustration of total volume of oil retained in the upper 50cm of a column.

Table 8 **Hypothetical Volumes of Oiled Sediment based on Experimental Results**

	Total Volume Retained (L)	
Oil Type	Top 10cm	Top 50cm
Weathered*	10.4	52.1
Emulsified**	38.9	38.9

* Experiments 10,11
** Experiments 16,17,22,23,24,25; penetration limited to 6cm

Although concentrations were highest in the granule sediment, penetration was limited so that the total volume of oil retained was greater in the pebble material as the granules and granule/pebble mixture became "plugged" when oil reached approximately 7cm (Table 9). In contrast to the results with the weathered oil conditions, the pebble material has much higher oil retention values with an emulsified oil.

Table 9 **Hypothetical Volumes of Emulsion in Sediment based on Experimental Results**

	Total Volume Retained (L)	
Sediment Type	Top 10cm	Top 50cm
Granules*	38.9	38.9
Pebbles**	23.7	118.

* Experiments 16,17,22,23,24,25
** Experiments 18,19; penetration limited to 7cm

The primary difference of the emulsion-in-sediment as compared to the weathered-oil-in-sediment is that pore spaces are significantly infilled by the emulsion. Whereas the weathered oil had maximum saturation percentages of 30%, 100% saturation was achieved in the emulsion.

The experiments identify two general types of sediment/oil conditions (Fig.12), which reflect the complex interaction between sediment properties (grain size, packing, void size, etc.) and oil properties (viscosity and stickiness). The two general conditions identified are:

> **"permeable conditions"** occur with lower viscosities and larger pore spaces, and oil drains freely through the sediments during falling tides. Oil is retained primarily a small capillary droplets at the grain-to-grain contacts. Oil concentrations tend to be lower than 30% saturation (i.e., 30% of the void space) but penetration of oil into the sediment can be substantial.
>
> **"impermeable conditions"** occur with higher viscosities and smaller pore sizes such that oil "plugs" pore spaces. The result is oil high concentrations near the surface with voids largely filled with oil (i.e., >75% saturation of void space) and limited oil penetration.

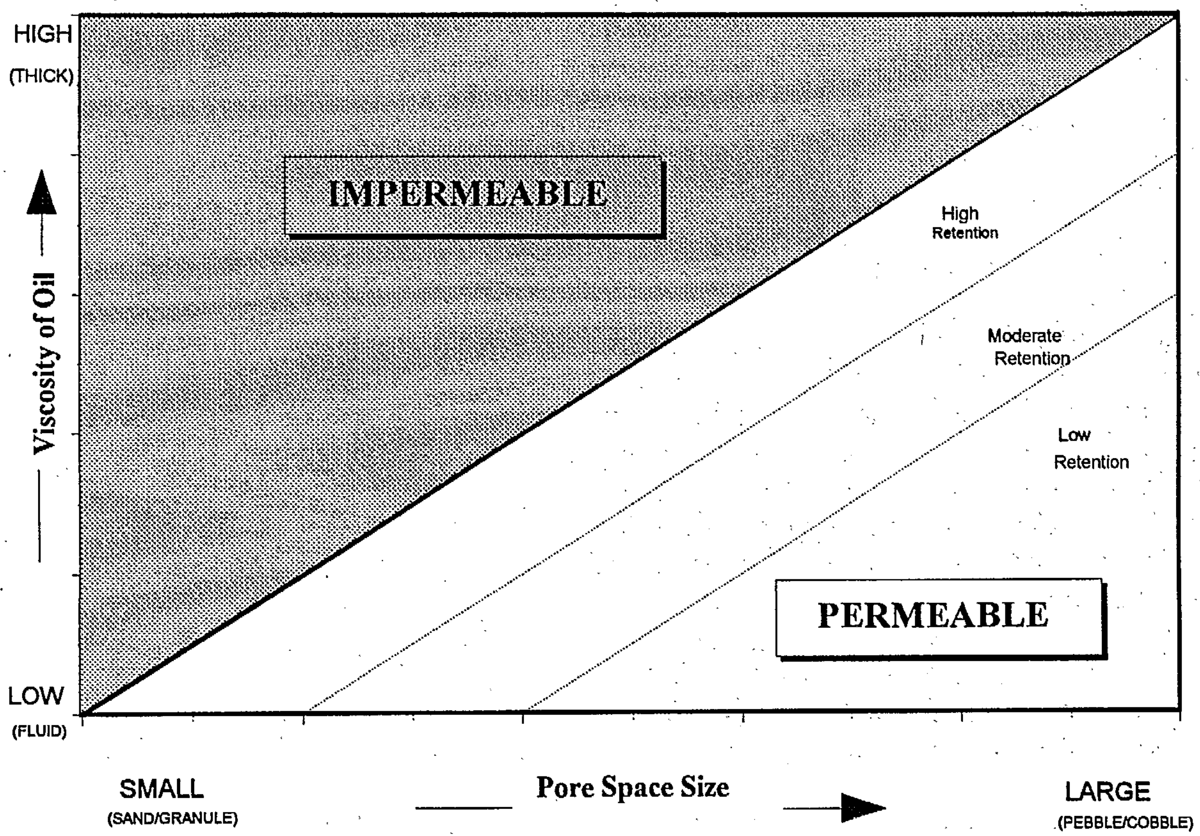


Figure 12. Conceptual diagram of the oil retention characteristics as a function of pore-space size and of viscosity.

4.1 PERMEABLE SEDIMENT/OIL CONDITIONS

Permeable or "freely-drained" sediment/oil conditions are those conditions which retain some oil as the oil layer passes through the sediment on a falling tide and where no pore-plugging occurs. For weathered, non-emulsified oil, the three sediment types tested all resulted in permeable sediment/oil conditions; that is, oil penetrated freely and was limited only by the depth of the water-table.

4.1.1 Penetration Potential

Table 10 uses experimental data to illustrate the difference in penetration potential for the different sediments. The results show that the penetration depths would be two orders of magnitude greater in pebbles than in granules, because the granules have a greater oil retention potential due to larger oil volumes captured at grain-to-grain contacts (i.e., there are more grain-to-grain contacts).

Table 10 Penetration Potential of Permeable Sediments with Weathered Oil

Initial Oiling Thickness (cm)	Granules[1]	Pebble/ Granule[2]	Pebbles[3]
0.5	5cm	5cm	5m
1.0	10cm	10cm	10m
10	100cm	100cm	100m

[1] based on Experiments 10,11; [2] based on Experiments 14,15; [3] based on Experiments 12,13

The data (Table 10) also illustrate that there is no difference between granules and the granule/pebble mixture in terms of penetration potential, as indicated in our permeability tests. The smaller grains determine the permeability of the sediment.

4.1.2 Retention Potential

As suggested by Figure 12, there is a large range of retention potential for permeable sediments. The retention increases with smaller grain sizes and more viscous oils. The greater number of grain-to-grain contacts in finer sediments, result in greater retention of oil (Table 11; non-emulsified oil data). That is, for a given viscosity of oil, more oil will be retained in finer sediments.

Table 11 Oil Retention as a Function of Grain Size in Permeable Sediments

Sediment	Retention (L/m^3)
Granules	104[1]
Granule/Pebble	97.5[2]
Pebble	0.9[3]

[1] Experiments 10,11; [2] Experiments 14,15; [3] Experiments 12,13

There are insufficient data, however, to determine the trend of data (e.g., exponential or linear) or the functional relationship with grain size.

The data do indicate that more oil is retained for increasingly viscous oils. Table 12 shows oil retention values as a function of oil viscosity. There is insufficient data to quantitatively define the trends.

Viscosities of the emulsion were several orders of magnitude higher than the non-emulsified oil. Retention values of the pebbles jumped from less than 0.9 L/m^3 for the weathered, non-emulsified oil (viscosities of 10-70 cP) to 237 L/m^3 for the emulsified oil (viscosity of 5,000 cP).

Table 12 Oil Retention as a Function of Viscosity

Viscosity (cP)	Granules (L/m^3)	Granule/Pebble (L/m^3)
5.0	85[1]	36[3]
11.5	104[2]	-
12.5	-	98[4]
4,300	450[5]	-
7,400	479[6]	370[7]

[1] Experiments 1,4,5; [2] Experiments 10,11; [3] Experiments 3,8,9; [4] Experiments 14,15; [5] Experiments 22-25; [6] Experiments 16,17 [7] Experiments 20-21

4.2 IMPERMEABLE SEDIMENT/OIL CONDITIONS

"Impermeable" sediment/oil conditions are those sediments where the pore space is sufficiently small and the oil sufficiently viscous that flow does not occur through the sediments (Figure 12). Oil penetrates for a short distance from the surface down into the sediment but then pores become plugged, so that further penetration does not occur and flow stops. This type of fluid-sediment interaction was observed during the emulsion/granule experiments. Oil penetrated approximately 5 to 6 cm into the granules then plugged the sediment such that further penetration did not occur; the water level was lowered to 15cm without any change in the penetration depth.

Although the concentrations in this surface, plugged layer were very high (about 400 L/m^3 or 100% saturation), the limited depth of penetration means that the overall volume of oil retained in the upper 0.5m of sediments would be less than that of permeable sediment/oil condition (see Table 8).

As indicated in Figure 12, both the viscosity and sediment determine if a condition will be "impermeable". The granule and granule/pebble mixture were impermeable to the high viscosity emulsions whereas the pebbles were permeable.

4.3 DISCUSSION

The results have important implications to the retention of oil on beaches. The results partially quantify some important relations between oil retention, oil character and beach sediments.

4.3.1 Permeable vs Impermeable Conditions

The most important implication to overall retention is the permeability of the beach sediments. **Impermeable sediment/oil conditions** will generally retain less oil because the oil is confined to a thin surface layer; high oil concentrations may occur within this surface layer but the overall volumetric retention is low (e.g. see Table 8). This result is confirmed by field observations during the *Exxon Valdez* where oil did not penetrate into the subsurface of many of the low-energy beach systems because of the fine sediments in these beaches. Similarly oil that was stranded at distances from the *Exxon Valdez* spill site tended to be highly viscous, either from weathering or due to emulsification, and did not penetrate as deeply into the sediments. Oil that is concentrated near the surface is more likely to reworked and redistributed, and therefore persistence is likely to be shorter than if deeper penetration occurs.

Permeable sediment/oil conditions have the potential for significant penetration and although the concentrations may not be as high as can occur within the surface layer of impermeable sediment/oil conditions, larger volumes of sediment may be oiled. Again, Table 8 provides an indication of the volume of material that can be oiled in comparison to impermeable conditions. Also as the viscosities of the permeating fluid increase, retention values can become quite high. For example comparison of Experiments 12&13 (weathered, non-emulsified oil in pebble sediment) to 18&19 (emulsified oil in pebble sediment) showed over a two hundred-fold increase in oil retention for the viscous emulsion.

The results confirmed observations from the *Exxon Valdez* where some coarse-sediment beaches were oiled to significant depths, sometimes greater than one metre in depth. Many of the Prince William Sound beaches have a boulder/cobble armour over glacial marine sediments; the permeable armour allowed penetration of oil through the surface armour with minimal retention but when the oil reached the finer, impermeable subsurface sediments, it "plugged", leaving a high concentration subsurface oil layer.

4.3.2 Incidental Observations

No standard tests exist for many of the experiments carried out as part of this project. A customized permeability test was developed and several "observational" techniques for visual documentation of oil concentrations were evaluated.

The permeability test provides a useful, repeatable index of sediment permeability; however, it cannot be directly related to a standard sediment coefficient of permeability (k). The coefficient of permeability provides a standard index of sediment permeability. Additional tests using the same testing apparatus may be useful in relating our index of permeability ("Q") to the coefficient of permeability (k).

Several tests of a Subsurface Oil Observation Index (SOOI) were developed. These included (a) visual observations, (b) smear tests and (c) colour tests. The colour test using a Munsell Soil Colour Chart appeared to provide to best means of quantifying subsurface oil concentrations. The technique appears to be capable of discriminating differences in saturation of 10% or better. There was also a distinguishable colour difference between non-emulsified oil and emulsified oil, so the technique may be useful in typing oil as well as indexing concentrations.

In practice, a Munsell-SOOI Index could be developed at the beginning of a spill incident and incorporated into the SCAT data acquisition program.

1. Sediment-oil interaction results in two major categories of oil retention - **impermeable conditions** and **permeable conditions.**

2. Permeability characteristics are determined by both the **oil viscosity** and the **sediment pore space.** Viscous oils and small pore spaces result in impermeable conditions whereas fluid oils and large pore spaces result in permeable conditions.

3. Under impermeable conditions, pore spaces become plugged by the oil; the result is typically a thin (<5cm), high concentration (typically 100% saturation) layer of oiled sediment that limits further penetration.

4. Under permeable conditions, oil freely percolates through the pore space with a residual amounts retained as a coatings of oil on the grain surfaces and as capillary droplets at the grain-to-grain contacts. Penetration depths and the total volume of oil retained within the sediments can be substantial; in the granules/weathered oil experiments, saturations of ~30% (about 100 L/m^3 of the 300L/m^3) were achieved and in the pebble/emulsified oil saturations of ~60% (about 200 L/m^3 of the 300L/m^3 pore space).

5. Oil retention is likely to be highest under permeable conditions where oils are viscous and sediments are relatively fine-grained so there are a large number of grain-to-grain contacts.

6. Visual observations indicate a strong potential for using standard soil colour charts for indexing both the type of oil and amount of oil retained in sediments. There are observable colour differences between concentrations differences as small as 5% saturation.

Folk, R.L., 1968. Petrology of sedimentary rocks. Hemphill's, Austin, Texas, 170pp.

Jahns, H.O., J.R. Bragg, L.C. Dash and E.H. Owens, 1991. Natural cleaning of shorelines following the *Exxon Valdez* spill. In Proceeding of the 1991 Oil Spill Conference, API Publication No. 4529, p. 167-176.

Owens, E.H., 1991a. Changes in shoreline oiling conditions 1.5 years after the 1989 Prince William Sound spill. Report by Woodward-Clyde Consultants, Seattle, WA, 52p.

Owens, E.H., 1991b. Shoreline conditions following the *Exxon Valdez* spill as of fall 1990. Report by Woodward-Clyde Consultants, Seattle, WA, presented at the 14th Annual Arctic and Marine Oil Spill Program Technical Seminar, 49p.

APPENDIX A

Sample Logs

SOCS PROJECT: BAG SAMPLE LIST

Exp. #	Material	Sample	Interval	Comments
1	Granule	#1	0 to -2 cm	oiled sediment after second tidal fall
1	Granule	#2	-20 cm	oiled sediment after second tidal fall
1	Granule	#3	-40 cm	oiled sediment after second tidal fall
1	Granule	#4	-50 cm	oil saturated sediment
2	Pebble	#5	0 to -2 cm	oiled sediment after second tidal fall
2	Pebble	#6	-20 cm	oiled sediment after second tidal fall
2	Pebble	#7	-40 cm	oil saturated sediment
2	Pebble	#8	-60 cm	oiled sediment after first tidal cycle
3	P/G Mix	#9	0 to -2cm	oiled sediment after second tidal fall
3	P/G Mix	#10	-20 cm	oiled sediment after second tidal fall
3	P/G Mix	#11	-40 cm	oil saturated sediment
3	P/G Mix	#12	-60 cm	oiled sediment after first tidal cycle
4	Granule	#13	-10 cm	oiled sediment after two tidal & three wash cycles
5	Granule	#14	-10 cm	oiled sediment after two tidal & three wash cycles
6	Pebble	#15	-3 to -6 cm	oiled sediment after two tidal & three wash cycles
7	Pebble	#16	-3 to -6 cm	oiled sediment after two tidal & three wash cycles
8	P/G Mix	#17	-10 cm	oiled sediment after two tidal & three wash cycles
9	P/G Mix	#18	-10 cm	oiled sediment after two tidal & three wash cycles
10	Granule	#19	-9.5 cm	oiled sediment after two tidal & three wash cycles
11	Granule	#20	-6.5 cm	oiled sediment after two tidal & three wash cycles
12	Pebble	#21	-6 cm	oiled sediment after two tidal & three wash cycles
13	Pebble	#22	-6 cm	oiled sediment after two tidal & three wash cycles
14	P/G Mix	#23	-10 cm	oiled sediment after two tidal & three wash cycles
15	P/G Mix	#24	-10 cm	oiled sediment after two tidal & three wash cycles
16	Granule	#25	0 to -3 cm	em. oiled sediment after two tidal & three wash cycles
17	Granule	#26	0 to -3 cm	em. oiled sediment after two tidal & three wash cycles
18	Pebble	#27	-10 cm	em. oiled sediment after two tidal & three wash cycles
19	Pebble	#28	-10 cm	em. oiled sediment after two tidal & three wash cycles
20	P/G Mix	#29	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles
21	P/G Mix	#30	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles
22	Granule	#31	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles
23	Granule	#32	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles
24	Granule	#33	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles
25	Granule	#34	-3 to -4 cm	em. oiled sediment after two tidal & three wash cycles

Note: sample weight typically between 500 and 750 grams.

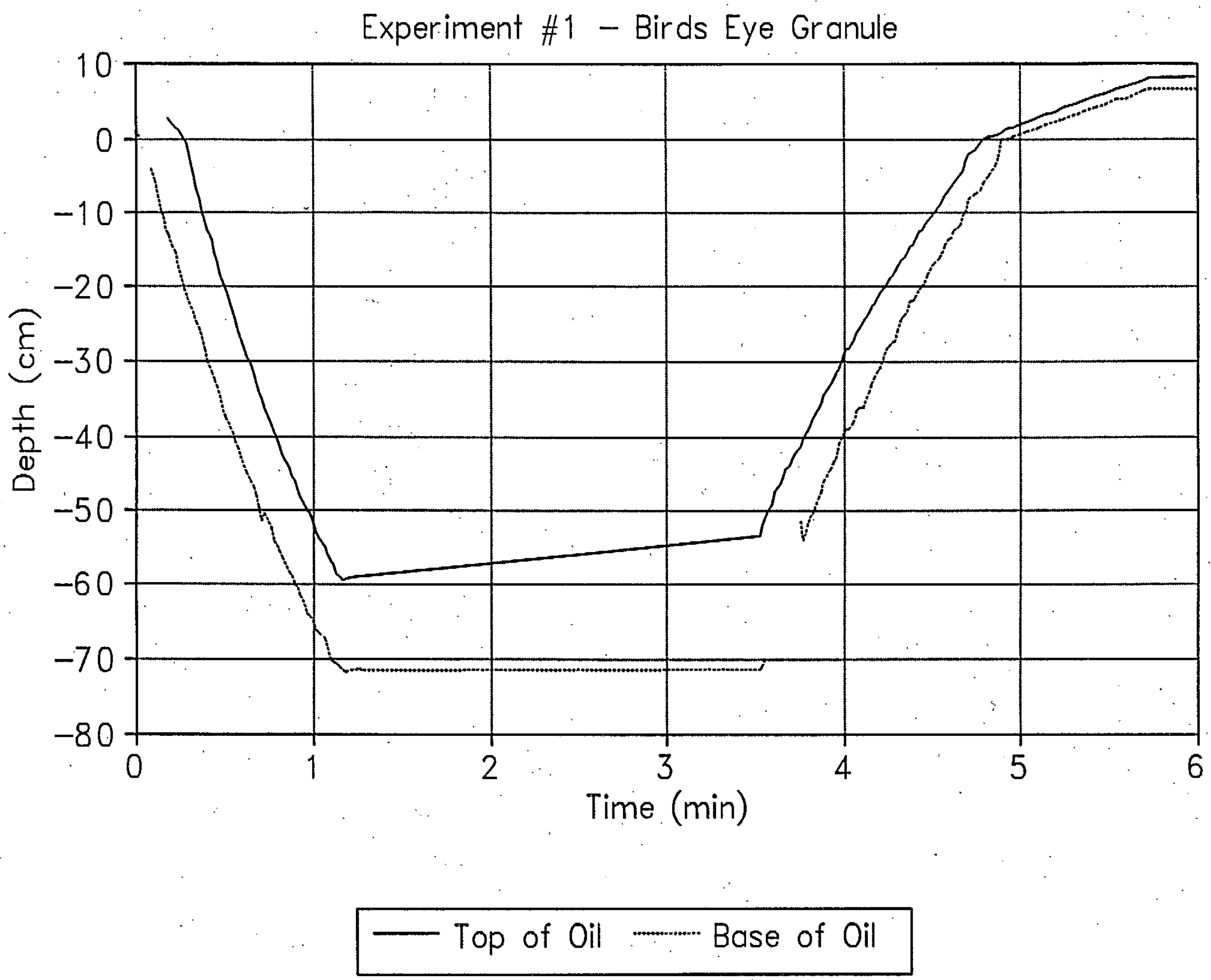
SOCS PROJECT: GC SAMPLE LIST

W = 22% weathered by volume (Federated Sweet Crude Oil)
NE = non-emulsified
EM = emulsified crude (70% saltwater : 30% weathered crude)
P/G MIX = 50/50 mix by volume of pebbles to granules

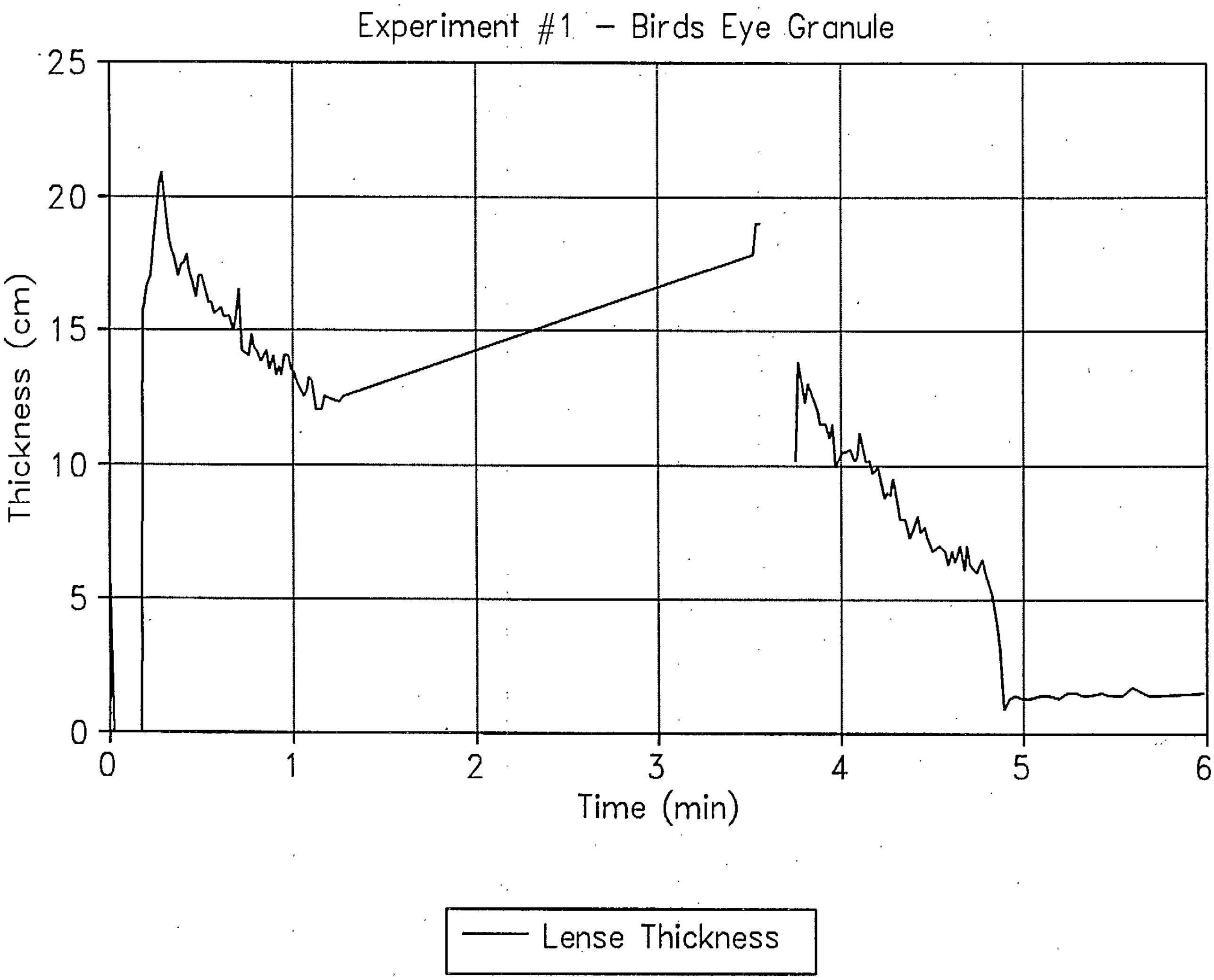
Exp. #	Material	Oil Type	Sample	Comments
2	Pebble	W,NE Crude	GC01	oil off surface of sediment column after one tidal cycle
3	P/G Mix	W,NE Crude	GC02	oil off surface of sediment column after one tidal cycle
*	*****	W,NE Crude	GC03	22% weathered, non-emulsified federated sweet crude
*	*****	W,NE Crude	GC04	22% weathered, non-emulsified federated sweet crude
4	Granule	W,NE Crude	GC05	oil off surface of sediment column after two tidal cycle
5	Granule	W,NE Crude	GC06	oil off surface of sediment column after two tidal cycle
6	Pebble	W,NE Crude	GC07	oil off surface of sediment column after two tidal cycle
7	Pebble	W,NE Crude	GC08	oil off surface of sediment column after two tidal cycle
8	P/G Mix	W,NE Crude	GC09	oil off surface of sediment column after two tidal cycle
9	P/G Mix	W,NE Crude	GC10	oil off surface of sediment column after two tidal cycle
10	Granule	W,NE Crude	GC11	oil off surface of sediment column after two tidal cycle
11	Granule	W,NE Crude	GC12	oil off surface of sediment column after two tidal cycle
12	Pebble	W,NE Crude	GC13	oil off surface of sediment column after two tidal cycle
13	Pebble	W,NE Crude	GC14	oil off surface of sediment column after two tidal cycle
14	P/G Mix	W,NE Crude	GC15	oil off surface of sediment column after two tidal cycle
15	P/G Mix	W,NE Crude	GC16	oil off surface of sediment column after two tidal cycle
16	Granule	W,EM Crude	GC17	emulsion off surface of sediment column after two tidal cycle
17	Granule	W,EM Crude	GC18	emulsion off surface of sediment column after two tidal cycle
18	Pebble	W,EM Crude	GC19	emulsion off surface of sediment column after two tidal cycle
19	Pebble	W,EM Crude	GC20	emulsion off surface of sediment column after two tidal cycle
20	P/G Mix	W,EM Crude	GC21	emulsion off surface of sediment column after two tidal cycle
21	P/G Mix	W,EM Crude	GC22	emulsion off surface of sediment column after two tidal cycle
22	Granule	W,EM Crude	GC23	emulsion off surface of sediment column after two tidal cycle
23	Granule	W,EM Crude	GC24	emulsion off surface of sediment column after two tidal cycle
24	Granule	W,EM Crude	GC25	emulsion off surface of sediment column after two tidal cycle
25	Granule	W,EM Crude	GC26	emulsion off surface of sediment column after two tidal cycle
26	Granule	W,EM Crude	GC27	emulsion off surface of sediment column after two tidal cycle

APPENDIX B

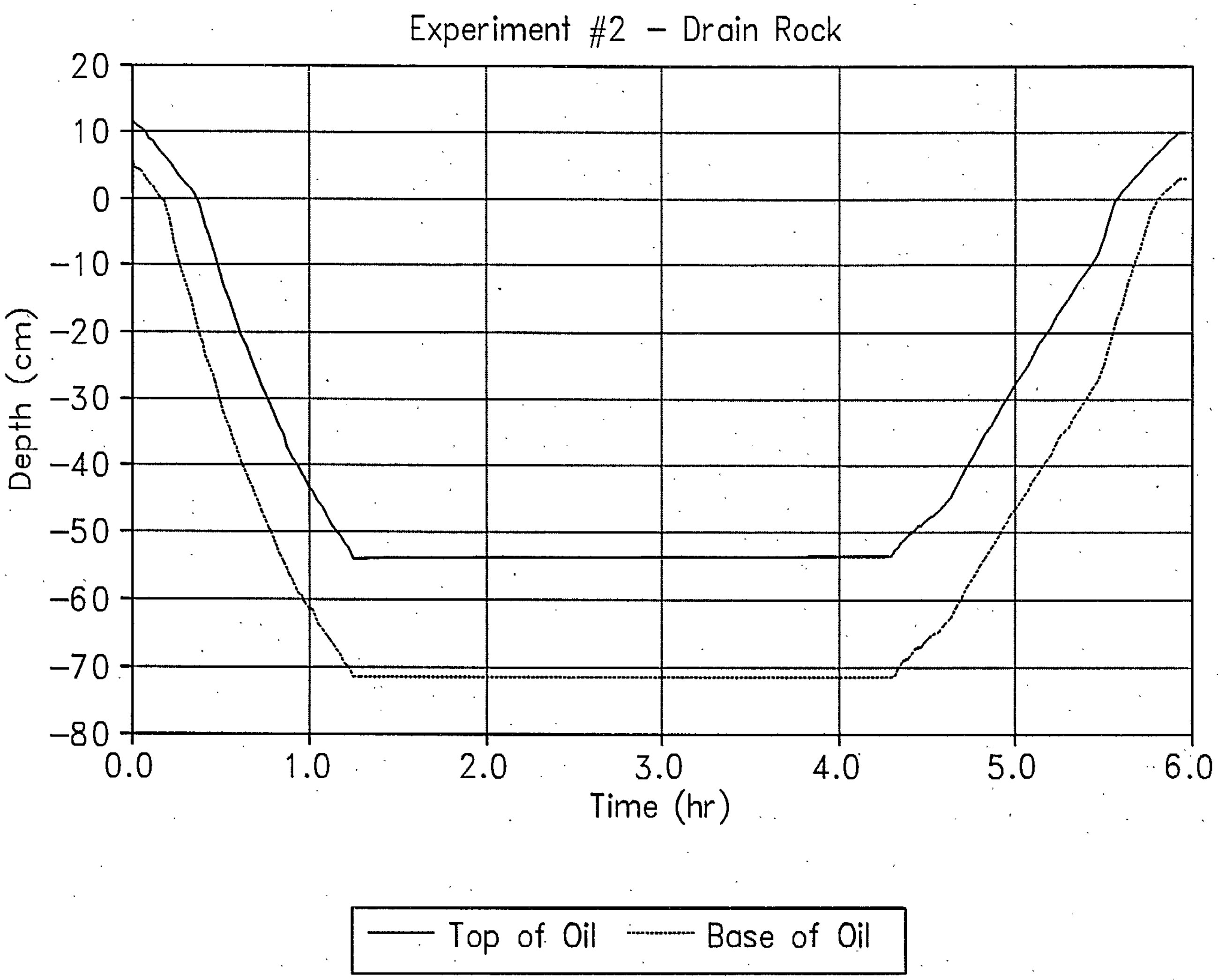
Time Series Plots



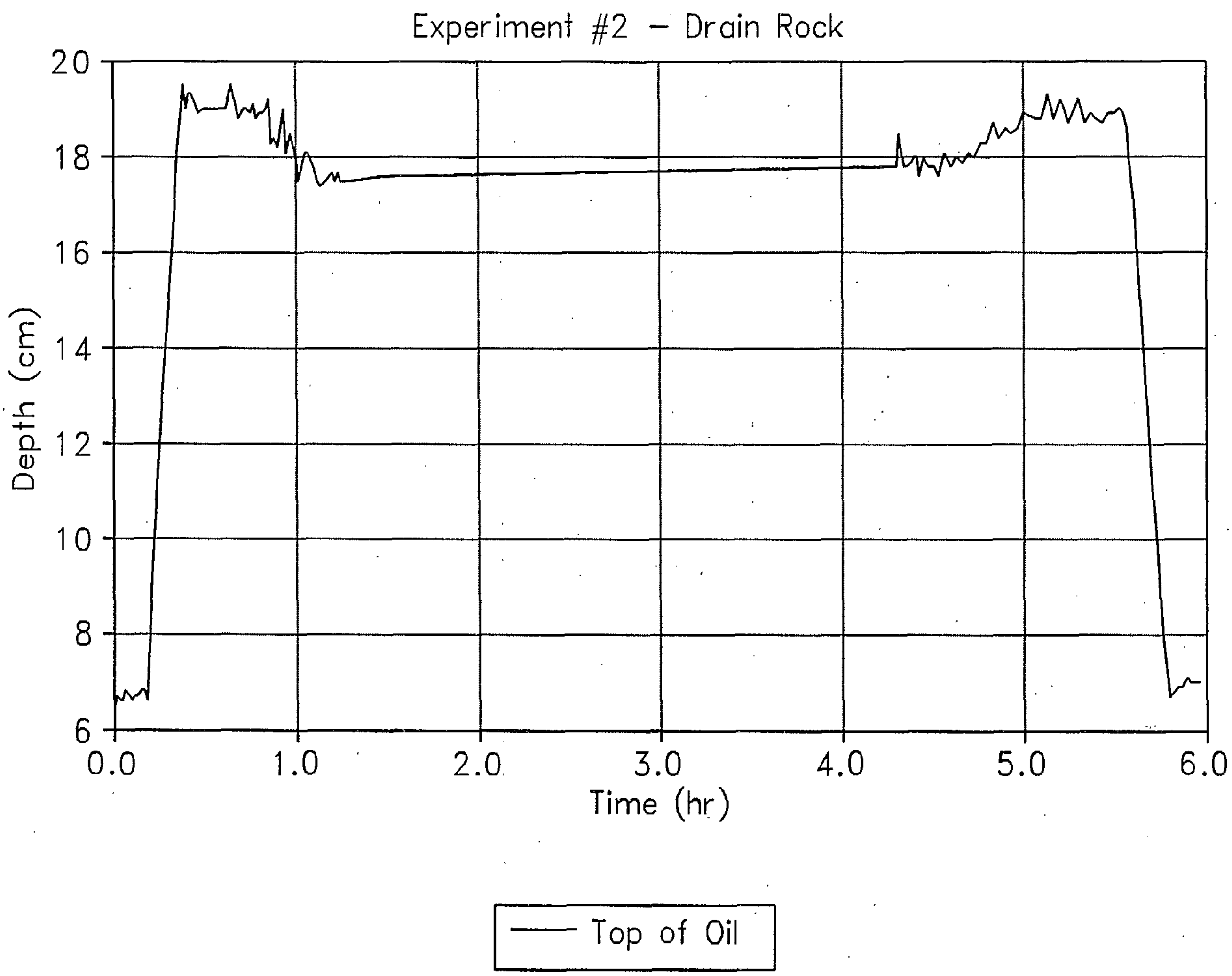
Experiment #1 - Birds Eye Granule
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Depth (cm)
0
1
2
3
4
5
6
Time (min)
Top of Oil
Base of Oil



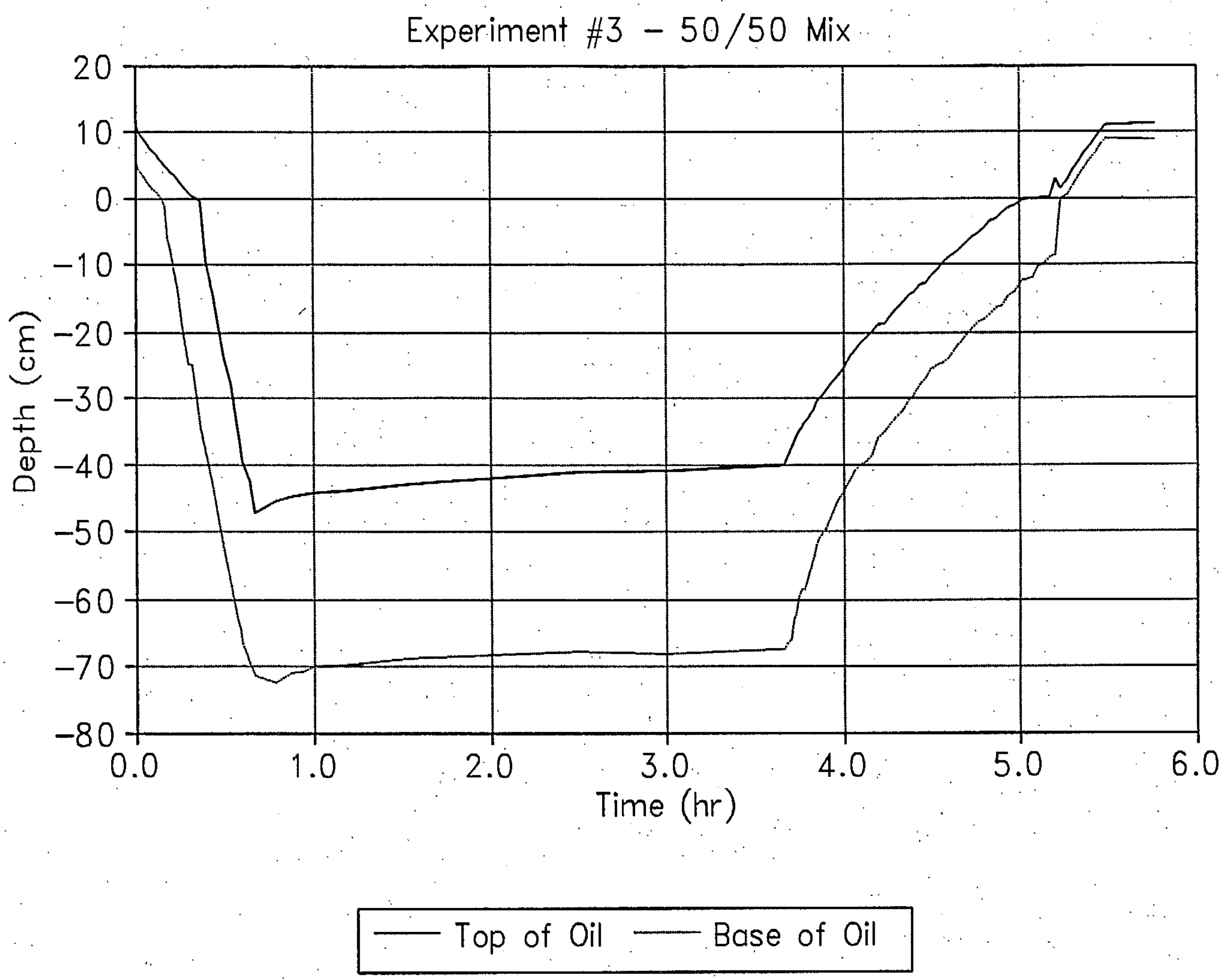
Experiment #1 - Birds Eye Granule
Thickness (cm)
Time (min)
0
5
10
15
20
25
0
1
2
3
4
5
6
Lense Thickness

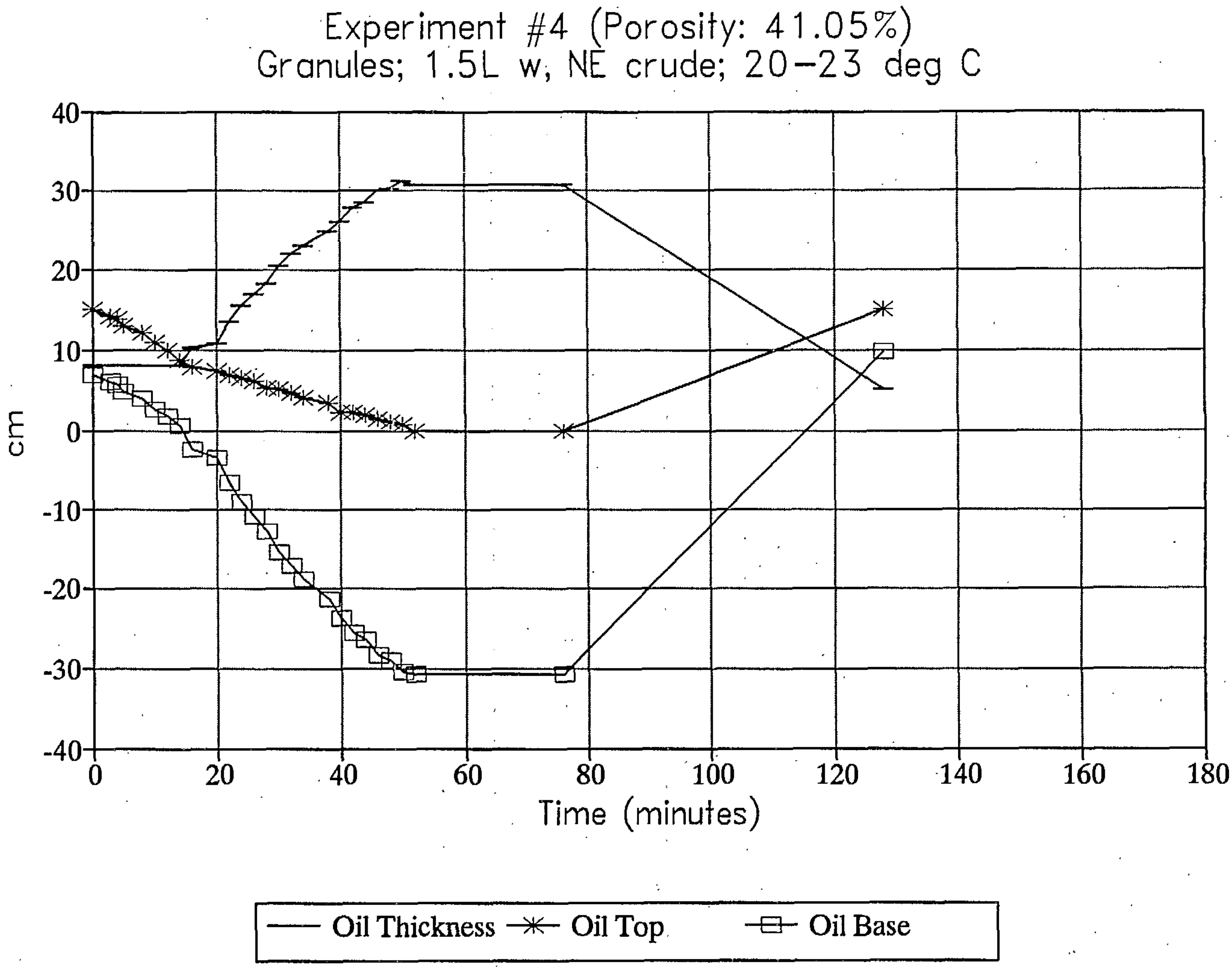


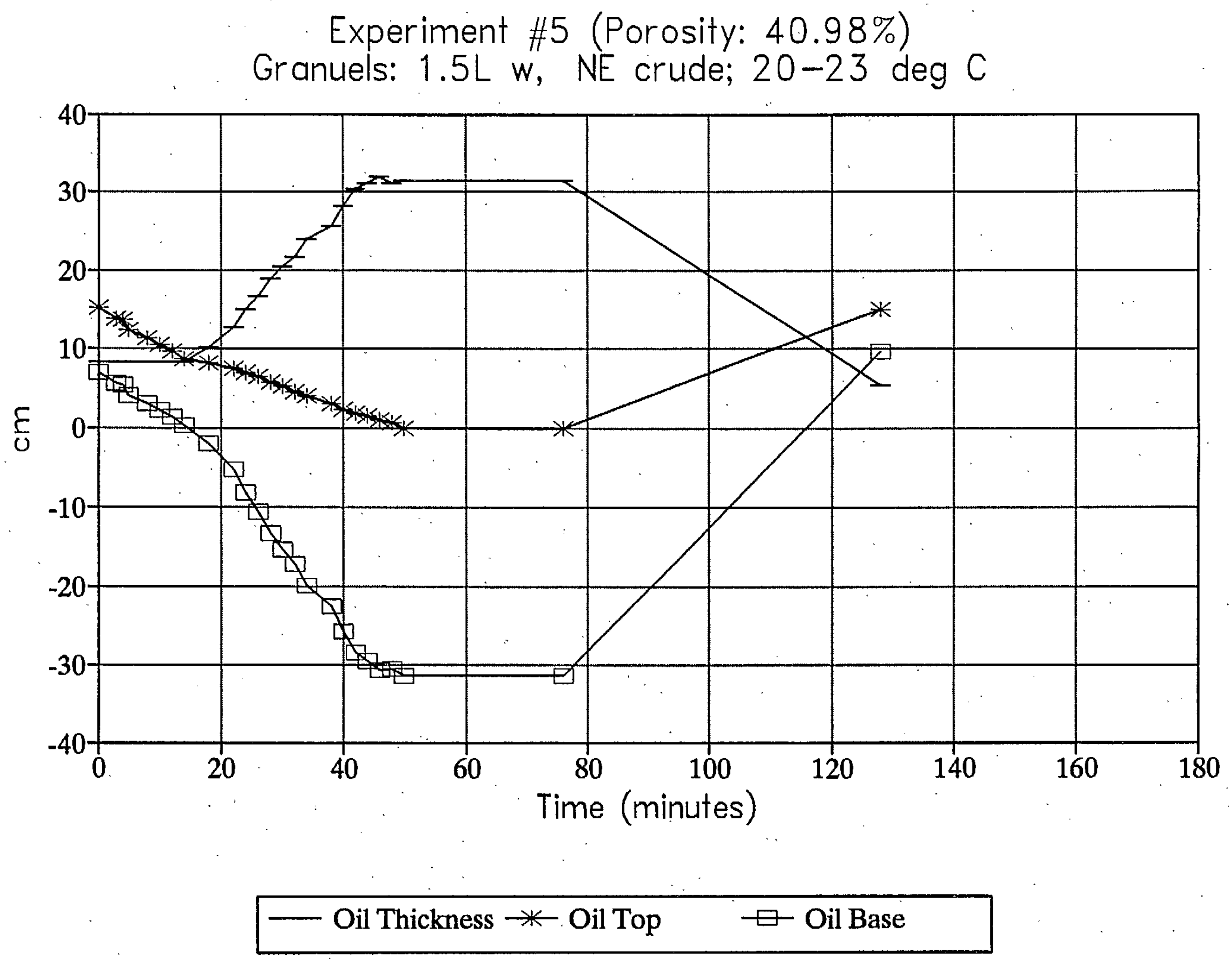
Experiment #2 - Drain Rock
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Depth (cm)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Time (hr)
Top of Oil
Base of Oil

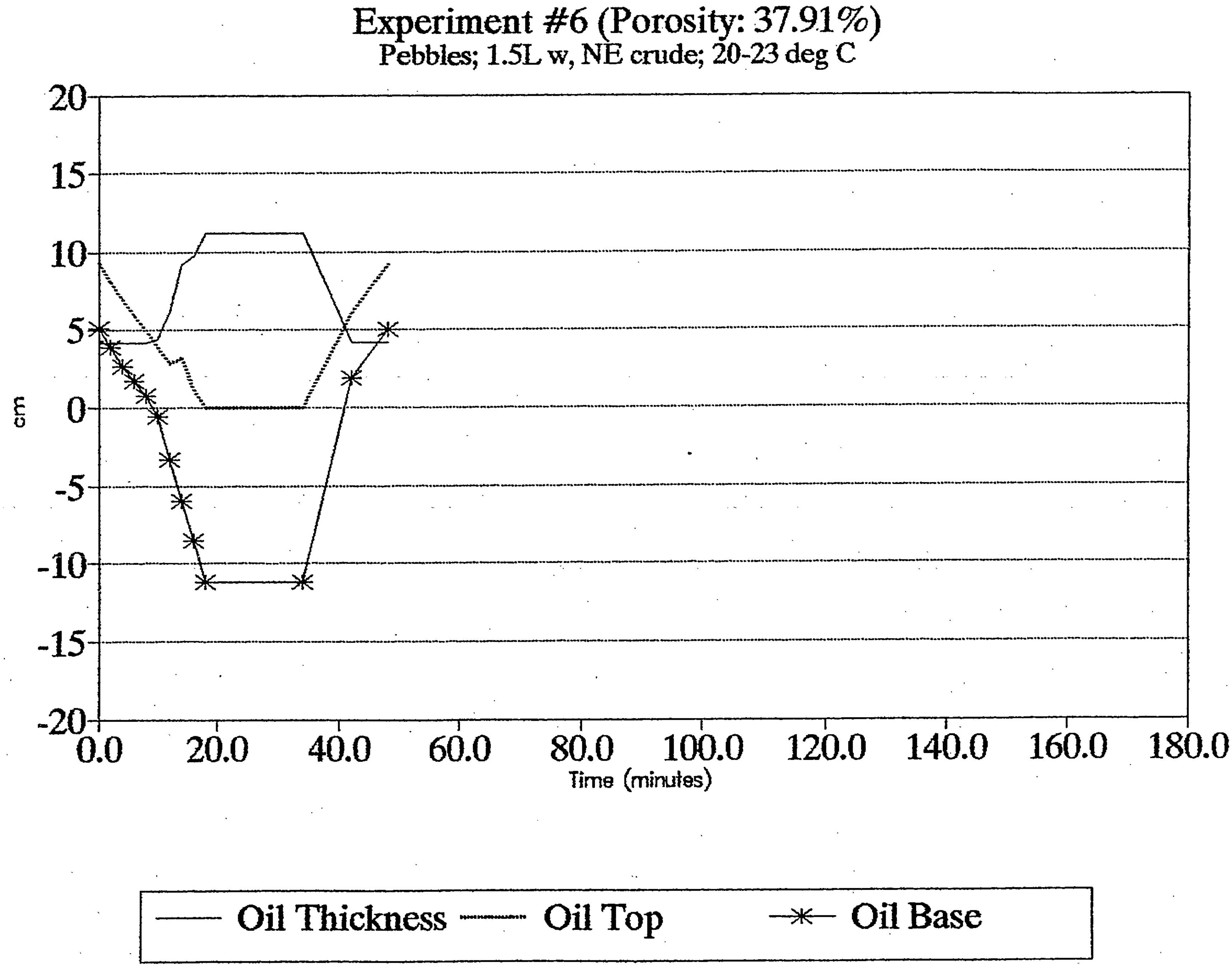


Experiment #2 - Drain Rock
Depth (cm)
20
18
16
14
12
10
8
6
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Time (hr)
Top of Oil

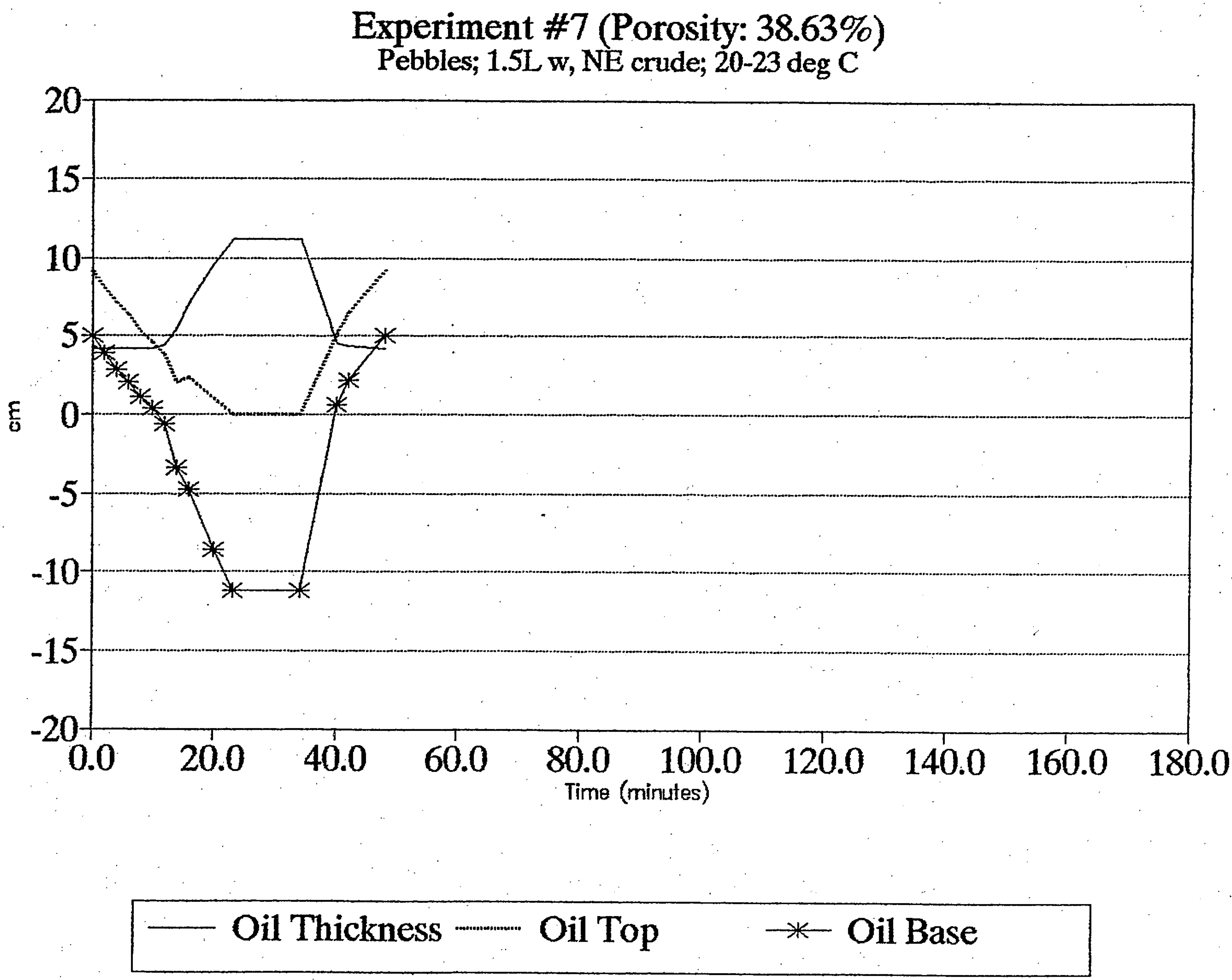

Experiment #3 - 50/50 Mix
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
Depth (cm)
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Time (hr)
Top of Oil
Base of Oil

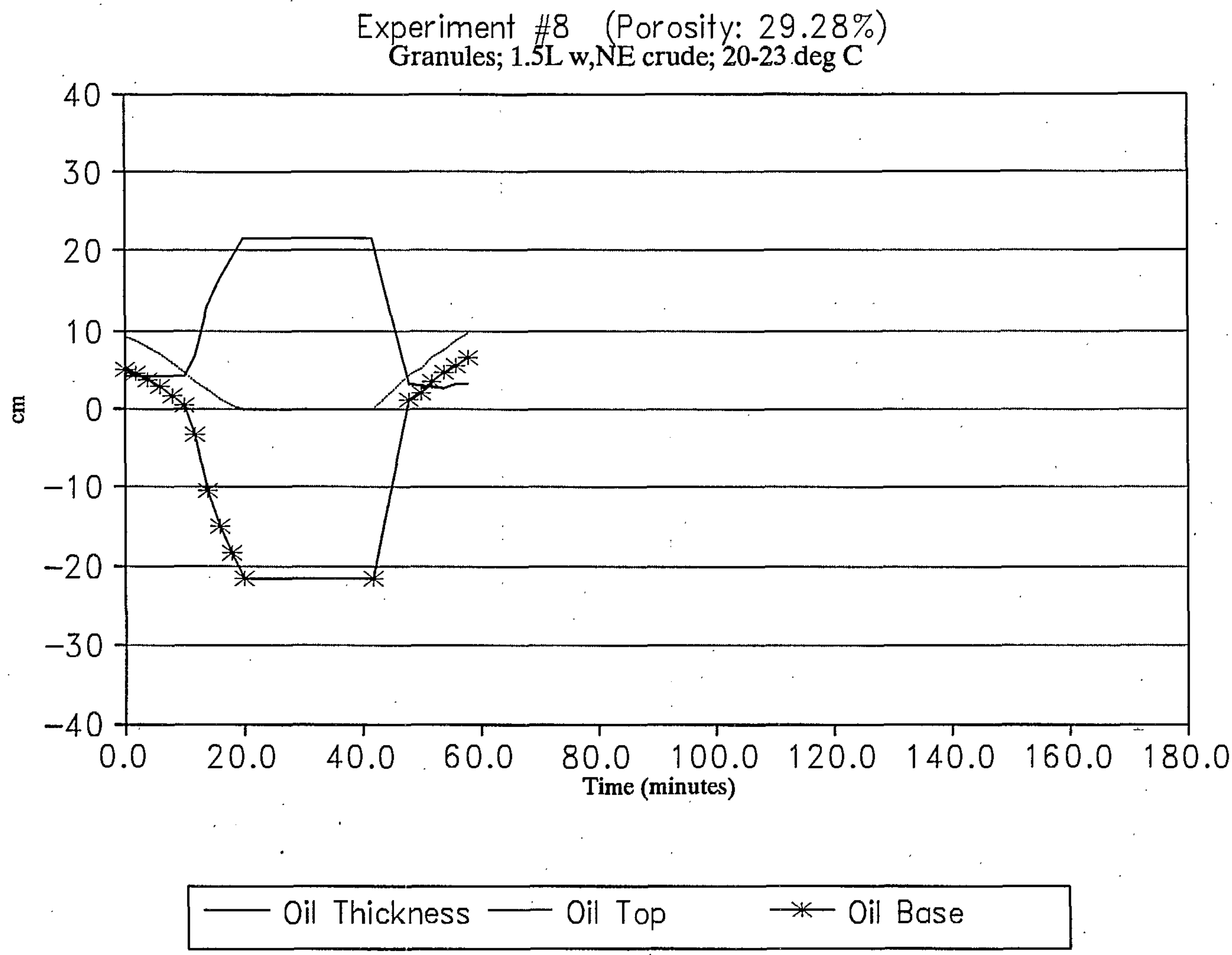

Experiment #4 (Porosity: 41.05%)
Granules; 1.5L w, NE crude; 20-23 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0
20
40
60
80
100
120
140
160
180
Time (minutes)
Oil Thickness
Oil Top
Oil Base


Experiment #5 (Porosity: 40.98%)
Granuels: 1.5L w, NE crude; 20-23 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0
20
40
60
80
100
120
140
160
180
Time (minutes)
Oil Thickness
Oil Top
Oil Base

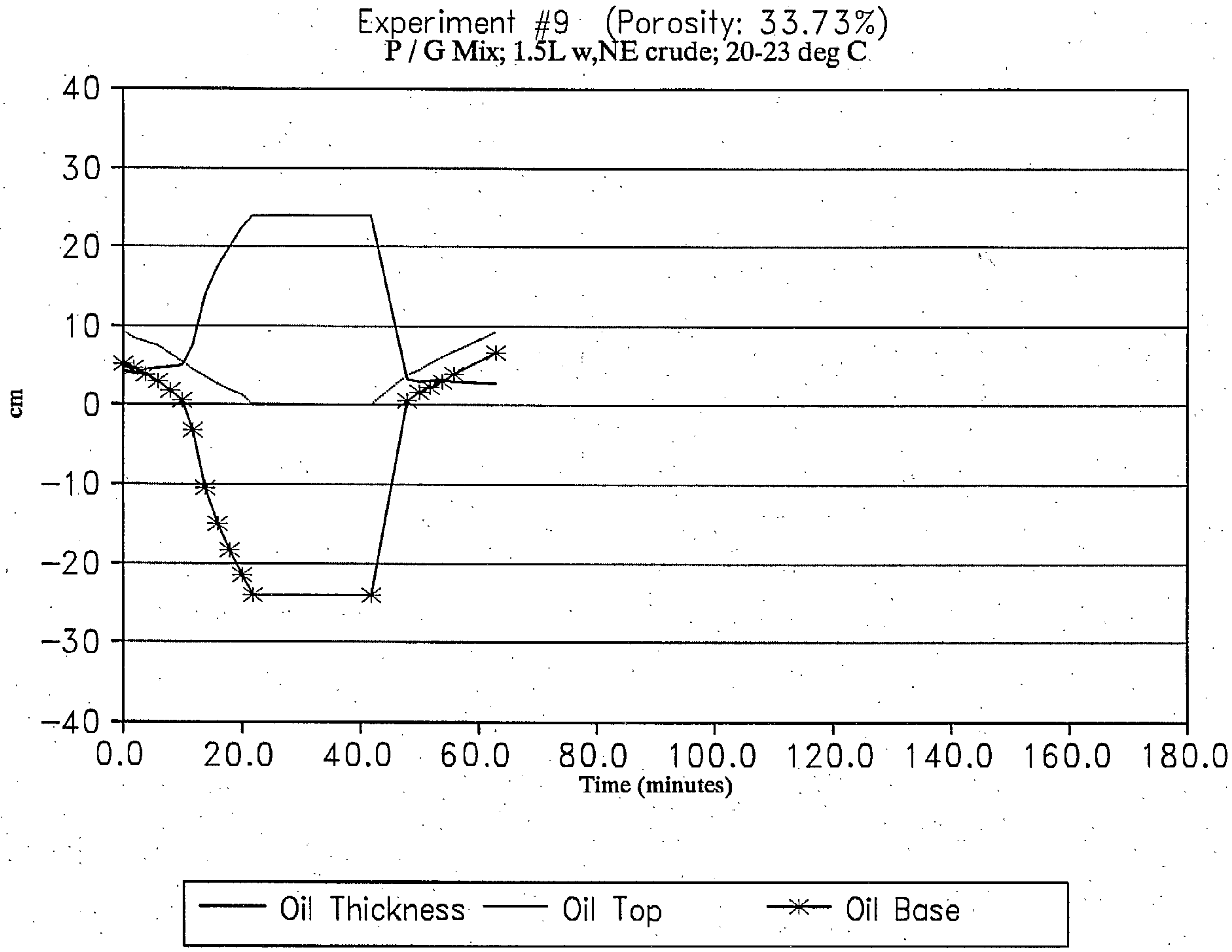


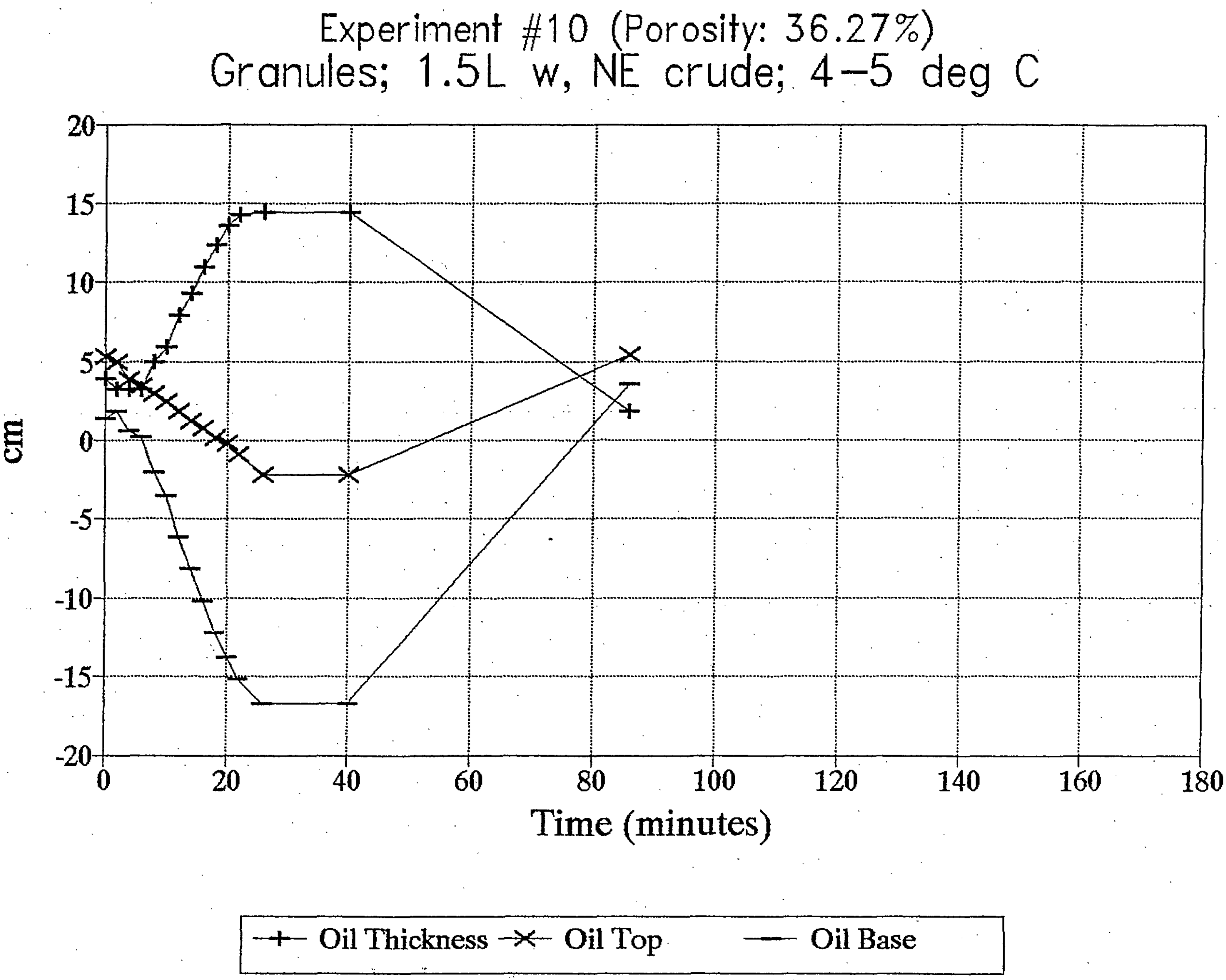
Experiment #6 (Porosity: 37.91%)
Pebbles; 1.5L w, NE crude; 20-23 deg C
20
15
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base

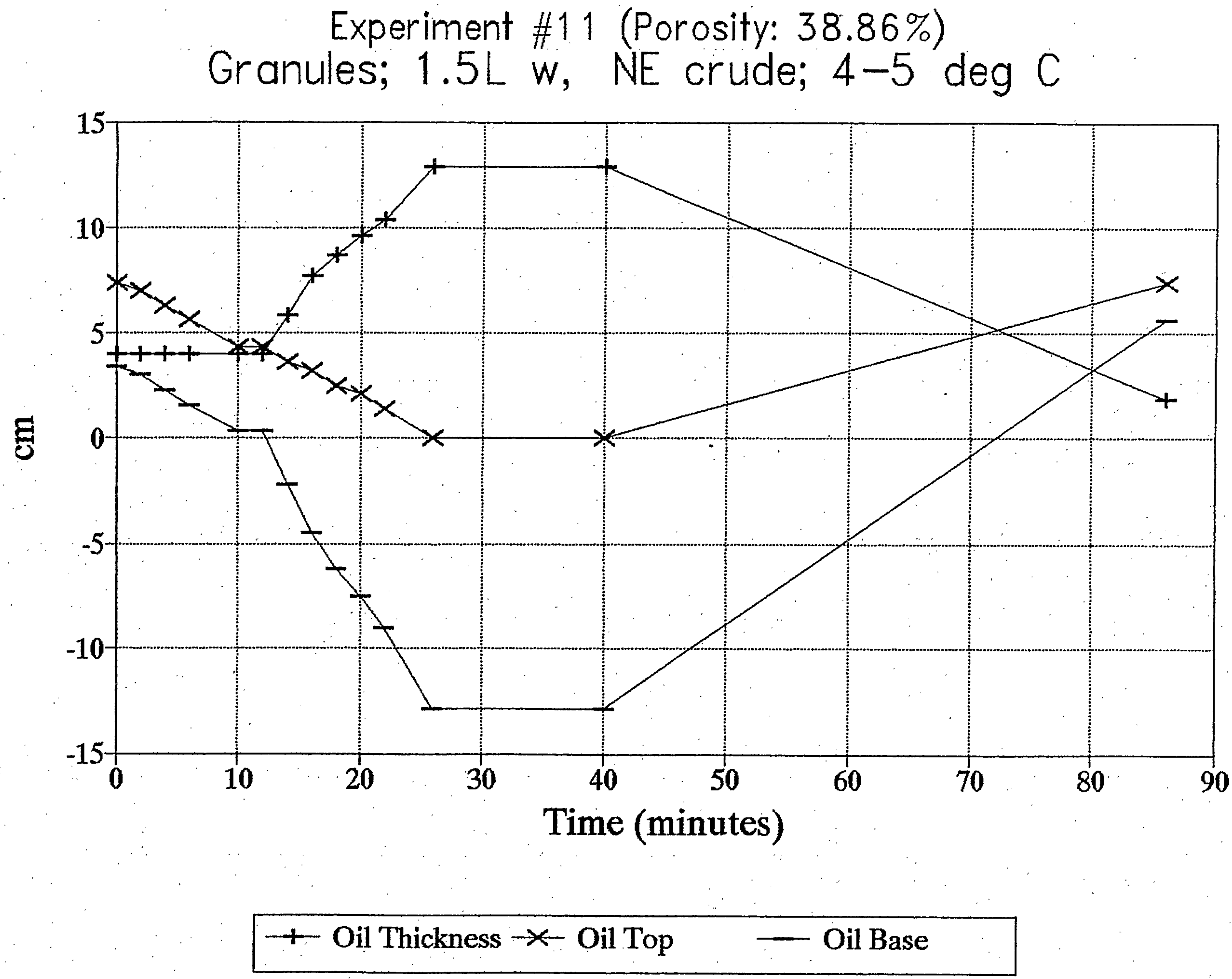

Experiment #7 (Porosity: 38.63%)
Pebbles; 1.5L w, NE crude; 20-23 deg C
20
15
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base



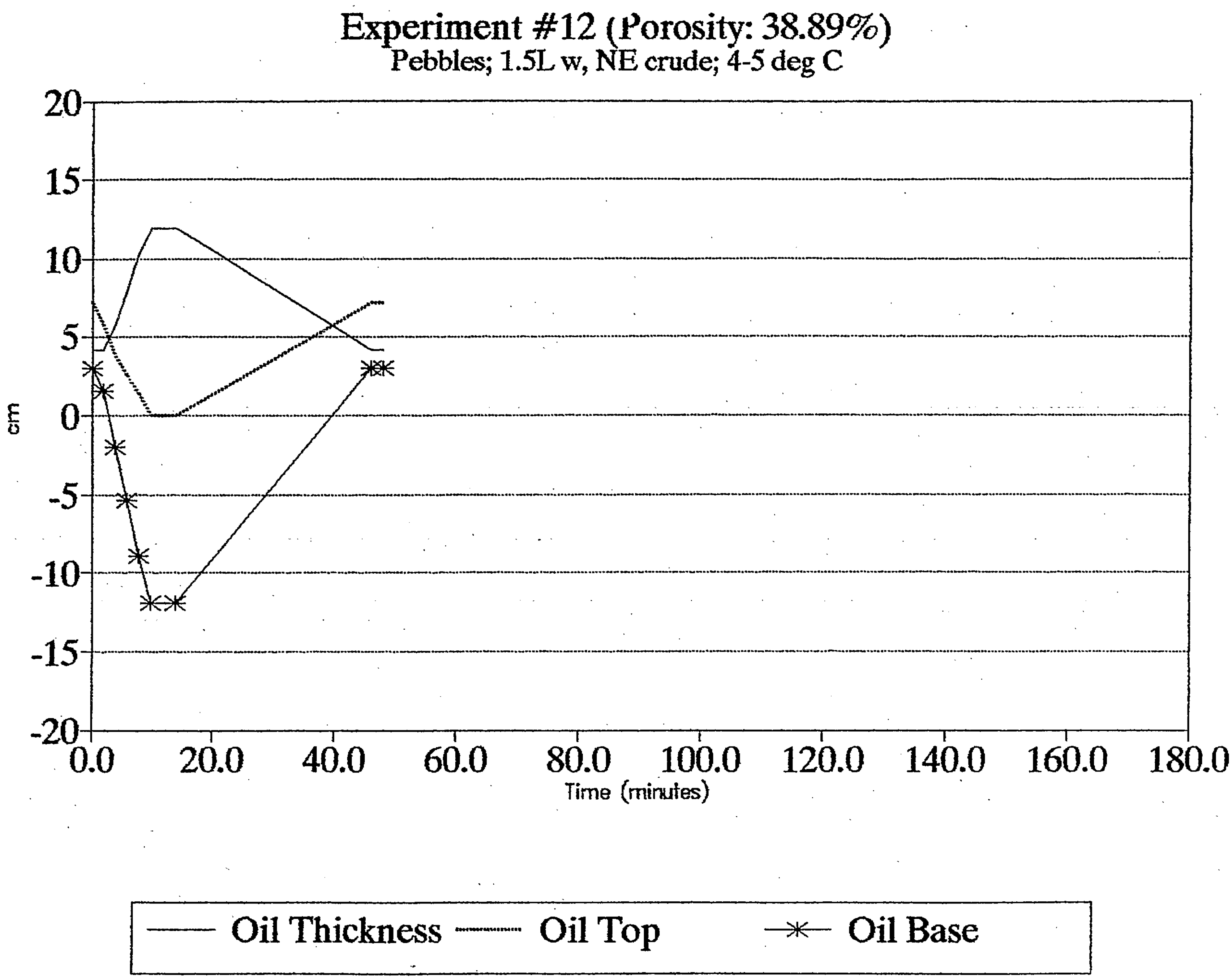
Experiment #8 (Porosity: 29.28%)
Granules; 1.5L w,NE crude; 20-23 deg C
40
30
20
10
0
−10
−20
−30
−40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base

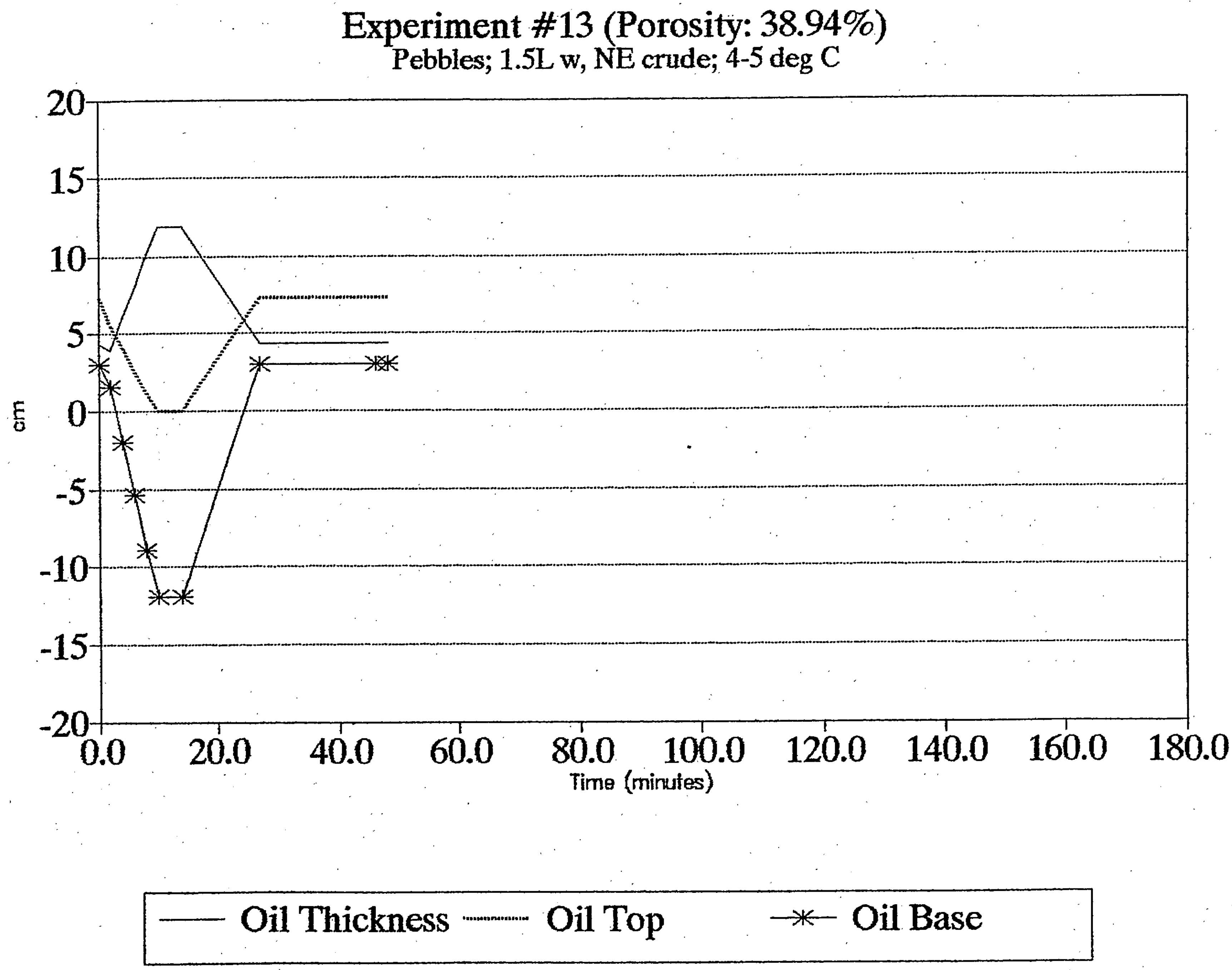

Experiment #9 (Porosity: 33.73%)
P / G Mix; 1.5L w,NE crude; 20-23 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base


Experiment #10 (Porosity: 36.27%)
Granules; 1.5L w, NE crude; 4-5 deg C
20
15
10
5
0
-5
-10
-15
-20
cm
0
20
40
60
80
100
120
140
160
180
Time (minutes)
Oil Thickness
Oil Top
Oil Base

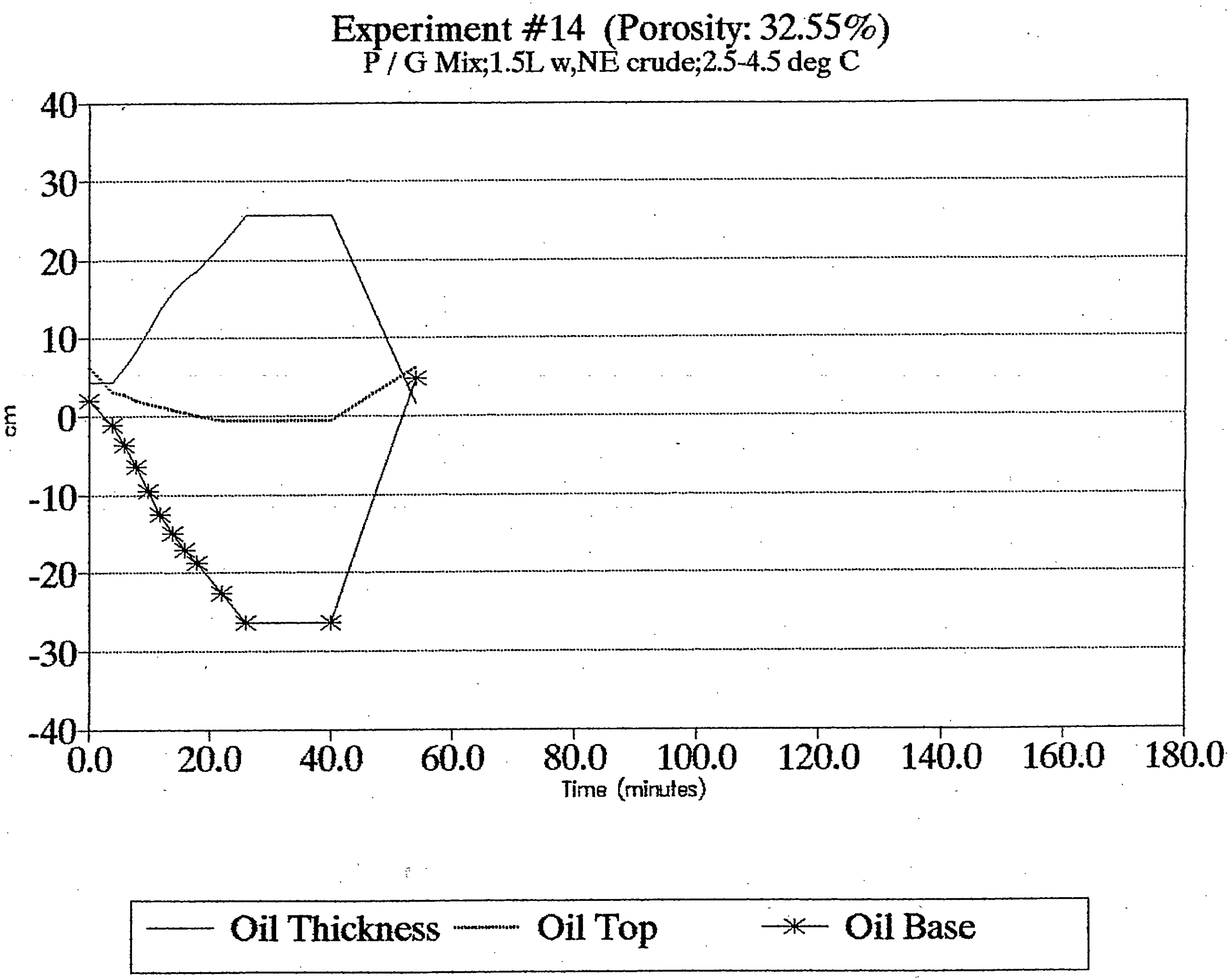


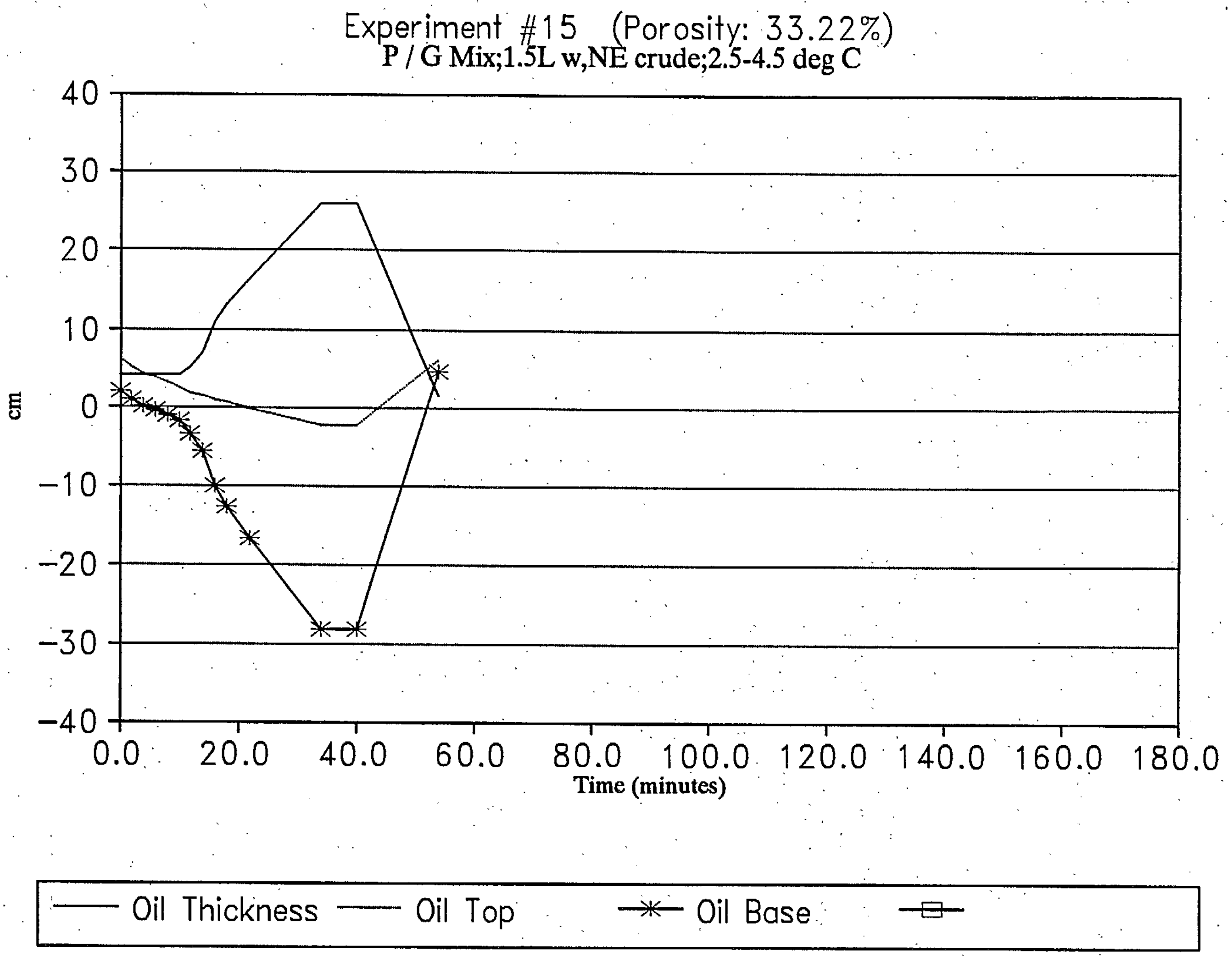
Experiment #11 (Porosity: 38.86%)
Granules; 1.5L w, NE crude; 4-5 deg C
15
10
5
0
-5
-10
-15
cm
0
10
20
30
40
50
60
70
80
90
Time (minutes)
Oil Thickness
Oil Top
Oil Base


Experiment #12 (Porosity: 38.89%)
Pebbles; 1.5L w, NE crude; 4-5 deg C
20
15
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base

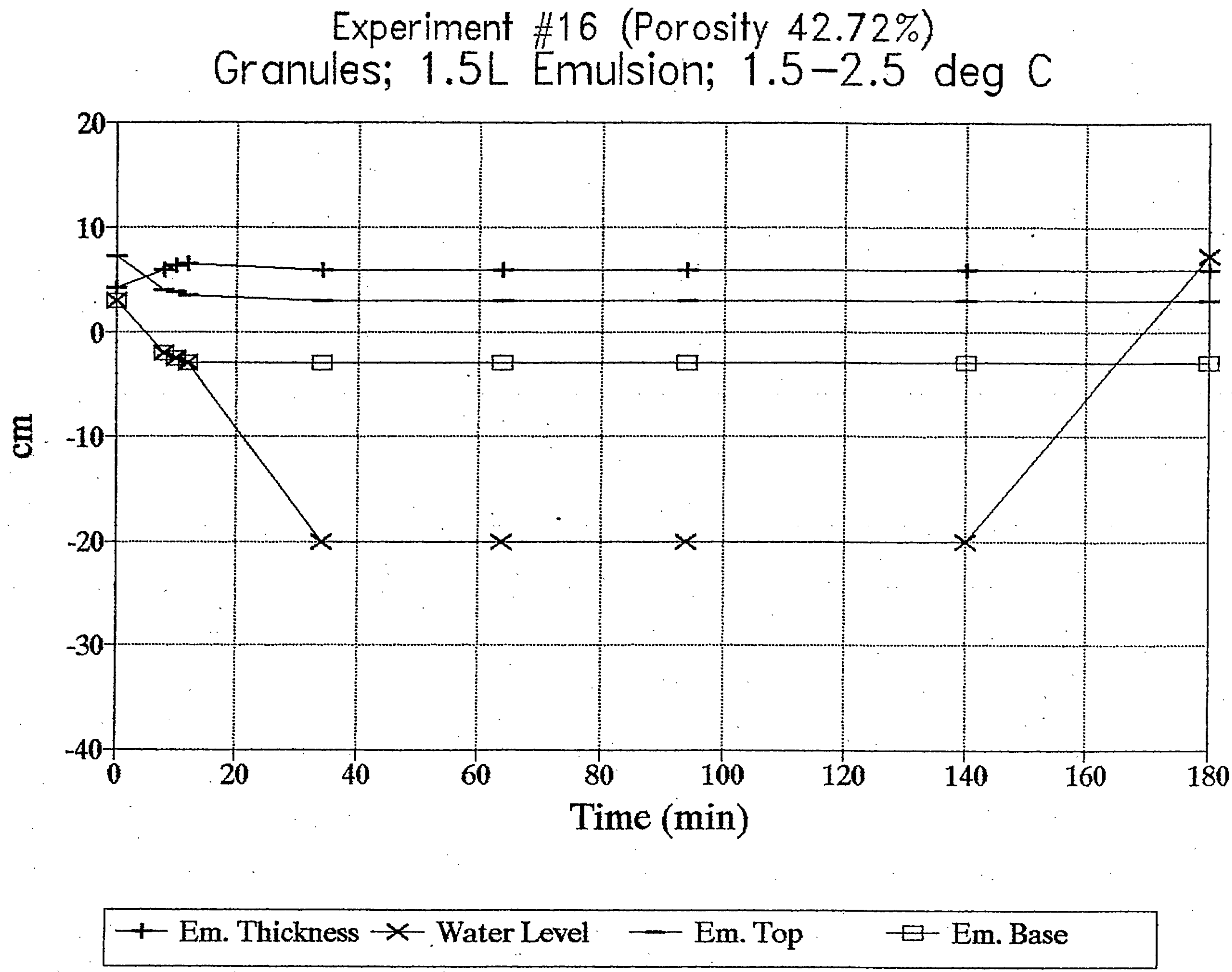


Experiment #13 (Porosity: 38.94%)
Pebbles; 1.5L w, NE crude; 4-5 deg C
20
15
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base

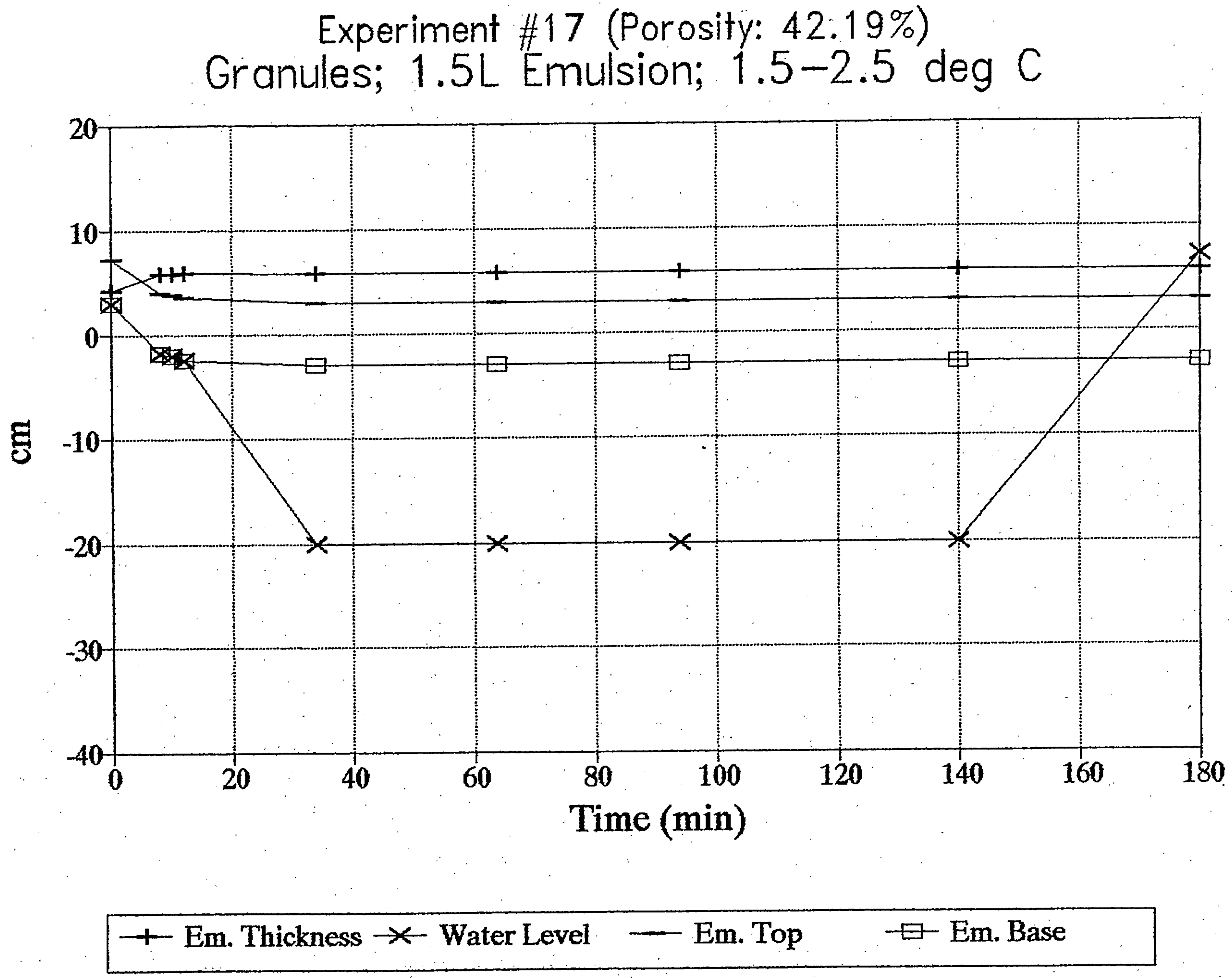

Experiment #14 (Porosity: 32.55%)
P / G Mix;1.5L w,NE crude;2.5-4.5 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base



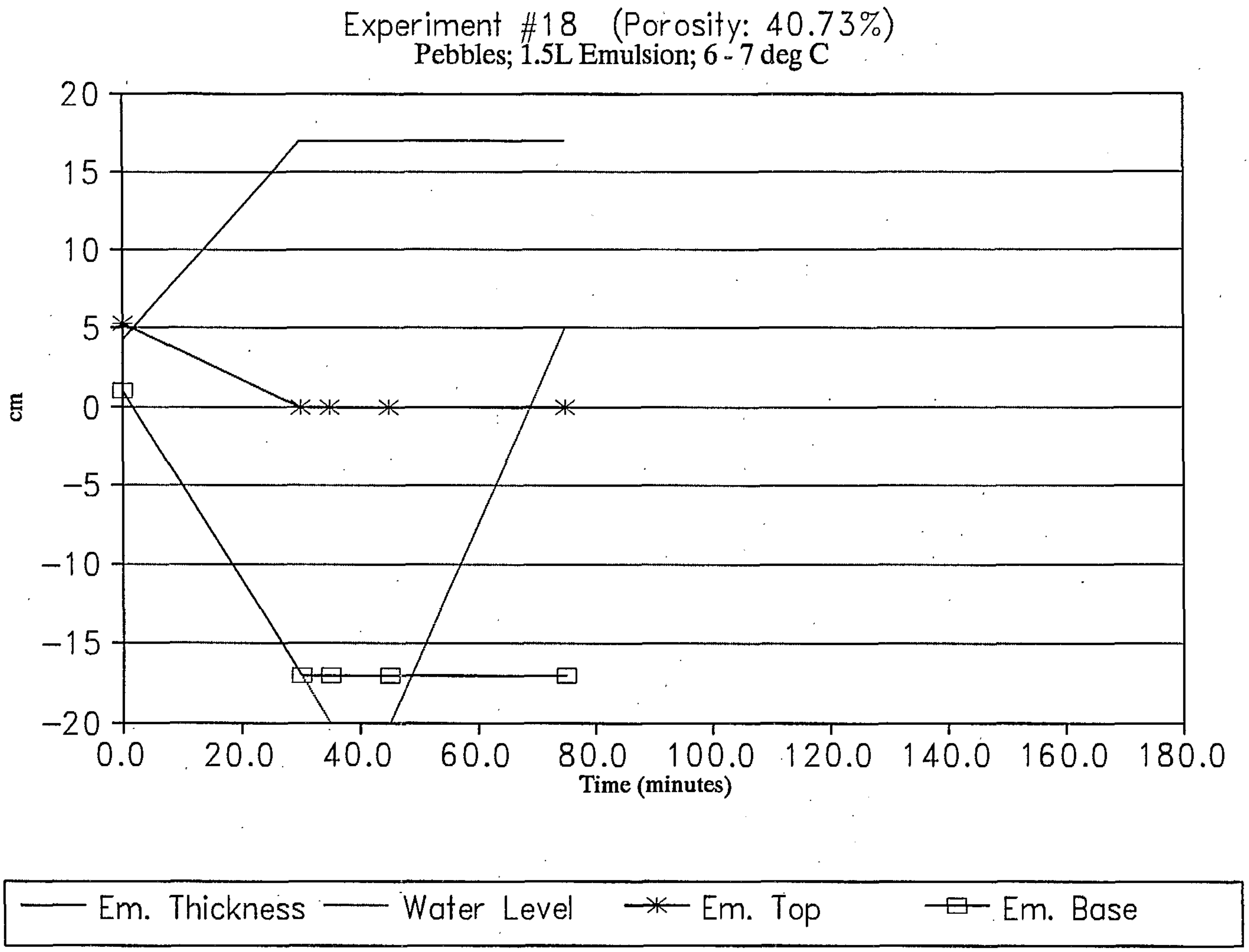
Experiment #15 (Porosity: 33.22%)
P / G Mix;1.5L w,NE crude;2.5-4.5 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Oil Thickness
Oil Top
Oil Base

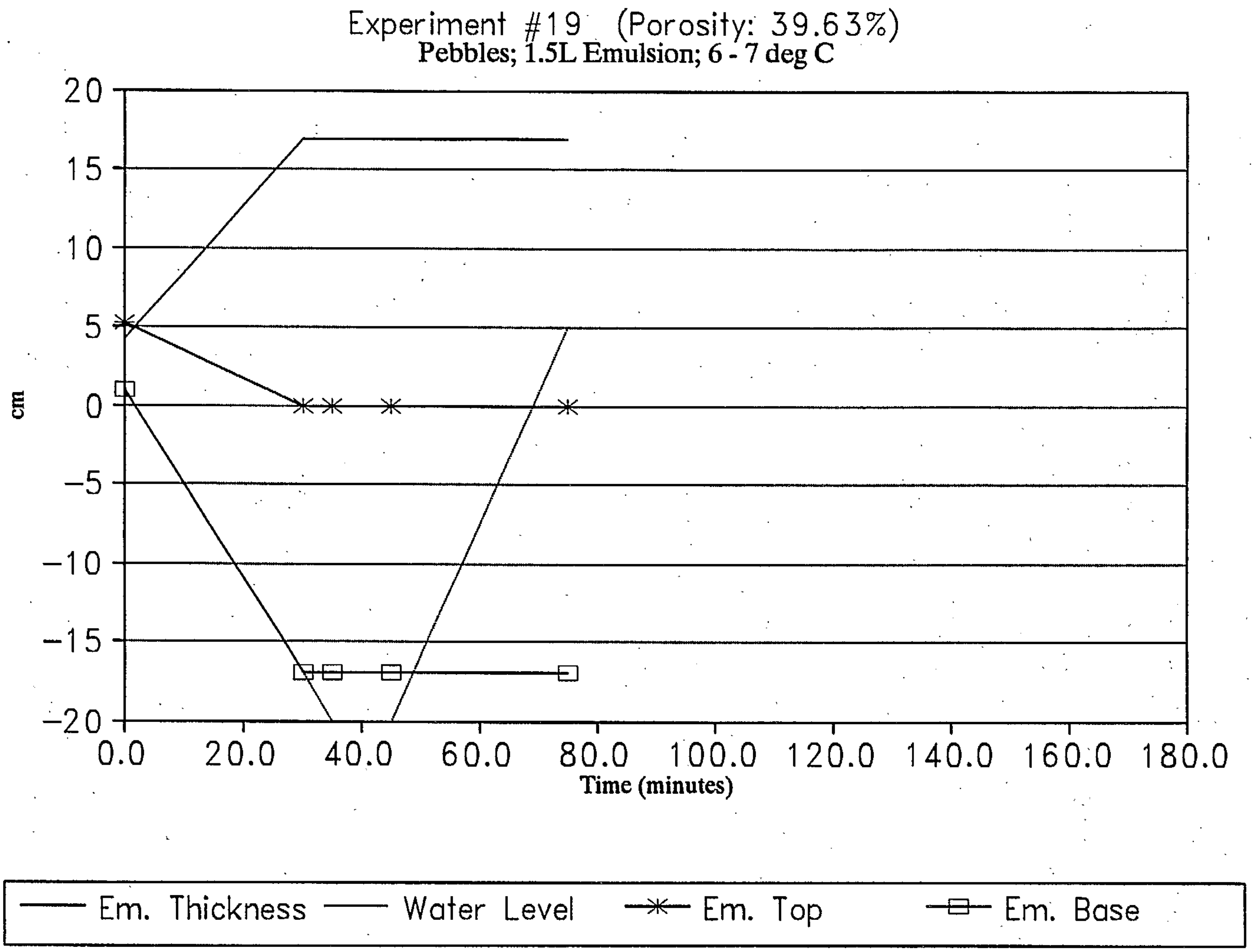


Experiment #16 (Porosity 42.72%)
Granules; 1.5L Emulsion; 1.5–2.5 deg C
20
10
0
-10
-20
-30
-40
cm
0
20
40
60
80
100
120
140
160
180
Time (min)
Em. Thickness
Water Level
Em. Top
Em. Base

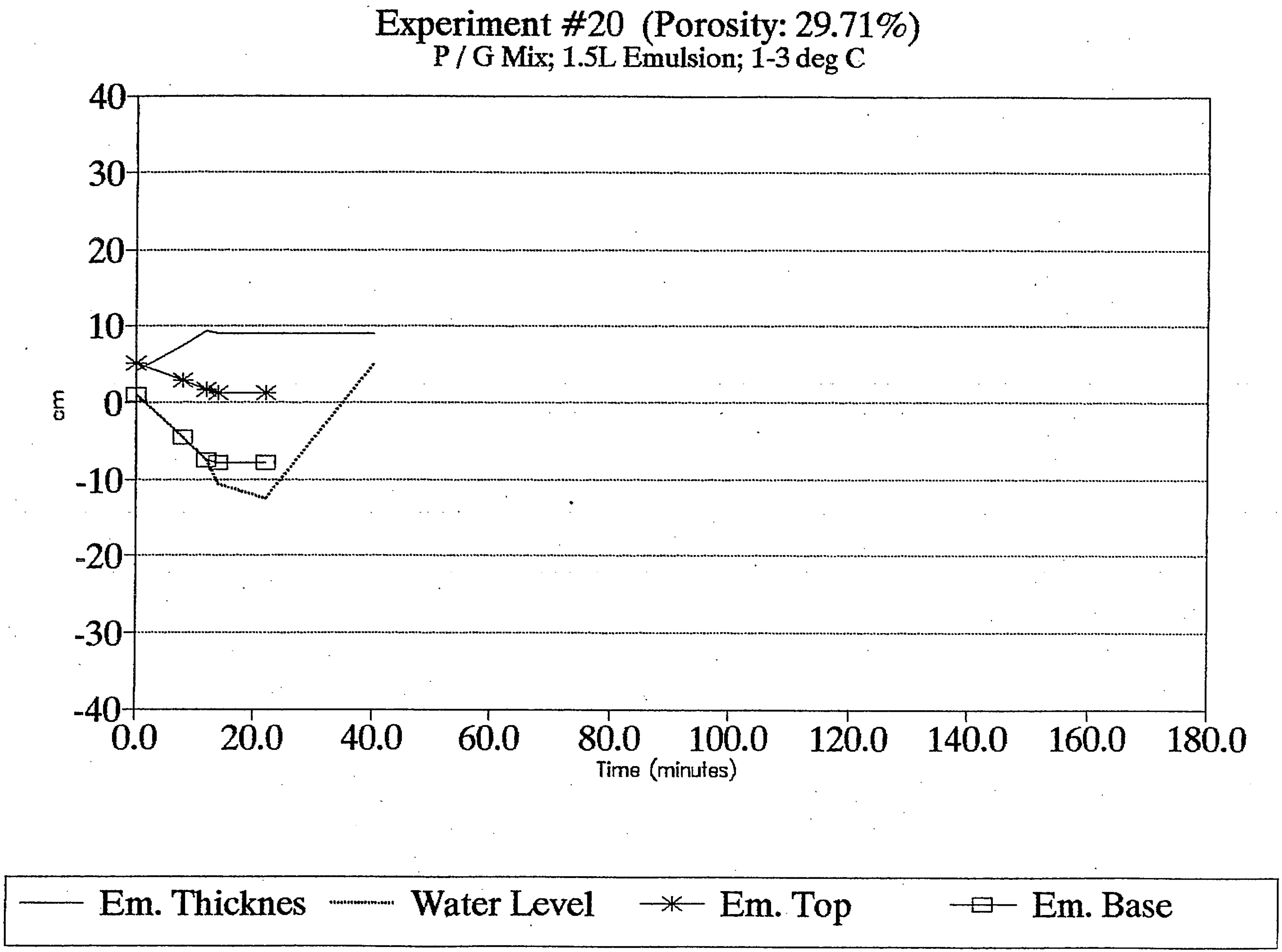


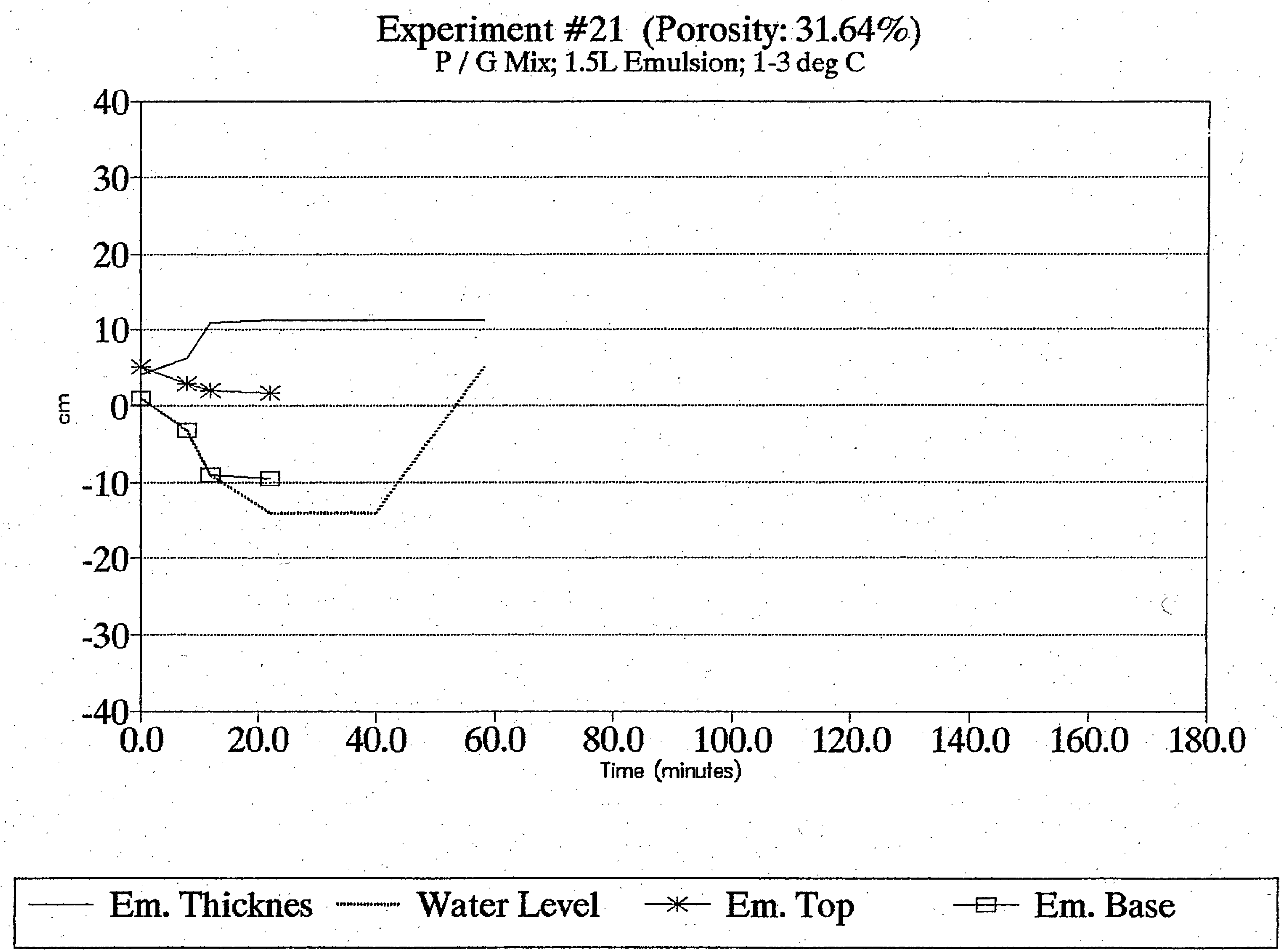
Experiment #17 (Porosity: 42.19%)
Granules; 1.5L Emulsion; 1.5-2.5 deg C
20
10
0
-10
-20
-30
-40
cm
0
20
40
60
80
100
120
140
160
180
Time (min)
Em. Thickness
Water Level
Em. Top
Em. Base

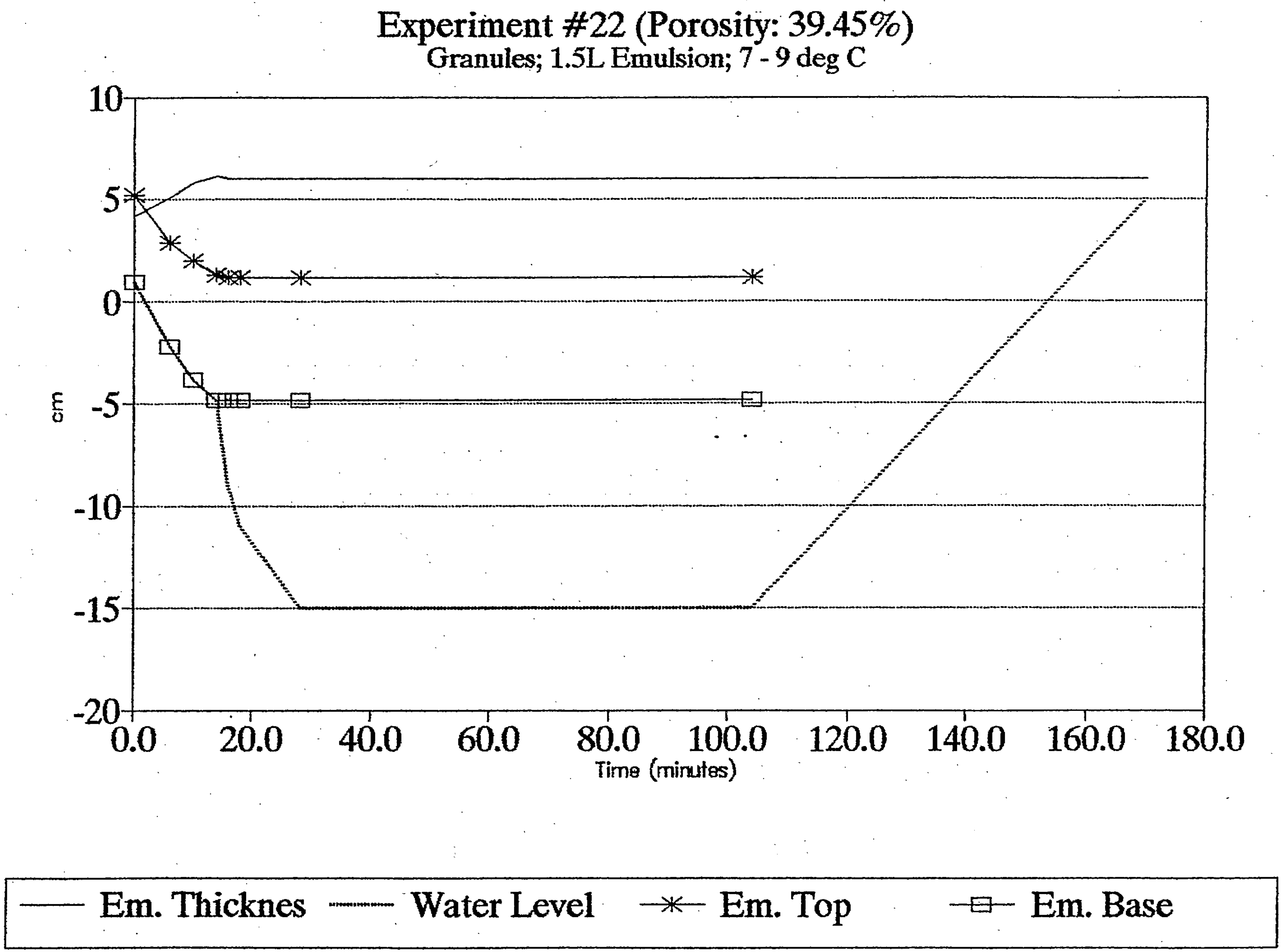

Experiment #18 (Porosity: 40.73%)
Pebbles; 1.5L Emulsion; 6 - 7 deg C
20
15
10
5
0
−5
−10
−15
−20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thickness
Water Level
Em. Top
Em. Base



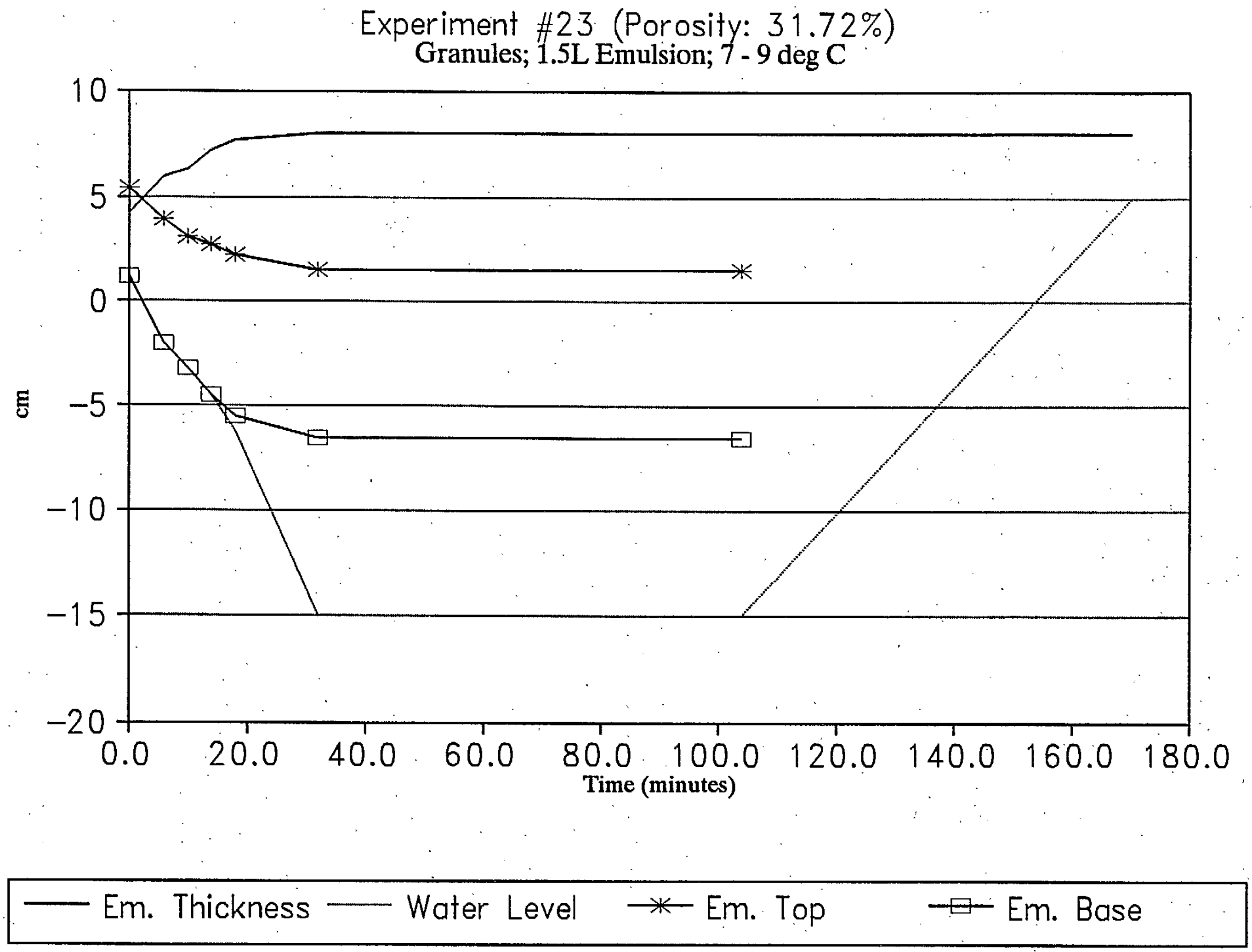
Experiment #19 (Porosity: 39.63%)
Pebbles; 1.5L Emulsion; 6 - 7 deg C
20
15
10
5
0
−5
−10
−15
−20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thickness
Water Level
Em. Top
Em. Base

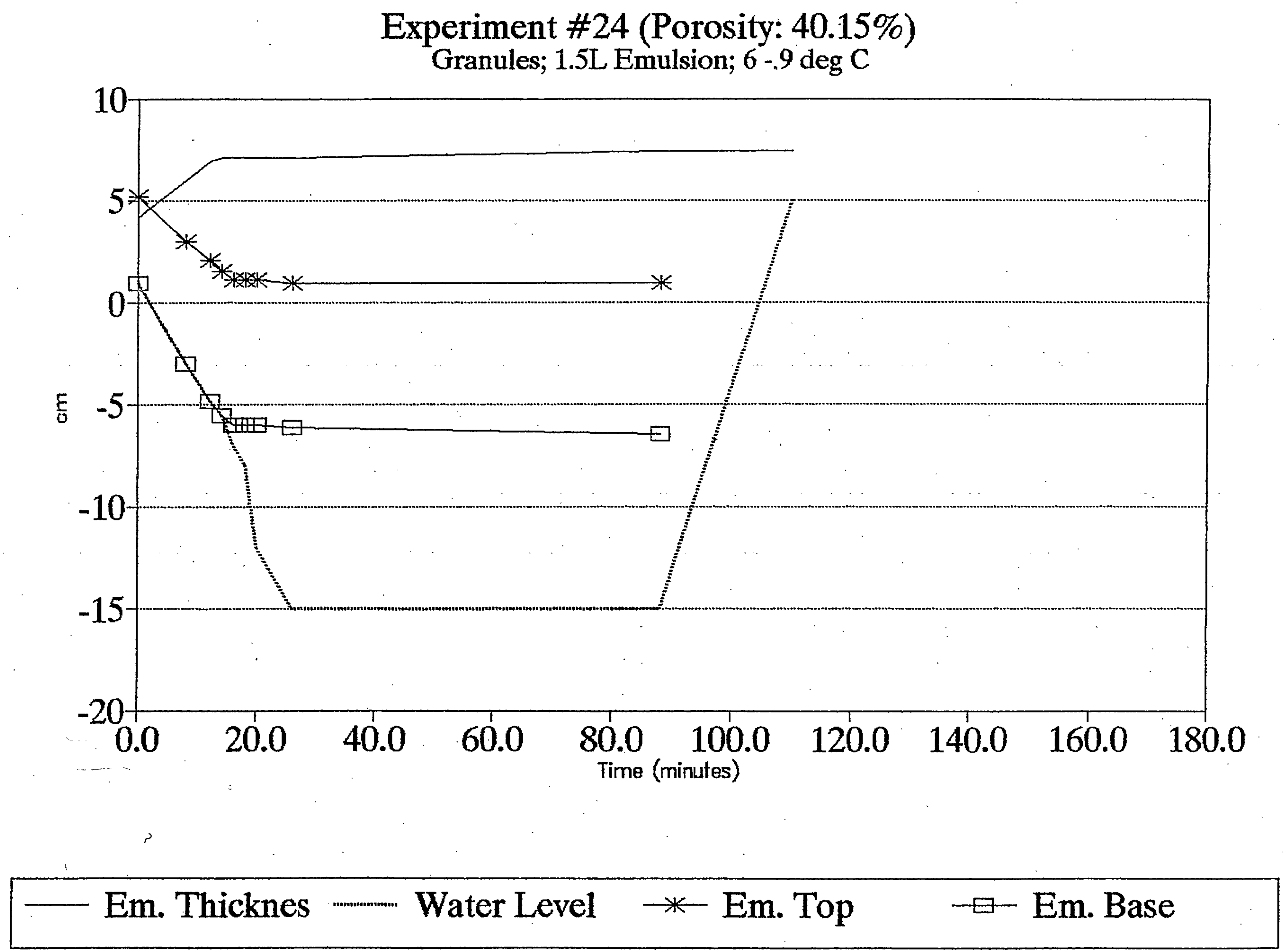

Experiment #20 (Porosity: 29.71%)
P / G Mix; 1.5L Emulsion; 1-3 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thicknes
Water Level
Em. Top
Em. Base


Experiment #21 (Porosity: 31.64%)
P / G Mix; 1.5L Emulsion; 1-3 deg C
40
30
20
10
0
-10
-20
-30
-40
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thicknes
Water Level
Em. Top
Em. Base



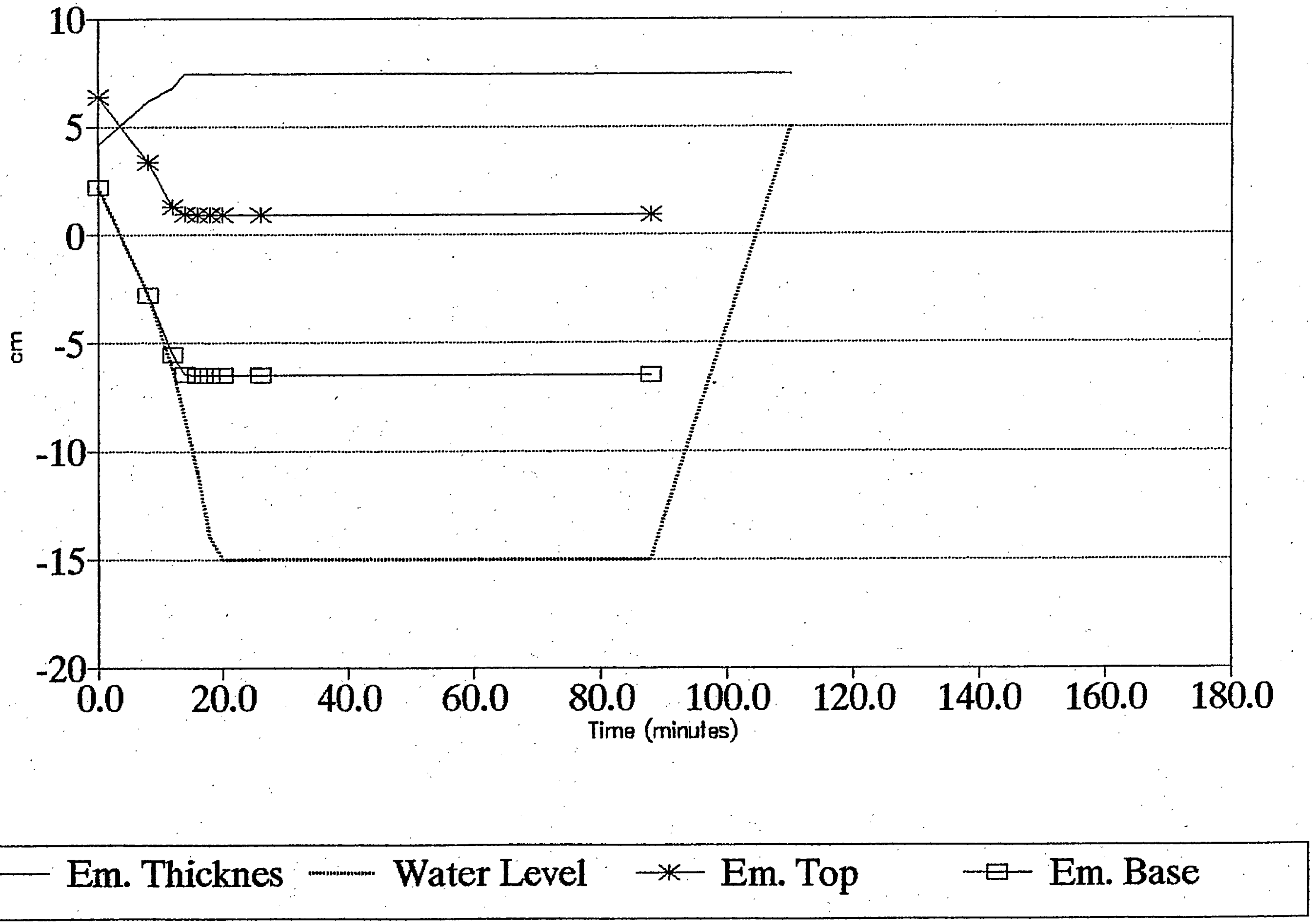
Experiment #22 (Porosity: 39.45%)
Granules; 1.5L Emulsion; 7 - 9 deg C
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thicknes
Water Level
Em. Top
Em. Base


Experiment #23 (Porosity: 31.72%)
Granules; 1.5L Emulsion; 7 - 9 deg C
10
5
0
−5
−10
−15
−20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thickness
Water Level
Em. Top
Em. Base



Experiment #24 (Porosity: 40.15%)
Granules; 1.5L Emulsion; 6 -.9 deg C
10
5
0
-5
-10
-15
-20
cm
0.0
20.0
40.0
60.0
80.0
100.0
120.0
140.0
160.0
180.0
Time (minutes)
Em. Thicknes
Water Level
Em. Top
Em. Base

Experiment #25 (Porosity: 37.37%)
Granules; 1.5L Emulsion; 6 - 9 deg C



APPENDIX C

Concentration Conversion Table

*OIL density assumed 0.9 g/cm3

GRANULES density = 1.71 g/cm3

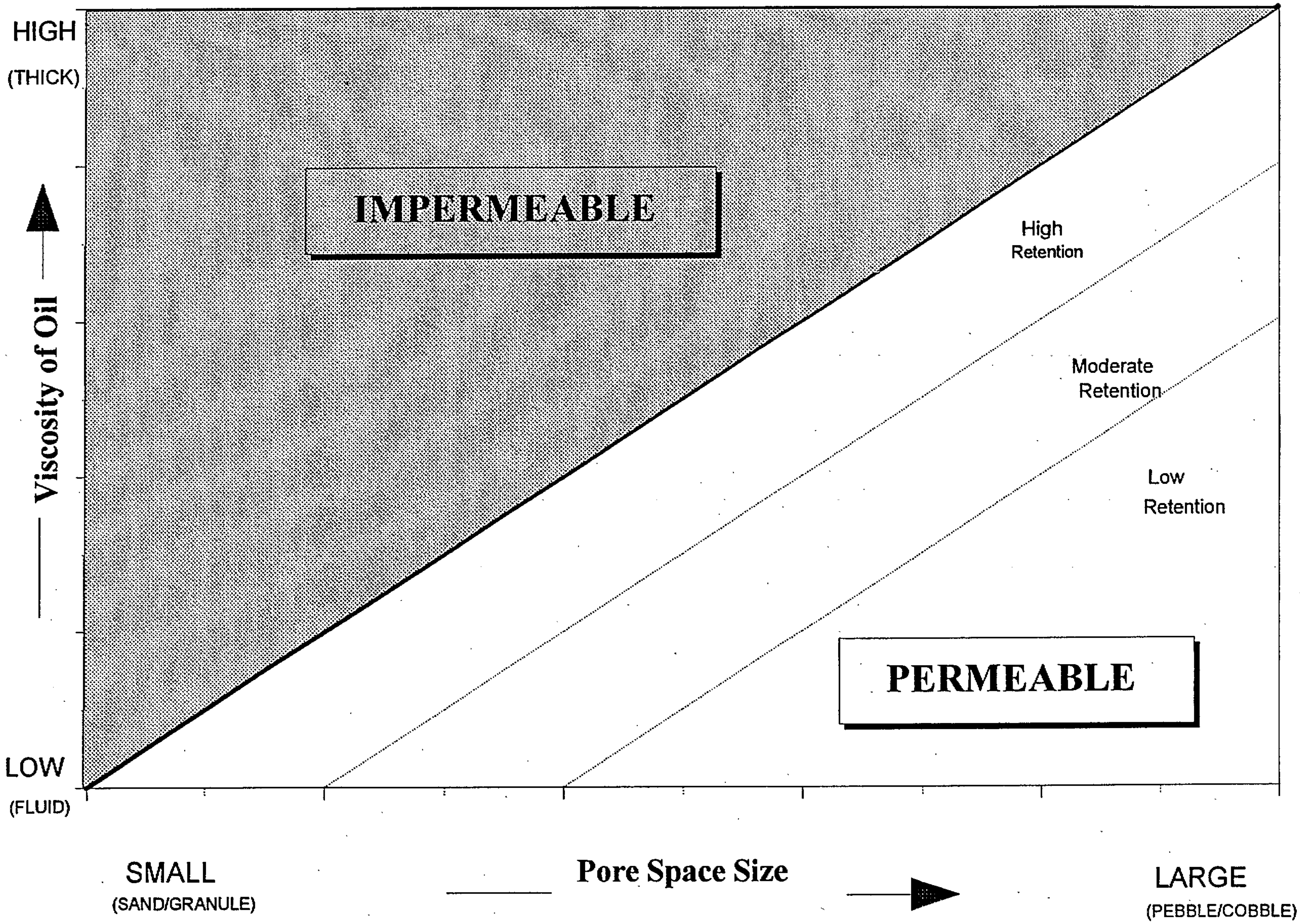
l/m3	g/kg*	wt %
50	26	2.6
100	53	5.3
150	79	7.9
200	105	10.5
250	132	13.2
300	158	15.8
350	184	18.4
400	211	21.1

P/G MIX (50:50 by volume) density = 1.72 g/cm3

l/m3	g/kg*	wt %
50	26	2.6
100	52	5.2
150	78	7.8
200	105	10.5
250	131	13.1
300	157	15.7
350	183	18.3
400	209	20.9

PEBBLES density = 1.73 g/cm3

l/m3	g/kg*	wt %
50	26	2.6
100	52	5.2
150	78	7.8
200	104	10.4
250	130	13.0
300	156	15.6
350	182	18.2
400	208	20.8


HIGH
(THICK)
Viscosity of Oil
LOW
(FLUID)
IMPERMEABLE
High
Retention
Moderate
Retention
Low
Retention
PERMEABLE
SMALL
(SAND/GRANULE)
Pore Space Size
LARGE
(PEBBLE/COBBLE)

DATE DUE

99-02-24			

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