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OIL RECOVERY AND FORMATION DAMAGE IN PERMAFROST, UMIAT FIELD, ALASKA

By Oren C. Baptist

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CONTENTS

ILLUSTRATIONS

TABLES

OIL RECOVERY AND FORMATION DAMAGE IN PERMAFROST, UMIAT FIELD, ALASKA[1]

by

Oren C. Baptist[2]

SUMMARY AND CONCLUSIONS

Umiat field contains the largest accumulation of oil discovered so far in Naval Petroleum Reserve No. 4 in Arctic Alaska. The Umiat anticline was tested with 11 wells; 6 produced oil in varying quantities. Behavior of the wells during testing was unpredictable. For example, one well was abandoned as a dry hole after all tests failed to recover any oil, yet an offset well, only 200 feet from the dry hole, produced 400 barrels of oil a day. The main oil reservoirs are less than 1,000 feet deep and are in the permanently frozen zone (permafrost). Reservoir pressures are low, and most primary production will be by expansion of gas-in-solution in the oil.

Because of the unusual reservoir conditions and the difficulties encountered in drilling and completing the wells, the Department of the Navy asked the Federal Bureau of Mines to make laboratory studies of the reservoir sand to determine the cause of well plugging and to provide laboratory information, to be used as an aid in estimating oil recovery from frozen reservoir rocks under solution-gas expansion from low-saturation pressure conditions.

Core samples were tested in the laboratory to determine the physical properties, clay content, and capillary behavior of the sands and their susceptibility to water damage. Larger core samples were tested under simulated permafrost conditions to determine the effect of freezing of interstitial water on oil recovery and the effect of gas-oil ratio on oil recovery, when the oil is produced by solution-gas expansion from low saturation pressures. Also determined were the effects of freezing of interstitial water on relative permeability to oil and on oil recoverable by gas drive after solution-gas expansion. The major results and conclusions are discussed.

Severe formation damage noted in some wells was not due to swelling clays, as supposed previously. No swelling clays were found in the 36 sandstone samples examined by X-ray diffraction methods. Other laboratory tests confirmed that the reservoir sands have only low to moderate sensitivity to

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1/ Work on manuscript completed February 1960.
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water. Laboratory results supporting these conclusions are summarized as follows: The predominant clay minerals are illite and kaolinite; the bulk-swelling capacity of the crushed sample is low, the ratio of water permeability to air permeability indicates moderate water sensitivity, and the position of the average curve showing the relation of air permeability to irreducible water saturation is that of sand having moderate sensitivity.

The failure of some wells to produce now seems to be the result of increased water saturation in the permafrost. Warm mud used in drilling the wells apparently thawed the surrounding formation and allowed water filtrate from the mud to invade the sand. When mud circulation ceased before a formation test, the invaded zone cooled rapidly, and the invading water soon froze, effectively plugging the sand.

Comparison of laboratory tests at temperatures of 26°, 70°, and 75° F. shows that freezing of interstitial water reduces both oil flow and oil recovery more than that due to increased oil viscosity. Freezing of interstitial water increases the volume of the water by several percent, thus reducing effective permeability to oil. It is not clear if this increase in immobile saturation, resulting from the freezing of water, also causes the decrease in oil recovery.

Recovery tests were made at 26° F. with the oil originally gas-saturated at 50, 100, and 150 p.s.i.g. Since the gas-oil ratio was directly proportional to saturation pressure, oil recovery also should have been directly proportional to pressure if all the gas released from solution were equally effective in displacing the oil. However, this was not true. Increasing the saturation pressure by 200 percent (from 50 to 150 p.s.i.g.) increased the oil recovery by only 55 percent (from 29 to 45 percent of initial oil).

The first gas released from solution expands as the pressure is lowered below the saturation pressure and displaces an equal volume of oil by pistonlike action, whereas the gas released after a high gas permeability is obtained displaces very little oil by viscous drag. Also, a small mass of gas released at low pressure expands to a large volume so that enough gas is available at low saturation pressures to complete the pistonlike-action phase of production and still have enough gas to produce additional oil by viscous drag. Consequently, a substantial recovery of oil can be expected from the Umiat field by using the depletion-drive method, even though the reservoir pressures are unusually low.

INTRODUCTION

President Harding created Naval Petroleum Reserve No. 4 in 1923 by Executive Order. This reserve, which has an area of 37,000 square miles, lies in northwestern Alaska between the Brooks Range and the Arctic Ocean.

The Department of the Navy, Office of Naval Petroleum and Oil Shale Reserves, conducted an extensive exploration program from 1944 through 1953 to appraise the oil potential of Naval Petroleum Reserve No. 4 and surrounding area (12, p. 1).[3/] This exploratory program located several structures having good petroleum possibilities, and several were tested with one or more wells. The largest accumulation of oil discovered was in the Umiat field, where estimates of recoverable reserves range from 30 to over 100 million bbl. (5, 10); the average of these estimates is about 70 million bbl. (12, pp. 135 and 147).

The Umiat field is close to the eastern boundary of the Reserve, (the Colville River) on the Arctic Coastal Plain, about midway between Brooks Range and the Arctic Ocean. Umiat is about 180 miles southeast of Point Barrow, one of the two permanent settlements in the Reserve and the main supply point during the exploratory program.

The Umiat structure was tested by drilling 11 wells (see fig. 1);[4/] 6 produced oil in varying amounts. The first three wells were drilled with conventional rotary methods, using water-base mud. Good shows of oil were noted in cores from two wells, yet the hole was repeatedly bailed dry without yielding either oil or water. Later wells were drilled with cable tools, using a strong brine as drilling fluid; these wells produced considerably more oil than those drilled with the rotary rig.

Oil was found at depths of 275 to 1,100 feet. The depth to the bottom of the permafrost ranges from 770 to 1,055 feet, and most of the oil is in the permafrost. Reservoir pressures are very low, the oil contains very little gas, and the sands are supposed to contain large amounts of montmorillonite clay, which swells when contacted with fresh water (5, 6).

Because of unusual reservoir conditions in the Umiat field and difficulties encountered in testing and completing the wells, the Navy asked the Bureau of Mines to make laboratory studies which would assist them in developing the field and in estimating petroleum reserves. The main objectives of this test program were to determine the cause of plugging in the wells drilled with rotary tools and to estimate oil recovery from frozen sand by depletion drive when the oil is gas-saturated at low pressures. This report gives the results of these studies, discusses the results, and postulates the mechanism responsible for severe well damage observed in several wells in the Umiat field.

ACKNOWLEDGMENTS

Special acknowledgment is given to the late Ralph H. Espach, former Chief of the Branch of Petroleum, Bureau of Mines, Region III, who initiated the work and sampled cores stored at Fairbanks, Alaska.

3/ Underlined numbers in parentheses refer to items in the bibliography at the end of this report. Page references refer to pages in items and not in this report.

4/ Well 1, a dry hole, is not shown in figure 1. This well is near the axis of the anticline, about 3 miles west of the western boundary of the map. Map adapted from Geol. Survey Prof. Paper 305(b), 1958 (6).

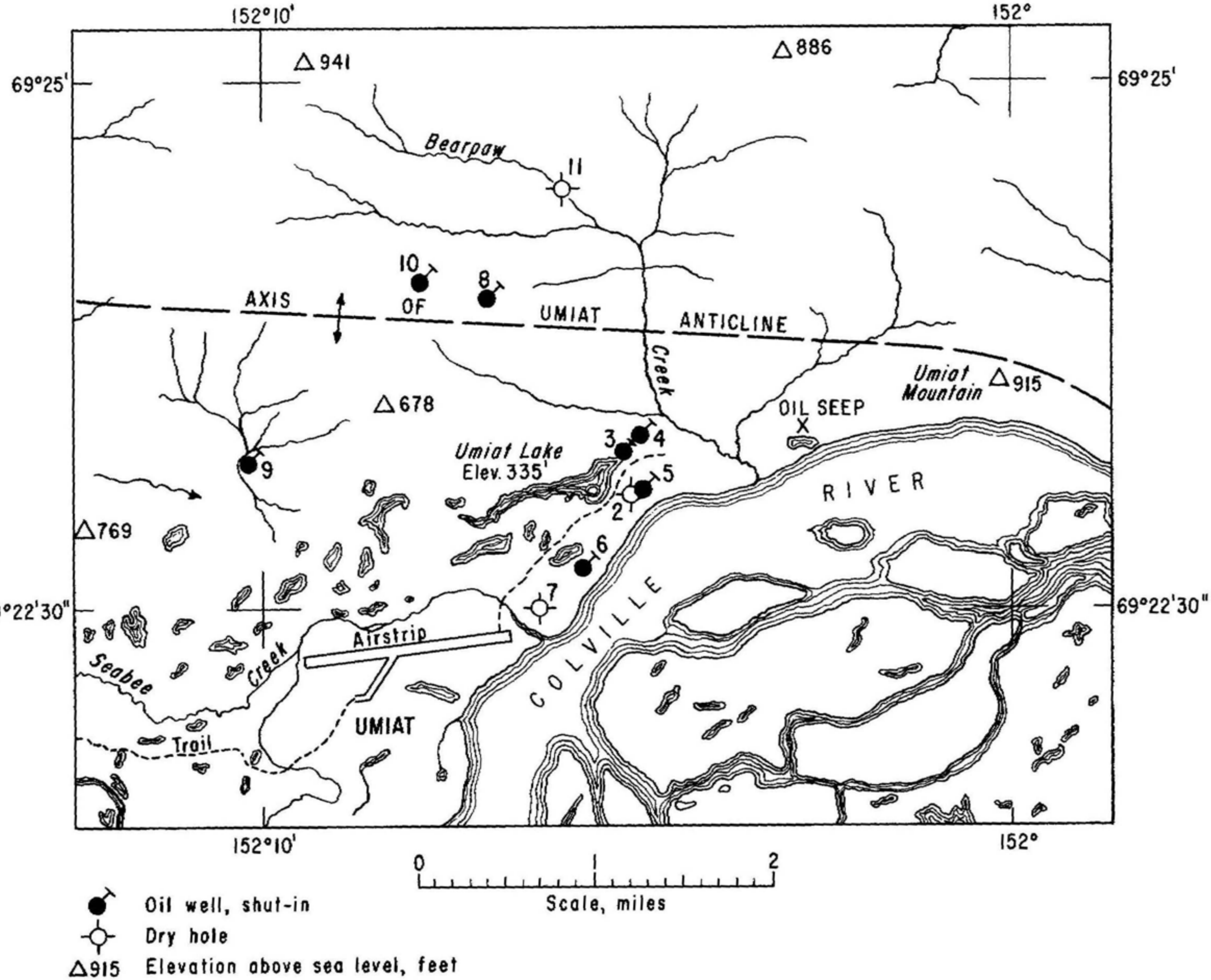

FIGURE 1. - Map of Umiat Area Showing Location of Wells.

NOMENCLATURE

The following symbols, definitions, units, and abbreviations are used in this report:

K_i - Permeability to helium gas, using the Klinkenberg method (determining the apparent permeability at three or more mean pressures and extrapolating these values to a value at infinite mean pressure, millidarcys (md.)).

K_a - Permeability to air, determined at only one mean pressure, millidarcys.

K_w - Permeability to distilled water containing 25 p.p.m. mercuric chloride as a bactericide (1), millidarcys.

IWS - Irreducible water saturation, determined in plug samples by the semipermeable-barrier method, sometimes called the capillary-pressure or restored-state method, percent of pore volume.

IBS - Irreducible brine saturation, determined in radial samples by flowing crude oil through brine-saturated samples until no more brine is produced. The brine contained 3,300 p.p.m. sodium chloride - thought to be close to the total salinity of the Umiat formation water, percent of pore volume.

RESERVOIR CHARACTERISTICS AND CONDITIONS

Producing Sands

The main oil-producing zones in the Umiat field are sandstones in the Grandstand formation of Cretaceous age. These light to medium gray sandstones are 5 to 100 feet thick and are composed mostly of subangular to subrounded grains of quartz and dark rock fragments, with some mica and carbonaceous material. The composition of the rock varies from slightly silty to shaly; very little of it is calcareous. The main sandstone beds are commonly massive, but few have laminae of siltstone and claystone (6).

The uppermost sandstone bed in the Grandstand formation is usually 50 to 75 feet thick; it is separated from the lower sandstone by 300 feet or more of gray shale. This shale sometimes contains a bed of sandstone, usually it does not. The lower sandstone is much greater in total thickness than the upper, but only the top 100 feet has good porosity and permeability. These beds of sandstone contain most of the oil so far discovered in the Umiat field and are referred to in this report as the upper and lower sands.

Depth to the producing sands depends upon the surface topography and subsurface structure. Measured to their tops, the shallowest upper sand well was number 5 at 248 feet, the deepest lower sand well, where the sand was found above the oil-water contact, was number 9 at 866 feet.

Formation Temperatures

Temperature surveys were made using thermistor cables in wells 4, 6, 9, and 11. The cables did not reach the base of the permafrost (near 32° F.) in these wells; however, the temperature gradients were rather uniform from a depth of 100 feet to the bottom of the cable. Therefore, the extrapolation of the observed temperature gradient used to estimate the depth to the base of the permafrost should be reliable. Temperature generally decreases from the surface to a depth of 70 to 100 feet, where the minimum temperature is about 20° F. Below 100 feet, the temperature increases with depth about 1.6° F. for each 100 feet (6). The estimated depth to the base of the permafrost in the four wells surveyed is given in table 1.

No temperature surveys were made in wells 1, 5, and 7, but the approximate depth to the base of the permafrost can be inferred from other data. Frozen mud was found in well 1 to a depth of 920 feet when it was cleaned after standing idle from September to the following June. In wells 5 and 7 the depth to the base of the permafrost, table 1, is that at which considerable water was first bailed from the hole.

TABLE 1. - Summary of permafrost data

Well number	1	4	5	6	7	9	11
Surface elevation........feet	810	483	335	337	330	424	481
Depth to top of lower sand....................do.	1,818	745	770	1/ 1,055	1,200	866	2,805
Elevation of top of lower sand, below sea level....do.	1,008	262	435	718	870	442	2,324
Depth to base of permafrost...............do.	920	890	800	770	827	1,055	770
Elevation of base of permafrost below sea level....................do.	110	407	465	433	497	631	289
Liquid produced from lower sand..................	Water	Oil	Oil 2/	Water 1/	Water	Oil	Water

1/ The lower sand was not reached in this well; depth was estimated by using interval between upper and lower sands in other wells. Position of oil-water contact in other wells indicates that lower sand contains water at this location.

2/ Salt water was bailed from a depth of 800 feet at 2 bbl. per hour when the well was first drilled; however, the well later produced very little water on a 93-day pumping test.

Available data indicate that the only part of the producing sands below the permafrost, but above the oil-water contact, is a narrow ring around the structure between wells 5 and 6. Thus most of the producing sands are in the permafrost zone, and expansion of gas in solution, aided by gravity drainage, is the only effective producing method.

Reservoir Pressures

Attempts to make pressure surveys in the wells, using wire line instruments, were unsuccessful, mainly because of ice bridges in the well. Numerous drill stem tests were made in various wells, and a series of bottom-hole pressures was usually recorded; however, no reliable formation pressures were recorded in most tests in the permafrost because no fluids entered the hole when the tool was opened.

A tabulation was made of available data relating to the rise of liquids in the hole during drilling and testing of the wells. Calculations of reservoir pressure from all reported static-fluid levels give such erratic results that no reliable pressures can be estimated. Wells 5 and 9 flowed a little oil by heads at times during testing, but it is not known whether this oil came from the upper or lower sand or both. If part of this oil came from the lower sand, then the reservoir pressure in the lower sand in well 9 must be about 350 p.s.i. This pressure would be close to the maximum in the lower oil reservoir, because the base of the lower sand in this well is close to the oil-water contact.

All data indicate that the range of reservoir pressures is about 50 p.s.i. in the high upper sand to 350 p.s.i. in the lower sand near the oil-water contact.

The producing gas-oil ratio was not determined during the production tests. Field personnel reported that only a small quantity of gas was produced with the oil on the pumping tests. Thus, apparently no gas cap was encountered in the upper or lower sands in any of the wells on the south side of the fault, which follows the crest of the anticline, and the saturation pressure of the oil is the same as, or lower than, the reservoir pressure. Well 8, north of the fault, had gas in the lower sand; static pressure was about 275 p.s.i.

EVIDENCE OF WELL DAMAGE

The first well drilled on the Umiat anticline was near the axis of the structure and several hundred feet downdip from the crest. The well crossed a fault, below which most of the Grandstand formation was repeated. Several good shows of oil were noted in cores; however, none of the drillstem tests recovered a significant amount of oil, and the well was abandoned.

Wells 2 and 3 had good shows of oil throughout both sands at depths less than 1,100 feet, but extensive testing failed to produce more than 50 bbl. a day. This insignificant production from thick sections of oil-saturated sand indicated that the sands contained swelling clays, which, when exposed to the fresh-water filtrate from the drilling mud, were expanding and blocking the flow of oil from the formation to the well. The first three wells were drilled with rotary rigs, using water-base mud; then experiments were made with different drilling methods to try to develop high oil-production rates.

Well 4 was drilled with cable tools, using strong brine as drilling fluid, in the belief that the brine would suppress expansion of interstitial clays. This well pumped 100 barrels of oil a day, encouraging further experiments.

Well 5 is only 200 feet from well 2, which was abandoned as a dry hole, and it is about the same elevation on the structure. Well 5 was drilled with cable tools, using brine, but it was reamed with a rotary, using crude oil as the drilling fluid. This well, the best in the field, pumped 300 to 400 barrels of oil a day on a 93-day production test. This rate was the capacity of the pump; the capacity of the well is unknown.

These field results confirmed that wells 2 and 3 were seriously damaged by drilling and completion procedures used; it was supposed that the extreme damage was due to montmorillonite clay in the sand (5, 6).

EXPERIMENTAL METHODS AND PROCEDURES

Samples Analyzed

Core samples representing the lower sand in well 2, the upper sand in well 3, and both sands in well 9 were analyzed. The sands should be productive in all three wells because of their location on the structure; however, well 2 was abandoned as a dry hole, probably because of the drilling and completion methods used. Core samples from well 11, representing the lower sand and the Chandler and Ninuluk formations were also analyzed. The Chandler formetion overlies the Grandstand, and the Ninuluk is above the Chandler. Well 11 is on the north flank of the anticline on the downthrown side of a major fault; it was abandoned as a dry hole.

Crushed Samples

The "skin" around each piece of core was chipped off to eliminate possible contamination of the sample by drilling mud. The cleaned section of the core was crushed, passed through a 28-mesh sieve, and divided into two parts.

One part of the crushed sample was dispersed in water, and the 12-micron and smaller fractions were removed by siphoning off the upper 7.3 cm. of water-clay suspension after it had settled for 10 minutes. The suspension was then filtered through a ceramic plate leaving a layer of clay on the porous surface. After the plate had been dried thoroughly, the clay was ready for identification by X-ray diffraction methods. This method of preparing clay samples is fast and convenient, and it has the advantage of orienting the clay particles parallel to the plate surface, which results in an increased peak on X-ray diffraction charts and aids in detecting small amounts of clay minerals in a mixture.

The samples were run on a Norelco Geiger-counter X-ray diffractometer, using nickel-filtered copper K-alpha radiation operated at a voltage of 40 kv., with a filament current of 20 ma. Scanning speed was 1° 2 theta per minute, the width of the receiving slit was 0.003 inch, and the divergence slits were

1°. The Norelco electronic circuit-panel recording unit was run at a chart speed of 30 inches per hour, and the rate meter was operated with a four-scale factor, one multiplier, and an 8-second time constant.

After X-ray charts were made, the untreated samples were placed on a platform about 1 inch above glycerol, which was heated to just below its boiling point. The glycerol vapor was allowed to condense on the sample for 20 to 30 minutes and was X-rayed again. Then the sample was ashed at a temperature of 600° C. for at least 1 hour, and the final X-ray chart was made.

The bulk-swelling capacity of the second part of the crushed sample was determined by slowly dropping a measured dry volume (5 cc.) into distilled water, which contained a small amount of wetting agent. After letting it stand for 24 hours, the wet volume of the sample was read. The increase in volume of the wet sample, as compared with its volume when dry, was used to compute the bulk-swelling percent. After the wet volume was read, the sample was thoroughly shaken and again allowed to stand for a day. Then the amount of fine material in the sample was estimated visually by noting the thickness of the layer that had settled on the coarser sand and the amount of clay that was still suspended in the water.

An assumption in the bulk-swelling test is that the measured dry volume will retain that volume after being dropped into water, if the sample does not swell. This assumption was periodically tested by dropping the dry volume into alcohol, which caused no interlayer expansion of clay minerals. These calibration tests showed that the reproducibility limits of the swelling test, using 5 cc. of dry volume, were plus or minus 0.2 to 0.3 cc.; therefore indicated swelling, no more than 6 percent, is insignificant. Reproducibility limits of the test could be decreased by increasing the size of the sample; however, larger volumes of crushed sample are not always available. Laboratory work done in connection with other studies has shown, that when even trace amounts of montmorillonite are present, the samples will swell 10 percent or more.

Plug Samples

Plug samples, about 2 cm. in diameter and 3 cm. long, were used for determination of porosity, gas permeability (K_i), water permeability (K_w), and irreducible-water saturation (IWS) by the semipermeable barrier method. This method, used to determine the practical (not actual) irreducible-water saturation, is often called the restored-state or capillary-pressure method. Tests of the plug samples were made by conventional methods, described in some detail in previous reports (1, 2, and 3).

For the K_w tests samples were soaked for 24 hours after being saturated. Drilling muds sometimes require as much as 72 hours to attain hydration equilibrium. A porous sample would require less time, and hydration undoubtedly was completed in the day allowed.

Radial Samples

A radial sample was prepared by cleaning the outside of a core section, 2 to 3 inches long, first by facing both ends with a diamond saw and then by drilling a 3/16-inch hole axially through the center. After cleaning with toluene and drying, the sample was ready for testing. Schematic diagrams of the apparatus developed for testing the radial samples are shown in figures 2 and 3.

The sample was saturated first with brine containing 3,300 p.p.m. sodium chloride and allowed to soak overnight, then it was mounted in the glass-walled cell shown in figure 3. The cell was mounted in the brine bath shown in figure 2, and Umiat crude oil was forced through the sample at room temperature. The oil displaced part of the interstitial brine. This was collected and measured until no more brine was produced by the flowing oil. The sample then contained the irreducible-brine saturation (IBS), and the remaining pore space was filled with dead oil. The dead oil was displaced with Umiat crude oil, which was saturated with natural gas to a predetermined saturation pressure; following this step, the remaining oil surrounding the sample was displaced with gas. The sample containing IBS and gas-saturated oil was chilled in the brine bath to 26° F. When the sample and apparatus reached temperature equilibrium, the sample was ready for determination of oil recovery by

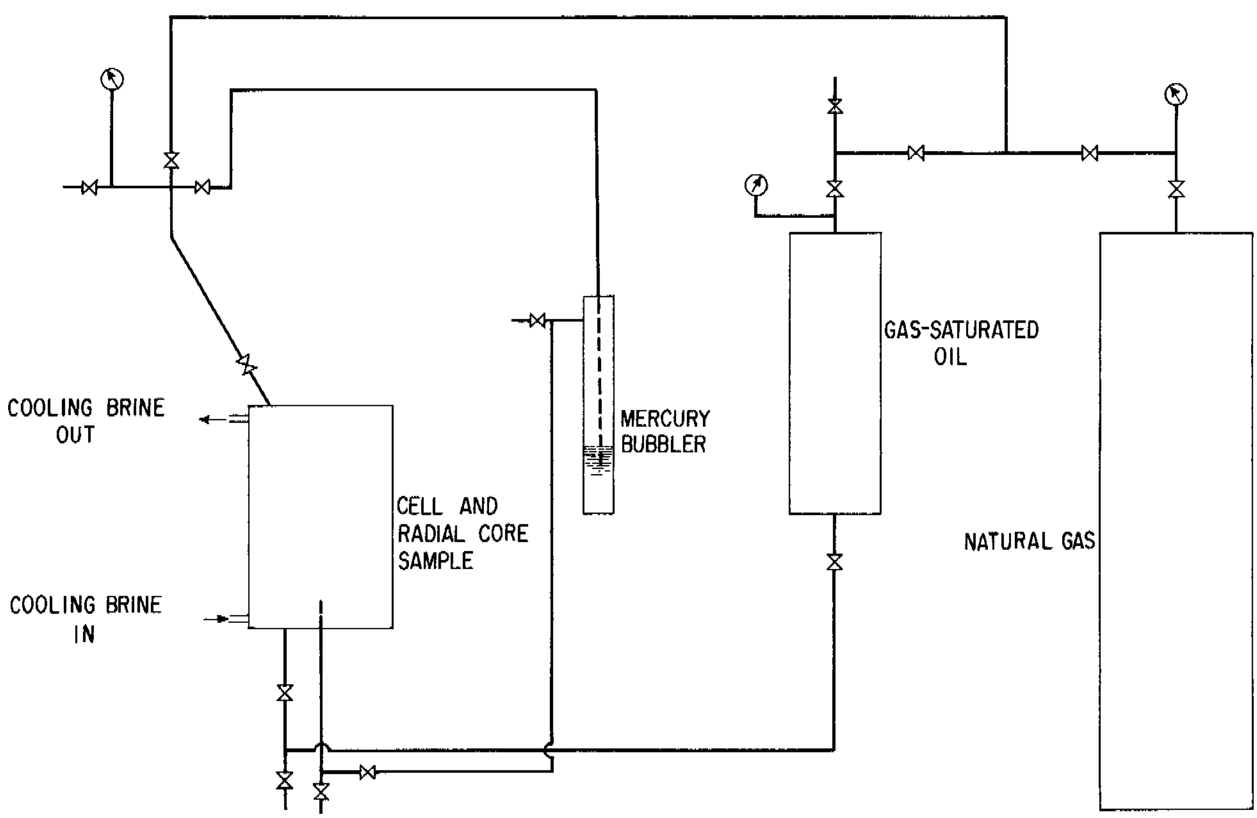

FIGURE 2. - Diagram of Apparatus Used to Determine Oil Recovery Under Simulated Permafrost Conditions.

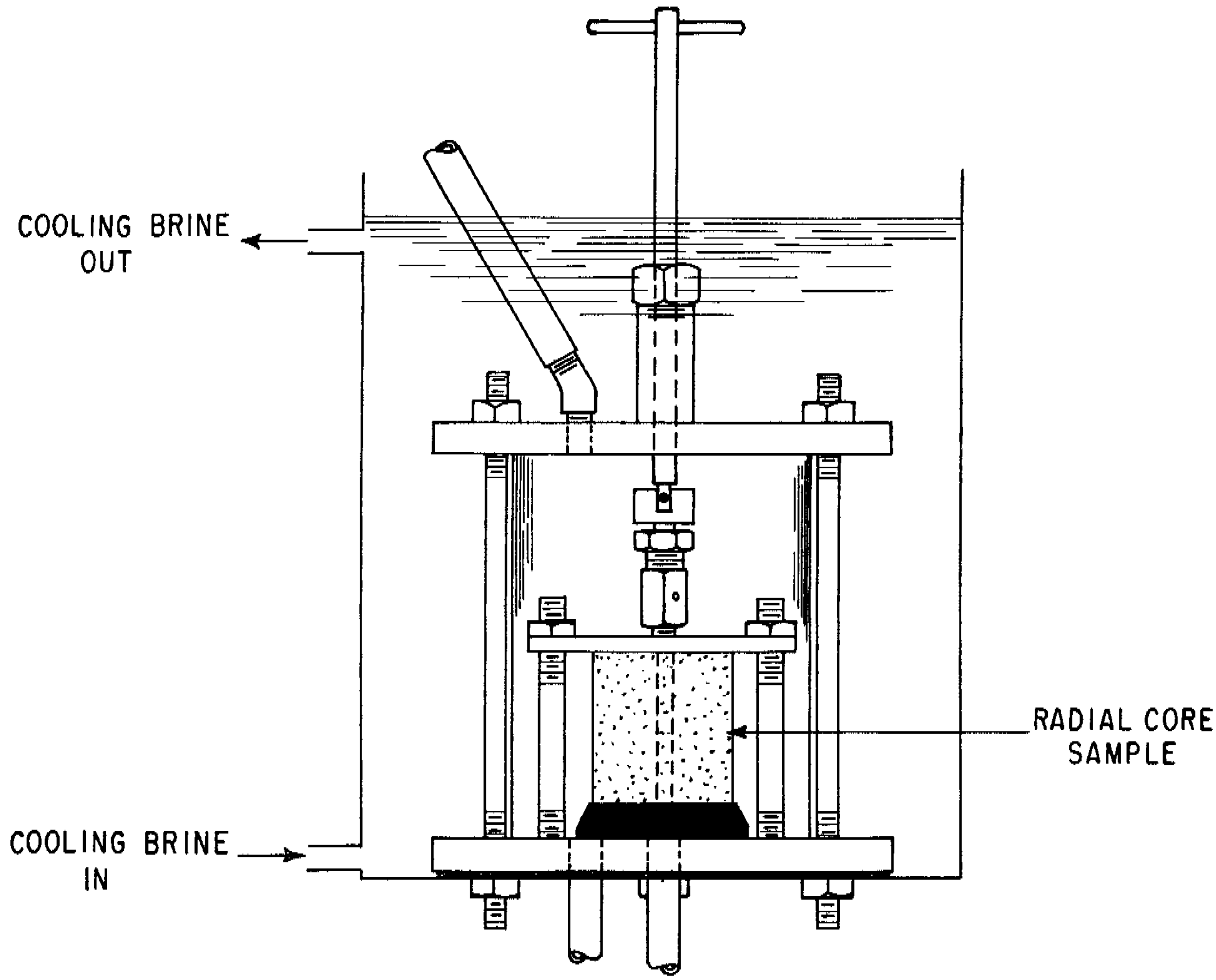

FIGURE 3. - Diagram of Cell of Apparatus Used to Determine Oil Recovery Under Simulated Permafrost Conditions.

solution-gas expansion. Cooling the gas-saturated oil from room temperature to 26° F. will result in some oil shrinkage and undersaturation; however, these changes should be small and have an insignificant effect on the results.

The recovery experiment was started by cracking the valve below the sample, allowing gas and oil to escape to atmospheric pressure, and slowly lowering the pressure in the system. The gas-filled space in the cell outside the sample was connected to the outflow tube below the center hole through a mercury-bubbler arrangement. As the pressure on the system was lowered, the expanding gas outside the sample bubbled through the mercury. This process allowed the pressure of the system to drop, while a slightly higher pressure outside of the sample was steadily maintained, assuring that all oil expelled from the sample by expanding solution gas would move to the center hole to be produced and measured. A differential pressure of 0.3 p.s.i. was maintained across the sample, and calibration experiments proved that this pressure forced all produced oil to the center hole without forcing more gas through the sample. Also, other calibration experiments showed that the amount of oil produced by gravity drainage was negligible and could be ignored.

After oil recovery by gas expansion was complete, what could be recovered further by gas drive was determined by driving gas through six of the samples under a low differential pressure until no more oil was produced. Gas-expansion and gas-drive experiments were made with these six samples, first at 75° F., and then at 26° F., to estimate the effect on oil recovery of freezing the interstitial water. Oil was gas-saturated in these tests to 100 p.s.i.g.

Another set of experiments was designed to determine the effect of gas-oil ratio on recovery by solution-gas expansion. A series of tests was made of several radial samples with the oil gas-saturated at 50, 100, and 150 p.s.i.g.; temperature of the brine bath was 26° F.

DISCUSSION OF RESULTS

Clay Mineral Identification

X-ray diffraction analyses were made of the fine material separated from 36 samples of producing and nonproducing sands in the Umiat field. These samples represented the upper sand in two wells, the lower sand in three wells, and sands in the Ninuluk and Chandler formations in one well. X-ray charts obtained from these 36 samples were unusually similar, and this similarity made it possible to summarize the results and give only the average values in table 2.

The strong d-spacing reflection from the untreated samples at about 9.98 A. (angstroms) could indicate the presence of illite, montmorillonite, or both. In the humid atmosphere of most laboratories montmorillonite usually gives a d-spacing of about 14 A.; however, the relative humidity in the Laramie laboratory is less than 10 percent, which is insufficient to rehydrate the dried montmorillonite. As a result, experience with numerous oil-well samples containing mixtures of illite and montmorillonite shows that only a single peak indicating a d-spacing of about 10 A. is observed.

To separate the superimposed illite and montmorillonite peaks, the sample is exposed to glycerol vapor. The glycerol enters between the montmorillonite layers and expands them, which results in a shift of the d-spacing from 10 A. to 17 A. or above. Since glycerol does not expand the illite layers, a glyceroled sample containing both illite and montmorillonite gives two distinct peaks on the chart, indicating d-spacings at about 10 A. (illite) and 17 A. or above (montmorillonite).

The d-spacings of the untreated and glyceroled Umiat samples shown in table 2 are virtually the same; therefore, the samples did not contain more than trace amounts of montmorillonite, if any. Montmorillonite flakes are strongly oriented by being deposited on the flat surface of the sample plates; so montmorillonite gives a strong X-ray reflection, making it possible to detect small amounts of this mineral in samples. If an appreciable amount of montmorillonite were present in the samples, it would have been detected by the methods used.

TABLE 2. - Summary of X-ray diffraction results

Well and sand	Depths, feet	Illite				Kaolinite, untreated		Chlorite, ashed	
		Untreated		Glyceroled					
		I1/	d2/	I	d	I	d	I	d
Umiat 2, lower.........	796 797 805 824 831	16	9.98	16	9.95	49	7.12	19	13.8
Umiat 3, upper.........	884 886 888 890	22	9.99	20	9.97	46	7.12	22	13.8
Umiat 9, upper.........	470 475 480	29	9.98	27	9.95	54	7.08	29	13.8
Umiat 9, lower.........	870 875 880 895 905 910 950 960 965 975	13	9.98	12	9.97	52	7.12	20	13.8
Umiat 11, Ninuluk......	2,110 2,120 2,130 2,140	28	9.99	27	9.99	60	7.09	25	13.7
Umiat 11, Chandler.....	2,295 2,310 2,325 2,350 2,375 2,385 2,395	16	9.96	14	9.96	55	7.12	15	13.8
Umiat 11, lower........	2,825 2,835 2,845	17	9.96	14	9.95	53	7.12	18	13.7

1/ Average intensity of X-ray reflection, arbitrary units. Intensity is given in units of peak height on charts; in the system used one unit equals 0.1 inch.

2/ Average lattice spacing (d-spacing) calculated from basal reflection, angstroms.

The main nonclay minerals identified in the samples were quartz and feldspar. Average intensity of the first order quartz peak was 19 units and that of feldspar 6 units.

Formation Damage Related to Clay Swelling or Permafrost

The rate of production from many sands may be reduced slightly or to a great extent, if the sands are invaded by fresh water during the drilling and completion of wells. Sands that are susceptible to serious productivity impairment are often called water sensitive. The two most common causes of productivity impairment in water-sensitive sands are: (a) Swelling of interstitial clay minerals caused by displacing the original formation brine with fresh water, and (b) reduction of relative permeability to oil by increasing the water saturation through water invasion. This latter type of damage occurs in all sands, but it is especially detrimental in sands having low original permeability.

Several tests have been used in the Laramie laboratory to estimate water sensitivity of producing sands. The most important of these are tests that determine types of clay minerals, amount of fine material of clay size, bulk-swelling capacity, ratio of water permeability to gas permeability, and irreducible-water saturation. Experience with many sands in the Rocky Mountain region has shown that a sand having a high water sensitivity will usually exhibit the following characteristics: (a) It will contain detectable amounts of a clay mineral that exhibits large interlayer expansion in water, and this clay usually will be either montmorillonite or mixed-layer montmorillonite; (b) it will contain a relatively large amount of clay-size material; (c) bulk swelling of a crushed sample of the sand will be greater than 15 percent, although a few exceptions to this rule have been observed; (d) the ratio of water permeability to gas permeability will be less than 0.3; and (e) the irreducible-water saturation will be unusually high for a given permeability, especially in the low permeability range.

Application of these standards to the results of the laboratory tests of samples of Umiat sands (tables 2 and 3) indicates that these sands have a low to moderate water sensitivity. This conclusion is based upon the following considerations: (a) The predominant clay minerals, as determined by X-ray diffraction analyses, are kaolinite and illite; no montmorillonite was detected; (b) the sands contain small to medium amounts of fine materials; (c) bulk swelling of the samples is very low--0 to 8 percent; (d) the K_w-K_i ratios, calculated from values listed in table 3, are mostly high (the average is about 0.67); (e) the relation of K_w to K_i is shown in figure 4;[5] (the position of this average curve, when compared with that of other sands exhibiting various degrees of water sensitivity (1, 3), again indicates the moderate sensitivity of the Umiat sands); and (f) the position of the average curve showing the

5/ The average curve for figure 4 was constructed by plotting the corresponding permeability values from table 3 for wells 2, 3, and 9, and then by drawing the average line through these points by the method of least squares. Results from well 11 were omitted from this plot, because this well was a dry hole, and the sands may not be representative of the oil-reservoir sands.

relation of Ki; to IWS in figures 5 and 6 is that of a sand having moderate sensitivity. The last point is discussed in more detail.

TABLE 3. - Physical properties and swelling capacity of upper and lower Grandstand sands and sands in the Ninuluk and Chandler formations

Well and sand	Depth, feet	Amount fine material	Bulk swelling, percent	Porosity, percent	Permeability, md.		IWS, percent pore volume
					K_i	K_w	
Umiat 2, lower....	796	Very small	8	19.7	272	220	15
	797	do.	2	18.3	-	35	20
	805	do.	0	17.1	100	85	21
	824	Small	6	-	-	-	-
	831	do.	0	15.5	15	10	28
Umiat 3, upper....	259	Medium	2	17.3	65	46	21
	274	do.	2	10.2	0	0	53
	352	Small	6	17.8	83	88	22
	355	Medium	4	17.4	55	25	24
Umiat 9, upper....	475	do.	4	14.8	23	14	23
	480	do.	0	9.7	1.3	<.5	49
Umiat 9, lower....	870	do.	8	19.1	232	136	18
	875	do.	2	17.2	154	32	18
	880	Small	4	18.2	274	172	15
	895	Medium	0	15.8	58	43	-
	905	do.	0	14.5	30	21	23
	910	do.	0	13.1	7	6	29
	950	do.	4	11.7	7.6	7	31
	960	do.	2	15.4	79	37	19
	965	do.	2	13.7	11	8	32
	975	do.	0	13.8	14	9	30
Umiat 11, Ninuluk.	2,110	Very small	4	24.1	300	97	5
	2,120	Medium	6	12.4	5.4	2.6	32
	2,130	do.	0	14.7	21	6.2	-
	2,140	do.	0	11.1	28	<.5	-
Umiat 11, Chandler.	2,295	do.	0	19.0	286	75	15
	2,310	Large	0	13.6	2.5	<.5	49
	2,325	do.	2	5.5	<.5	0	100
	2,350	Medium	2	19.3	87	17	20
	2,375	Small	2	14.2	2.6	0	50
	2,385	Medium	0	23.3	5.2	2.6	26
	2,395	Large	0	12.6	1.2	0	85
Umiat 11, lower...	2,825	Small	0	18.3	145	160	14
	2,835	do.	0	10.4	139	118	20
	2,845	do.	2	14.5	445	370	10

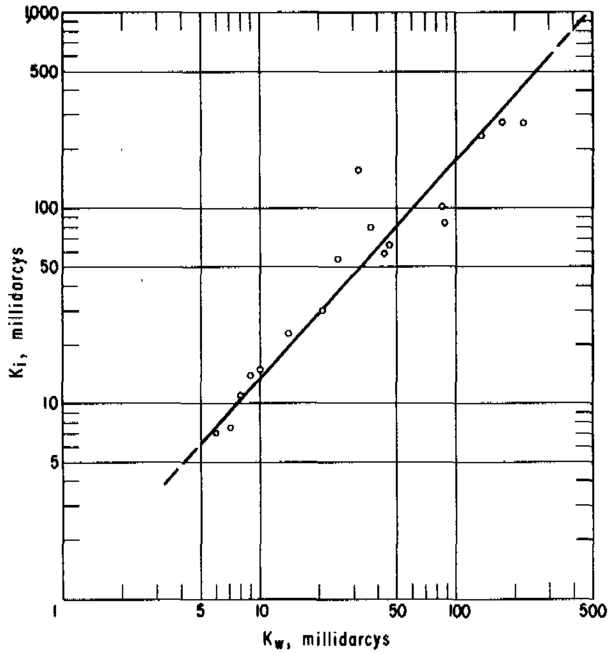

FIGURE 4. - Relation of Water Permeability to Gas Permeability.

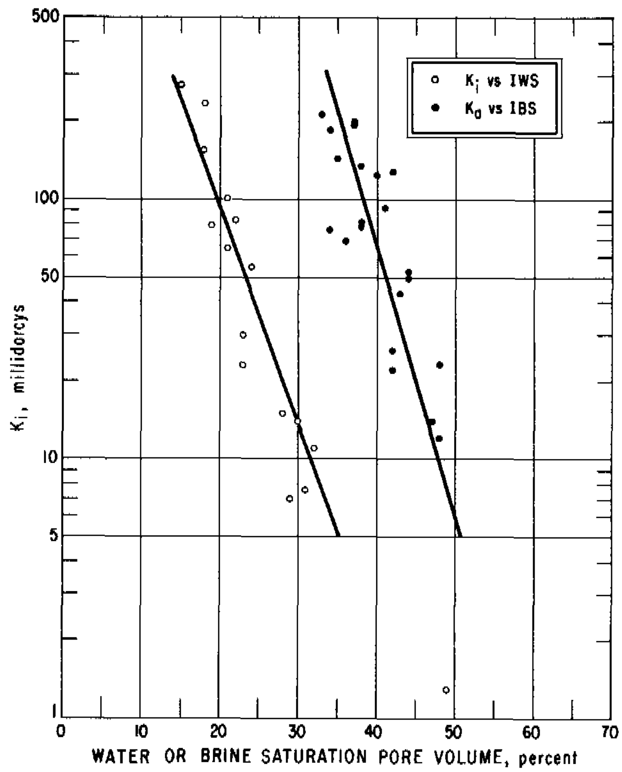

FIGURE 5. - Relation of Gas Permeability to Irreducible-Water and Irreducible-Brine Saturations.

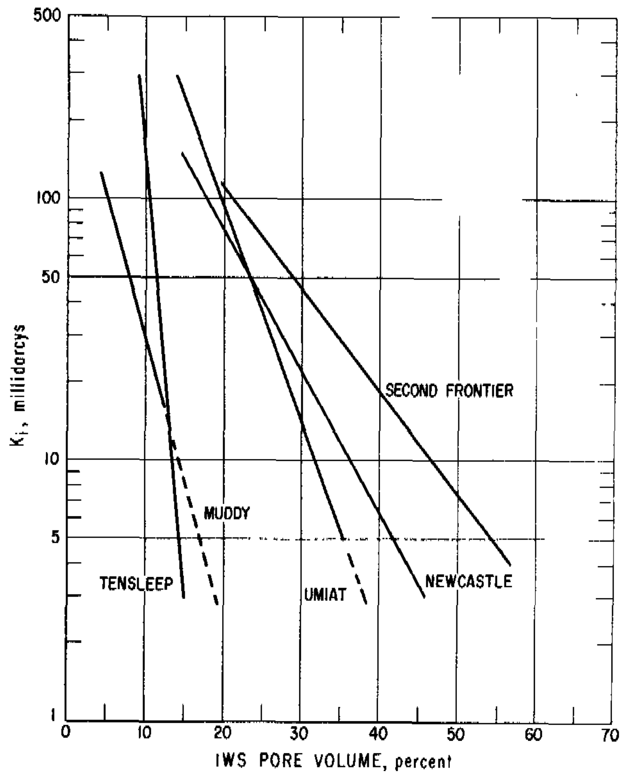

FIGURE 6. - Average Relation of Gas Permeability to Irreducible-Water Saturations, Umiat and Four Reservoir Sands in Wyoming.

If IWS, as determined in several samples from the same sand, is plotted against the corresponding K_i, the trend of the plotted points usually will indicate a general relation between these two variables. When a line is fitted to these data points by the method of least squares, the resultant curve shows the average relation of IWS to K_i. If several such average curves, representing different sands, are placed on the same plot for easy comparison, the relative position of each curve is related to the clay content, capillary behavior, and water sensitivity of the sand (3).

Figure 5 shows the average relation of IWS to K_i for the Umiat sands, and figure 6 shows this average relation with respect to that of four oil-producing sands in Wyoming. Since IWS increases with increasing water sensitivity for a given permeability, especially in the low-permeability range, the position of the average lines on figure 6 indicates that the sensitivity of the Umiat sands is higher than that of the Muddy and Tensleep, slightly less than that of the Newcastle, and much less than that of the second Frontier. Muddy and Tensleep exhibit low water sensitivity, Newcastle shows low to moderate sensitivity, and the second Frontier is highly water-sensitive in the wells represented in figure 6.

Since evidence indicates that Umiat reservoir sands exhibit low to moderate water sensitivity, some other set of physical conditions must have caused the serious formation damage noted in several wells. Evidence, too, suggests that well damage is related to the freezing temperatures and the low pressures in the reservoir sands. Let us study wells 2 and 5 in order to postulate the probable causes of production failure.

Well 2 was drilled with a rotary rig, using water-base mud, and was abandoned as a dry hole. The hole was bailed dry with all the upper sand and the upper part of the lower sand exposed in the open hole. Circulating mud warmed the area around the well bore, which thawed the formation water and allowed water filtrate from the mud to invade the formation. This decreased oil saturation and increased water saturation. When circulation of the warm mud was stopped in preparation for a formation test, water in the formation froze and formed an impermeable barrier around the well bore. Reservoir pressure was not great enough to force oil through this frozen barrier, and the hole was bailed dry without producing oil.

Now consider well 5, which was drilled close to well 2 but drilled first with cable tools, using a small quantity of brine (containing about 100,000 p.p.m. sodium chloride) for the drilling fluid. This method thawed the sand comparatively little, because the drilling fluid soon reached the temperature of the formation. Furthermore, the brine drilling fluid that did enter the sand, due to pressure differential and diffusion, would increase the salinity of the formation water. Increasing the salinity of the formation water would prevent it from refreezing when the formation temperature returned to normal, and all mobile water would be produced ahead of the oil on a production test. Thus no formation damage resulted from the methods used to drill well 5, resulting in a well that pumped as much as 400 barrels of oil a day and perhaps could have produced more if a larger pump had been available.

Reduction of Oil Permeability and Oil Recovery Due to Freezing of Interstitial Water

A set of experiments was made on six radial samples to obtain a qualitative index of oil recovery by solution-gas expansion and additional oil recovery by gas drive, as well as the effect of freezing of interstitial water on these two recovery processes.

The average oil recovery from these six samples at 26° F., shown in table 4, is 28 percent of the initial oil by gas expansion and 23 percent more by gas drive. Maximum recovery was by gas drive, because it was continued after gas breakthrough until no more oil was produced.

After the experiments were completed at 26° F. they were repeated at 75° F. to compare results with those taken when the interstitial water was frozen. Average recovery by solution-gas expansion of four samples run at 75° F. was 40 percent of the initial oil; this compares with an average of 29 percent for the same four samples tested at 26° F.

To test further the effects of freezing of interstitial water on movement of oil, the relative permeability of two samples to oil was tested at room temperature and then below the freezing point of the water. Two radial samples were saturated with water and driven with Umiat crude oil at 70° F. until no more water was produced; the permeabilities to oil were noted. The samples were cooled to 26° F., and the permeabilities to oil were determined again. Permeabilities of the samples at 70° and 26° F. are, respectively, for the first, 30 and 23 md. (23.3 percent reduction), and for the second, 19 and 13 md. (31.5 percent reduction). Since calculation of permeability includes the change with temperature in oil viscosity, permeability values in each sample would have been the same at the two temperatures if no extraneous factors were involved. Thus, average reduction in permeability value attributable to freezing the water is 27 percent. Lowering the temperature from 70° to 26° F. actually reduced the rate of oil flow by 54 percent.

Part of the decrease in oil recovery, caused by lowering the temperature from 75° to 26° F. may be due to increased oil viscosity at the lower temperature; however, this loss seems too great to be caused solely by increased viscosity.

Average water saturation of the four samples tested at 26° and 75° F. is 41 percent of pore space (see table 4). Since the volume of water increases about 9 percent when it freezes, freezing of the interstitial water increased the immobile water saturation from 41 to 45 percent of pore space. This increase of immobile saturation may cause additional constriction of connections between pore spaces within the rock, thereby reducing both relative permeability to oil and oil recovery.

TABLE 4. - Oil-recovery experiments, solution-gas expansion followed by gas drive, temperatures 26° and 75° F.

Well and sand	Depth, feet	Porosity percent	Air permeability, millidarcys	Initial saturations, percent pore volume		Solution-gas expansion				Gas drive			
						Recovery, initial oil, percent		Residual oil, percent pore volume		Recovery, initial oil, percent		Residual oil, percent pore volume	
				Brine	Oil	26°	75°	26°	75°	26°	75°	26°	75°
Umiat 2, lower	796	16.5	196	37	63	34	48	42	33	21	20	28	20
	797	15.1	49	44	56	27	29	41	39	7	9	36	34
	805	14.6	92	41	59	17	-	49	-	28	-	33	-
Umiat 3, upper	259	18.2	128	42	58	36	-	38	-	34	-	19	-
	352	17.7	134	38	62	31	50	43	34	26	23	27	16
	355	16.3	52	44	56	25	33	42	38	19	34	32	19

It is not known whether the deleterious effect due to increased oil viscosity and expansion of water is responsible for all the reduction phenomena observed. It is possible that other factors (some unknown, others half-guessed) may be as harmful as either of the factors already discussed. For example, if ice crystals in the capillary system were dislodged by some mechanism and freed for transport by the moving oil, these crystals could cause very serious blocking of the flow channels.

Oil Recovery by Depletion Drive Under Permafrost Conditions

A second series of recovery experiments was made to determine the relation of solution gas-oil ratio to oil recovery under simulated permafrost conditions, when the oil is produced entirely by solution-gas expansion. This series was conducted at a temperature of 26° F. Recoveries obtained when the oil was gas saturated at 50, 100, and 150 p.s.i.g. are given in table 5, and the average relation of recovery to saturation pressure is plotted in figure 7. Average oil recoveries with the oil initially gas-saturated at 50, 100, and 150 p.s.i.g. are 29, 40, and 45 percent of the initial oil, respectively.

Laboratory analyses were made on a sample of Umiat crude oil combined with a natural gas (mostly methane). Results of a differential liberation at 25° F. between saturation pressure, 328 p.s.i.a., and atmospheric pressure, gave 22.5 cu. ft. of gas (measured at 14.4 p.s.i.a. and 60° F.) released from solution per bbl. of residual oil at 60° F. for each 100 p.s.i. pressure drop (4).

Since volume of gas in solution is directly proportional to pressure in this gas-saturated system, increasing the saturation pressure from 50 to 100 p.s.i.g. increased 100 percent the amount of gas released from solution during the recovery experiment; however, oil recovery was increased only 38 percent--from 29 to 40 percent of the initial oil. The proportional increase in recovery, as related to the increase of gas in solution, was even less for saturation pressure increase from 100 to 150 p.s.i.g.

The first gas that comes out of solution, as the pressure is lowered below the saturation pressure, expands and displaces an equal volume of oil by pistonlike action. This phase of oil recovery continues until the equilibrium-free-gas saturation is reached. After that point, gas begins to flow, relative permeability to gas increases rapidly, and the rate of oil production declines steadily; it may cease eventually even though gas flow continues.

TABLE 5. - Oil-recovery experiments, solution-gas expansion from three saturation pressures, temperature 26° F.

Well and sand	Depth, feet	Porosity, percent	Air permeability, millidarcys	Initial saturations, percent pore volume		Solution-gas expansion: Recovery, initial oil, percent — Saturation pressure, p.s.i.g.			Solution-gas expansion: Residual oil, percent pore volume — Saturation pressure, p.s.i.g.		
				Brine	Oil	50	100	150	50	100	150
Umiat 2, lower..	797	15.1	26	42	58	26	-	-	36	-	-
	805	14.6	81	38	62	36	-	-	40	-	-
Umiat 3, upper..	259	18.2	142	35	65	25	43	47	49	37	35
	352	17.7	123	40	60	24	39	50	45	33	29
	355	16.3	43	43	57	33	29	49	39	41	30
Umiat 9, upper..	470	16.1	76	34	66	-	45	-	-	35	-
	475	13.9	22	42	58	33	40	42	39	35	34
Umiat 9, lower..	870	17.4	195	37	63	-	51	-	-	30	-
	875	17.2	184	34	66	24	32	37	50	45	42
	880	17.8	211	33	67	26	38	48	50	42	35
	895	14.7	69	36	64	-	42	-	-	37	-
	900	12.4	23	48	52	-	40	-	-	31	-
	905	14.3	26	42	58	-	49	-	-	30	-
	910	13.3	14	47	53	-	48	-	-	27	-
	950	12.3	12	48	52	-	29	-	-	37	-
	970	14.6	78	38	62	35	41	44	40	37	30

As a result of these two types of production during depletion drive, the first gas released from solution displaces an almost equal volume of oil, whereas the energy content of the gas released during the period of high gas permeability is largely wasted.

Another factor making possible considerable recoveries from reservoirs that have usually low pressures is that, although the mass of gas in solution is small, its volume is greatly increased when released from solution. Thus a small drop in pressure below the saturation point provides a sufficient volume of gas to complete, not only the piston-action phase of the recovery process, but at least part of the viscous-drag phase.

As an example of gas volumes in the reservoir, suppose that Umiat reservoir oil were gas-saturated at 200 p.s.i.a. and that the pressure dropped to 100 p.s.i.a., then 0.55 bbl. of gas would be released in the reservoir from each barrel of original oil. If this gas displaced an equal volume of oil, recovery would be much greater than that usually experienced in depletion-drive reservoirs. This example illustrates that at even low pressures a reservoir oil may contain more energy than needed to complete the depletion-drive recovery process.

Increasing waste of reservoir energy at increasing gas-oil ratios accounts for the rise of the curve with increase in pressure shown in figure 7. If this curve were extrapolated to higher pressures, an ultimate recovery by this process would be realized at some rather low pressure--perhaps not more than 500 p.s.i.g. These results and observations agree in principle with published literature concerning recovery from depletion-drive reservoirs (11, p. 536): "Oil recoveries from reservoirs exceeding 500 p.s.i. in pressure and 100 cu. ft. per bbl. solution gas are controlled more by fluid-flow characteristics than by reservoir energy."

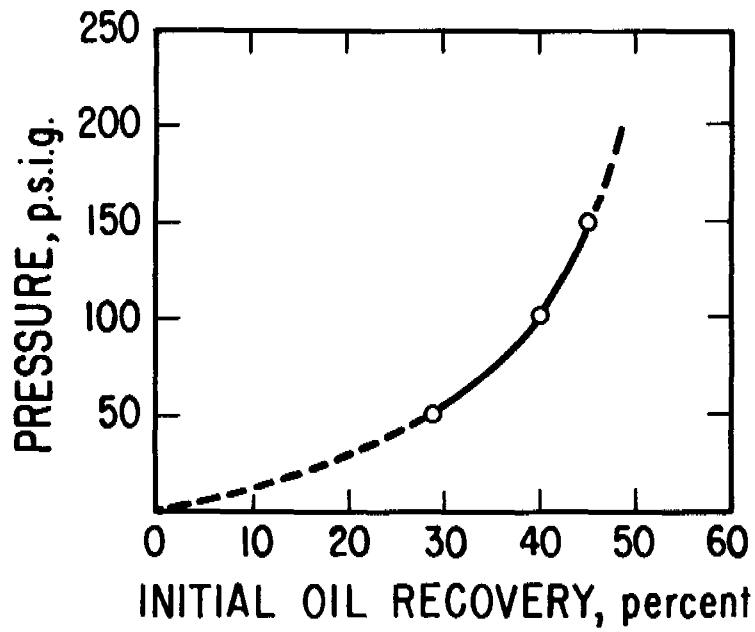

FIGURE 7. - Average Relation of Saturation Pressure to Oil Recovery at 26° F.

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