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OIL DISPLACEMENT BY DIFFERENT SURFACTANT AND POLYMER WATERFLOOD SYSTEMS

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OIL DISPLACEMENT BY DIFFERENT SURFACTANT

AND POLYMER WATERFLOOD SYSTEMS

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ABSTRACT

DISSERTATION

OIL DISPLACEMENT BY DIFFERENT SURFACTANT

AND POLYMER WATERFLOOD SYSTEMS

Rheological studies for four different fluid systems of oil recovery by waterflooding were conducted in this research. The fluid systems are: conventional waterflooding, polymer waterflooding, polymer-surfactant waterflooding, and surfactant waterflooding. The cone and plate viscometer was used for such purpose for most of the investigated solutions, and the obtained data fit the power law equation. A Cannon Ubbelohde Capillary Viscometer was also used for the viscosity measurements for different solutions used in the oil displacement experiments. A Du Nouy tensiometer was also used to investigate the property of surface and interfacial tension of the different solutions. It was clear that surfactants always had a great influence on these properties when added to either brine or polymer-brine solutions.

A study of the oil displacement mechanism was also conducted throughout the course of this research using Berea sandstone core samples. The sand samples were equal in length (≈ 20.0 cm) and diameter (3.81 cm) but different in absolute permeability and porosity. A Hasseler core holder was used as a flow cell. The brine concentration for the conventional waterflood runs, or that water to be used as solvent for other solutions, was maintained at 1.0 percent NaCl solution. Conventional waterflood, polymer waterflood, polymer-surfactant waterflood and surfactant waterflood tests were compared according to their ultimate oil recovery and flood efficiencies under constant rate of injection. A polymer-surfactant waterflood as one phase is recommended and a proposal for a new approach of improving the recovery efficiency is given based on theoretical and experimental findings.

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CHAPTER I

INTRODUCTION

Many new techniques are being developed to increase oil recovery since 50 percent of the oil in the reservoirs is still in place. Each of these secondary recovery techniques has its own specific characteristics and objectives which would best suit the reservoir conditions in question. There are many reasons why this oil has been left behind or trapped. Some of these reasons are attributed to the reservoir rock properties such as mineral composition, packing, wettability, pore size, distribution, and homogeneity, which are hard to control. Some others are related to reservoir fluid characteristics and the adaptation of the materials and techniques being used in the secondary recovery process.

Capillary forces and the mobility ratio of the displacing relative to the displaced fluid are always behind any success or failure of any secondary recovery technique.

A residual oil saturation remains in the rock which has been waterflooded because, under usual reservoir conditions, the driving force which can be generated is inadequate to expel oil trapped by capillary forces. Since these capillary forces can be reduced by reducing the

interfacial tension, a surfactant waterflooding technique was introduced to the oil industry many years ago.

It has been known also for many years that efficiency of a water flood can be improved by lowering the water-oil mobility ratio in the system. Such a change leads to better sweep efficiency and also to more efficient oil displacement in the swept zone. Sweep efficiency is affected by many factors of which the mobility ratio is an important one. Mobility ratio M is defined here as the ratio of water to oil mobilities:

$$M = (k_w/\mu_w)/(k_o/\mu_o) \ .$$

If the mobility ratio is greater than one, the mobility ratio is unfavorable and water, being more mobile than oil, would finger through the oil zone resulting in poor oil recovery efficiency. If it is favorable (one or less), the displacement of oil by water occurs more or less in a pistonlike fashion. The argument for polymer flooding is that, in comparison with conventional waterflooding, greater fractions of reservoir volume may be swept. Increased sweep efficiency, however, depends on lowering the mobility of the injected water. The degree of mobility reduction is proportional to the apparent viscosity of the solution and to the reduction in reservoir permeability to water caused by passage of the polymer solution.

There has been a lot of research done on polymers and surfactant flooding, which has investigated the problems encountered in both techniques. Problems are adsorption, plugging and retention of polymer molecules throughout the formation, and surfactant losses by adsorption in the porous media.

Very recently a new technique was introduced to the oil industry. It is the use of micellar (sometimes called microemulsions, swollen micelles, soluble oils) solutions. These solutions basically contain surfactants, hydrocarbons and water. Micellar solutions are used to recover oil by miscible type water flooding. No technique has yet been developed to make use of the data available about polymers and surfactants in order to introduce a combined mixture of the two to the porous media.

CHAPTER II

STATEMENT OF THE PROBLEM

A conventional waterflood system has been known as the most common secondary recovery technique for oil reservoirs. Such a system has proved its economic advantages, but failed to offer an effective displacement mechanism because of water fingering. For this reason, water soluble additives started to be used in waterflood treatments. Polymers, surfactants, and other chemicals were used in an attempt to improve the recovery efficiency of the waterflood system.

The objective of this research consists of the following items:

(1) To understand and compare the ultimate oil recovery produced by different waterflood systems, namely, conventional waterflood, polymer waterflood, polymer-surfactant waterflood, and surfactant waterflood.

(2) Study of the displacement mechanism involved in all tested waterflood systems.

(3) Study of the physical changes in porous media due to the flowing of different fluid systems.

(4) Rheological study of fluid systems which includes viscosity, surface, and interfacial tension.

In order to accomplish these objectives, the research work was conducted according to the following pattern:

A. Rheological Study of the fluids.

The viscosity of each waterflood system was measured by a cone-and-plate viscometer. Data were taken at a shear rate ranging from 1.15 to 230 sec^{-1}. The surface and interfacial tension of solutions were measured by a Cenco-Du-Nouy tensiometer, and all rheological experiments were conducted at room temperature.

B. Flow of Different Waterflood Systems Through Porous Media.

(1). Berea sandstone core samples were used for oil displacement tests.

(2) Constant injection rate and temperature prevailed during all oil displacement runs.

(3) Different sequences of waterflood systems were also tested in oil displacement runs.

(4) The effect of polymer molecular weight (ranging from 600,000 to over 5,000,000) and concentration in a polymer waterflood system was also investigated with respect to the oil displacement runs.

(5) Concentration of different surfactants, as well as different polymer-surfactant waterflood systems, were also tested during the displacement phase.

Polyethylene oxide was used in this research work as the polymer phase, as well as 8 non-ionic and two ionic water soluble surfactants.

CHAPTER III

LITERATURE REVIEW

CHEMISTRY OF SURFACTANTS

Surfactant chemistry derives from a characteristic and necessary feature of a surfactant--the presence of a strongly hydrophilic group and a strongly hydrophobic group linked together in the same molecule. Regardless of the exact chemical nature of these groups, surfactants have a certain set of physico-chemical properties in common.

The word surfactant is a shortened form of the rather awkward term, surface active agent, and denotes the outstanding property of these compounds: They tend to concentrate at the surface of an aqueous solution and to alter its surface properties. Modern detergents usually contain about 10% to 30% of surfactant.

The common set of surfactant properties are: surface phenomena, micelles and the chemical origins.

Because of the presence of the hydrophilic group, a surfactant is more or less readily soluble in water. However, the hydrophobic group is repelled by water so that there is a tendency for that portion of the molecule to leave the aqeuous solution. This leads to a higher concentration at the surface or boundaries than in the main body of the solution. At the surface of the solution--the air-water interface--

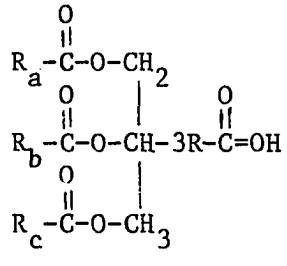
the surfactant molecules orient themselves with the hydrophilic groups in the water phase, the hydrophobic groups extending as far as possible in the other direction, still consistent with the molecular dimensions and geometry and with the intermolecular forces acting upon them. The result of this oriented surface film is the lowering of the surface tension of the water, and a greater tendency toward bubble and foam formation. In the presence of an immiscible liquid--oil--and water, a similar layer tends to form at the liquid-liquid interface, hydrophilic groups oriented toward the water, hydrophobic toward the other liquid. This promotes dispersion and emulsification as droplets. At liquid-solid interfaces, a similar phenomenon occurs. In all of these cases an equilibrium exists between the surface molecules at the interface and the interior ones, with molecules constantly entering and leaving the two regions. On the other hand, the simultaneous attraction and repulsion of the surfactant molecule by water may be pictured as the mechanism responsible for surface adsorption. If the solid surface contains chemically active centers, they may exert strong attraction for either the hydrophobic or the hydrophilic groups with the result of strong adsorption effects.

The other common characteristic phenomenon of surfactants in aqueous solution is the aggregation of their molecules into larger, oriented groups called micelles. In the micelles of an aqueous solution the molecules are oriented with their hydrophobic portions clustered together, the hydrophilic ends extending outward. Such ordering results from repulsion of the hydrophobic groups by the water, further aided by attraction of the groups for each other. The micelles are in

equilibrium with the solution, and one may picture relatively free passage of the surfactant molecules back and forth between the two. Sizes and shapes of micelles can be determined by various physico-chemical means. Depending on such factors as the chemical nature and architecture of the surfactant, the salt content of the solution, and the temperature, they may be spheres, ellipsoids, or cylinders, and may average tens or hundreds of molecules per micelle.

The common chemical origin of surfactants stems from their general structures--molecules in which a hydrophilic group is linked to a hydrophobic group.

The most prevalent hydrophobic group used in surfactants is the hydrocarbon radical having a total of from 10 to 20 carbon atoms. Commercially, there are two main sources of supply for radicals in sufficient quantity and in a suitable price range: agriculture (and fishing) and the petroleum industry. Agriculture contributes fats and oils, which are predominantly triglyceride esters of fatty acids and which are readily hydrolyzed to the fatty acids themselves as given by equation 1;



(1)

The hydrophobic groups contributed by the petroleum industry are principally hydrocarbons, deriving originally from the paraffins of crude oil. The chain lengths most suitable for detergent hydrophobes, C_{10} to C_{20}, occur in the crude oil cuts boiling somewhat higher than gasoline, namely kerosene and beyond. The main components of kerosene

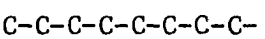
are saturates ranging from about $C_{10}H_{22}$ to $C_{15}H_{32}$, ordinarily containing 10% to 25% of straight chain, linear, homologs (Equation 2). There are larger amounts of branched chain isomers, of which equation 3 represents one of the hundreds of structures which may be present. In addition, quantities of saturated cyclic derivatives, naphthenes, may be present also, $C_{10}H_{20}$ to $C_{15}H_{30}$, exemplified by equation 4, and minor amounts of polycyclic derivatives. The paraffins have the disadvantage of being chemically unreactive so that direct conversion to surfactants is rather difficult. Instead, it is usually preferred to go by way of other intermediates, most commonly olefins, equation 5, alkylbenzenes, equation 6, or alcohols. These contain active centers--the double bond, the benzene ring, or the OH-group--which are more reactive than the paraffins themselves and more easily liked to hydrophilic groups to make surfactants.

The hydrophilic groups of today's surfactants are of two classes--those which ionize in aqueous solution and those which do not. The hydrophilic property of the former derives from a strongly acidic or basic character which permits the formation of true, highly ionizing salts upon neutralization. On the other hand, the nonionic hydrophilic groups have a multiplicity of elements which are individually rather weak hydrophiles but which have a cumulative effect; increasing their numbers in the group increases the hydrophilicity of the aggregate to the degree desired.

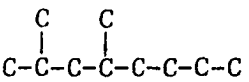
The more common hydrophilic groups include:

Sulfonate

Sulfate



(2)



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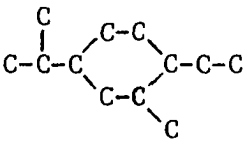

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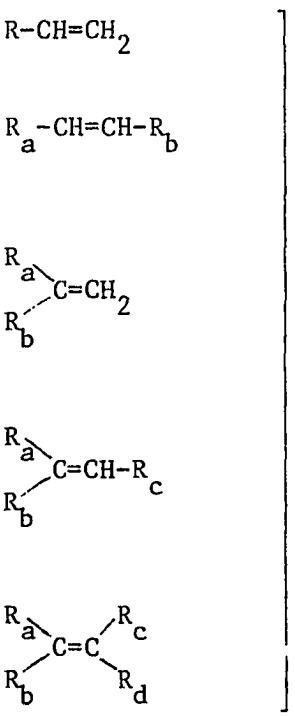


(5)

(6)

Carboxylate

Quarternary Ammonium

Polyoxyethylene

Sucrose

Polypeptide

The first four are ionic and the last three nonionic, in the terminology of surfactant chemistry.

The hydrophobic groups, the hydrophilic groups, and the modes of linking them together may be formulated and combined to give surfactants in unlimited variety. The most important three categories are: the anionic, cationic, and nonionic surfactants.

The anionic surfactants are those which give negatively charged surfactant ions in aqueous solution, usually originating in sulfonate, sulfate, or carboxylate groups [$RSO_3Na \rightarrow RSO_3^- + Na^+$].

Cationic surfactants are those which give a positively charged surfactant ion in aqueous solutions [$RN(CH_3)_3Cl \rightarrow RN(CH_3)_3^+ + Cl^-$].

Cationic and anionic surfactants neutralize each other when present in the same solution together.

Nonionic surfactants contain hydrophilic groups which do not ionize appreciably in aqueous solution. The ones of greatest commercial importance contain a polyether hydrophobe group derived from ethylene oxide. They comprise perhaps 20% to 25% of the total volume of surfactants produced.

THE USE OF SURFACTANTS IN OIL INDUSTRY

A new application of surfactants is the introduction of suitable surfactants into producing oil wells in order to increase the rate of crude oil production. Also, surfactants are being used in the water flooding, or secondary oil recovery, operation in an attempt to recover some of the two-thirds of the total volume of oils which remain in the field after primary production.

Waterflooding is a useful method of oil recovery from subterranean formations. It has, however, a relatively poor displacement efficiency (13). This poor efficiency is due to the property of immiscibility which the water, as the flooding liquid, has with the oil it seeks to displace. There is a relatively high interfacial tension between the water and the oil. It is very well known, on the other hand, that the displacement efficiency decreases with increasing interfacial tension.

Typically, the interfacial tension between flooding water and oil may range from about 5 to about 50 dynes per centimeter. Surfactants have been used in waterflooding to reduce the interfacial tension. In 1959, Alberto Salinas (43) investigated the effect of an oil-soluble surfactant slug on water flood recovery. The surfactant he used in his experimental work was a new product of the Mud Control Laboratories, Inc., and was marketed under the name of Control-Flow. This Control-Flow material was described as a thick brown liquid which is soluble in all proportions in most hydrocarbons. It also reduces the interfacial tension of oil-brine to zero when the concentration is greater than 1 percent, but has little effect on the surface tension of the oil. As a result of

his oil displacement experiments, he concluded that (1) little adsorption appeared to be present using oil-soluble surfactants in a water-wet core, (2) the surface active agent had a strong action on the oil-brine interfacial tension, but no additional oil recovery was obtained from water-wet cores.

Ahearn, et al. (1) describe and claim using as surfactants petroleum sulfonates that effect an interfacial tension of 0.03 dyne per centimeter; these are prepared by sulfonating at least a portion of sulfonatable constituents which occur in the 700-1100°F boiling range, and have an average molecular weight between 452 and 702. Typical surfactants which have been proposed for this purpose include alkyl pyridinium salts, sodium lauryl sulfate, certain sulfonates, glycosides, sodium oleate, quaternary ammonium salts, etc. Ahearn et al. concluded that the type of surfactants they proposed as waterflood additives have been proven to recover no more than a few percent of the residual oil which remains in a reservoir after conventional waterflooding when tested under conditions reasonably simulating actual field operations.

In connection with the use of surfactants in waterflooding, the surfactants often have not created the most favorable contact angle between the flooding water and the oil in the formation. Desirably, the contact angle should be as close to 180 degrees, measured through the oil, as possible for best results in recovering the oil.

Dunlop and Foster (13) introduced a solution of a mixture of petroleum sulfonates as an additive to the flooding water. They emphasized that it is particularly preferable to employ a restricted mixture of petroleum sulfonates having a median molecular weight from

about 400 to about 430. Their invented solution mixture may be aqueous or hydrocarbonaceous. One recommendation they offered was that the mixture of petroleum sulfonates is preferably injected in an aqueous solution which also contains sodium chloride, sodium carbonate, and inorganic polyphosphates.

The amount of sulfonate surfactant to use in a given oil recovery operation may vary considerably, depending upon factors such as the salt content of the water employed, the type of oil, the nature of the oil-bearing formation, and the ability of the surfactant to reduce the interfacial tension between the oil and the flood water (1, 19).

The composition of the aqueous solution that Reisberg (25, 41) introduced contains both low molecular weight alkyl aryl sulfonates which are water soluble and high molecular weight alkyl aryl sulfonates which are water insoluble, low molecular weight alkyl aryl sulfonates being present in at least critical micelle concentration with amphiphilic molecules to be made up of high molecular weight alkyl aryl sulfonates penetrating and swelling the micelles. The interfacial tension between the aqueous solution containing this mixture and the residual oil in the reservoir was substantially reduced enabling more oil be be displaced with greater efficiency.

The work done by Inks and Lahring (30) was to determine the effectiveness in increasing oil production by injecting water containing small quantities of a nonionic surfactant. The surfactant selected was PLURONIC L64, a block copolymer based on ethylene and propylene oxide, with the following structure:

$$HO[CH_2CH_2-O]_a[\underset{\underset{CH_3}{|}}{CH}-CH_2-O]_b[CH_2CH_2O]_cH$$

Their surfactant waterflood was applied in the field to determine the commercial feasibility of such a process. According to the data collected over ten years of application, they stated that the surfactant resulted in an increase of about 9 percent in secondary oil production. Other benefits derived from the surfactant injection were lower calcium scale build up and lower injection pressure that resulted in reduced power consumption and reduced erosion of the pumps (lower maintenance costs).

Surfactants can also be used as basic constituents of what is called micellar solutions. Gogarty (21, 22) states that miscible-type waterflooding is possible with the miceller solutions because of their phase behavior with reservoir fluid(s). The basic components of miceller solutions are surfactant, hydrocarbon and water. They may also contain small amounts of electrolytes and co-surfactants such as alcohols. Miceller solution slug mobility, by way of viscosity control, is made equal to or less than the combined oil and water mobility. Their properties depend upon the type and composition of basic components used in their formulation. The constituent in smallest concentration that imparts the greatest change in micellar solution properties is salt, which affects the viscosity and phase stability. Gogarty also stated that, rheologically, the micellar solutions may behave as Newtonian fluids at low shear rates while at higher rates the fluids are non-Newtonian and follow a power law relationship.

Laboratory results indicated that micellar solutions are effective agents in miscible-type floods and displaces 100 percent of the oil in the reservoir contacted. In addition, surfactant loss by absorption on porous media is relatively small.

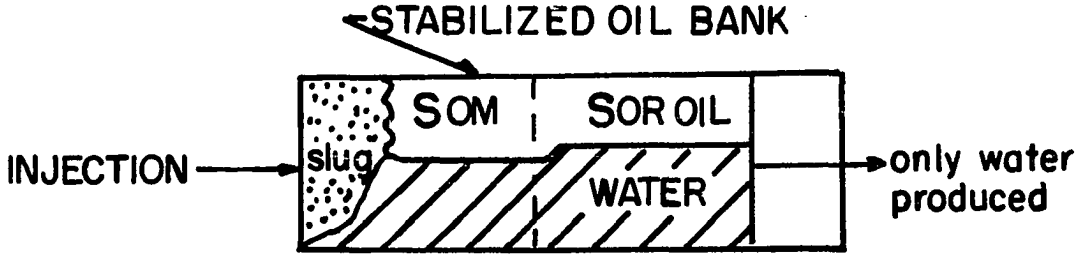
Davis and Jones (12) discussed the displacement mechanisms of these micellar solutions through their laboratory work. An idealized schematic representation of the miceller displacement process is given in Figure 3.1.

The reservoir was simulated in terms of a glass micromodel and in consolidated Berea sandstone cores. Oil was displaced miscibly, while interstitial water was displaced immiscibly by the injected micellar solution slug. As a result of their investigation they have concluded that the micellar solution slug completely removes oil from the portion of rock it contacts, which is the same conclusion reached by Gogarty. An oil bank forms ahead of the micellar solution slug in a previously waterflooded reservoir. They also concluded that usually high oil recoveries are obtained with very small slugs of micellar solution if the slug and thickened water compositions are correct. A 5 percent PV slug recovered all of the oil from a 4 ft x 2 in Berea core. A theory and series of equations were presented that describe several aspects of the displacement flow behavior.

Gogarty and Surkalo (21) also presented the results of such a process for a field test in Eastern Illinois oilfield area. Most of the given results confirm to a great degree what was previously predicted.

Halbert, Jr. (23) had also tested a simple micellar solution for its oil displacement capabilities in a sandstone core (30). The

A. SATURATION AT THE END OF SLUG INJECTION



B. SATURATION AFTER START OF THICKENED WATER INJECTION

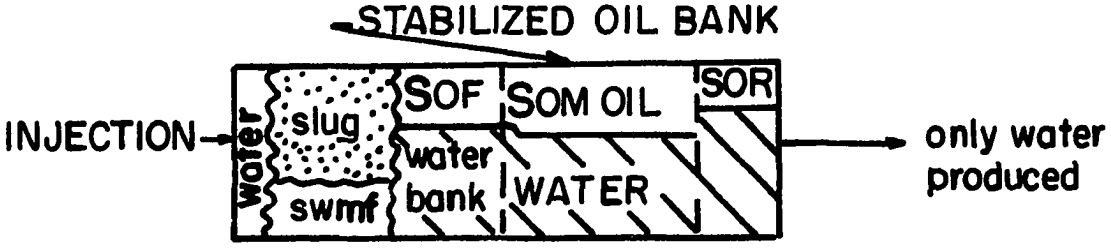


FIGURE 3.1 IDEALIZED SCHEMATIC OF FLUID SATURATION BEFORE OIL BREAK-THROUGH.

micellar solution was prepared using crude oil (30.1°API), water and a phosphate ester surfactant. The surfactant [KLEARFACAA-420] is an anionic, biodegradable liquid that exhibits solubilizing properties within a broad pH spectrum. The surfactant was found to be an excellent solubilizer of crude oil and water. Surfactant concentration in the micellar solution was 15 percent by volume in a sour crude oil-water system. Oil displacement tests showed in this study that the micellar solution employed was capable of displacing 90 percent of the core's oil saturation.

During the last four years, use and development of surfactant flooding had increased tremendously. Much research work had been conducted as well as field application.

References (17, 19, 21, 39) are discussing a similar but not the same technique presented earlier by Gogarty (21, 22) and Al-Rikabi (2). The technique which has been studied in the lab was then applied to different pilot test areas. It consists mainly of four specific stages: a preflood of low salinity water to displace the high-salinity formation water, followed by a slug of chemical solution that contained a surfactant, a builder and mobility-control agent. In the fourth stage is a controlled-mobility drive solution (which was a different type of polymer in each of the three cases), and at the end, an ordinary waterflood. The distribution of slug sizes and the different chemical concentrations were based on previous laboratory simulated type of work results for every case.

The significant difference between this technique and the one presented by Gogarty is the miscibility of the surfactant under

consideration. Gogarty used a surfactant slug that is miscible with the reservoir crude (Haraflood process or technique), where miscibility in this case implies zero interfacial tension between this slug and the reservoir crude oil. The other technique does not depend on such miscibility between crude oil and water, but relies on very low interfacial tension between a water solution/dispersion of a surfactant and the reservoir crude oil.

CHEMISTRY OF POLYMERS

Polymers are of great interest to the petroleum industry because they are useful in secondary recovery processes. They were originally suggested for waterflood use because they have the ability to decrease mobility of the flood water when present in relatively small concentrations. Before talking about the behavior of polymer solutions and the displacement mechanisms associated with such behavior in porous media (44, 45), a brief description of a polymer seems to be recommended. For more detailed information, the reader is invited to consult any chemistry text book.

A polymer is a rather large molecule built up by the repetition of many small primary molecules chemically bound together. The basic unit or the primary molecules of the polymer are usually referred to as "monomer units." The number of monomer units in a polymer is usually called the "degree of polymerization." The number of monomer units can be as low as two (Dimers), and may be very high so that giant polymer molecules are formed with molecular weights of several million. Polymers composed of a single repeating monomer unit are known as

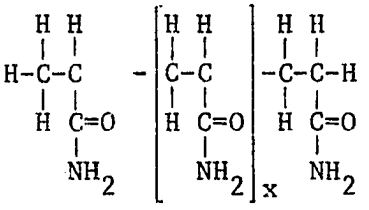
"homopolymers" and those composed of two or more monomer units are known as copolymers (16). The repetition of the monomer units may be linear to form chains, or the chains may be interconnected to form a three-dimensional network (nonlinear). Example of a simple type of polymer (linear polymer) is given by (Polyoxymethylene):

$$-CH_2-O-[O-CH_2]-O-CH_2-O-$$

or

$$B-[A]_x-S$$

A is the monomer unit, x the degree of polymerization, B and S are the end groups. Another example of a well known polymer in the oil industry, namely polyacrylamide, is given by (long-chain polymer):



The monomer unit here is composed of carbon (C), hydrogen (H), nitrogen (N), and oxygen (O).

The physical properties of the polymer solution (long-chain polymers) are entirely governed by the monomer unit, irrespective of the end group constituents (15). The forces of attraction along polymer chains (or the bonding force between the monomer units) are either primary or secondary bond forces. Usually the secondary bond forces of attraction are weak relative to the primary. One of the most important primary bonding forces between the monomer units are the covalent bonds. A good example of the secondary bond forces is the hydrogen bonding among the molecules of the given polyacrylamide solutions.

Among the parameters that would determine the physical properties of a polymer solution are the molecular weight, the molecular weight distribution and the configuration which the polymer takes while in solution (37, 52). Viscosity of a polymer solution (apparent and intrinsic viscosity) is a straight function of polymer molecular weight and concentration (4).

Classification of polymers is a very wide and difficult goal because of the very many varieties of polymers and their physical properties (9, 17). The most common and classical classification was that given by Carothers (6) and modified later by Flory (16). These classifications suggest that there are only two groups of polymers: condensation and addition polymers. The details of such classification is beyond the scope of this work and the reader is referred to the preceding references as well as Billmeyer (4).

Natural gums, such as guar gum, fatty acid soaps, glycerine, etc. were used by the oil industry as polymeric materials during the early stages of the industry. Synthetic polymers are the most commonly used during the last ten to fifteen years. Partially hydrolyzed polyacrylamide, polyvinyl alcohol, polyacrylic acid, hydroxyethylcellulose, and polyethylene oxide are among this group. The common property between these synthetic polymers which made them good candidates for secondary recovery operations is that they are water soluble materials.

Polymer solutions studies conducted in the lab were after two main targets: development and modification of non-Newtonian flow theories in porous media, and physical and experimental interpretations to the behavior of polymer solutions in oil displacement mechanisms. Little information about pilot floods using these polymer

solutions could be found in the last four years of published papers. A brief summary of all these activities could be found in the following pages.

REVIEW OF CURRENT TECHNICAL PAPERS

The study of non-Newtonian flow through porous media has lately received considerable consideration; for a recent comprehensive review, refer to Savins (45). Savins' report includes a brief discussion and comments for every research work which has been done in this area up to the year 1969.

Research of Jewett and Schurz

R. L. Jewett and G. F. Schurz presented a comprehensive tabulation for 61 polymer flood field project test results, initiated between 1964 and 1969 (31). Tables include reservoir and fluid properties for each project. Linear, highly soluble, partially hydrolyzed polyacrylamide was the only polymer used in these 61 projects. The objective behind this research consists of: first, to determine those reservoir and fluid characteristics under which this process is most applicable, i.e. screening fields suggested as future polymer flood candidates; and second, to compare field results with others produced by simulation to establish program validity. They have proposed a 2-D computer program which can calculate the behavior of both conventional waterfloods and polymer floods.

They concluded that, on the basis of the results of field projects, polymer flooding has been found to be successful. In addition, the screening device is helpful to eliminate fields for potential applications.

Research of Wang and Caudle

G. C. Wang and B. H. Caudle (52) developed a streamline mathematical model to study oil recovery by viscous waterfloods for any desired well spacing. They investigated the combined effects of permeability stratification, polymer concentration and viscous water slug size for a five spot injection pattern by means of the proposed model. A glycerin water mixture was used for the viscous water for a series of four flooding experiments to determine the type of displacement to be programmed for the model. Twenty-five feet long sand packed tubing and half inch internal diameter was used as the flow cell. Viscosity of displaced oil ranged between 10 and 50 cp. Permeability of sand packs was 5.6 Darcy for the first two runs and 4.7 for the last two. The displacement performance of the glycerine solution flooding was reported as a modified piston-like type.

Five different permeability profiles ranging from homogeneous to highly stratified were tested. Wide ranges of slug sizes and viscosities were assumed along with assumed viscosities of displaced and displacing phase to study the effect of slug size on oil recovery using the model. Values for connate water saturation were assumed to define the effect of connate water on oil recovery. Computer results indicated that viscous water floods would give greater percentage increase (over conventional water floods) in oil recoveries for stratified than homogeneous reservoirs. Other sets of results indicated that the effect of connate water saturation on oil recovery becomes insignificant as the degree of permeability stratification approaches a large number. As a final conclusion stated in this research, it was found more

advisable to use a high viscosity, small size slug in flooding a homogeneous formation, while stratified reservoirs do better with the use of a large diluted slug.

Research of Smith

Frank W. Smith (49) conducted tests with three different partially hydrolyzed polyacrylamides. Polymer H was described as having a molecular weight between 3 and 10 million, with high degree of hydrolysis; Polymer M, having molecular weight of about 3 million with the degree of hydrolysis as H; Polymer L, having the lowest molecular weight and very low degree of hydrolysis. For all flow experiments the polymer concentration was 0.05% in a sodium chloride brine solution (the concentration ranged from 0.5% to 10%). Formaldehyde was used as a bactericide. Polymer solutions were filtered through a coarse fritted glass disc Bunhner funnel. The solution pH was reported as 7.0 ± 0.5. PH adjustment for absorption experiments was carried out by adding sodium bicarbonate (0.034%) to the polymer solutions. Filtration of polymer solutions through millipore filters having closely controlled pore diameter was also used to determine the effective diameter of the dissolved polymer molecules. Another filtration was conducted through all-plastic filter holders. The concentration of the filtered polymer solution coming out from the all-plastic filter holders was tested to determine the effectiveness of each filter in removing polymer from solution.

Adsorption experiments were conducted on three different absorbents: silica powder, calcium carbonate powder, and crushed Berea sandstone. The results showed that absorption of polymer varies from

one type mineral surface to another (calcium carbonate indicated greater affinity than silica). On the other hand, polymer absorption seems to increase with salt concentration. Flow experiments of polymer solutions were performed through synthetic alundum discs and Berea discs. Several conclusions were given for this research concerning the effect of flow rate and temperature, rock and fluid properties, and polymer molecular weight, on polymer solution properties:

(1) As the brine salinity increases, mobility reduction due to polymer solution decreases.

(2) Mobility reduction increases with the increase of polymer molecular weight.

(3) The mobility of polymer solutions in porous media decreases as the flow rate increases.

(4) Mechanical degradation of polymer solutions occurs at very high fluid velocities.

(5) Temperature variation seems to have little effect on mobility reduction by polymer.

Research of Mungan

Necmettin Mungan (35) reported a number of laboratory tests for four polymer solutions (12). The first two are ionic (polyelectrolyte) polymers manufactured by Dow Chemical Company, Pusher 500 and Pusher 700. The molecular weights were reported as 3-7 and 2-3 million, respectively. The third and fourth are nonionic polymers, products of Union Carbide (polyethylene oxide), Polyox-coagulant having molecular weight of 5-7 million, and WSR-301 with a molecular weight of 3-4 million. Deaerated distilled water and reagent grade chemicals were

used in all solutions. All polymer solutions were filtered through millipore filters, and formaldehyde was used as bactericide. All experiments were conducted under the same temperature conditions (70 ± 1°F). The pH of polymer solution number one ranges from 8.2 to 9.8 according to the polymer concentration of 500 and 2500, respectively. Polymer solution (Pusher 500) was used for most of this research.

Cannon-Fenske viscometer was used for the rheological study of polymer solutions, and a few measurements were performed using a Fan Model 35 rotational viscometer. Viscosity measurements were made over a wide range of shear rates going from 7 to 2000 sec^{-1}. A Newtonian flow behavior was also assumed.

Two methods were applied to determine adsorption: static and dynamic, through pretreated Silica No. 16 media. Other experiments reported by Mungan were oil displacement tests. They were conducted in Hele-Shaw and consolidated Berea sandstone models. The models represented one quarter of a 5-spot pattern.

Mungan reported the results of his rheological studies as follows:

(1) Polyelectrolytes develop greater viscosity than the non-ionic polymers of comparable molecular weight.

(2) The higher molecular weight gives higher viscosity for all polymer concentrations and shear rates.

(3) For all shear rates the apparent viscosity increases with increasing polymer concentration.

Adsorption results were reported as being varied from 30 to 225 µg/g. It was found that the adsorption of polymer solution through

porous media is a straight function of the surface area to which it is exposed. It was also reported that adsorption results using the dynamic method are more reliable than of the static method.

It was also concluded from the displacement tests that a small volume slug of polymer solution ahead of the ordinary injection water would increase the oil recovery. A slug of varying rather than constant polymer concentration was recommended.

Research of Nouri and Root

Hossein H. Nouri (27, 28) experimented with solutions of polyacrylamide (average molecular weight 1.0 to 14.0 million), polyethylene oxide (average molecular weight 200,000 to 4,000,000), and polysaccharide (15, 16). Sandstone cores of Berea and Torpedo sands were used for the fluid flow displacement tests. Core samples were ranging between 5 and 9 cm long, and from 3.5 to 3.8 cm in diameter.

Nouri stated that the rheological data obtained for a total of 88 concentrations of twelve different polymers appeared to fit the power law model. All polymer solutions were found to be non-Newtonian in behavior except for the 2.0 percent solution of WSR-35 and the 0.025 percent solution of NP-20 which were found to be Newtonian. He also concluded that polymer solution viscosity increases with the molecular weight and concentration of the polymer. In a series of tests to investigate the effect of sodium chloride concentration on polymer solution viscosity, he found that the latter and its shear dependence decreased with increasing sodium chloride concentration. Temperature effect on viscosity of polymer solutions was also investigated and was found to decrease as the solution temperature increases. Flow experiments

were conducted through core samples both under constant pressure and constant flow rate conditions. The flow behavior was expressed in terms of a resistance factor-velocity relationship. The output results indicated that, at high flow rates (high velocity), the polymer solution behaves as a pseudoplastic fluid which decreases the value of the resistance factor. At low flow rates (low velocity), the polymer solution behaves as a Newtonian fluid, which gives a relatively high and constant value for the resistance factor.

For more understanding of the flow behavior of polymer solutions through porous media, Nouri developed some factors which relate the fluid properties to the flow characteristics [reduced friction factor-Reynolds number]. The developed factor was tested for more than four different polymer solutions, and it was proven that their behavior follows the proposed correlation in most cases.

Oil displacement results revealed that oil recovery could be increased using polymer flooding over conventional waterflooding, but only a small reduction in residual oil saturation can be expected from polymer injection.

Similar research was conducted by Jose Ferrer in 1972 (14). Ferrer added two critical and important conclusions through his discussion. First, the partially hydrolyzed polyacrylamides can be controlled more than the polyethylene oxide in secondary recovery processes. Second, capillary forces must be taken into consideration for any polymer flooding project.

Research of Tost and Stokke

Marvin E. Tost and Olaf M. Stokke (54) presented a rather constructive study in the field of polymer filtration, hoping that other people in the industry might follow up their steps and work all together through publications to overcome the problem of polymer plugging. They stated that, since it has been noticed in so many cases that injection of polymer solutions into the oil bearing formation without being filtered would lead to severe plugging at the wellbore or at varying distances from the injection well, an effective filtration technique is badly needed. Unfortunately, today's filters are not sufficient. They reported that up-flow and down-flow sand filters were rejected because they can't achieve the required degree of filtration (removal of particles > 1.0 μ). Cartridge type filters were also rejected because their field experiences were not encouraging and because there was a buildup of slime layers ("gels" of polymer) on those used in earlier field tests.

Tost and Olaf introduced a method to evaluate filter aid performance, and they used such a method to support their newly presented diatomaceous earth filtration process. They claim that such a process is capable of providing the desired quality of polymer solutions. The drawback for their invention would be the selection of the proper grade (or permeability) of filter aid to use.

Research of Dauben and Menzie

Dauben and Menzie (10, 11) investigated the effect of the physical properties of the porous media on the flow behavior of polyethylene oxide solutions. The polyethylene oxide used, manufactured

by Union Carbide Corporation (under the trade name of Polyox), has molecular weights ranging from 200,000 for Polyox WSR-35 to over 500,000 for Polyox Coagulant. The solvent used was distilled water with the addition of specific amounts of isopropanol. The flow cell for displacement tests consisted of a stainless steel flow cell packed with glass beads (with diameters ranging from 53 to 300 microns).

An apparent contrast was noticed between Dauben and Menzie research results and those reported by Sadowski (42) and Christopher (7). They found that there was little indication of permeability reduction using polyethylene oxide solutions (little plugging effect). They also found that the mobility of the polymer solutions during the displacement tests was lower than would be predicted from rheological measurements. The apparent viscosities of the solutions were also found to increase with molecular weight, concentration of the polymer, rate of flow, and decrease with increase in pore size.

CHAPTER IV

FLUID BEHAVIOR CLASSIFICATION

There is one common factor between solids, liquids and all these intermediate phase mixtures. If we apply a stress or load on any of them, they will deform or strain. The deformation may be instantaneous or it may continue with time. Since it is common experience that scientific knowledge is meagre and unsatisfactory unless it can be expressed quantitatively, it is obviously of importance for us to be able to express the relationships between stress, strain and time. When expressed mathematically such relationships are known as rheological equations of state. A brief discussion is presented here for the rheological equations of state of the more important classes of rheological fluids.

NEWTONIAN FLUID [The Ideal Fluid]

The stress-deformation behavior of this ideal fluid is best considered by imagining two parallel plates of very large area (A) separated a distance r by the ideal fluid. A shear force F is applied to the top plate only, i.e. there is a shear stress = F/A, and the top plate moves with a uniform velocity u. Fluids which obey the following simple relation

$$\tau = -\mu(du/dr)$$

where the constant μ is known as the coefficient of viscosity, are known as Newtonian fluids. Water and many other simple liquids closely approach Newtonian fluids. τ is the shear stress and (du/dr) is the shear rate. If we plot shear stress against shear rate for a Newtonian fluid, the slope of the straight line would be the coefficient of viscosity.

NON-NEWTONIAN FLUIDS

All fluids which deviate from the simple characteristics of a Newtonian fluid are non-Newtonian. Examples are given like polymer melts and solutions, drilling muds, emulsions, etc. For the sake of argument, non-Newtonian fluids can be subclassified as:

(a) Time-independent fluids.

(b) Time-dependent fluids.

(c) Viscoelastic fluids.

Time-Independent Fluids

The simplest example of this class is the Newtonian fluid, where,

$$\tau = -\mu\left(\frac{du}{dr}\right)$$

The apparent viscosity μ is constant.

The other types of fluids included in this class are usually classified according to the relationship between the shear rate and shear stress only (time is not a factor).

The Bingham plastic-fluids can be described as follows: Fluids which are considered to have an internal structure which collapses

above a yield stress τ_y, and above which the shear rate increases linearly with the shear stress. The defining equation for this fluid behavior may be written as

$$(\tau - \tau_y) = -\mu_p\left(\frac{du}{dr}\right) \qquad \tau \geq \tau_y$$

$$\frac{du}{dr} = 0 \qquad |\tau| < \tau_y$$

μ_p is defined as the plastic viscosity, and τ_y as the yield stress. Although the Bingham fluids could be referred to as the ideal plastic behavior (in a strictly rheological sense), such behavior is not observed in polymer melts or solutions.

The second type of fluids aside from Bingham plastics do not have yield points, but their apparent viscosities are some nonlinear function of shear stress and possibly duration of shear. There are two subgroups included in this second type known as pseudoplastic and dilatant materials. The most common equation used to represent and differentiate between them was given by Ostwald-de-Waele:

$$\tau = -\mu\left(\frac{du}{dr}\right)^{n-1}\left(\frac{du}{dr}\right)$$

If $n = 1$, the equation would represent a Newtonian behavior. For $n > 1.0$, the apparent viscosity would increase with increasing shear rate, which characterizes a dilatant behavior (or "shearthickening"). If $n < 1.0$, the apparent viscosity decreases with increasing shear rate, which introduces the pseudoplastic behavior characteristics of fluids (or "shear thinning").

Many equations and rheological models have been proposed to describe previous behavior of fluids. The reader can refer to Savin's

summary paper for more details on non-Newtonian flow behavior in porous media and the rheological models of interest (45).

Time-Dependent Fluids

These are non-Newtonian fluids, whose apparent viscosity remains constant at a fixed value of shear rate and temperature, but changes with the duration of shear. Two types are known, namely thixotropic and rheopectic fluids. Thixotropic fluids are those in which the shear stress decreases with time under a constant shear rate. Rheopectic fluids, on the other hand, are those in which the shear stress increases with time under a constant shear rate. A thixotropic material is often pseudoplastic, but the reverse is not very common.

Viscoelastic Fluids

The general properties of these materials are intermediate to those of classical solids and liquids. Polymer melts and polymer solutions have been noted to have a viscoelastic behavior as well as the dispersion of one Newtonian fluid in another.

Many attempts have been made to develop equations which would describe viscoelastic behavior. Unfortunately, and because of the complexity involved in such fluid behavior, it is commonly found that the more simple rheological equations of state do not fit experimental observations, particularly those made at high rates of shear. The mathematically derived equations, on the other hand, involve so many constants that they are difficult to evaluate. More details of interest could be found in a rheology reference.

CHAPTER V

EXPERIMENTAL APPARATUS AND PROCEDURE

FLOW THROUGH POROUS MEDIA

Flow Cell

The flow cell is a Hasseler core holder type. It was constructed of stainless steel with an internal diameter of 1.810" and length of the barrel is 9.50". The rubber sleeve diameter used was 1.5". The upstream end plug was held in position by tie rods connecting two end plates. The downstream end plug is adjustable according to the core length through the adjusting screw of the core holder. The inlet port is a 1/4" threaded hole. The outlet ports through the downstream plug are 1/4" threaded holes. One port is for vacuuming the core, and the other is for flowing measurements. Removing air trapped in the space between the rubber boot and the barrel of the Hasseler core holder to help the placement of the core in the Hasseler is conducted through a vacuum outlet in the middle of the barrel. The same outlet could be used for applying enough gas pressure behind the rubber boot to seal off the core inside and prevent leaking around the core.

Sandstone cores used in this research were Berea sands furnished by Cleveland Quarries Company of Ohio. The diameter of these cores were 1.5" and they were of a cylindrical shape. Primary use of these cores is for flow studies. Table V-1 gives a complete summary of the

TABLE V-1

PHYSICAL PROPERTIES OF CORE SAMPLES

Core No.	Length cm	Diameter cm	Bulk Volume cm^3	Porosity %	Absolute Permeability md
1	20.16	3.81	229.84	21.75	336.0
2	20.16	3.81	229.84	24.15	322.0
3	20.16	3.81	229.84	20.97	325.0
4	20.16	3.81	229.84	18.38	274.0
5	20.16	3.81	229.84	21.75	241.0
6	20.16	3.81	229.84	22.19	325.0

TABLE V-2
SUMMARY OF THE SURFACTANTS USED

	Trade Name	Manufacturer	Class and Formula	Use	Type	Remarks
S_1	Polycomplex A-11	Guardian Chemical Corp.				
S_2	Tergitol NP-27	Union Carbide Corp.	Nonylphenyl polyethylene glycol ether	Emulsifier Detergent	Nonionic	Water soluble detergent
S_3	Igepal CO-630	GAF Corp.	Nonylphenoxypoly (ethyleneoxy) ethanol	Detergent	Nonionic	Water soluble surfactant
S_4	Igepal CO-530	"	"	"	"	The hydrophobic-hydrophilic balance of this product lies at the borderline between oil and water solubilities
S_5	Igepal CA-630	"	octylphenoxypoly (ethyleneoxy) ethanol	Detergent	Nonionic	Water soluble surfactant
S_6	Igepal CA-897	"	"	Emulsifier Stabilizer	Nonionic	
S_7	Klearfac AA-420	Wyandotte Chemicals Corp.	Free acid of an organic phosphate ester	Solubilizer Emulsifier Wetting	Anionic	
S_8	Klearfac AA-270	"	"	Emulsifier Solubilizer	Anionic	
S_9	Pluronic L-62	"	A series of condensates of ethylene oxide with hydrophobic bases formed by condensing propylene oxide with propylene glycol	Detergent	Nonionic	Typical molecular weights: L-62: 2000 L-64: 2900
S_{10}	Pluronic L-64	"				

six cores used in the oil displacement test. The porosity values were determined by two methods, and it will be discussed later on with the procedure.

Physical Properties of Surfactants

Ten different surfactants, manufactured by four chemical companies, were used in this research. Table 5-2 describes some of the important characteristics of each.

Physical Properties of Polymers

The polymer used in this research is polyethylene oxide, furnished by Union Carbide. The summary of this water soluble polymer used is given in Table V-3.

TABLE V-3

Polymer Trade Name	Approximate Average Molecular Weight
Polyox WSR-205	600,000
Polyox WSR-301	4,000,000
Polyox Coagulent	> 5,000,000

The preparation of polymer solutions is very critical. Polymers like those used in this research would lose some of their viscosity and elasticity if any high speed blending or mechanical agitation is used. This is because long chained polymer molecules would be disturbed by high shear rates. The solvent used for these polymer solutions is a distilled water with certain concentration of sodium chloride. The polymer granules are initially wetted by the solvent. After complete

dispersion of the granules, the rest of the solvent could be added to achieve the required concentration of the polymer solution. Hand agitation was used to help establish the dispersion of the molecules. The polymer solutions were allowed to set for at least two days and not more than three before use.

Isopropanol was added to the polymer solutions as an auto-oxidation inhibitor. The pH of the polymer solutions was lowered to 4 1/2 to 5 1/2 by acetic acid in certain concentration. A bactericide, usually 0.1% by volume of 40% formaldehyde solution, was used in the polymer solutions.

Pumping Equipment and Pressure Measurement

Schematic diagram of the pumping set-up is shown in figure 5-1. A one-quarter horsepower, 1750 rpm motor, 2 zenith pumps, equipped with a zero-max gear reducer and a Grahamn transmission to maintain a constant rate of flow through the cores. The zenith pump is capable of pumping fluids at a constant rate over a wide range of flow rates and the rate was fixed at 0.05 cc/sec for the flood tests. One of the zenith pumps was used mainly for brine flow, and the second was used for oil which was pumped into the top of the reservoirs of polymer, polymer plus surfactant and brine plus surfactant solutions. The oil was Phillips Petroleum Company product, with viscosity value of 1.51 cps and specific gravity of 0.747 at 25°C. The pressure differential was measured by a mercury manometer connected in the line just before entering the flow cell. The manometer was capable of measuring pressure drops up to 30 psi, and for higher values, a pressure gauge was used.

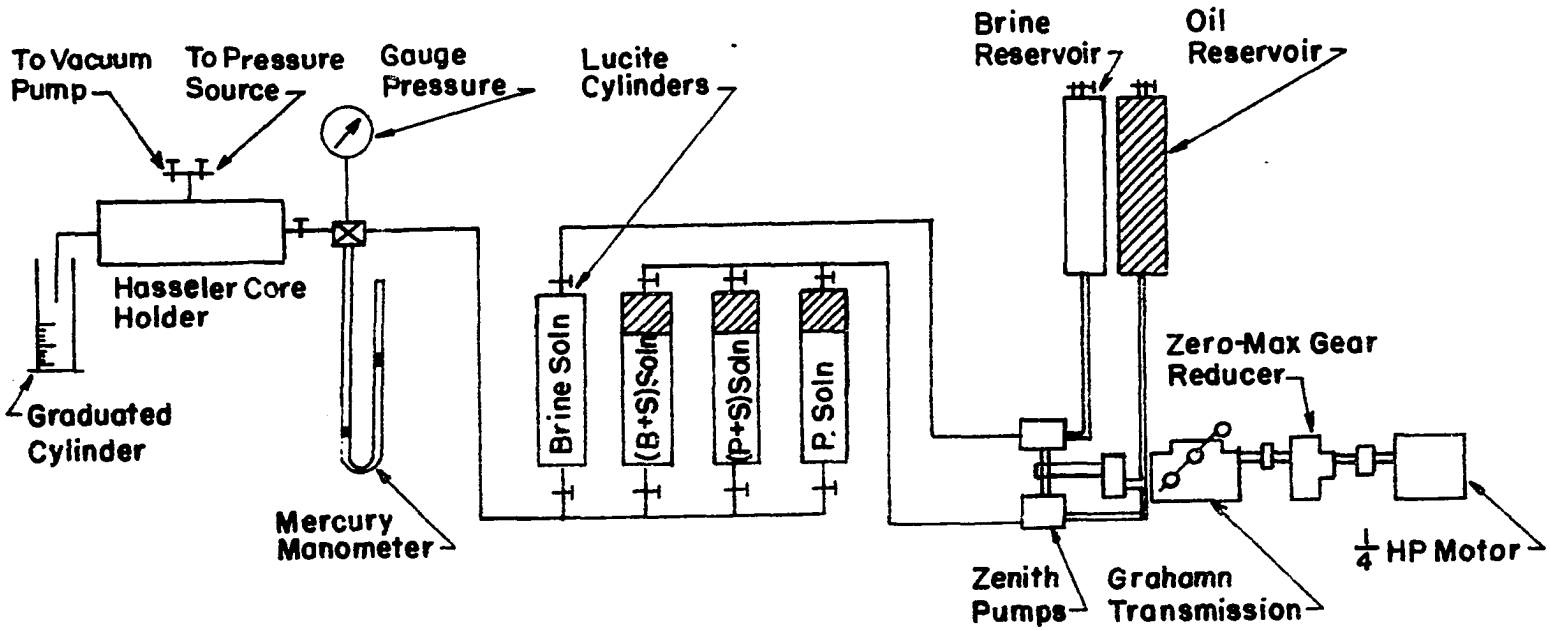


FIGURE 5-1

SCHEMATIC DIAGRAM OF THE EXPERIMENTAL SET-UP FOR DISPLACEMENT TESTS.

All valves were 1/4 inch stainless steel valves as were all the flow lines.

The brine was 1.0 percent concentration of NaCl solution.

Procedure

The Hasseler core holder was first weighed. The vacuum was then connected to remove the air trapped in the space between the rubber boot and the barrel of the Hasseler core holder, thus expanding the boot to a full diameter and helping the placement of the core in the Hasseler. The core was then locked inside by the downstream end plug after being weighed dry. The Hasseler with the core placed inside was again weighed to check the predetermined dry core weight. Pressure was then applied to the space between the barrel of the core holder and the rubber boot (200 psi). The core was then evacuated for at least one hour after which the upstream valve to the core was opened and a one percent NaCl brine allowed to flow through the core. The vacuum pump continued to run until the core was completely saturated and brine came over into the trap on the vacuum line. The vacuum was then disconnected and a constant pumping rate of brine took place. Several readings for the pressure drop, time and amount of brine collected in the graduated cylinder were taken for the absolute permeability calculations (to brine).

The Hasseler core holder was again weighed to determine the core porosity (knowing the density of the brine). Porosity could also be checked by knowing the dry weight of the core, density of sand grains (2.65) and the bulk volume of the core. It has been found that there was no serious deviation between the two calculated porosities.

Oil was then pumped into the flow cell at constant rate, displacing the brine. Samples of the efflux (brine) were periodically taken [cc of brine collected, ΔP and time] until no more brine was recovered. Pumping of oil was continued for the sake of collecting enough data to calculate the effective permeability of the core to oil at residual brine saturation. The amount of brine collected after saturating the core with oil would indicate the value of the residual water saturation as well as the oil saturation of the core. The flow rate was determined by measuring the time required for a measured volume of liquid to be discharged.

The brine and oil saturation steps were repeated every time before each series of displacement runs. A complete run consisted of the following steps.

(1) Saturate the core with 1.0 percent NaCl solution (brine).

(2) Measure the absolute permeability to brine at 100 percent saturation as mentioned previously.

(3) Weight the core (and the core holder) saturated with 100 percent brine.

(4) Pump the oil until no brine comes out of the core (irreducible water saturation).

(5) Measure the effective permeability to oil at irreducible brine saturation.

(6) Flood the core with brine (at constant injection rate) and take efflux readings, pressure drop and time elapsed.

After a waterflood, several pore volumes of naphtha were injected through the core to remove the oil remaining. Then the core was dried with dry air for at least two hours.

A polymer flood, as well as any combination of flooding system in one run, follows the same procedure as a waterflood run with the exception that a polymer solution (and any other different flooding solution) was injected in step no. 6. Several pore volumes of naphtha were then injected through the core as before. The core was dried by air and steps no. 1 through 5 were repeated using brine and then mineral oil.

Either one of the following two combinations of flooding system was used in oil displacement experiments.

Combination No. 1:

1.1 Conventional waterflood

1.2 Polymer waterflood

1.3 Polymer-surfactant waterflood

1.4 Surfactant waterflood

1.5 Conventional waterflood

This system was used in runs no. 1, 2, 3, 4, and 5 (on cores no. 1, 2, 3, 4, and 5).

Combination No. 2:

2.1 Conventional waterflood

2.2 Surfactant waterflood

2.3 Polymer waterflood

2.4 Polymer-surfactant waterflood.

Such combination was used through run no. 6 (core no. 6).

It was decided that, in order to compare oil recovery efficiency for any of the floods to that of a conventional waterflood in the same core, a control water flood (or index) was run.

RHEOLOGY OF FLOODING SOLUTIONS

Cone and Plate Viscometer

The cone and plate viscometer is an eight speed--0.3, 0.6, 1.5, 3.0, 6.0, 12.0, 30.0, and 60 rpm--Wells-Brookfield Micro Viscometer, model LVT, with a model A laboratory stand, a type N constant temperature bath, and an immersion springs assembly. The viscometer has a cone 2.4 cm in radius, with an angle of 1.57 degrees, and a full scale torque of 673.7 dyne-cm.

Viscosity measurements for more than 70 different samples were taken at 25° ± 1/2°C.

The density of the solutions were determined from an analytical balance using a ten gram pycnometer, and all of the solutions had a density very close to the density of brine used (1.00 x).

Cannon-Ubbelohde Capillary Viscometer

Viscosity of all solutions used in displacement tests were measured using Cannon-Ubbelohde Capillary Viscometer at 25°C. Great care was recommended with respect to the calibration constant of the viscometer at 25°C, and the cleanliness of the capillary of the viscometer itself.

Tensiometer

The surface and interfacial tensions of different solutions used in this research were conducted at 25°C ± 1/2°C, using the Cenco-du Nouy Tensiometer number 70545.

CHAPTER VI

DISCUSSION OF RESULTS

VISCOSITY OF SOLUTIONS

Fluid viscosity is defined as its physical property responsible for the frictional drag, or shear resistance of the body which develops when specific load or stress is applied. A total of 69 viscosity measurements for different solutions were carried out during this research by means of a cone-and-plate viscosimeter (39), as well as 12 others using a Cannon-Ubbelohde Capillary viscometer. Some results of the 69 viscosity runs are shown in Figures 6.1 to 6.4, while a summary of all these results is given in Table A-1 through Table A-25, Appendix A. The data appeared to fit the power law model to a great extent, and the power law constants are given in Table VI-1. The flow behavior index "n" in the power law is a quantitative index for comparing the degree of non-Newtonian behavior exhibited by the fluid. For n = 1, it indicates a Newtonian fluid as in the case of 0.036% WSR-301 + 0.005% Pluronic L-64, 0.2% WSR-301 + 0.0005% Tergitol NP-27, and 0.2% WSR-301 + 0.0005% Igpal CA-630. For n less than one, it indicates a pseudoplastic behavior, and 25 samples were found to have such value. The rest of the samples tested were essentially dilatant (n > 1.0). Analysis of Table VI-1 also shows that:

TABLE VI-1

TABULATED DATA OF POWER LAW CONSTANTS

Polymer	Polymer Concentration %	Surfactant	Surfactant Concentration %	k	n
Polyox WSR301	0.036			0.025	0.95
	0.036	Polycomplex A-11	0.05	0.0115	1.029
			0.005	0.01	1.023
			0.0005	0.007	1.099
	0.036	Tergitol NP-27	0.05	0.008	1.056
			0.005	0.0076	1.053
			0.0005	0.0072	1.127
	0.036	IGPAL CO-630	0.05	0.01	1.026
			0.005	0.0087	1.05
			0.0005	0.0058	1.15
	0.036	IGPAL CO-530	0.05	0.005	1.15
			0.005	0.0035	1.23
			0.0005	0.007	1.09
	0.036	IGPAL CA-630	0.05	0.0048	1.16
			0.005	0.0044	1.19
			0.0005	0.0066	1.09
	0.036	IGPAL CA-897	0.05	0.0085	1.05
			0.005	0.007	1.1
			0.0005	0.005	1.19
	0.036	Klearfac AA-420	0.05	0.0056	1.13
			0.005	0.007	1.11
			0.0005	0.0064	1.12
	0.036	Klearfac AA-270	0.05	0.145	0.573
			0.005	0.009	1.04
			0.0005	0.007	1.09
	0.036	Pluronic L-62	0.05	0.008	1.088
			0.005	0.01	1.018
			0.0005	0.0062	1.118
	0.036	Pluronic L-64	0.05	0.009	1.05
			0.005	0.012	1.00
			0.0005	0.008	1.08
	0.2			0.250	0.801

TABLE VI-1 (Continued)

Polymer	Polymer Concentration %	Surfactant	Surfactant Concentration %	k	n
Polyox WSR 301	0.2	Polycomplex A-11	0.05	0.05	1.04
			0.005	0.04	1.034
			0.0005	0.0215	1.131
	0.2	Tergitol NP-27	0.05	0.046	1.053
			0.005	0.038	1.055
			0.0005	0.042	1.00
	0.2	IGPAL CO-630	0.05	0.061	0.98
			0.005	0.058	0.989
			0.0005	0.041	1.03
	0.2	IGPAL CO-530	0.05	0.03	1.06
			0.005	0.036	1.05
			0.0005	0.038	1.04
	0.2	IGPAL CA-630	0.5	0.045	1.035
			0.005	0.04	1.034
			0.0005	0.05	1.00
	0.2	IGPAL CA-897	0.05	0.061	0.977
			0.005	0.055	0.982
			0.0005	0.062	0.98
	0.2	Klearfac AA-420	0.05	0.047	1.03
			0.005	0.041	1.03
			0.0005	0.056	0.988
	0.2	Klearfac AA-270	0.05	0.04	0.875
			0.005	0.051	0.939
			0.0005	0.056	0.981
	0.2	Pluronic L-62	0.05	0.058	0.978
			0.005	0.056	0.975
			0.0005	0.059	0.959
	0.2	Pluronic L-64	0.05	0.055	0.992
			0.005	0.055	0.978
			0.0005	0.060	0.956
	0.05			0.036	0.931
	0.05	Tergitol NP-27	0.05	0.0415	0.901
	0.05	IGPAL CO-630	0.05	0.019	0.921

TABLE VI-1 (Continued)

Polymer	Polymer Concentration %	Surfactant	Surfactant Concentration %	k	n
Polyox WSR205	0.05			0.0205	0.882
	0.05	Polycomplex A-11	0.05	0.028	0.823
Polyox Coagulant	0.05			0.0475	0.777
	0.05	Pluronic L-62	0.05	0.068	0.635

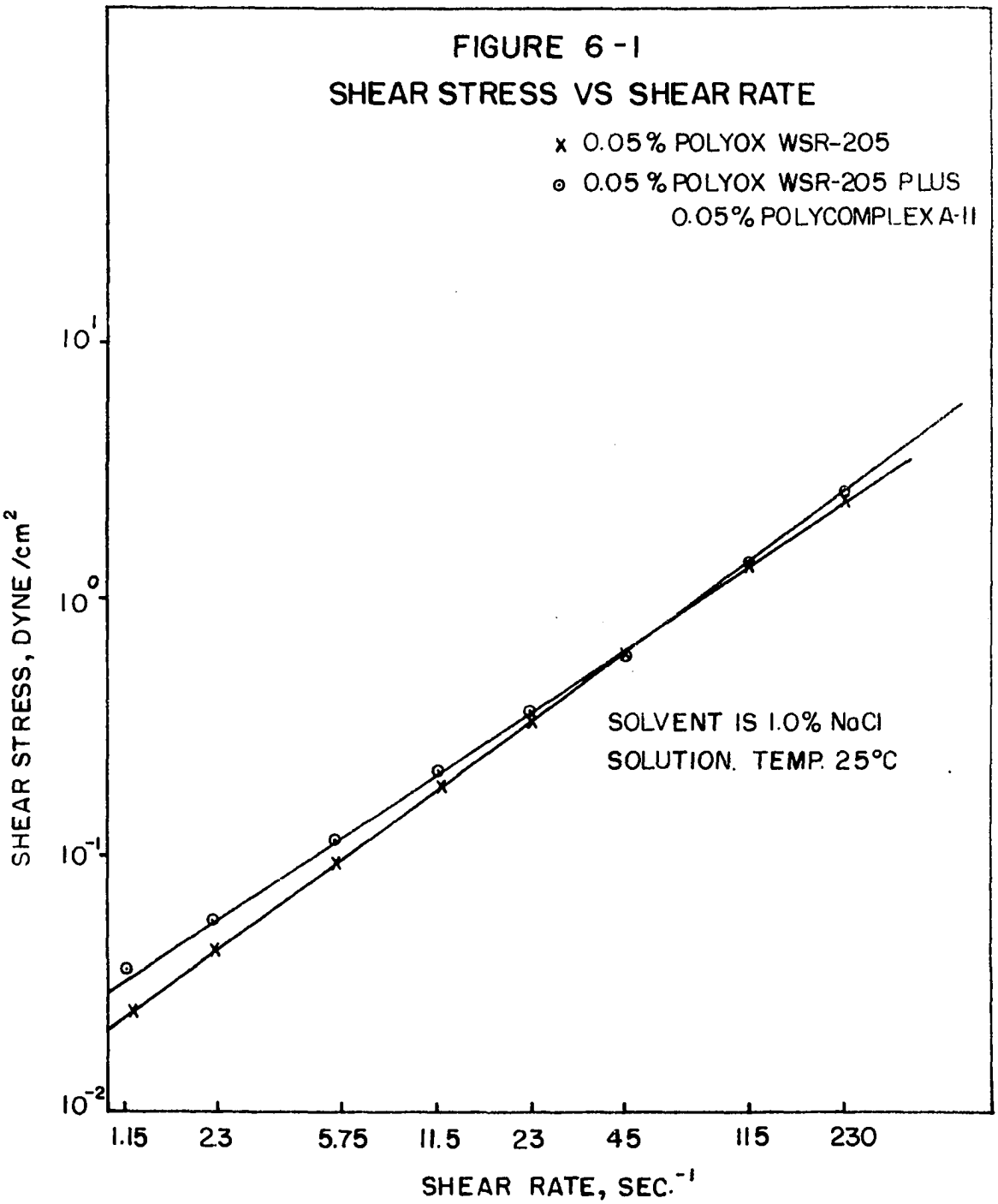


FIGURE 6-1
SHEAR STRESS VS SHEAR RATE
x 0.05% POLYOX WSR-205
⊙ 0.05% POLYOX WSR-205 PLUS
0.05% POLYCOMPLEX A-II
SOLVENT IS 1.0% NaCl
SOLUTION. TEMP. 25°C
SHEAR STRESS, DYNE/cm²
10¹
10⁰
10⁻¹
10⁻²
1.15
2.3
5.75
11.5
23
45
115
230
SHEAR RATE, SEC.⁻¹

FIGURE 6-2

SHEAR STRESS VS SHEAR RATE

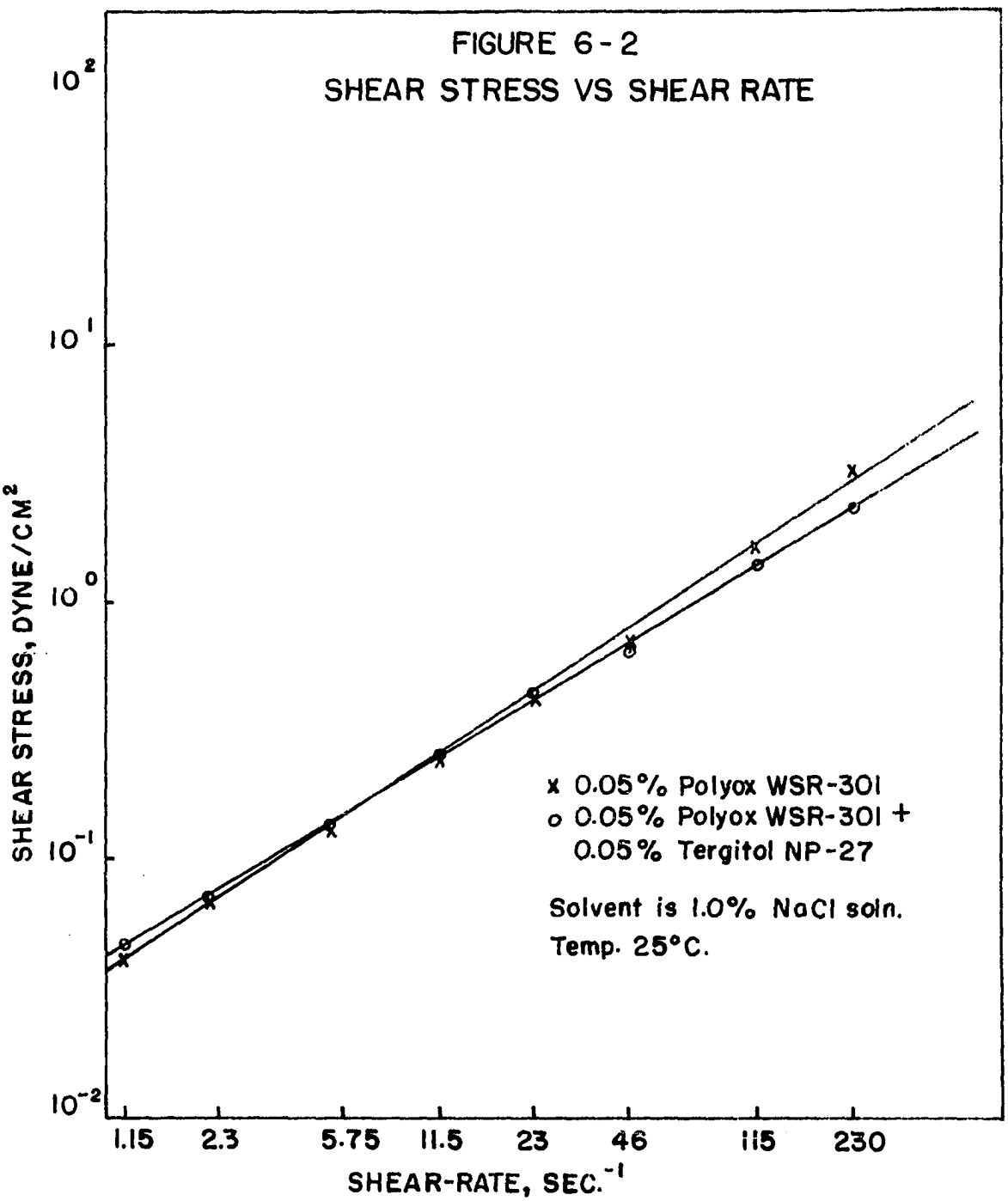


FIGURE 6-3

SHEAR STRESS VS SHEAR RATE

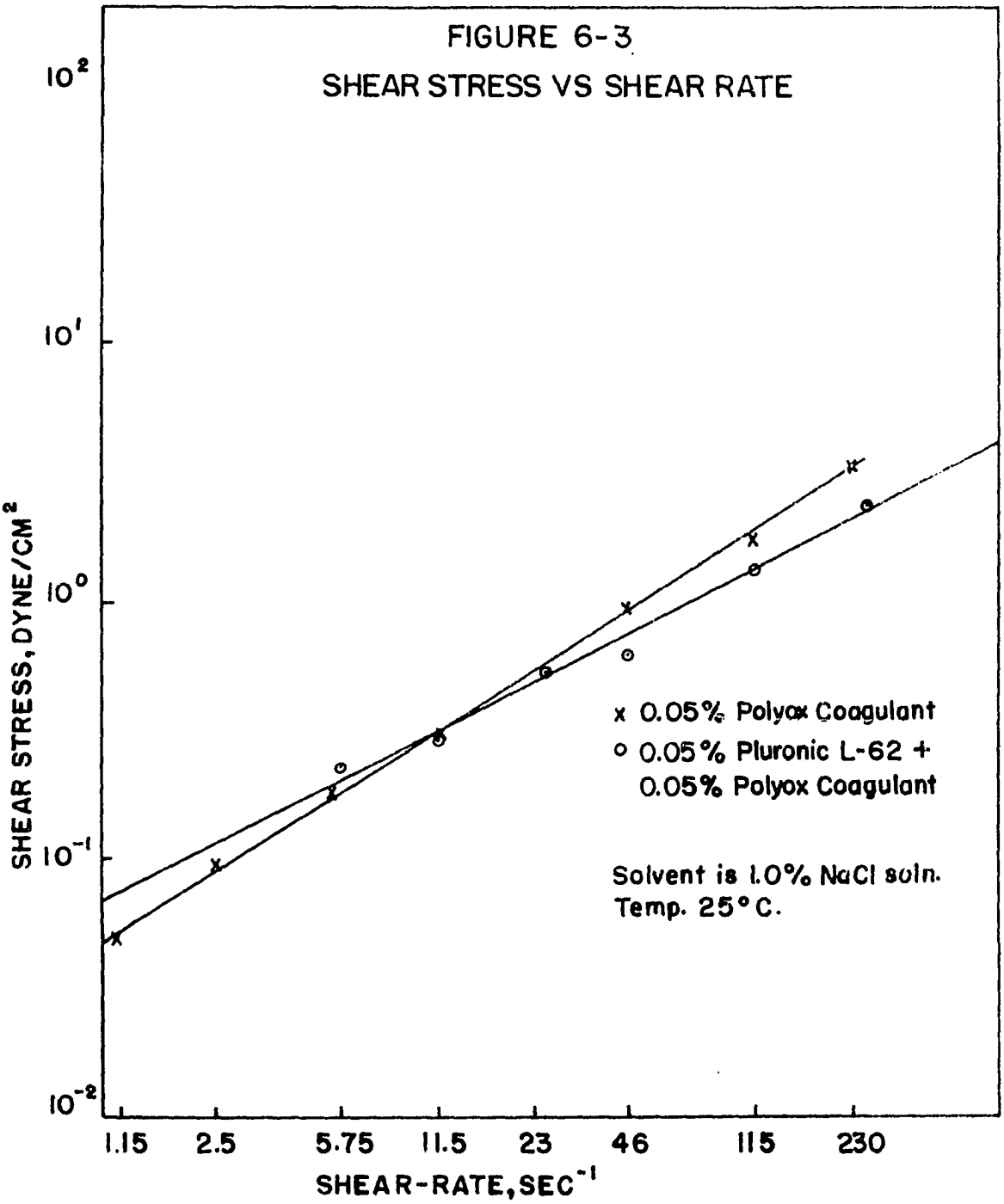
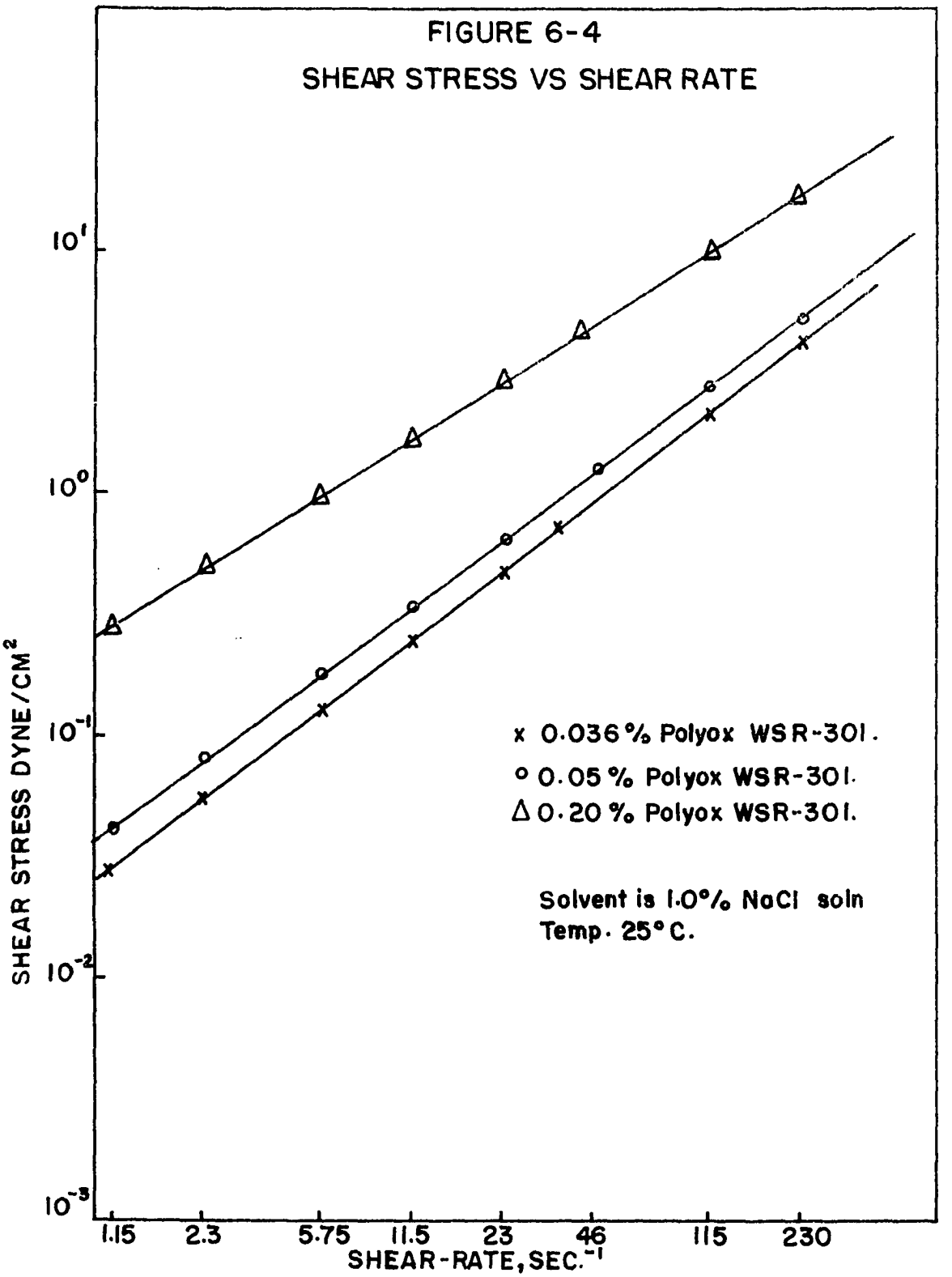


FIGURE 6-4

SHEAR STRESS VS SHEAR RATE



(1) Viscosity of polymer solutions increases with the increase of polymer concentration and polymer molecular weight.

(2) Viscosity of a given concentration of polymer solution is always higher than the viscosity of the polymer surfactant mixtures tested in this research.

(3) For all practical purposes, addition of surfactants, within the range of concentrations tested, to a polymer solution has very little effect on viscosity reduction.

Figures 6-5 through 6-9 show some of the viscosity, shear rate relationship for a number of tested samples. It can be noticed that the viscosity of polymer solutions at high shear rates was always higher than those of polymer-surfactant mixtures. However, at low shear rates, the above criterion does not hold all the time.

Viscosity data obtained by means of Cannon-Ubbelohde Capillary viscometer are tabulated in Table VI-2. Analysis of the results given in Table VI-2 shows also that the more viscous solutions are formed by the higher molecular weight polymers, whereas the viscosity of the surfactant solutions do not differ much from each other.

SURFACE AND INTERFACIAL TENSION MEASUREMENTS

Research workers in the field of secondary recovery of oil by conventional waterflooding agree that the unrecovered oil is retained (or trapped) by the capillary forces in the porous media. These capillary forces are hard to beat with any rate of injection pressure commonly used in a waterflooding process from the practical point of view (31).

FIGURE 6-5

VISCOSITY-SHEAR RATE RELATIONSHIP

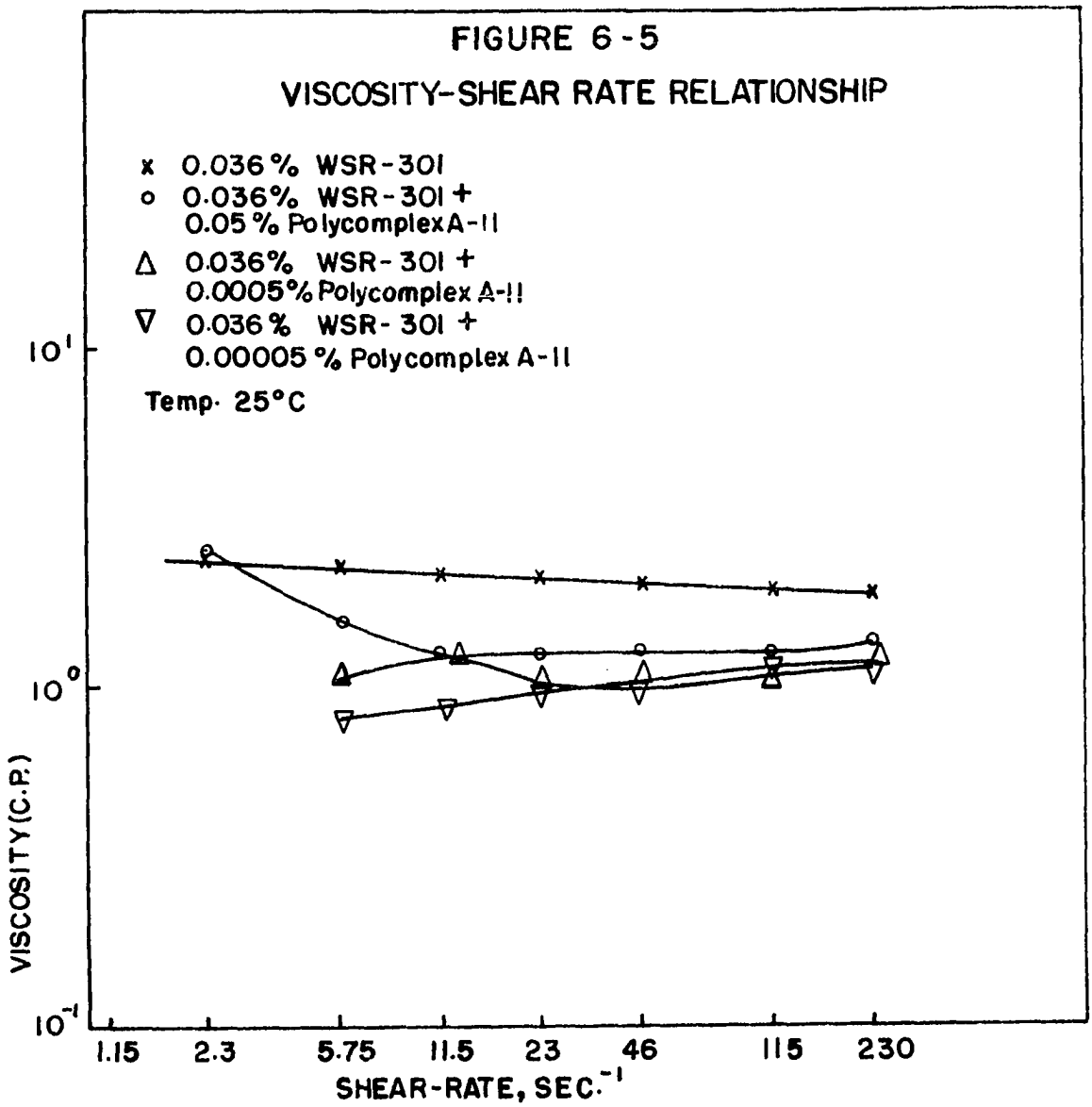


FIGURE 6-6

VISCOSITY - SHEAR RATE RELATIONSHIP

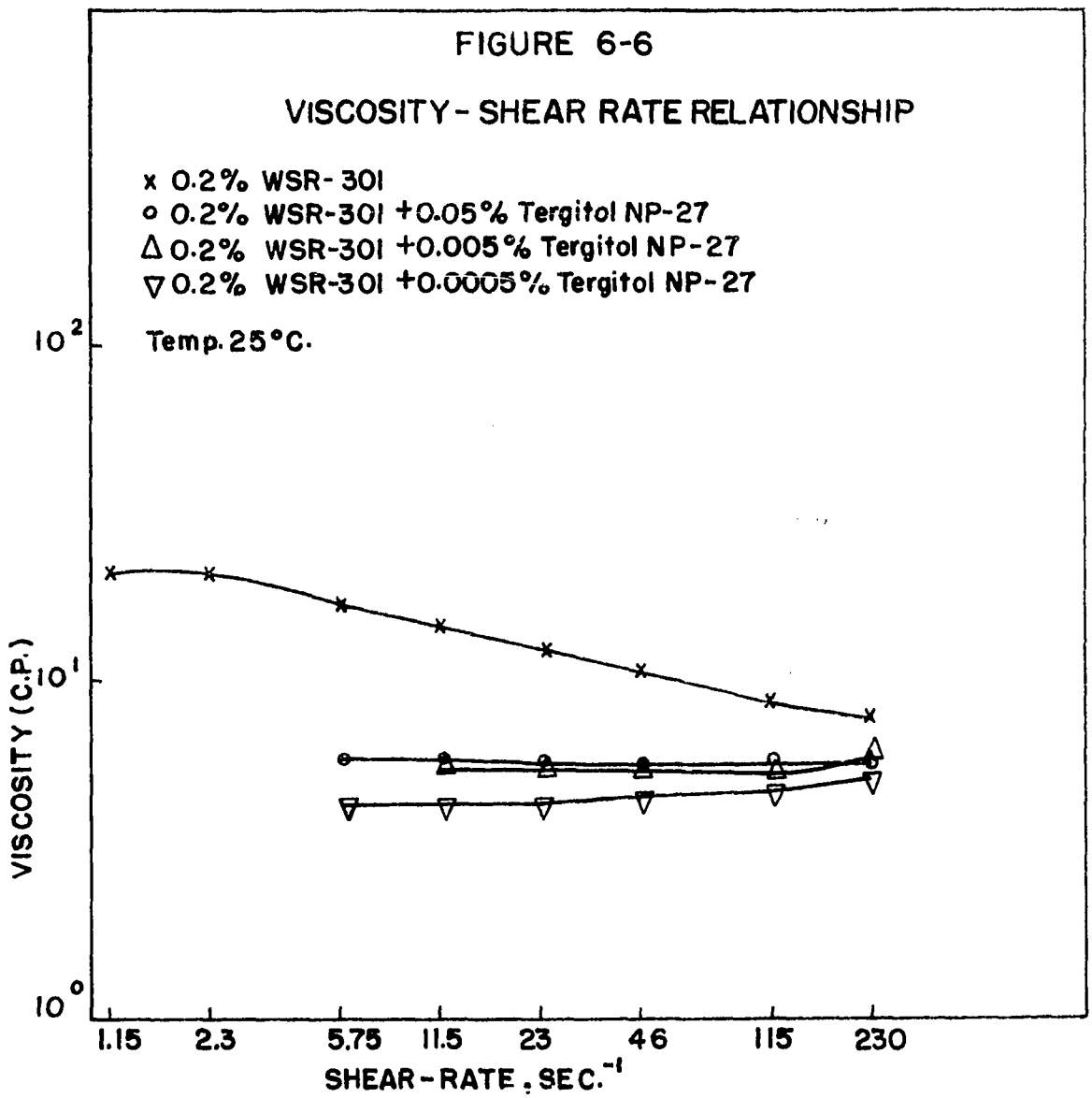


FIGURE 6-7

VISCOSITY-SHEAR RATE RELATIONSHIP

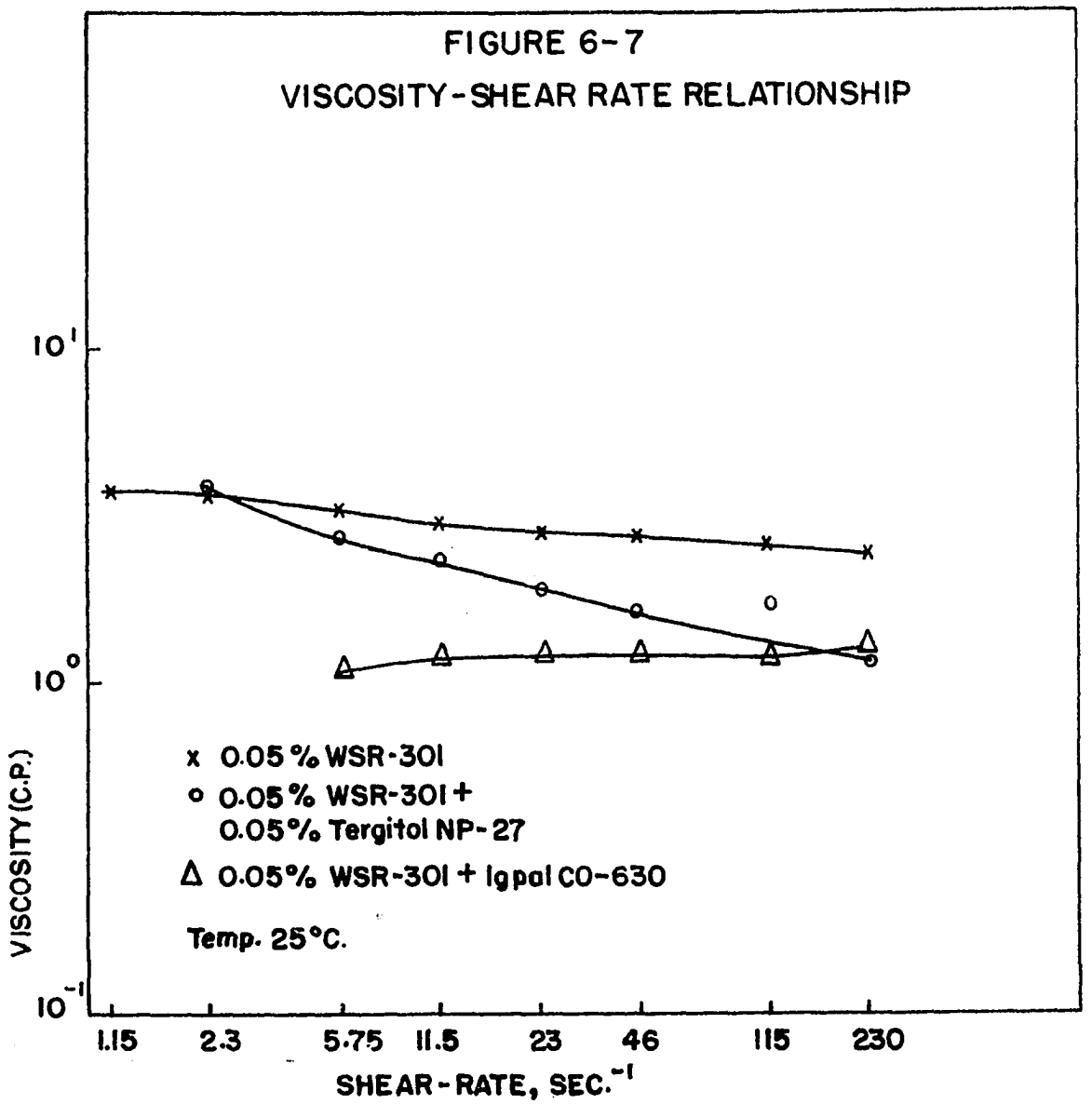


FIGURE 6-8

VISCOSITY-SHEAR RATE RELATIONSHIP

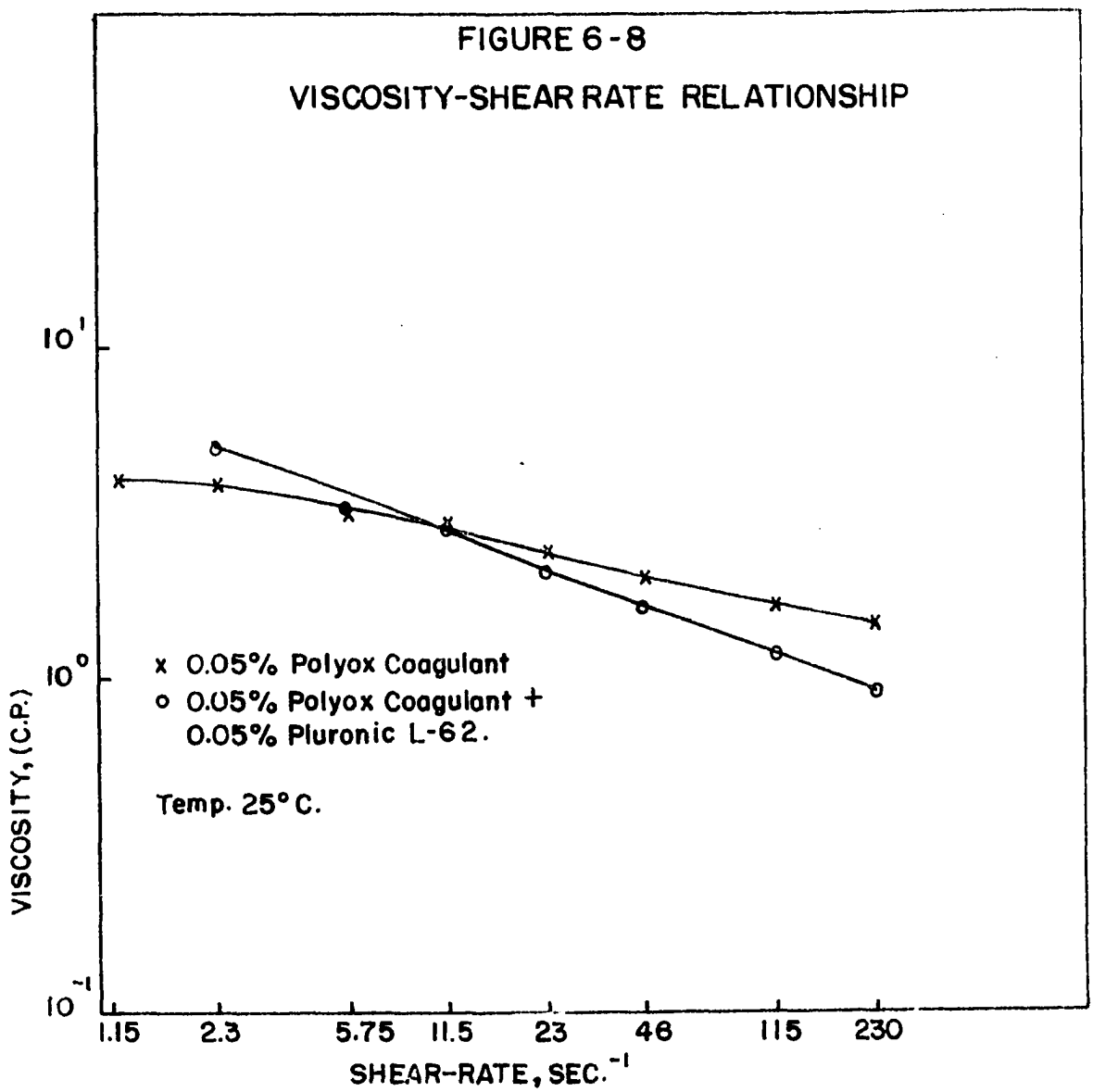


FIGURE 6-9

VISCOSITY-SHEAR RATE RELATIONSHIP

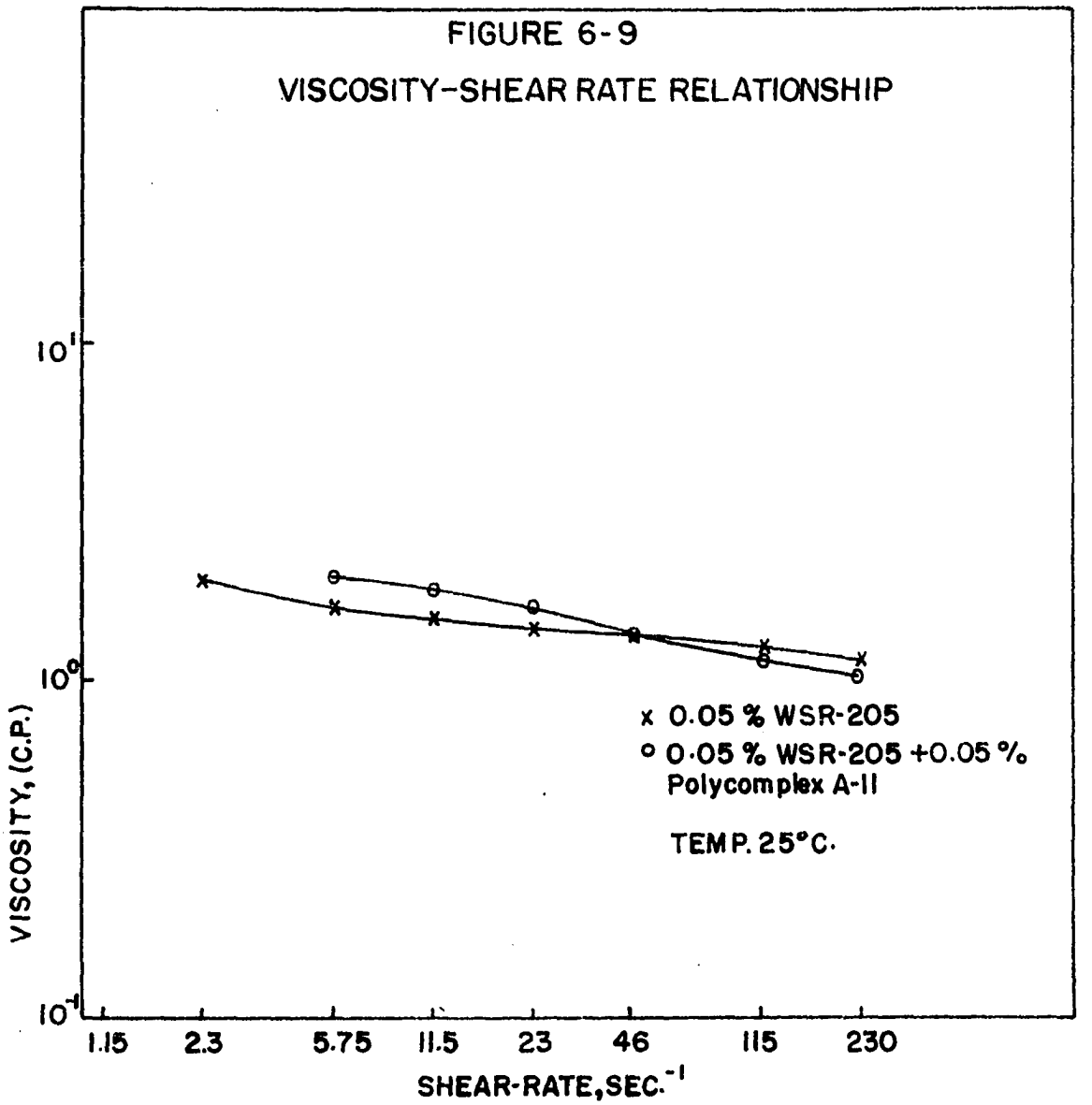


TABLE VI-2

THE CANNON-UBBELOHDE CAPILLARY VISCOMETER RESULTS

Solution Tested	Measured Viscosity (cp)	Density gm/cc at 25°C
0.05% Polyox WSR-205	1.129	1.003
0.05% Polyox WSR-301	1.72	1.0039
0.05% Polyox Coagulant	1.90	1.0032
0.05% Polyox WSR-205 + 0.05% Polycomplex A-11	1.129	1.0033
0.05% Polycomplex A-11 Solution	0.9073	1.0042
0.05% Polyox WSR-301 + 0.05% Polycomplex A-11	1.79	1.0045
0.05% Polyox WSR-301 + 0.05% Tergitol NP-27	1.77	1.0078
0.05% Polyox WSR-301 + 0.05% Igpal CO-630	1.76	1.0036
0.05% Polyox Coagulant + 0.05% Pluronic L-62	1.54	1.0036
0.05% Tergitol NP-27 Solution	0.9072	1.0041
0.05% Igpal CO-630 Solution	0.932	1.0041
0.05% Pluronic L-62 Solution	0.914	1.0041

Temperature at which measurements were taken: 25°C

The capillary forces are known to be the result of many factors. Among these factors, there is surface and interfacial tension of the fluids involved in the system, pore size and pore geometry, besides the wettability properties of the reservoir rock. Since nothing can be done to alter the pore size or the pore geometry and packing systems of grains of any reservoir rock, investigators are inclined to work on how to control surface and interfacial tension of liquid-liquid or liquid-solid systems involved. Surfactants offer such an approach to solve this problem of decreasing the intensity of the capillary forces through a significant reduction in interfacial tension between the displacing and displaced (oil) phases in the recovery process.

The surface and interfacial tension of ten different surfactants (most of them are non-ionic) were studied in this research. Tables VI-3 and VI-4 give a complete summary for 148 surface and interfacial tension measurements obtained by Cenco-Du Nouy (ring method), tensiometer at room temperature. The surfactant concentration varied between 0.05 and 0.0005 percent by volume of polymer solutions. The polymer concentrations tested were 0.036, 0.05, and 0.2 percent by weight for Polyox WSR-301, 0.05 percent by weight for Polyox WSR-205, and 0.05 percent by weight for Polyox Coagulant solution. The solvent was 1.0 percent concentration by weight of NaCl with distilled water.

Based on the data given in Table VI-3, several remarks can be made:

(1) Surface tension property of polymer solutions decreases with the increase of polymer concentration. For Polyox WSR-301 polymer solution, the surface tension decreased from 55.9 dyne/cm to 53.4

TABLE VI-3

SURFACE TENSION MEASUREMENTS

Type of Polymer	Concentration of Polymer %	Polymer Reading Dyne/cm	Concentration of Surfactant %	1	2	3	4	5	6	7	8	9	10
WSR-301	0.0363	55.9	0.05	20.4	23.6	25.9	24.3	24.1	37.3	27.0	30.8	33.9	35.5
			0.005	35.8	25.4	27.5	25.5	29.6	49.1	30.5	44.5	37.5	39.7
			0.0005	53.5	46.4	51.9	49.7	53.7	55.4	52.5	54.5	46.5	50.3
	0.20	53.4	0.05	22.9	24.2	26.0	24.5	24.7	42.2	27.3	31.7	34.9	35.8
			0.005	32.8	24.6	26.1	26.9	32.1	50.0	31.6	44.8	38.2	39.0
			0.0005	53.1	41.0	49.9	49.8	50.2	53.2	52.3	53.3	43.0	53.5
	0.05	55.5	0.05	?	24.3	25.0							
WSR-205	0.05	42.3	0.05	21.4									
Coagulant	0.05	55.3	0.05										30.8

	Surface Tension
0.05 percent S_1 in 1.0 NaCl Solution	21.7
0.05 percent S_2 in 1.0 NaCl Solution	24.1
0.05 percent S_3 in 1.0 NaCl Solution	25.0
0.05 percent S_9 in 1.0 NaCl Solution	

The numbers 1 through 10 refer to the different kinds of surfactants listed in the same order as in Chapter V.

dyne/cm as the polymer concentration increased from 0.036 percent to 0.2 percent by weight. However, such effects do not appear to exert any important influence of the behavior of these solutions in porous media.

(2) The polymer molecular weight has certainly an effect on the polymer solution surface property. It can be noticed that the surface tension of Polyox WSR-205, with an average molecular weight of 600,000, is much less than for Polyox WSR-301, with an average molecular weight of 4×10^6, under the same experimental conditions.

(3) Addition of surfactants to the polymer solutions developed outstanding surface modification properties. For example, an addition of 0.05 percent of polycomplex A-11 to a 0.036 percent polymer solution reduced the surface tension value from 55.9 dyne/cm to 20.4 dyne/cm.

The interfacial tension values for the same solutions are summarized in Table VI-4. The data conveys the fact that using surfactants along with a polymer solution has modified the original interfacial tension properties of the polymer solutions. Several conclusions can be stated here based on the data given in Table VI-4:

(1) The change in interfacial tension properties of polymer solutions is very slightly affected by polymer molecular weight. There is only an increase of 0.4 dyne/cm in the interfacial tension value between the Polyox WSR-205, having an average molecular weight of 600,000, and the Polyox Coagulant, having an average molecular weight of over 5 million.

(2) There seems to be a direct relationship between the interfacial tension value of a given polymer solution and the polymer concentration in the solution itself.

TABLE VI-4

INTERFACIAL TENSION MEASUREMENTS

Type of Polymer	Concentration of Polymer %	Polymer Reading Dyne/cm	Concentration of Surfactant %	1	2	3	4	5	6	7	8	9	10
WSR-301	0.0363	12.4*	0.05	--	--	--	--	--	--	--	--	--	.2
			0.005	10.6	3.1	4.5	4.0	3.2	8.1	--	5.8	3.1	4.5
			0.0005	12.5	10.0	10.2	10.6	9.7	11.3	7.5	11.4	7.9	8.3
	0.20	12.5*	0.05	--	--	--	--	--	1.2	--	--	--	.5
			0.005	10.4	1.2	--	4.4	3.1	8.0	--	4.6	2.6	3.8
			0.0005	12.6	10.0	9.2	10.1	10.5	11.8	8.5	11.6	7.2	9.9
	0.05	13.5**	0.05	--	--	--							
WSR-205	0.05	13.3**	0.05	--									
Coagulant	0.05	13.7**	0.05										--

* oil specific gravity (0.918)
** oil specific gravity (0.747)

	Interfacial Tension
0.05 percent S_1 in 1.0 percent NaCl Solution	--
0.05 percent S_2 in 1.0 percent NaCl Solution	--
0.05 percent S_3 in 1.0 percent NaCl Solution	--
0.05 percent S_9 in 1.0 percent NaCl Solution	--

The numbers 1 through 10 refer to the different kinds of surfactants listed in the same order as in Chapter V.

(3) Interfacial tension of all polymer solutions tested, and for all polymer concentrations, showed a tremendous modification in value (decrease) due to the addition of surfactants. The higher the concentration of the surfactant the lower will be the value of the interfacial tension of the polymer solution.

(4) All polymer solutions investigated showed less than one dyne/cm readings of interfacial tension values when 0.05 percent concentration of any surfactant was added. Three exceptions were recorded where the interfacial tension values produced were as low as 0.2 dyne/cm for 0.036% Polyox WSR-301 + 0.05% Pluronic L-62, and as high as 1.2 dyne/cm for 0.2% Polyox WSR-301 + 0.05% Igpal CA-897.

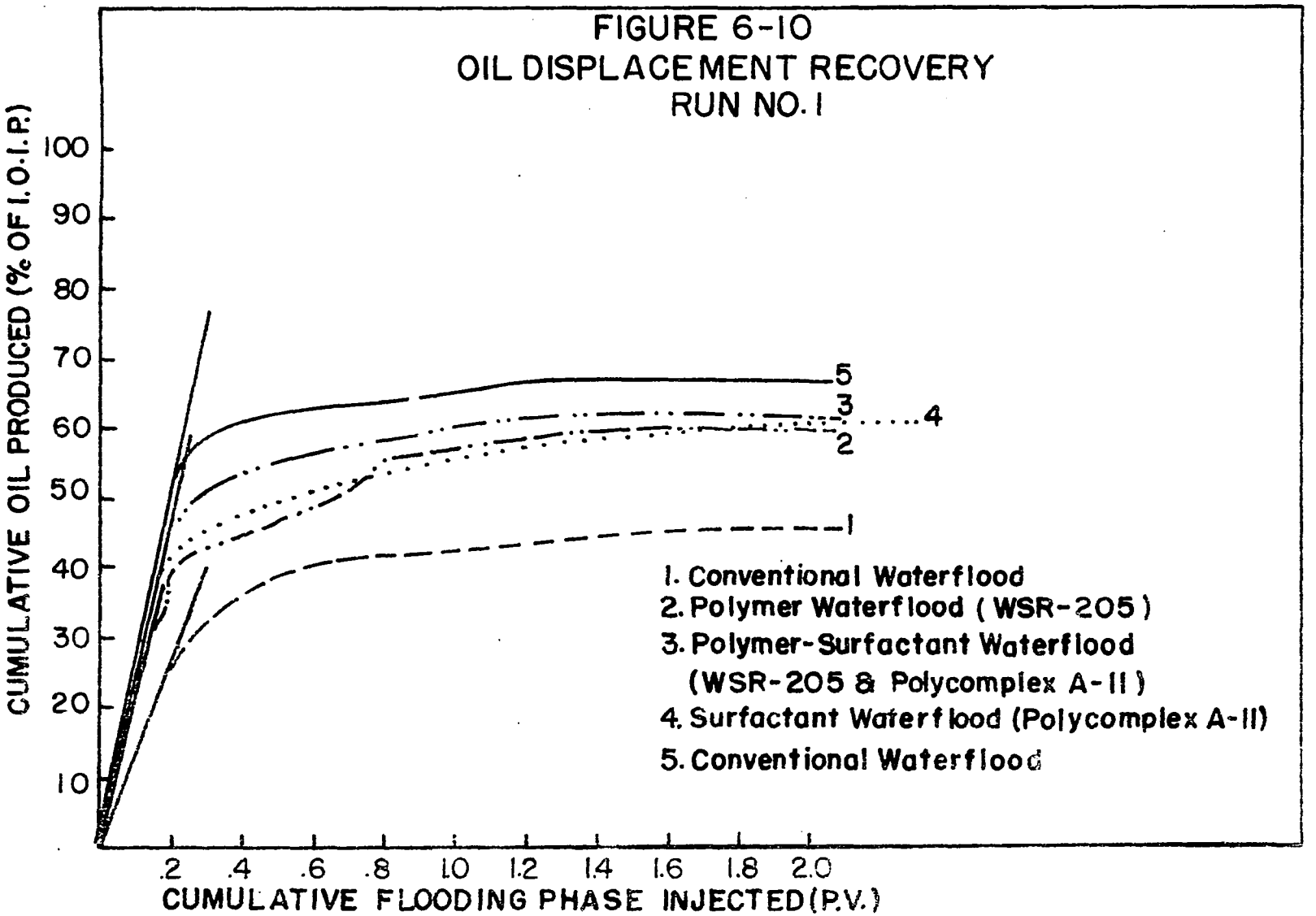
Because of the encouraging results obtained in this surface and interfacial tension test work, the displacement mechanism of oil seems to depend to a great extent on the reduction in the interfacial tension of the oil-"polymer-surfactant" waterflood system (41).

OIL DISPLACEMENT TESTS

Several combinations of different waterflooding systems were investigated in this research in an attempt to compare and select the one system which can offer more oil and best recovery efficiency. Another attempt was also made to study the mechanism of oil displacement using such a variety of flooding systems.

All the experiments were performed with constant rate pumps, and the rate was constant at the value of 0.05 cc/sec. Brine concentration (NaCl) was also constant at 1.0 percent by weight throughout all the recovery experiments. Tabulated results are given in Appendix

FIGURE 6-10
OIL DISPLACEMENT RECOVERY
RUN NO. 1



D. Figure 6-10 shows the results of cumulative oil recovered as a per cent of initial oil in place (% I.O.I.P.) vs cumulative flooding phase injected as a fraction of pore volume, for run no. 1. The five given runs were conducted on the same core, and under the same experimental conditions. The polymer waterflood was composed of 0.05 percent by weight of WSR-205 added to the brine. The polymer-surfactant waterflood was composed of 0.05 percent by weight of WSR-205 in a brine solution plus 0.05 percent by volume of Polycomplex A-11 surfactant. The surfactant waterflood was an emulsion of 0.05 percent by volume of Polycomplex A-11 added to the brine. The conventional waterflood phase is just the 1.0 percent NaCl concentration (by weight) in distilled water. It can be seen from Figure 6-10 that all curves are characterized by three distinct phases. The initial steep slopes of all curves is before breakthrough occurs, where the slope of the first waterflood run was less steep than the other four. The second phase is indicated by the section of the plot with a lower slope after breakthrough has already occurred. It is very noticeable that the mechanism of oil displacement by polymer waterflooding system has different characteristics during this second phase. The third phase is the flat section of the curves where essentially all of the pores hosting the oil had broken through. The difference between these flat levels is an indication as to how much oil was being produced as well as the physical changes which might have occurred to the core sample during these five flooding runs. The physical changes in the core body can be distinguished by comparing the results of the conventional waterflood runs no. 1 and 5. Breakthrough of the first run occurred after 0.2 P.V. of fluid injected

into the core, while breakthrough of the 5'th run took place after 0.22 P.V. of the same fluid has been injected. Cumulative oil recovered as percent of I.O.I.P. is 25.5 for the first run, while it goes up to 55.0 for the fifth run. Figure 6-10 can also show that breakthrough of the polymer-surfactant waterflood (curve no. 3) took place after 45 percent of I.O.I.P. has already been produced which is a higher value than the other flooding systems involved. This indicates that there is more than one mechanism taking place in such a process which not only had given higher recovery at breakthrough but also gave higher percentage of ultimate oil recovery. In the case of polymer flooding technique, the basic concept is to establish a favorable mobility ratio between the reservoir oil and the displacing phase (which is the polymer solution) (3), whereas in surfactant waterflooding technique, the main objective is to reduce the interfacial tension between reservoir oil and water in order to improve the oil recovery efficiency (30). Polymer-surfactant waterflood mechanism to be suggested is a combination of a favorable mobility ratio condition (due to the polymer) and the reduction in the interfacial tension of the oil-"Polymer-surfactant" system due to the surfactants present has resulted in higher recovery of oil.

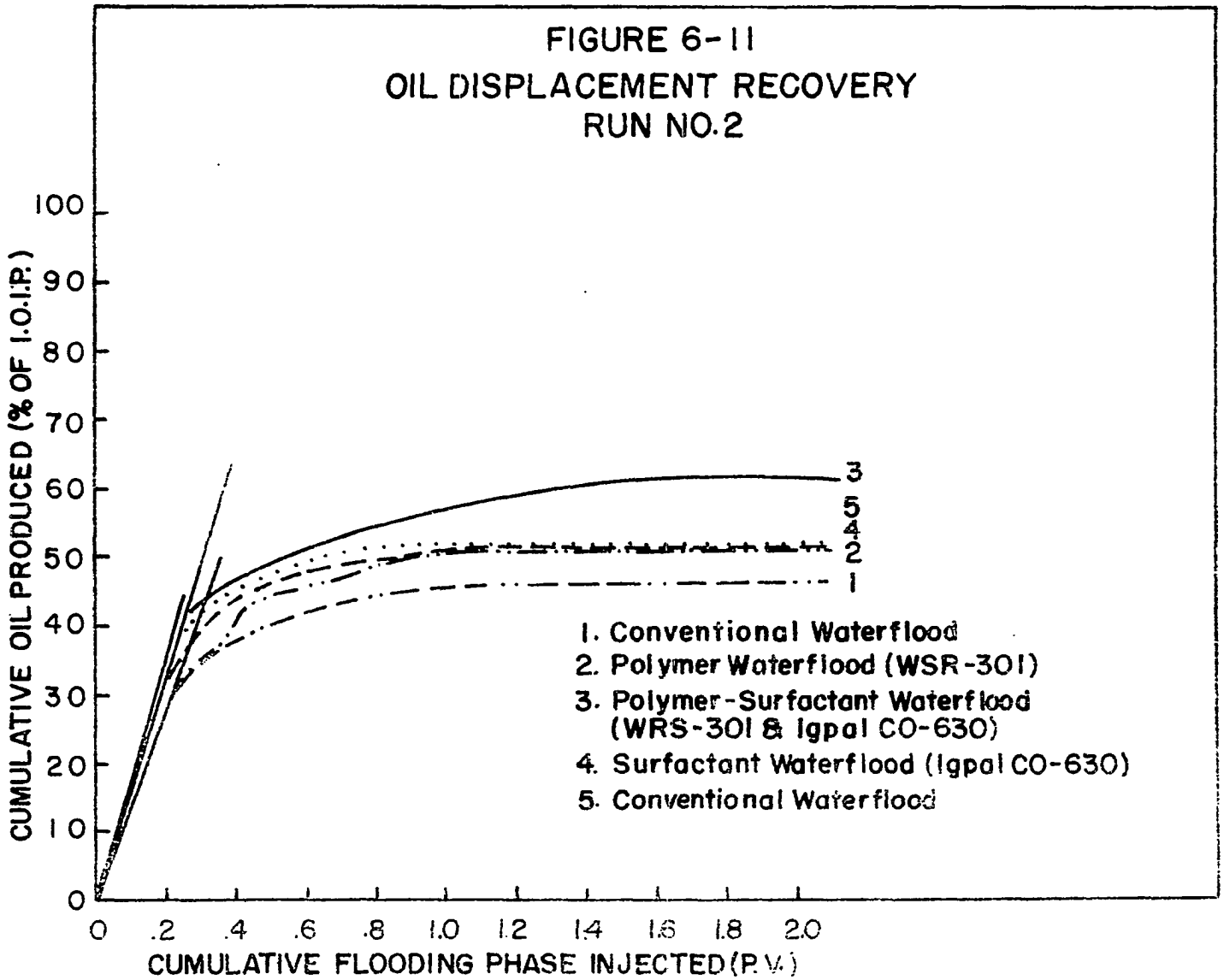
Run no. 2 was performed in the same sequence of flooding systems as in run no. 1, but the characteristics of the solutions were different. Figure 6-11 shows the displacement results obtained from run no. 2 using the following materials:

(1) The conventional waterflood was the same brine composition as in run no. 1 (and all other runs).

FIGURE 6-11

OIL DISPLACEMENT RECOVERY

RUN NO.2



(2) The polymer waterflood was a solution of 0.05 percent by weight of Polyox WSR-301 in brine.

(3) The polymer-surfactant waterflood composition was 0.05 percent by weight of Polyox WSR-301 in brine plus 0.05 percent by volume of Igpal CO-630 surfactant.

(4) The surfactant waterflood composition was 0.05 percent by volume of Igpal CO-630 in brine emulsion.

The three phases previously stated in reference to run no. 1 can also be seen for every flood system involved in run no. 2. The same behavior of the polymer waterflood mechanism during the second phase can be very well noticed. The author does not understand such behavior but appreciates its being in a favorable direction. It may well contribute to an overall hydrodynamic stability of the system. Surfactant waterflood and polymer waterflood gave almost identical results, same P.V. (0.24) injected before breakthrough occurred and same ultimate oil recovery after 2.0 P.V. of the flooding solutions were injected. The only difference in reaching this agreement in results was the time elapsed during each displacement run. For the polymer waterflood run, cumulative recorded time before breakthrough occurred was 1500 sec, and the recorded time at the end of process (after 2.0 P.V. of the solution was injected) was 6755 seconds. However, for the surfactant waterflood run, recorded times were 3000 and 12,654 seconds, respectively. The difference in oil displacement time between these two flood systems is a direct function of their two different mechanisms in porous media.

The polymer-surfactant waterflood curve in figure 6-11 shows also the highest oil recovery value for the same reference of 2.0 P.V.

injected fluid. The breakthrough took place after .26 P.V. was injected at a cumulative injection time of 1800 seconds. This is not very much different cc of P.V. injected from both polymer and surfactant waterflooding runs, but the difference in oil recovery was almost 10 percent more for the combined polymer-surfactant waterflood system. This proves the effectiveness of such combined emulsion in improving the recovery of oil. The final conventional waterflood run (no. 5 in the series) would also indicate that the flow pattern inside the core has been changed, either due to adsorption of surfactants and/or polymer molecules on the pore surfaces, or due to some plugging of a certain number of pores by polymer molecules, or all three effects would have taken place during the course of this experiment.

As a confirmation of previous results and speculations, a third run was conducted using a high molecular weight polymer, and another surfactant. The order of flood phases conducted through the same core at different stages of run no. 3, as previously mentioned in the procedure, Chapter V, were as follows:

(1) Conventional waterflood

(2) Polymer waterflood of 0.05 percent by weight of Polyox Coagulant (M.W. > 5×10^6) in brine

(3) Polymer-surfactant waterflood consisting of 0.05 percent by weight Polyox Coagulant in brine solution and 0.05 percent by volume of Pluronic L-62 surfactant.

(4) Surfactant waterflood composed of an emulsion of 0.05 per cent by volume of Pluronic L-62 in brine.

Oil displacement results of this run number 3 is presented in Figure 6-12. The conventional waterflood performance curve seems to

be in good agreement with previous results given through run 1 and 2, while the other three are rather different. The third phase on the displacement performance curve does not practically exist for the polymer waterflooding, the polymer-surfactant waterflooding, or the surfactant waterflooding. All three curves seem to have increasing values as the flooding process continues. Also, the polymer waterflood did not give as high a recovery value as was expected, considering that a favorable mobility ratio was tested during this research. The polymer-surfactant waterflood did give similar recovery output to those previously given by different surfactants, lower molecular weight polymer waterfloods. The only exception was the oil recovery due to surfactant waterflood, which gave a value of 65.5 percent of initial oil in place. By examining some of the experimental results obtained during this run, a better analysis of such data could be reached. Reduction of core permeability was obvious as it will be discussed later in this chapter, and the reasons related to such reduction is attributed to plugging of the core by the high molecular weight polymer molecules and/or continuous absorption of surfactant and polymer molecules on the pore surface. Although we can only speculate on other reasons, it seems likely that some type of interaction between polymer, surfactant molecules, and the surface contacted by these solutions in the reservoir occurs. Burcik (5) has suggested that in such a case molecules may become attached to the surface on the porous media and that a high velocity of flow is needed to uncoil these bound molecules. These molecules may impede the movement of fluid in the flow channels. Others (10) attributed such reduction in permeability

due to the flow of polymer, polymer and surfactant solutions to an anomalous viscosity effect especially with polyethylene oxide solutions. So, plugging of the core was inevitable, even though some investigators (26, 29) claim that a sorption of non-ionic surfactant molecules and/or polyethylene oxide molecules (as those used in this research) by the porous media is reversible.

Another experimental datum which is worthwhile to mention about this run is the oil saturation time before conducting the series of floods included in run no. 3. In accordance with the numbers shown in Figure 6-12, the different saturation periods were 1.61 hrs before the conventional waterflood, 3.24 hrs before the polymer surfactant waterflood, 22 hours before the polymer surfactant waterflood, and 45 hours before the surfactant waterflood. Such a continuous increase in oil saturation periods is further good evidence of core plugging, but in spite of this physical change in the core flow channels, the surfactant waterflood has resulted in high oil recovery values. In an attempt to combine all previous reasons and factors involved in oil displacement mechanism using different flooding solutions, some alteration has been made in the displacement system during the laboratory work. Three complete runs, 4, 5, and 6, were conducted through cores 4, 5, and 6, respectively. Run no. 5 was just a repeat experiment of no. 4, and the results are shown on Figure 6-13.

The sequence of flood systems conducted during run no. 5 was as follows:

(1) Conventional waterflood

(2) Polymer waterflood [0.05 percent by weight of Polyox WSR-301 in brine solution].

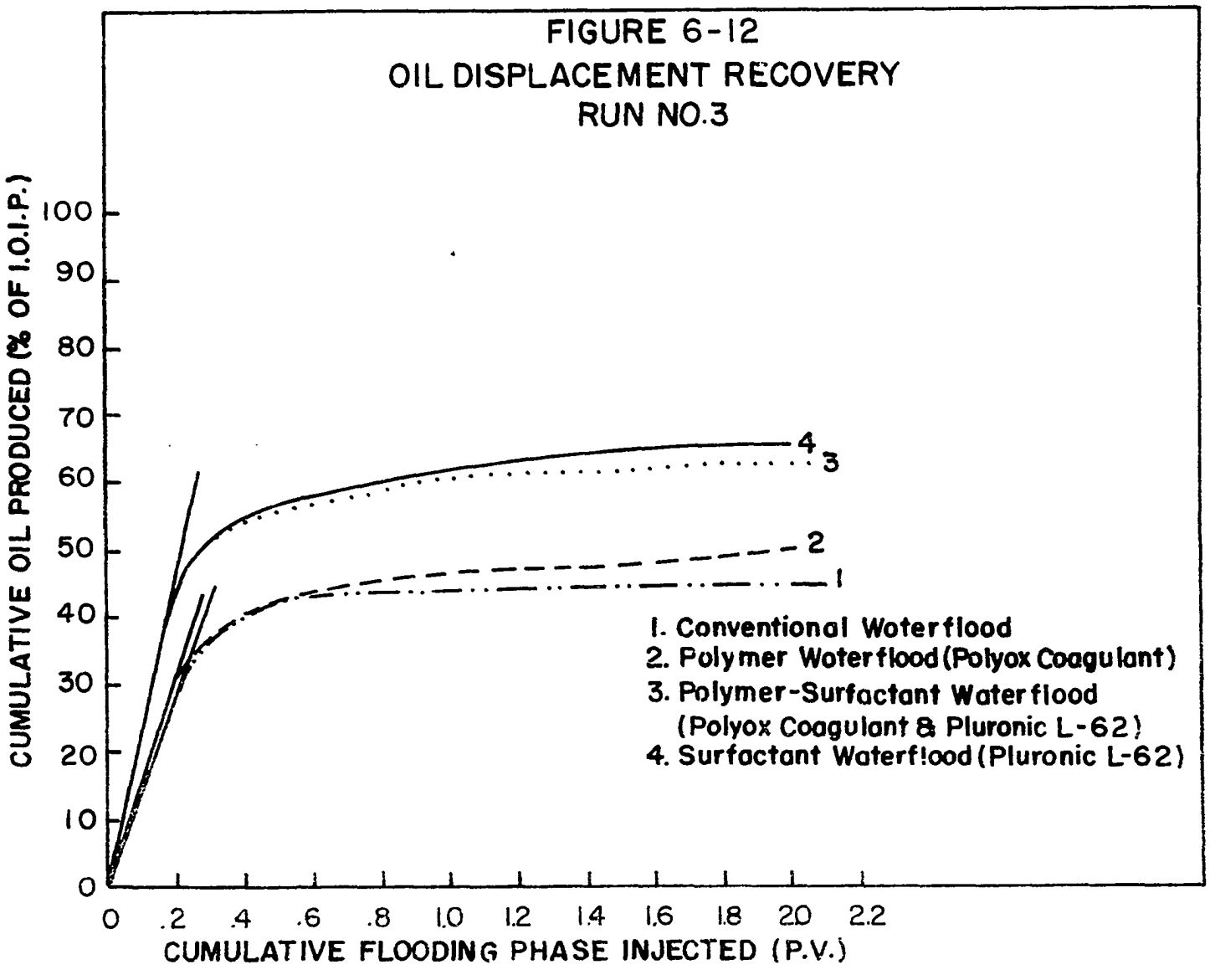


FIGURE 6-12
OIL DISPLACEMENT RECOVERY
RUN NO.3
CUMULATIVE OIL PRODUCED (% OF I.O.I.P.)
100
90
80
70
60
50
40
30
20
10
0
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
CUMULATIVE FLOODING PHASE INJECTED (P.V.)
4
3
2
1
1. Conventional Waterflood
2. Polymer Waterflood (Polyox Coagulant)
3. Polymer-Surfactant Waterflood
(Polyox Coagulant & Pluronic L-62)
4. Surfactant Waterflood (Pluronic L-62)

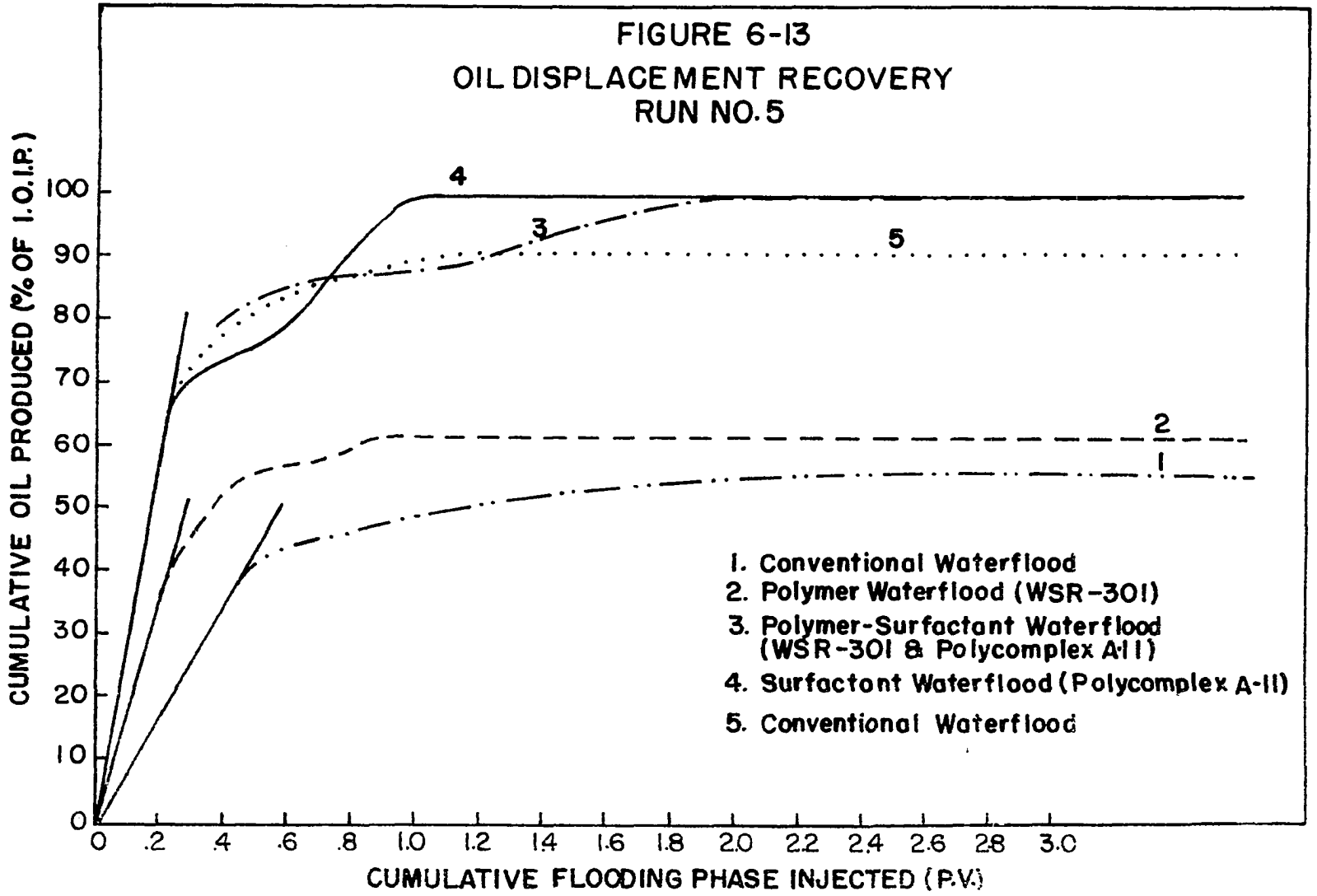


FIGURE 6-13
OIL DISPLACEMENT RECOVERY
RUN NO. 5
CUMULATIVE OIL PRODUCED (% OF I.O.I.P.)
0
10
20
30
40
50
60
70
80
90
100
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
CUMULATIVE FLOODING PHASE INJECTED (P.V.)
1. Conventional Waterflood
2. Polymer Waterflood (WSR-301)
3. Polymer-Surfactant Waterflood (WSR-301 & Polycomplex A-11)
4. Surfactant Waterflood (Polycomplex A-11)
5. Conventional Waterflood

(3) Polymer-surfactant waterflood [0.05 percent by weight of Polyox WSR-301 in brine solution + 0.05 percent by volume of Polycomplex A-11 surfactant].

(4) Surfactant waterflood [0.05 percent by volume of Polycomplex A-11 dissolved in brine solution].

(5) Conventional waterflood

The three phases in all displacement curves are well developed as can be seen in Figure 6-13, and the cumulative oil produced as a percentage of initial oil in place varies greatly from one flood system to another. The polymer-surfactant and surfactant waterflood systems produced 100 percent of the initial oil in place, whereas the waterflood system (no. 5 in Figure 6-13) had given 90 percent of the initial oil in place. Such great improvement in the recovery efficiency must be related to some improvement in the displacement mechanism of the reservoir oil. By checking the absolute permeability values to brine for the different stages of this run, it was found that it varied from 241.0 md for the first conventional waterflood system to 1.0 md for the fifth or last stage (same conventional waterflood system). Depending on such great change in the physical properties of the porous media, the cores can be considered practically plugged. Since there were very macroscopic particles suspended in the displacing aqueous solutions, this plugging result is attributed to either one, two, or all of the three following reasons:

(1) Physical plugging of flowing channels inside the core which have a diameter $\leq$ the diameter of the polymer molecules and the suspended particles. [Concentration of suspended particles were higher at the inlet end of the flow cell than the outlet end.]

(2) Chemical interaction between the surface of the porous media and the non-ionic surfactant molecules.

(3) Adsorption of polymer molecules by contacted surface of the porous media.

Then plugging of the core has resulted in a higher recovery efficiency of oil displacement. Meanwhile, we know from this research as well as from previous investigations (31, 42) that favorable mobility ratio, and very low interfacial tension condition, are very effective parameters in improving the oil recovery mechanism. As a result, plugging of cores in a very specific way did not help decreasing oil recovery in a polymer-surfactant waterflood system. On the contrary, such plugging had improved the mechanism and effectiveness of the other working factors in the system, favorable mobility ratio property due to the addition of the polymer and low interfacial tension condition due to the surfactants.

In discussing the results of run no. 6, shown in Figure 6-14, the same interpretation would be given even though the sequence of flood systems was different.

Flood Efficiency Results

Table VI-5 summarizes the results and the relationship between the flood efficiency of every flood system for all displacement runs. The flood efficiency was calculated as follows:

$$\text{Flood Efficiency} = \frac{\text{Original Oil Saturation} - \text{Final Oil Saturation}}{\text{Original Oil Saturation}} * 100.0$$

Figure 6-15 and 6-16 are schematic diagrams of the calculated results.

FIGURE 6-14

OIL DISPLACEMENT RECOVERY
RUN NO. 6

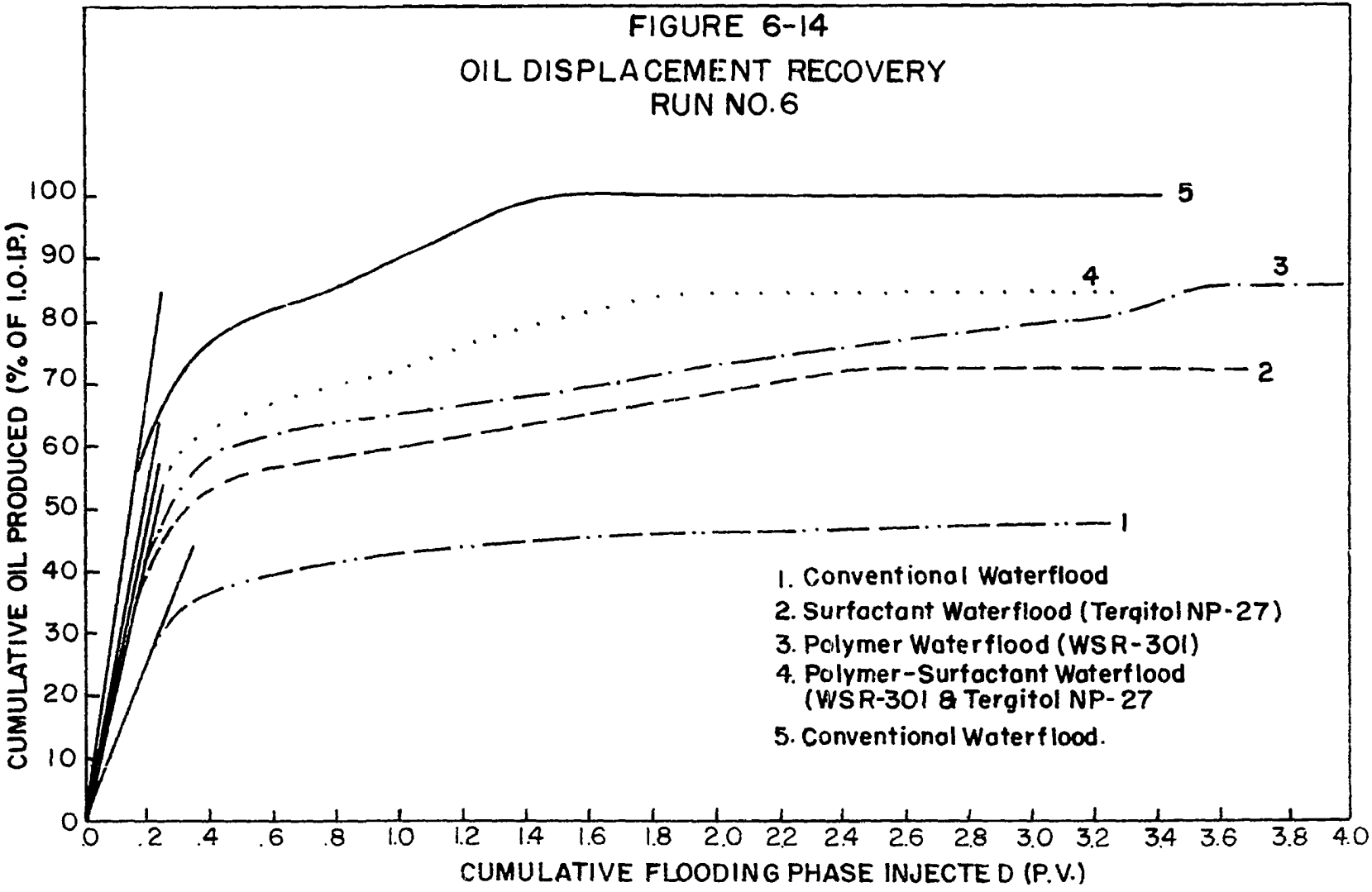


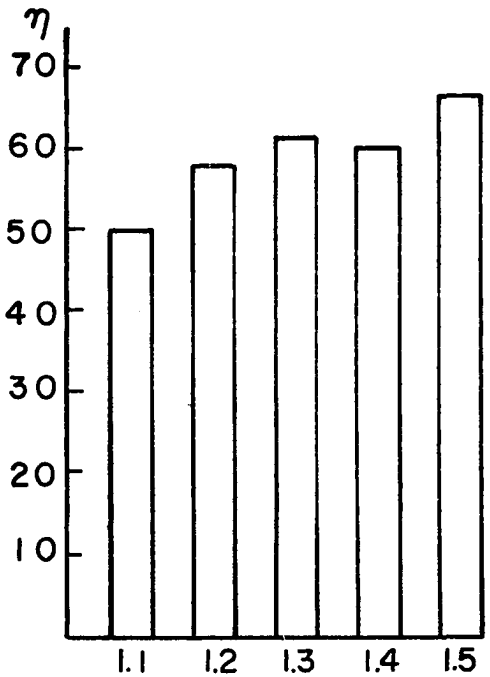
TABLE VI-5

FLOOD EFFICIENCY DATA

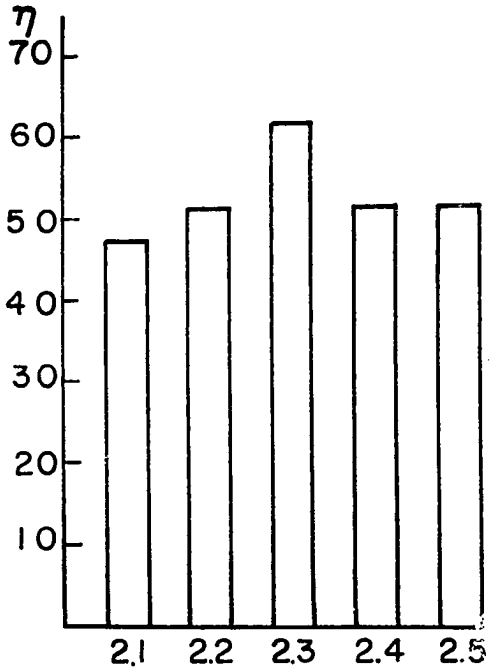
Run No.	Flood System	Flood Efficiency %	Approximate Breakthrough Time (sec)
1.1	Conventional W.F.*	49.90	2000
1.2	Polymer W.F.	58.00	1000
1.3	Polymer-Surfactant W.F.	61.37	1500
1.4	Surfactant W.F.	60.47	1800
1.5	Conventional W.F.	66.25	7000
2.1	Conventional W.F.	47.15	3000
2.2	Polymer W.F.	51.32	1200
2.3	Polymer-Surfactant W.F.	61.43	1700
2.4	Surfactant W.F.	51.47	3000
2.5	Conventional W.F.	51.60	8200
3.1	Conventional W.F.	45.10	2550
3.2	Polymer W.F.	50.30	3000
3.3	Polymer-Surfactant W.F.	62.80	3600
3.4	Surfactant W.F.	65.28	6000
4.1	Conventional W.F.	44.83	3370
4.2	Polymer W.F.	50.00	1671
4.3	Polymer-Surfactant W.F.	67.5	1400
4.4	Surfactant W.F.	61.9	8028
5.1	Conventional W.F.	55.88	2500
5.2	Polymer W.F.	61.4	1800
5.3	Polymer-Surfactant W.F.	100	1790
5.4	Surfactant W.F.	100	1900
5.5	Conventional W.F.	91	--
6.1	Conventional W.F.	51.3	1500
6.2	Surfactant W.F.	72.34	1248
6.3	Polymer W.F.	85.71	1150
6.4	Polymer-Surfactant W.F.	84.62	7200
6.5	Conventional W.F.	100.0	10860

W.F. = Waterflood

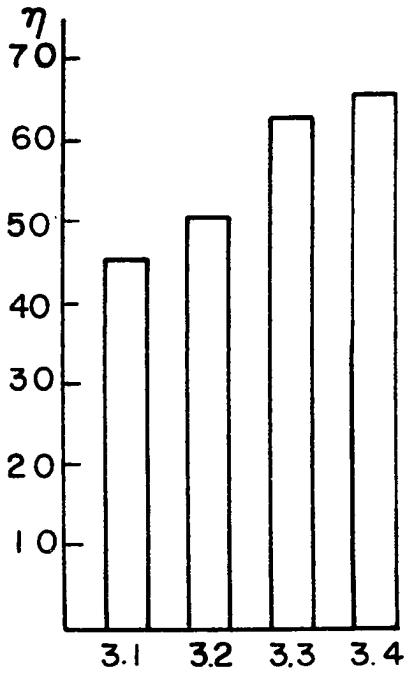
FIGURE 6-15
FLOOD EFFICIENCY RESULTS



RUN NO.1



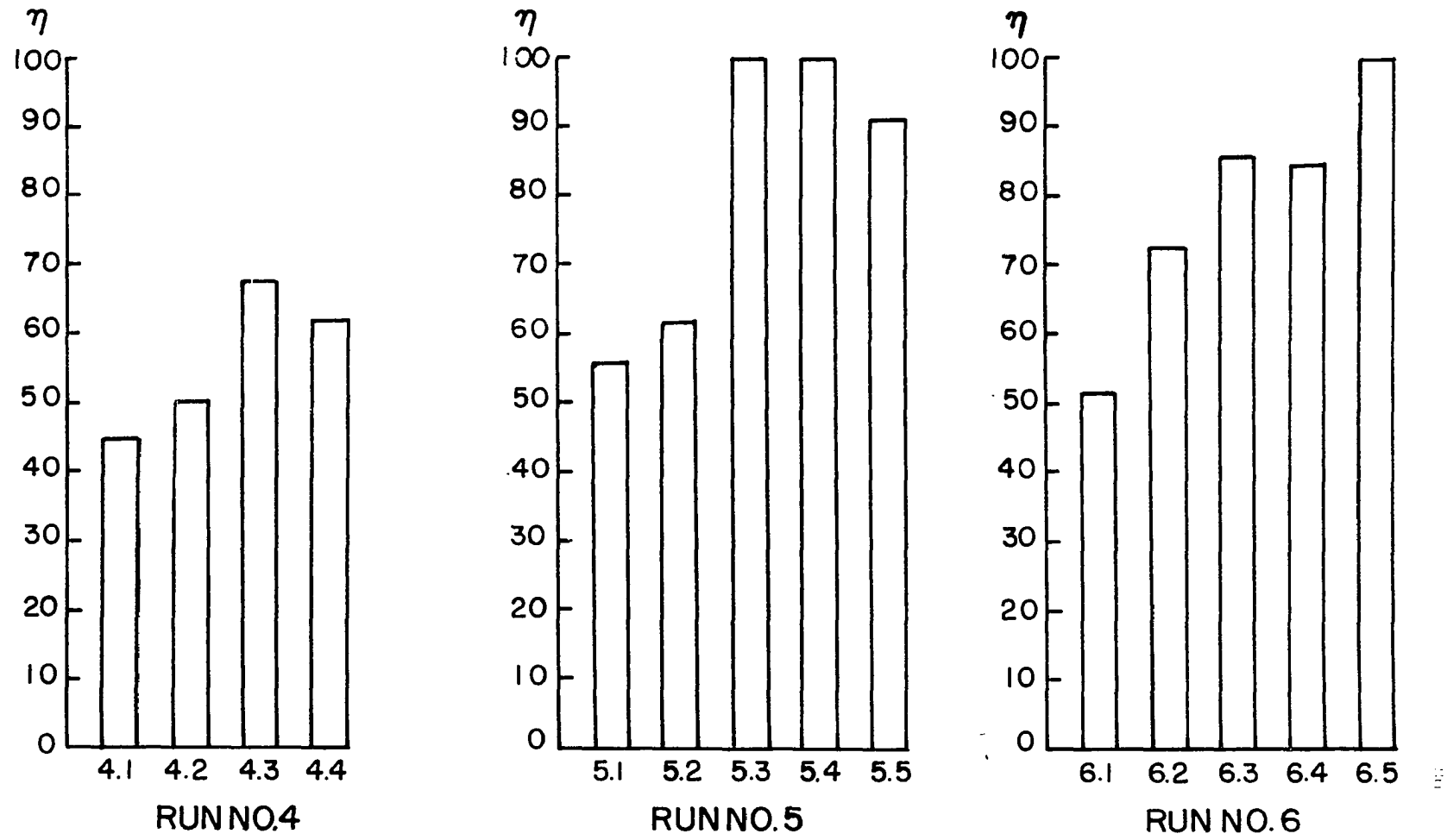
RUN NO. 2



RUN NO. 3

FIGURE 6-16

FLOOD EFFICIENCY RESULTS



Conductivity of the Porous Media

The permeability of a porous medium is always a determining factor in the study of fluid flow behavior through reservoir rock. It is a measure of the ability of a porous medium to transmit fluids. Absolute, effective, and relative permeability concepts were developed to describe the flow behavior of different fluid systems.

Table VI-6 shows the absolute permeability measurements to brine for 5 core samples used in different oil recovery flood systems. It can be noted from this table that the reduction in the absolute permeability value at the end of run no. 5 and 6 has almost reached 100 percent whereas it is lower in runs 1, 2 and 3. This conclusion is also related to the kind of changes introduced to the displacement procedure in order to understand more clearly the mechanism. It has been mentioned earlier that suspended particles were allowed to migrate with the aqueous flowing solutions of runs 4, 5 and 6 and the concentration of these particles was higher at the inlet end of the flowing cell than at the outlet end. So that one hundred percent reduction in core permeabilities was a direct response, on one hand, to the accumulation of these particles inside the pores and, on the other, to a partial adsorption of polymer and surfactant molecules on the surface of the rock.

It can also be noticed from Table VI-6 that during all of the runs, there is a sudden drop in the absolute permeability value of the core sample after the conventional waterflood was conducted. Although the reason is not known and since it happened in all cases, relative comparison between the results obtained would be valid. Several remarks could also be obtained from the same table:

TABLE VI-6

ABSOLUTE PERMEABILITY VALUES OF POROUS MEDIA

Run No.	Flood System	Absolute Permeability to brine (before) md	Absolute Permeability Reductions (%) wrt the original value
1	Conventional Waterflood	336.25	
	Polymer waterflood (0.05% WSR 205)	125.47	62.68
	Polymer-Surfactant Waterflood (0.05% WSR 205 + 0.05% Polycomplex A-11)	36.79	89.10
	Surfactant Waterflood (0.05% Polycomplex A-11)	35.56	89.4
	Conventional Waterflood	26.67	92.0
2	Conventional Waterflood	322.55	
	Polymer Waterflood (0.05% WSR 301)	165.24	48.67
	Polymer-Surfactant Waterflood (0.05% WSR 301 + 0.05% Igpal CO-630)	79.34	75.40
	Surfactant Waterflood (0.05% Igpal CO-630)	56.58	82.46
	Conventional Waterflood	37.74	88.30
3	Conventional Waterflood	325.25	
	Polymer Waterflood (0.05% coagulant)	124.85	61.61
	Polymer-Surfactant Waterflood (0.05% Coagulant + 0.05% Pluronic L-62)	68.04	79.10
	Surfactant Waterflood (0.05% Pluronic L-62)	28.69	91.18
5	Conventional Waterflood + solid particles	241.0	
	Polymer Waterflood (0.05% WSR-301)	69.0	71.37
	Polymer-Surfactant Waterflood (0.05% WSR-301 + 0.05% Polycomplex A-11)	5.3	97.80
	Surfactant Waterflood (0.05% Polycomplex A-11)	1.98	99.18
	Conventional Waterflood	2.00	99.18
6	Conventional Waterflood + solid particles	325.4	
	Surfactant Waterflood (0.05% Tergitol NP-27)	52.0	84.02
	Polymer Waterflood (0.05% WSR 301)	6.0	98.16
	Polymer-Surfactant Waterflood (0.05% WSR 301 + 0.05% Tergitol NP-27)	3.0	99.08
	Conventional Waterflood	1.8	99.45

(1) In runs no. 1 and 2, the relative reduction in the absolute permeability of the core sample after the polymer-surfactant waterflood system was conducted is lower than that occurred after either the polymer or the surfactant waterflood. This might indicate that adsorption of polymer and surfactant molecules in the aqueous solution occurs more readily if they do not exist together in the same emulsion. It would also indicate that the displacement mechanism is more efficient when both the favorable mobility ratio aspect and the establishment of low values of interfacial tension at the displacement front exist together during the flooding process.

(2) High molecular weight polymer solutions (Polyox Coagulant of run 3.2) develop plugging to the permeability the porous media.

(3) A combination of a low molecular weight polymer (Polyox WSR-205 having M.W. ≈ 600,000) and surfactant (non-ionic, Polycomplex A-11) waterflood system would give high oil recovery (62.0% of initial oil in place, and less plugging effect (3% reduction of the reservoir permeability).

Relative permeability ratio, cumulative oil produced, pressure drop between injection and producing well, and the water-oil ratio or mobility ratio are among other parameters which would define the displacement mechanism in any flow system. Efflux measurements were taken during this experimental work and graphs were plotted. These graphs are presented in Figures 6-17 through 6-23. The cumulative oil and flooding solution was plotted versus time, and smoothed curves were drawn. Slopes were taken at various positions from these curves to determine the instantaneous flood fluid-oil ratios. Flood fluid-

oil ratio will be abreviated as (FF-O) ratio for simplicity during the discussion. Tabulated efflux measurements of all flood systems conducted are presented in Appendices B, C, and D, and the results of some of these runs will be discussed in the following paragraphs.

Description of all flood systems included in every run was given earlier in this chapter.

A comparison of the relative permeability ratio of the flowing fluids in run no. 2 is presented in figure 6-17. These graphs indicate that the relative permeability ratio of the first conventional waterflood was more favorable than that of the other flood systems. That is, at a given relative permeability ratio, the saturation of oil for the first conventional waterflood system is the highest. Also, continuous shifting of curves toward the right is another indication that the core is undergoing a continuous plugging.

"Flood-fluid"-oil ratio (F.F.) or mobility ratio versus cumulative oil produced is presented in Figure 6-18. The plot shows that the polymer-surfactant waterflood system recovered more oil at breakthrough and after breakthrough than any other flood system in this run. The oil recovery of the surfactant waterflood system at breakthrough was the poorest.

Figure 6-19 of run no. 3 can also indicate that the polymer-surfactant waterflood system oil recovery was the highest at breakthrough and after breakthrough.

The pressure drop versus cumulative oil produced is presented in Figure 6-20 for run no. 2, in Figure 6-21 for run no. 3, and in Figure 6-22 for run no. 1. In three sets of curves in the three figures, common remarks can be made:

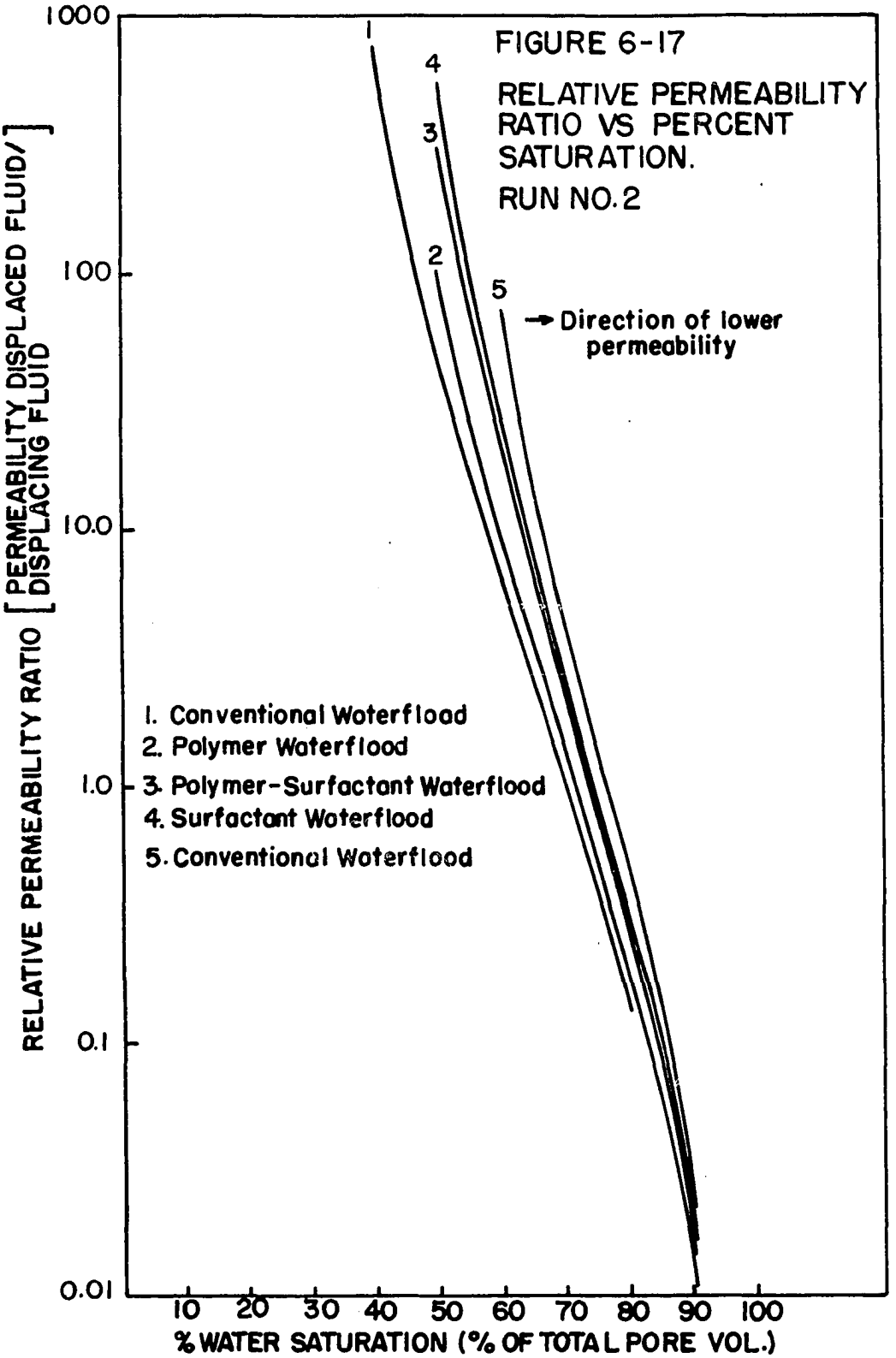


FIGURE 6-17
RELATIVE PERMEABILITY RATIO VS PERCENT SATURATION.
RUN NO. 2
1000
100
10.0
1.0
0.1
0.01
RELATIVE PERMEABILITY RATIO [PERMEABILITY DISPLACED FLUID / DISPLACING FLUID]
10 20 30 40 50 60 70 80 90 100
% WATER SATURATION (% OF TOTAL PORE VOL.)
1
2
3
4
5
→ Direction of lower permeability
1. Conventional Waterflood
2. Polymer Waterflood
3. Polymer-Surfactant Waterflood
4. Surfactant Waterflood
5. Conventional Waterflood

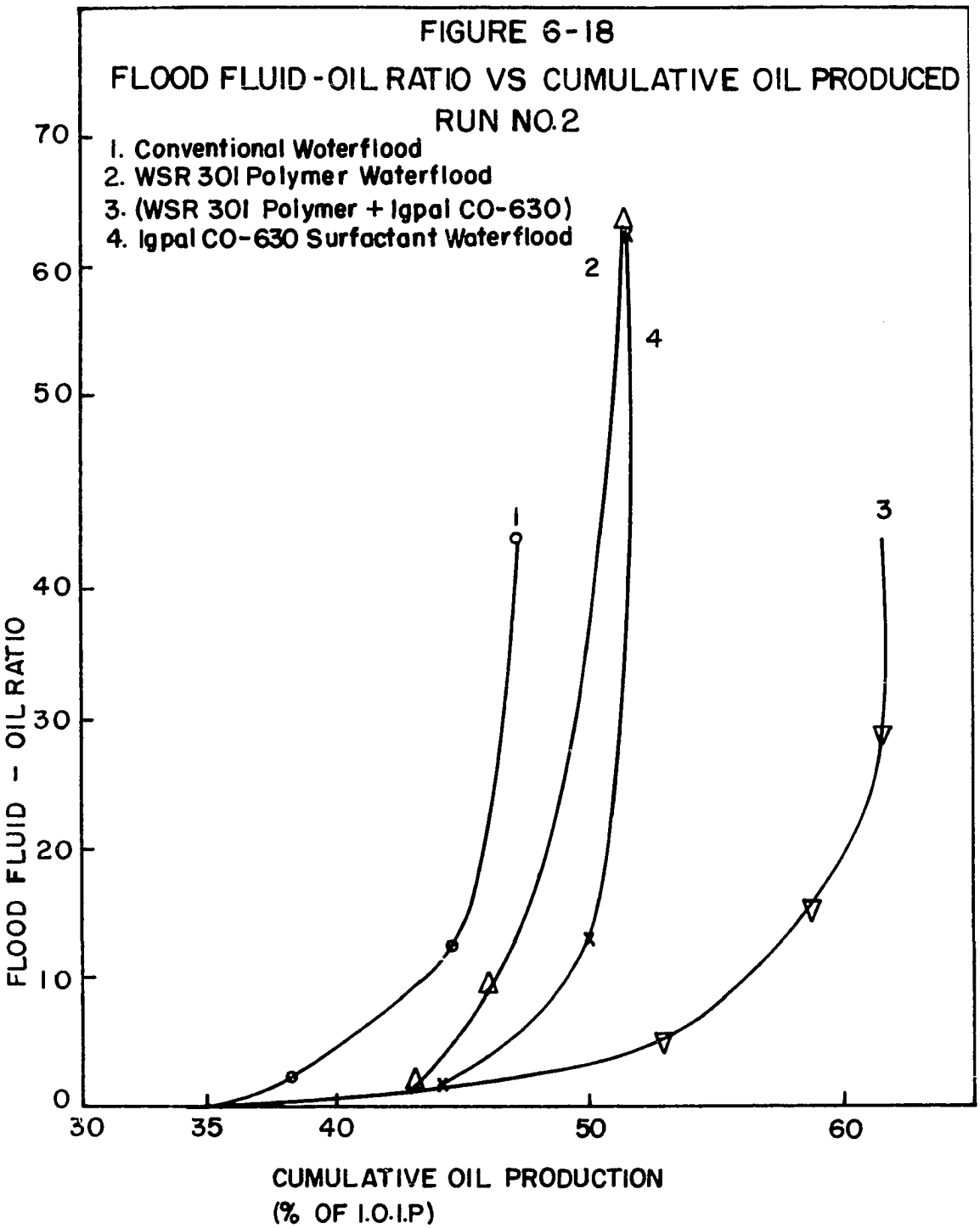
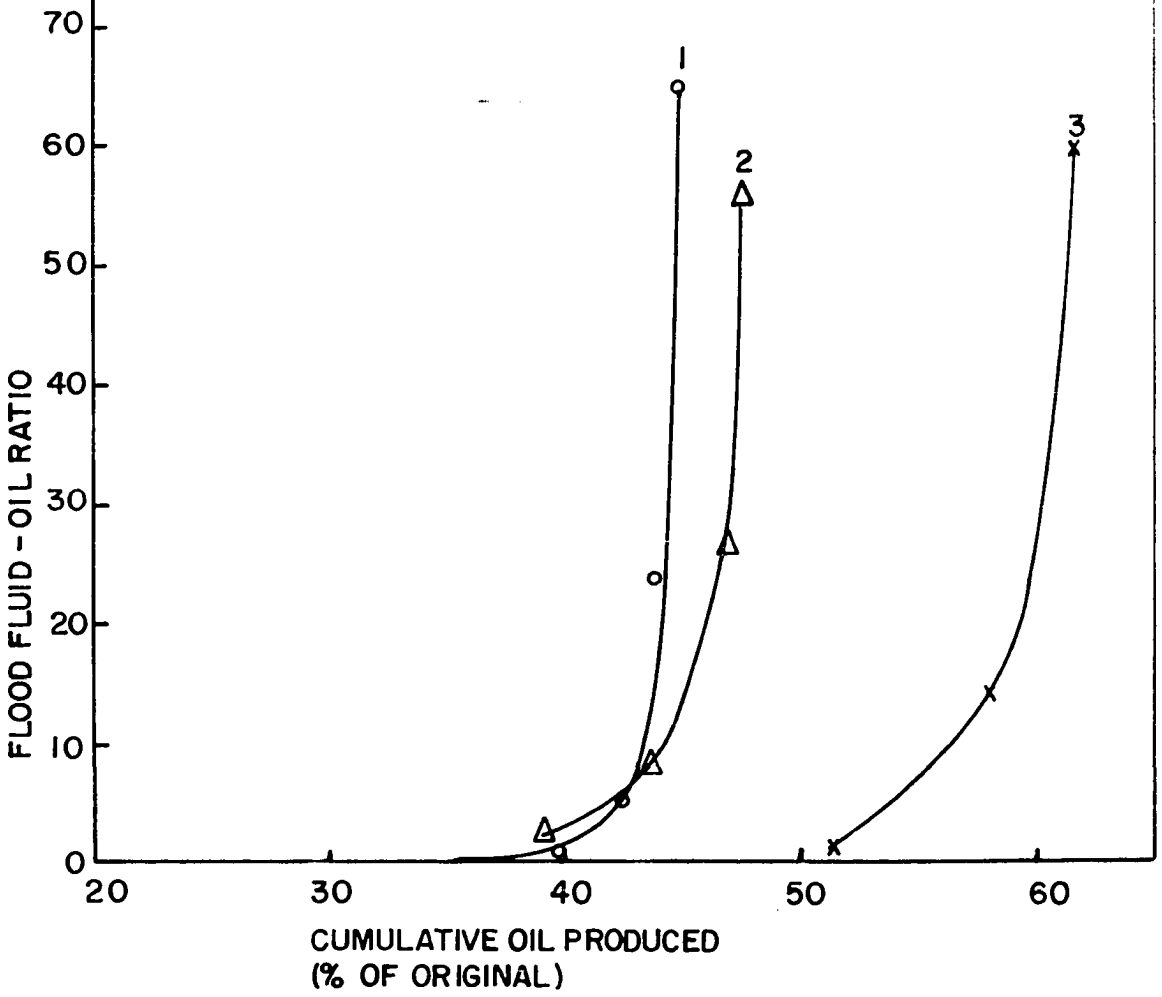


FIGURE 6-18
FLOOD FLUID-OIL RATIO VS CUMULATIVE OIL PRODUCED
RUN NO.2
1. Conventional Waterflood
2. WSR 301 Polymer Waterflood
3. (WSR 301 Polymer + Igpal CO-630)
4. Igpal CO-630 Surfactant Waterflood
FLOOD FLUID - OIL RATIO
0
10
20
30
40
50
60
70
30
35
40
50
60
CUMULATIVE OIL PRODUCTION
(% OF I.O.I.P)
1
2
3
4

FIGURE 6-19

FLOOD FLUID-OIL RATIO VS CUMULATIVE OIL PRODUCED
RUN NO.3

1. Conventionol Waterflood
2. Polyox Coagulant Polymer Waterflood
3. (Coagulant + Pluronic L-62 Surfactant) Waterflood



(1) All pressure differential values drop after breakthrough, except for WSR-301 polymer waterflood system in run 2, and the coagulant polymer waterflood system in run 3. Pressure only dropped after breakthrough for these two specific polymer waterfloods and it started to rise again.

(2) Higher pressure drop is needed to displace the oil using different flood systems other than the well known conventional type.

The last figure to be presented is for run no. 5. Figure 6-23 shows the relationship between the relative permeability ratio versus cumulative oil produced in this run. The system of curves given in this figure is just similar to those produced through run 4 and 6. It can be seen that the reduction in core permeability as the curves shift to the right continued until there was no more damage that could happen to the porous media. In spite of that, ultimate recovery of the last three flooding systems in this run was 100 percent as mentioned earlier.

In this study, it was found that reduction in the absolute permeability to oil and water resulted after polymer solution, surfactant solution, and polymer-surfactant solution were flowed through a core. This reduction differs from one system to another, but it was generally higher for polymer waterflood system than the others.

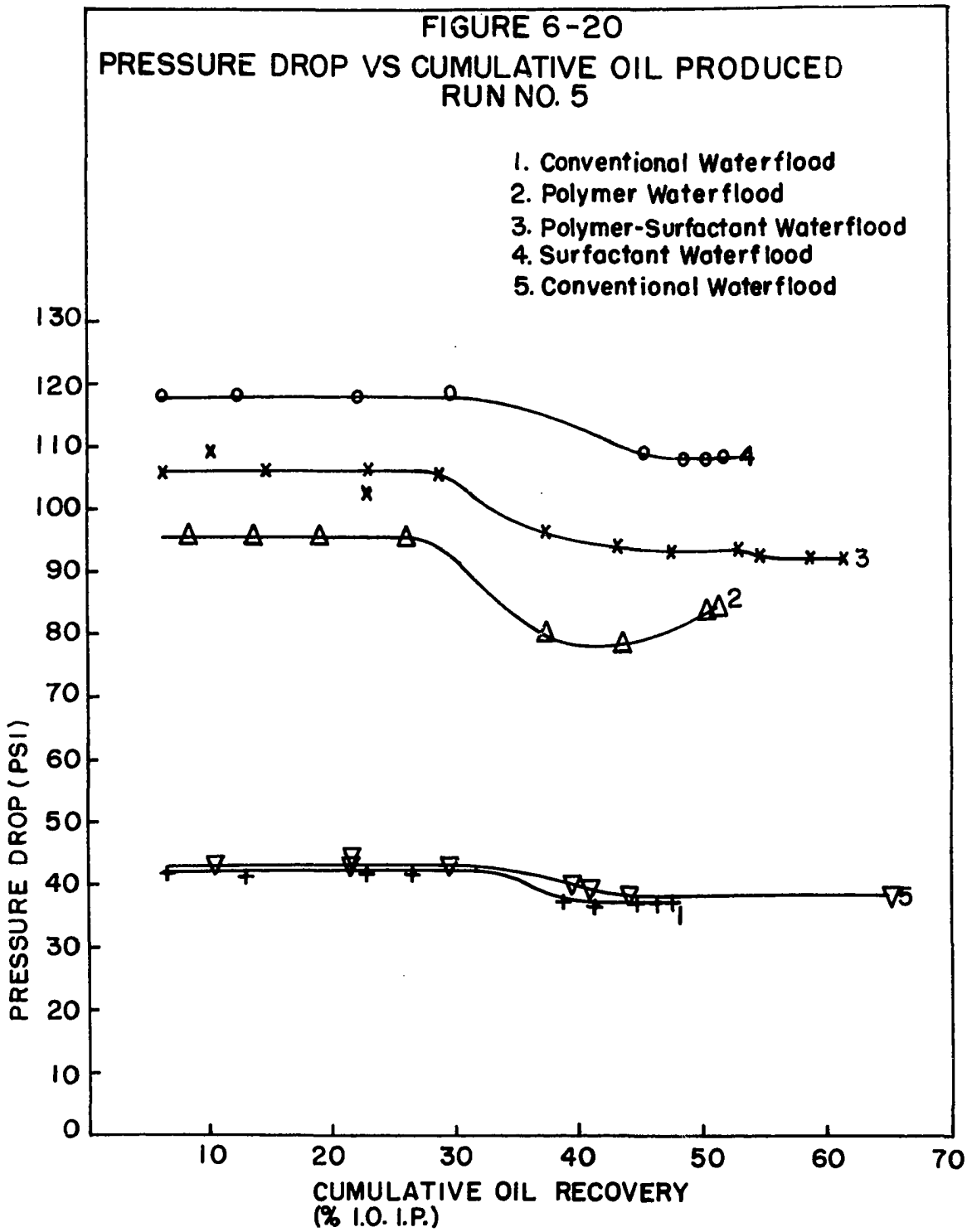


FIGURE 6-20
PRESSURE DROP VS CUMULATIVE OIL PRODUCED
RUN NO. 5
1. Conventional Waterflood
2. Polymer Waterflood
3. Polymer-Surfactant Waterflood
4. Surfactant Waterflood
5. Conventional Waterflood
PRESSURE DROP (PSI)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
10
20
30
40
50
60
70
CUMULATIVE OIL RECOVERY
(% I.O. I.P.)

FIGURE 6-21

PRESSURE DROP VS CUMULATIVE OIL PRODUCED
RUN NO. 3

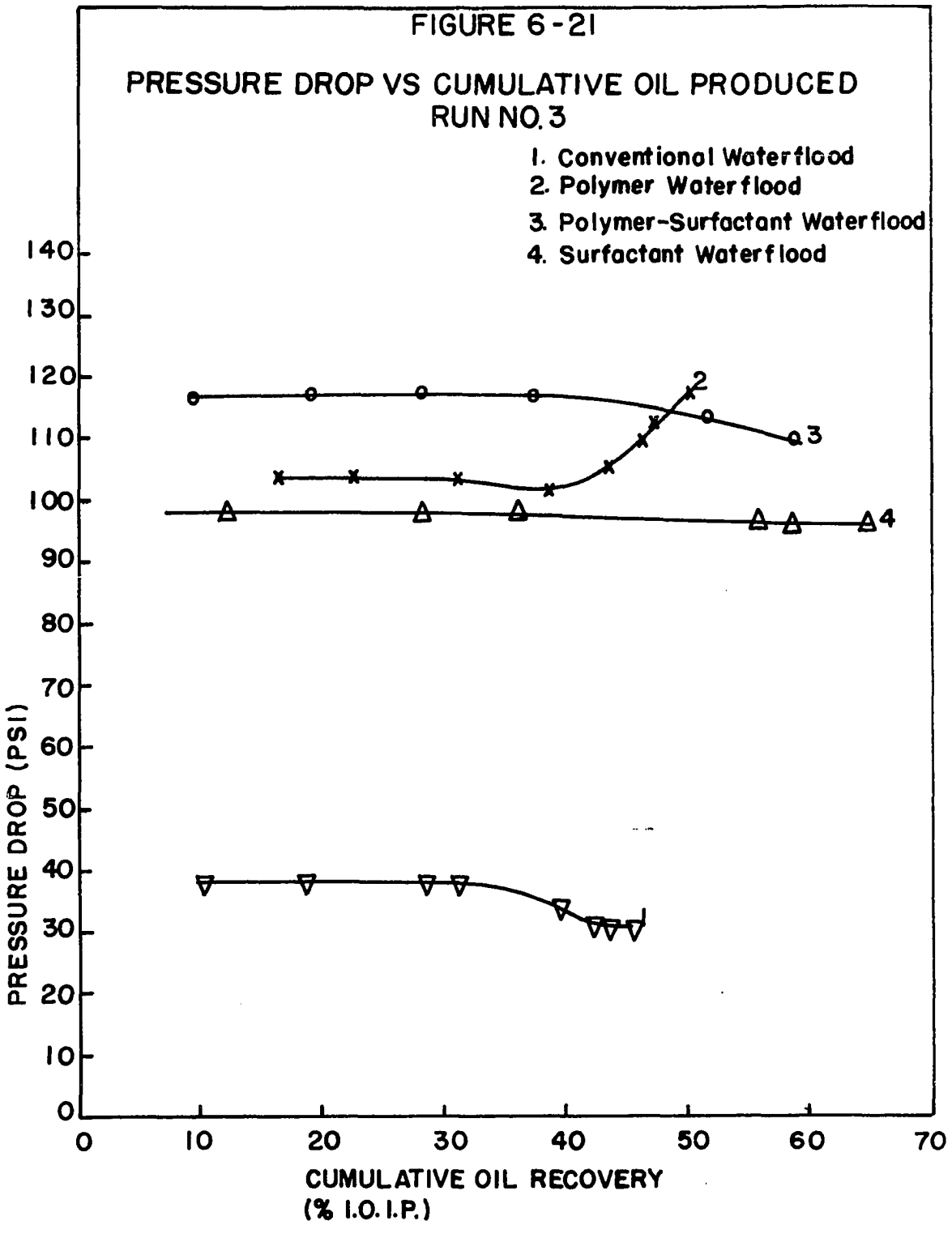
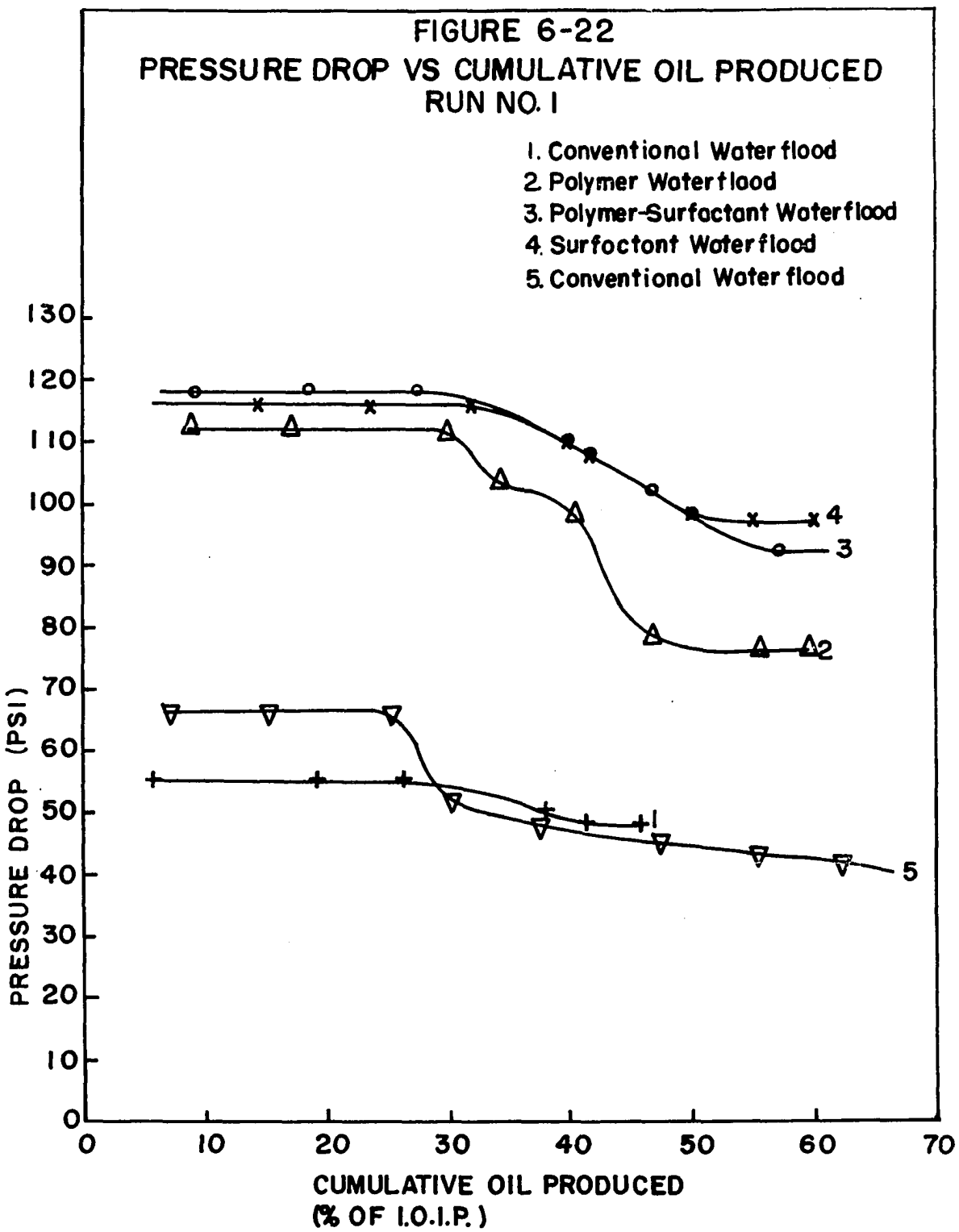


FIGURE 6-22
PRESSURE DROP VS CUMULATIVE OIL PRODUCED
RUN NO. 1



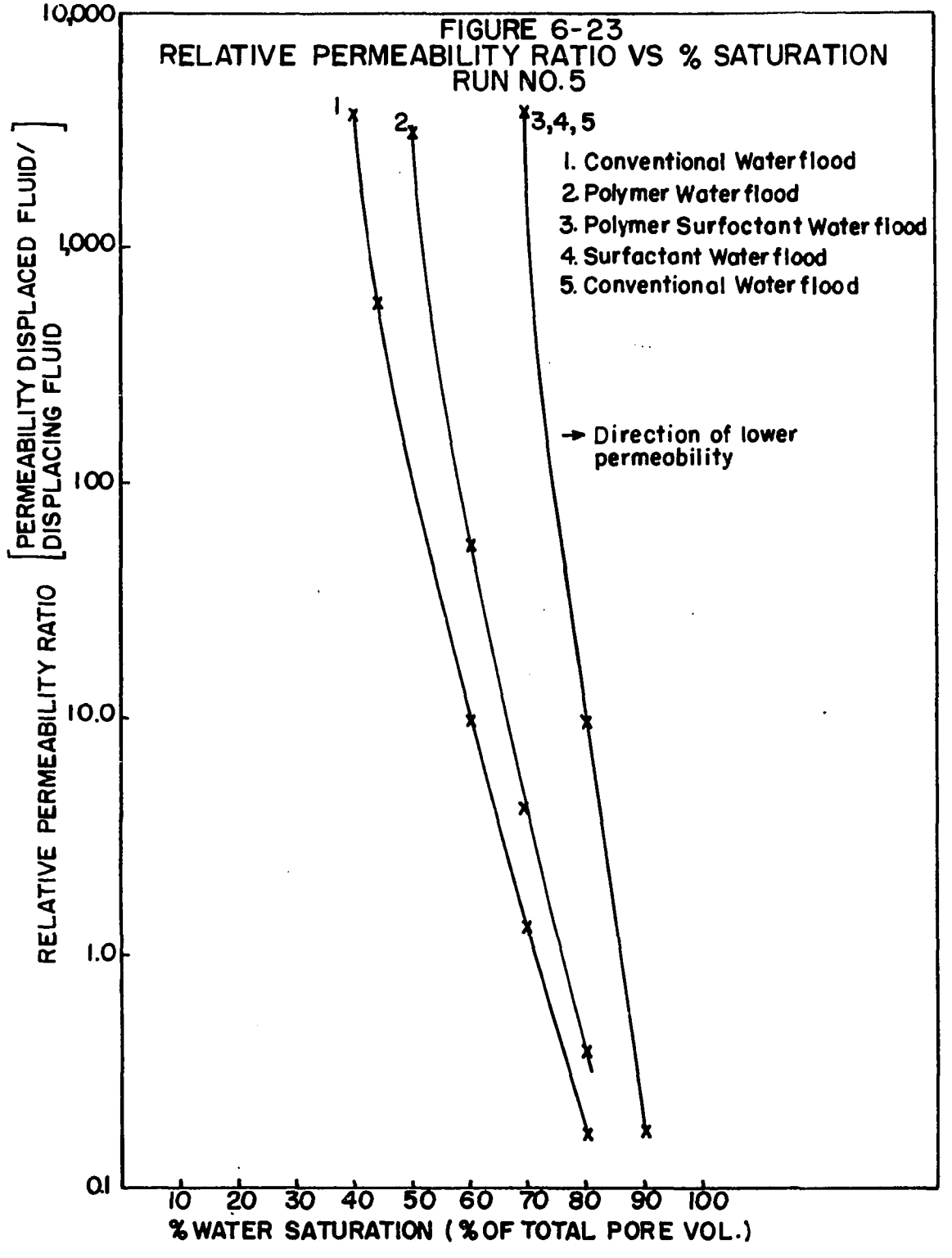


FIGURE 6-23
RELATIVE PERMEABILITY RATIO VS % SATURATION
RUN NO. 5
1
2
3,4,5
1. Conventional Waterflood
2. Polymer Waterflood
3. Polymer Surfactant Waterflood
4. Surfactant Waterflood
5. Conventional Waterflood
→ Direction of lower permeobility
RELATIVE PERMEABILITY RATIO [PERMEABILITY DISPLACED FLUID / DISPLACING FLUID]
10,000
1,000
100
10.0
1.0
0.1
10 20 30 40 50 60 70 80 90 100
% WATER SATURATION (% OF TOTAL PORE VOL.)

CHAPTER VII

CONCLUSIONS

The following conclusions have been reached as a result of the experimental work done in this research. The conclusions are subject to the limitations of the experimental work and physical conditions of the apparatus used.

1. All polymer solutions as well as polymer surfactant solutions appeared to fit the power law model.

2. Some of the polymer-surfactant solutions (38 out of 69 tested samples) showed dilatancy behavior, especially at low shear rates.

3. Viscosity of polymer solutions studied was always higher than polymer surfactant solutions.

4. Surface tension of polymer solutions decreases with the increase in concentration of surfactant additives.

5. Surfactants reduce the value of the interfacial tension of polymeric solutions noticeably. The reduction increases with the concentration of the surfactant additive for a given polymer solution.

6. The interfacial tension property for all polymer and polymer-surfactant solutions used in the oil displacement tests were all far below 1.0 dynes/cm^2.

7. Oil recovery by polymer injection was always higher that that for conventional waterflooding.

8. Polymer-surfactant flood efficiency proved to be always higher than polymer injection only.

9. Little absorption appeared to be present using surfactants and/or polymers. However, no attempt was made to determine this absorption.

10. The oil displacement mechanism which proved to be the most effective consisted of a combination of a favorable mobility ratio and low interfacial tension conditions at the flood front.

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NOMENCLATURE

k	Power law constant
k_w	Effective permeability to water
k_o	Effective permeability to oil
k_{rB}	Relative permeability to water
k_{ro}	Relative permeability to oil
k_{ro}/k_{rB}	Relative permeability ratio
M	Mobility ratio
n	Power law constant
S	Surfactant
S_w	Water saturation as a fraction of the pore volume
S_{wi}	Irreducible water saturation
S_w^*	Dimensionless quantity
S_{oM}	Oil saturation in the stabilized zone
S_{oR}	Residual oil saturation prior to start of the miscible flood
S_{oF}	Oil saturation after invasion of the water bank
S_{WMF}	Average water saturation in the zone occupied by slug after invasion of the water bank.
P*S	Polymer-surfactant waterflood
B*S	Surfactant waterflood
$\frac{du}{dr}$	Shear Rate

Greek Symbols:

τ	Shear stress
τ_y	Yield stress
μ	Apparent viscosity
μ_p	Plastic viscosity
ϕ	Porosity
μ_w	Water viscosity
μ_o	Oil viscosity

APPENDIX A

VISCOMETRIC DATA

The mathematical relationships for the Wells-Brookfield Viscometer are:

$$\text{Shear stress (dyne/cm}^2\text{)} = \frac{T}{\frac{2}{3}\pi r^3}$$

$$\text{Shear rate (sec}^{-1}\text{)} = \frac{\omega}{\sin\theta}$$

$$\text{Viscosity (cp)} = \frac{\text{shear stress x 100}}{\text{shear rate}}$$

where

T = % Full Scale Torque (dyne-cm)

r = cone radius (cm)

ω = cone speed (rad/sec)

θ = cone angle (degrees)

TABLE A-1

1. 0.036 Percent Polyox WSR 301 in 1.0 percent NaCl Solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.6	2.30	.24	0.054	2.35
1.5	5.75	.55	0.128	2.23
3.0	11.50	1.07	0.250	2.17
6.0	23.00	2.04	0.475	2.06
12.0	46.00	3.95	0.92	2.0
30.0	115.00	9.4	2.19	1.90
60.0	230.00	18.69	4.35	1.89

TABLE A-2

2. 0.036 Percent Polyox WSR 301 plus 0.05 percent S_1

(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.6	2.3	0.25	0.058	2.52
1.5	5.75	0.40	0.09	1.56
3.0	11.5	0.62	0.145	1.26
6.0	23.0	1.23	0.285	1.24
12.0	46.0	2.45	0.57	1.24
30.0	115.0	6.10	1.42	1.24
60.0	230.0	12.95	3.014	1.31

3. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_1

(Solvent concentration is 1.0%)

0.6	2.3	--	--	--
1.5	5.75	0.25	0.058	1.008
3.0	11.50	0.60	0.14	1.217
6.0	23.0	1.00	0.235	1.020
12.0	46.0	2.10	0.480	1.00
30.0	115.0	5.40	1.260	1.09
60.0	230.0	10.96	2.55	1.11

4. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_1

(Solvent concentration is 1.0%)

1.5	5.75	0.20	0.046	0.80
3.0	11.50	0.43	0.10	0.87
6.0	23.00	0.95	0.22	0.96
12.0	46.00	2.00	0.465	1.01
30.0	115.00	5.59	1.300	1.13
60.0	230.00	11.18	2.600	1.13

TABLE A-3

5. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_2

(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.6	2.3	0.09	0.021	0.913
1.5	5.75	0.22	0.052	0.904
3.0	11.50	0.45	0.105	0.913
6.0	23.00	1.00	0.23	1.00
12.0	46.00	2.00	0.47	1.021
30.0	115.00	5.10	1.18	1.03
60.0	230.00	10.80	2.508	1.09

6. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_2

(Solvent concentration is 1.0%)

0.6	2.3	0.07	0.017	0.74
1.5	5.75	0.20	0.047	0.82
3.0	11.50	0.43	0.10	0.87
6.0	23.00	0.95	0.22	0.96
12.0	46.00	1.99	0.46	1.00
30.0	115.00	5.10	1.18	1.03
60.0	230.00	9.98	2.322	1.01

7. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_2

(Solvent concentration is 1.0%)

1.5	5.75	0.20	0.045	0.78
3.0	11.50	0.40	0.093	0.81
6.0	23.00	0.090	0.21	0.913
12.0	46.00	1.8	0.42	0.913
30.0	115.00	4.98	1.16	1.01
60.0	230.00	9.98	2.32	1.01

TABLE A-5

11. 0.036 Percent Polyox WSR 301 plus 0.05 Percent [illegible]

(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress (Dynes/cm^2)	[illegible]
3.0	11.5	0.35	0.082	[illegible]
6.0	23.0	0.80	0.185	[illegible]
12.0	46.0	1.80	0.42	[illegible]
30.0	115.0	5.10	1.19	[illegible]
60.0	230.0	11.39	2.65	[illegible]

12. 0.036 Percent Polyox WSR 301 plus 0.005 Percent [illegible]

(Solvent concentration is 1.0%)

3.0	11.5	0.3	0.073	[illegible]
6.0	23.0	0.77	0.18	[illegible]
12.0	46.0	1.76	0.41	[illegible]
30.0	115.0	5.37	1.25	[illegible]
60.0	230.0	12.90	3.0	[illegible]

13. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent [illegible]

(Solvent concentration is 1.0%)

3.0	11.5	0.43	0.10	[illegible]
6.0	23.0	0.94	0.219	[illegible]
12.0	46.0	1.98	0.46	[illegible]
30.0	115.0	5.15	1.2	[illegible]
60.0	230.0	11.39	2.65	1.15

TABLE A-4

8. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_3
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	0.25	0.058	1.001
3.0	11.5	0.51	0.119	1.03
6.0	23.0	1.10	0.255	1.108
12.0	46.0	2.06	0.48	1.04
30.0	115.0	5.25	1.22	1.06
60.0	230.0	10.80	2.51	1.09

9. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_3
(Solvent concentration is 1.0%)

3.0	11.5	0.47	0.109	0.948
6.0	23.0	1.00	0.235	1.02
12.0	46.0	1.98	0.46	1.0
30.0	115.0	5.15	1.2	1.04
60.0	230.0	10.7	2.5	1.08

10. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_3
(Solvent concentration is 1.0%)

3.0	11.5	0.40	0.093	0.81
6.0	23.0	0.95	0.22	0.956
12.0	46.0	1.90	0.45	0.98
30.0	115.0	5.33	1.24	1.08
60.0	230.0	12.03	2.8	1.22

TABLE A-5

11. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S

(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
3.0	11.5	0.35	0.082	0.713
6.0	23.0	0.80	0.185	0.80
12.0	46.0	1.80	0.42	0.89
30.0	115.0	5.10	1.19	1.035
60.0	230.0	11.39	2.65	1.15

12. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_4

(Solvent concentration is 1.0%)

3.0	11.5	0.3	0.073	0.635
6.0	23.0	0.77	0.18	0.8
12.0	46.0	1.76	0.41	0.89
30.0	115.0	5.37	1.25	1.08
60.0	230.0	12.90	3.0	1.30

13. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_4

(Solvent conc-ntration is 1.0%)

3.0	11.5	0.43	0.10	0.870
6.0	23.0	0.94	0.219	0.952
12.0	46.0	1.98	0.46	1.00
30.0	115.0	5.15	1.2	1.04
60.0	230.0	11.39	2.65	1.15

TABLE A-8

20. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_7
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
3.0	11.5	0.37	0.085	0.739
6.0	23.0	0.90	0.21	0.913
12.0	46.0	1.85	0.43	0.935
30.0	115.0	4.94	1.15	1.00
60.0	230.0	10.53	2.45	1.065

21. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_7
(Solvent concentration is 1.0%)

3.0	11.5	0.46	0.108	0.913
6.0	23.0	0.99	0.23	1.0
12.0	46.0	2.11	0.49	1.065
30.0	115.0	5.80	1.35	1.174
60.0	230.0	12.25	2.85	1.239

22. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_7
(Solvent concentration is 1.0%)

3.0	11.5	0.41	0.096	0.835
6.0	23.0	0.95	0.22	0.957
12.0	46.0	2.02	0.47	1.02
30.0	115.0	5.50	1.28	1.113
60.0	230.0	11.40	2.65	1.152

TABLE A-9

23. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_8
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
3.0	11.5	2.54	0.59	5.13
6.0	23.0	3.82	0.89	3.87
12.0	46.0	5.60	1.3	1.13
30.0	115.0	9.45	2.2	1.91
60.0	230.0	14.04	3.267	1.42

24. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_8
(Solvent Concentration is 1.0%)

3.0	11.5	0.5	0.115	1.00
6.0	23.0	1.03	0.240	1.04
12.0	46.0	2.08	0.485	1.05
30.0	115.0	5.37	1.250	1.087
60.0	230.0	11.50	2.67	1.161

25. 0.036 Percent WSR 301 plus 0.0005 Percent S_8
(Solvent concentration is 1.0%)

6.0	23.0	0.92	0.215	0.935
12.0	46.0	1.83	0.425	0.924
30.0	115.0	5.37	1.25	1.087
60.0	230.0	11.40	2.65	1.152

TABLE A-10

26. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_9
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
3.0	11.5	0.60	0.140	1.22
6.0	23.0	1.02	0.238	1.035
12.0	46.0	2.28	0.530	1.15
30.0	115.0	5.93	1.38	1.20
60.0	230.0	12.46	2.90	1.261

27. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_9
(Solvent concentration is 1.0%)

3.0	11.5	0.52	0.12	1.04
6.0	23.0	1.03	0.240	1.04
12.0	46.0	2.20	0.51	1.10
30.0	115.0	5.58	1.30	1.13
60.0	230.0	11.60	2.70	1.174

28. 0.036 percent Polyox WSR 301 plus 0.0005 percent S_9
(Solvent concentration is 1.0%)

3.0	11.5	0.41	0.095	0.826
6.0	23.0	0.90	0.21	0.913
12.0	46.0	1.98	0.46	1.00
30.0	115.0	5.8	1.35	1.173
60.0	230.0	11.65	2.71	1.178

TABLE A-11

29. 0.036 Percent Polyox WSR 301 plus 0.05 Percent S_{10}
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	0.25	0.0575	1.0
3.0	11.5	0.51	0.118	1.03
6.0	23.0	1.07	0.25	1.08
12.0	46.0	2.15	0.50	1.09
30.0	115.0	5.93	1.38	1.20
60.0	230.0	12.00	2.8	1.22

30. 0.036 Percent Polyox WSR 301 plus 0.005 Percent S_{10}
(Solvent concentration is 1.0%)

0.6	2.3	0.12	0.0275	1.19
1.5	5.75	0.30	0.07	1.22
3.0	11.5	0.60	0.14	1.22
6.0	23.0	1.22	0.285	1.24
12.0	46.0	2.41	0.560	1.22
30.0	115.0	5.97	1.390	1.21
60.0	230.0	12.25	2.850	1.24

31. 0.036 Percent Polyox WSR 301 plus 0.0005 Percent S_{10}
(Solvent concentration is 1.0%)

3.0	11.5	0.5	0.115	1.00
6.0	23.0	1.03	0.24	1.04
12.0	46.0	1.07	0.50	1.087
30.0	115.0	5.95	1.385	1.20
60.0	230.0	12.42	2.89	1.257

TABLE A-12

32. 0.2 Percent Polyox WSR 301 in 1.0 Percent NaCl Solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.3	1.15	1.1	0.240	20.86
0.6	2.30	2.1	0.465	20.20
1.5	5.75	4.36	0.96	16.69
3.0	11.50	7.72	1.7	14.78
6.0	23.00	13.17	2.9	12.60
12.0	46.00	22.71	5.0	10.86
30.0	115.00	45.43	10.0	8.69
60.0	230.00	79.49	17.5	7.61

TABLE A-13

33. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_1
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.6	2.3	0.50	0.118	5.13
1.5	5.75	1.30	0.30	5.20
3.0	11.50	2.70	0.63	5.48
6.0	23.0	5.80	1.35	5.87
12.0	46.0	11.17	2.6	5.65
30.0	115.0	29.22	6.8	5.91
60.0	230.0	60.16	14.0	6.087

34. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_1
(Solvent concentration is 1.0%)

1.5	5.75	1.03	0.24	4.17
3.0	11.5	2.15	0.5	4.35
6.0	23.0	4.5	1.05	4.56
12.0	46.0	9.00	2.1	4.56
30.0	115.0	22.78	5.3	4.61
60.0	230.0	47.27	11.0	4.783

35. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_1
(Solvent concentration is 1.0%)

0.6	2.3	0.25	0.058	2.52
1.5	5.75	0.70	0.16	2.78
3.0	11.50	1.60	0.37	3.21
6.0	23.00	3.65	0.85	3.69
12.0	46.00	7.95	1.85	4.02
30.0	115.00	23.21	5.4	4.69
60.0	230.00	51.57	12.0	5.22

TABLE A-14

36. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_2
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.2	0.28	4.87
3.0	11.5	2.5	0.58	5.04
6.0	23.0	5.4	1.25	5.43
12.0	46.0	10.7	2.50	5.43
30.0	115.0	28.8	6.70	5.83
60.0	230.0	55.87	13.00	5.65

37. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_2
(Solvent concentration is 1.0%)

1.5	5.75	0.99	0.23	4.00
3.0	11.50	2.11	0.49	4.26
6.0	23.00	4.40	1.03	4.47
12.0	46.00	9.02	2.1	4.56
30.0	115.00	22.80	5.3	4.61
60.0	230.00	49.42	11.50	5.00

38. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_2
(Solvent concentration is 1.0%)

0.6	2.3	0.40	0.093	4.04
1.5	5.75	1.03	0.24	4.17
3.0	11.50	2.11	0.49	4.26
6.0	23.00	4.20	0.98	4.26
12.0	46.00	8.40	1.95	4.24
30.0	115.00	20.63	4.8	4.17
60.0	230.00	41.73	9.71	4.22

TABLE A-15

39. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_3
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.46	0.34	5.91
3.0	11.50	2.9	0.68	5.91
6.0	23.00	5.63	1.31	5.69
12.0	46.00	11.20	2.6	5.652
30.0	115.00	27.9	6.5	5.65
60.0	230.00	55.87	13.0	5.65

40. 0.2 Percent Polyox WSR 301 plut 0.005 Percent S_3
(Solvent concentration is 1.0%)

3.0	11.50	2.75	0.64	5.565
6.0	23.00	5.46	1.27	5.52
12.0	46.00	10.7	2.5	5.43
30.0	115.00	25.80	6.00	5.22
60.0	230.00	54.15	12.60	5.47

41. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_3
(Solvent concentration is 1.0%)

1.5	5.75	1.05	0.245	4.26
3.0	11.50	2.15	0.50	4.35
6.0	23.00	4.34	1.01	4.391
12.0	46.00	9.02	2.1	4.565
30.0	115.00	22.99	5.35	4.652
60.0	230.00	45.55	10.6	5.168

TABLE A-16

42. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_4
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75		0.19	3.30
3.0	11.50		0.41	3.56
6.0	23.00		0.85	3.69
12.0	46.00		1.8	3.91
30.0	115.00		4.7	4.08
60.0	230.00		9.2	4.00

43. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_4
(Solvent concentration is 1.0%)

3.0	11.50	0.48	4.17
6.0	23.0	1.00	4.35
12.0	46.0	2.05	4.45
30.0	115.0	5.3	4.60
60.0	230.0	11.0	4.78

44. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_4
(Solvent concentration is 1.0%)

0.6	2.30	0.91	3.95
1.5	5.75	0.235	4.08
3.0	11.50	0.49	4.26
6.0	23.0	1.00	4.35
12.0	46.0	2.05	4.45
30.0	115.0	5.3	4.60
60.0	230.0	11.3	4.91

TABLE A-17

45. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_5
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.6	2.3	0.47	0.110	4.78
1.5	5.75	1.18	0.275	4.78
3.0	11.5	2.50	0.57	4.96
6.0	23.0	5.03	1.17	5.09
12.0	46.0	10.3	2.4	5.22
30.0	115.0	25.83	6.01	5.23
60.0	230.00	52.0	12.1	5.26

46. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_5
(Solvent concentration is 1.0%)

3.0	11.5	2.15	0.5	4.35
6.0	23.0	4.51	1.05	4.56
12.0	46.0	9.02	2.1	4.56
30.0	115.0	23.21	5.4	4.69
60.0	230.0	47.27	11.0	4.78

47. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_5
(Solvent concentration is 1.0%)

0.6	2.30	0.5	0.117	5.09
1.5	5.75	1.20	0.28	4.87
3.0	11.5	2.45	0.57	4.96
6.0	23.0	5.07	1.18	5.13
12.0	46.0	10.1	2.35	5.11
30.0	115.0	25.35	5.9	5.13
60.0	230.0	49.4	11.5	5.00

TABLE A-18

48. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_6
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.46	0.34	5.91
3.0	11.5	2.88	0.67	5.83
6.0	23.0	5.60	1.3	5.65
12.0	46.0	11.17	2.60	5.65
30.0	115.0	27.50	6.40	5.56
60.0	230.0	53.90	12.54	5.45

49. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_6
(Solvent concentration is 1.0%)

0.6	2.3	0.52	0.121	5.26
1.5	5.75	1.28	0.3	5.22
3.0	11.5	2.58	0.6	5.22
6.0	23.0	5.16	1.20	5.22
12.0	46.0	10.10	2.35	5.11
30.0	115.0	24.90	5.8	5.04
60.0	230.0	49.4	11.5	5.00

50. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_6
(Solvent concentration is 1.0%)

1.5	5.75	1.46	0.34	5.91
3.0	11.50	2.92	0.68	5.91
6.0	23.00	5.84	1.36	5.91
12.0	46.0	11.39	2.65	5.76
30.0	115.0	27.93	6.5	5.65
60.0	230.0	54.58	12.7	5.52

TABLE A-19

51. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_7
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.22	0.285	4.96
3.0	11.50	2.50	0.58	5.04
6.0	23.00	5.10	1.19	5.17
12.0	46.00	10.53	2.45	5.32
30.0	115.0	26.65	6.2	5.39
60.0	230.00	53.72	12.5	5.45

52. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_7
(Solvent concentration is 1.0%)

3.0	11.50	2.30	0.53	4.60
6.0	23.00	4.64	1.08	4.69
12.0	46.00	9.24	2.15	4.67
30.0	115.00	23.64	5.5	4.78
60.0	230.00	48.13	11.2	4.87

53. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_7
(Solvent concentration is 1.0%)

1.5	5.75	1.42	0.33	5.74
3.0	11.50	2.71	0.63	5.48
6.0	23.00	5.24	1.22	5.30
12.0	46.00	10.53	2.45	5.33
30.0	115.00	26.22	6.1	5.30
60.0	230.00	50.71	11.8	5.13

TABLE A-20

54. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_8
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	0.8	0.18	3.13
3.0	11.5	1.46	0.34	2.96
6.0	23.0	2.28	0.53	2.30
12.0	46.0	4.94	1.15	2.50
30.0	115.0	10.96	2.55	2.22
60.0	230.0	19.77	4.6	2.0

55. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_8
(Solvent concentration is 1.0%)

1.5	5.75	1.13	0.265	4.61
3.0	11.5	2.20	0.51	4.43
6.0	23.0	4.20	0.98	4.26
12.0	46.0	7.95	1.85	4.02
30.0	115.0	18.05	4.2	3.65
60.0	230.0	36.53	8.5	3.69

56. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_8
(Solvent concentration is 1.0%)

1.5	5.75	1.29	0.30	5.22
3.0	11.5	2.62	0.61	5.3
6.0	23.0	5.16	1.20	5.21
12.0	46.0	10.10	2.35	5.10
30.0	115.0	24.93	5.8	5.04
60.0	230.0	49.42	11.5	5.00

TABLE A-21

57. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_9
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.35	0.315	5.47
3.0	11.5	2.66	0.62	5.39
6.0	23.0	5.37	1.25	5.43
12.0	46.0	10.74	2.5	5.43
30.0	115.0	25.78	6.0	5.22
60.0	230.0	50.7	11.8	5.13

58. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_9
(Solvent concentration is 1.0%)

1.5	5.75	1.33	0.31	5.39
3.0	11.5	2.6	0.60	5.21
6.0	23.0	5.07	1.18	5.13
12.0	46.0	9.9	2.3	5.00
30.0	115.0	24.5	5.7	4.96
60.0	230.0	47.3	11.0	4.78

59. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_9
(Solvent concentration is 1.0%)

1.5	5.75	1.29	0.30	5.22
3.0	11.5	2.60	0.60	5.21
6.0	23.0	5.07	1.18	5.13
12.0	46.0	9.84	2.29	4.97
30.0	115.0	24.07	5.6	4.87
60.0	230.0	43.06	10.02	4.36

TABLE A-22

60. 0.2 Percent Polyox WSR 301 plus 0.05 Percent S_{10}
(Solvent concentration is 1.0%)

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
1.5	5.75	1.30	0.30	5.22
3.0	11.5	2.60	0.61	5.30
6.0	23.0	5.37	1.25	5.43
12.0	46.0	10.53	2.45	5.33
30.0	115.0	26.22	6.1	5.30
60.0	230.0	50.7	11.8	5.13

61. 0.2 Percent Polyox WSR 301 plus 0.005 Percent S_{10}
(Solvent concentration is 1.0%)

1.5	5.75	1.27	0.295	5.13
3.0	11.5	2.58	0.6	5.22
6.0	23.0	5.16	1.2	5.22
12.0	46.0	9.9	2.3	5.00
30.0	115.0	24.49	5.7	4.96
60.0	230.0	47.70	11.1	4.83

62. 0.2 Percent Polyox WSR 301 plus 0.0005 Percent S_{10}
(Solvent concentration is 1.0%)

1.5	5.75	1.37	0.32	5.56
3.0	11.5	2.62	0.61	5.30
6.0	23.0	5.20	1.21	5.26
12.0	46.0	9.9	2.3	5.00
30.0	115.0	24.07	5.6	4.87
60.0	230.0	43.19	10.05	4.37

TABLE A-23

63. 0.05 Percent Polyox WSR 205 in 1.0 Percent NaCl solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.3	1.15			
0.6	2.3	0.19	0.046	2.0
1.5	5.75	0.39	0.09	1.66
3.0	11.5	0.77	0.18	1.56
6.0	23.0	1.42	0.33	1.43
12.0	46.0	2.7	0.63	1.36
30.0	115.0	6.02	1.4	1.22
60.0	230.0	11.17	2.6	1.13

64. 0.05 Percent Polyox WSR 205 plus 0.05 Percent S_1 (Solvent concentration is 1.0%)

0.3	1.15			
0.6	2.30			
1.5	5.75	0.51	0.118	2.05
3.0	11.5	0.9	0.21	1.83
6.0	23.0	1.55	0.36	1.57
12.0	46.0	2.7	0.63	1.37
30.0	115.0	5.59	1.3	1.13
60.0	230.0	10.09	2.35	1.02

TABLE A-24

65. 0.05 Percent Polyox Coagulant in 1.0 Percent NaCl Solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress ($Dynes/cm^2$)	Viscosity (cp)
0.3	1.15	0.20	0.046	4.00
0.6	2.30	0.39	0.091	3.96
1.5	5.75	0.75	0.175	3.04
3.0	11.50	1.42	0.33	2.97
6.0	23.00	2.36	0.55	2.39
12.0	46.00	4.0	0.93	2.02
30.0	115.00	8.20	1.90	1.65
60.0	230.00	14.4	3.35	1.45

66. 0.05 Percent Polyox Coagulant plus 0.05 Percent S_9

(Solvent concentration is 1.0%)

0.6	2.30	0.50	0.115	5.0
1.5	5.75	0.82	0.19	3.3
3.0	11.5	1.40	0.33	2.87
6.0	23.0	2.06	0.48	2.09
12.0	46.0	3.20	0.75	1.63
30.0	115.0	5.8	1.35	1.17
60.0	230.0	9.02	2.1	0.913

TABLE A-23

63. 0.05 Percent Polyox WSR 205 in 1.0 Percent NaCl solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress (Dynes/cm^2)	Viscosity (cp)
0.3	1.15			
0.6	2.3	0.19	0.046	2.0
1.5	5.75	0.39	0.09	1.66
3.0	11.5	0.77	0.18	1.56
6.0	23.0	1.42	0.33	1.43
12.0	46.0	2.7	0.63	1.36
30.0	115.0	6.02	1.4	1.22
60.0	230.0	11.17	2.6	1.13

64. 0.05 Percent Polyox WSR 205 plus 0.05 Percent S_1
(Solvent concentration is 1.0%)

0.3	1.15			
0.6	2.30			
1.5	5.75	0.51	0.118	2.05
3.0	11.5	0.9	0.21	1.83
6.0	23.0	1.55	0.36	1.57
12.0	46.0	2.7	0.63	1.37
30.0	115.0	5.59	1.3	1.13
60.0	230.0	10.09	2.35	1.02

TABLE A-25

67. 0.05 Percent Polyox WSR 301 in 1.0 NaCl Solution

Viscometer Speed (rpm)	Shear Rate (sec^{-1})	Percent Full Scale Torque	Shear Stress (Dynes/cm^2)	Viscosity (cp)
0.3	1.15	0.20	0.042	3.65
0.6	2.3	0.33	0.076	3.30
1.5	5.75	0.80	0.180	3.13
3.0	11.50	1.50	0.34	2.95
6.0	23.00	2.75	0.64	2.78
12.0	46.00	5.37	1.25	2.72
30.0	115.00	12.0	2.8	2.43
60.0	230.00	23.2	5.4	2.35

68. 0.05 Percent Polyox WSR 301 plus 0.05 Percent S_2 (Solvent concentration is 1.0%)

0.6	2.30	0.35	0.078	3.39
1.5	5.75	0.54	0.15	2.6
3.0	11.50	1.1	0.26	2.26
6.0	23.00	1.80	0.42	1.83
12.0	46.00	3.05	0.71	1.54
30.0	115.00	8.20	1.9	1.65
60.0	230.00	11.2	2.6	1.13

69. 0.05 Percent Polyox WSR 301 plus 0.05 Percent S_3 (Solvent concentration is 1.0%)

0.6	2.30			
1.5	5.75	0.26	0.06	1.04
3.0	11.50	0.57	0.132	1.15
6.0	23.00	1.08	0.25	1.108
12.0	46.00	2.32	0.54	1.174
30.0	115.00	5.80	1.35	1.174
60.0	230.00	12.35	2.875	1.25

APPENDIX B

CUMULATIVE OIL PRODUCED (% I.O.I.P.)

vs

PRESSURE DROP

TABLE B-1

RUN NO. 1

Run No. 1.1

Pressure (ΔP) P.S.I.	Cumulative Time sec.	Cumulative Brine Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
52.0	520	2	2	5.41
53.0	1010	4	4	10.81
55.0	1499	6	6	16.22
54.0	1723	7	7	18.92
54.0	2355	10	9.5	25.68
51.0	3570	22	14.0	37.84
50.0	4244	32	15.0	40.54
48.0	4780	41	15.25	41.22
48.0	12650	63	16.00	43.24
48.0	13708	80	17.00	45.95
48.0	14710	100	17.00	45.95

Run No. 1.2

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Polymer Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
112	410	2	2	8.51
112	567	4	4	17.02
106	862	7	7	29.79
101	994	9	8	34.04
98	1060	10	9.5	40.43
86	1331	14	10.0	42.55
78	1800	25	11.0	46.81
76	2254	35	12.0	51.06
76	2480	40	13.0	55.32
75	3170	56	13.5	57.45
74	3930	74	14.0	59.57
74	4472	87	14.0	59.57
74	4967	100	14.0	59.57

TABLE B-1

Run No. 1.3

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (P*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
118.0	778	2	2	9.09
116.5	966	4	4	18.18
113.0	1210	6	6	27.27
108.0	1460	9	9	40.91
98.0	1770	13	11	50.00
94.0	2160	20	12.0	54.55
92.0	2774	30	12.5	56.82
92.0	3630	44	13.0	59.09
92.0	5160	70	13.5	61.36
92.0	6900	100	13.5	61.36

Run No. 1.4

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (B*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
116.0	813	3	3	13.95
115.0	1115	5	5	23.26
112.0	1396	7	7	32.56
110.0	1550	8.5	8.5	39.53
108.5	1610	9.0	9.0	41.86
103.0	1929	12.5	10.0	46.51
98.0	2715	23.0	10.5	48.84
97.5	3375	32.5	11.0	51.16
97.0	6565	79.0	12.25	58.14
97.0	7940	100.0	13.00	60.47

TABLE B-1

Run No. 1.5

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Brine Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
66	1900	3	3	15.0
56	2860	5	5	25.0
52	3548	6	6	30.0
45	5617	9.5	9.5	47.5
43	6561	11.0	11.0	55.0
42	8638	16.0	12.0	60.0
42	10585	21.0	12.25	61.25
42	12865	27.25	12.50	62.50
41	16108	37.0	12.75	63.75
40	17191	40.0	12.75	63.75
40	23177	60.5	13.25	66.25

TABLE B-2

RUN NO. 2

Run No. 2.1

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Brine Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
40.5	450	2.5	2.5	6.2
40.5	997	5.0	5.0	12.4
41.5	1790	9.0	9.0	22.3
41.5	2035	10.5	10.5	26.1
43.5	2387	13.0	13.0	32.3
38.0	3092	21.5	15.5	38.5
37.5	3593	30.0	16.5	40.9
37.0	4609	50.0	18.0	44.7
37.0	5850	78.0	18.5	45.9
37.0	6700	100.0	19.0	47.1

Run No. 2.2

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Polymer Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
95.5	532	3.0	3.0	7.9
95.5	771	5.0	5.0	13.2
95.5	993	7.0	7.0	18.4
95.5	1301	10.0	10.0	26.3
80.0	1926	19.0	14.0	36.8
78.0	2278	25.0	16.5	43.4
78.0	2877	35.0	17.5	46.1
79.0	3760	50.0	19.0	50.00
83.0	5709	82.5	19.5	51.32
84.0	6755	100.0	19.5	51.32

TABLE B-2

Run No. 2.3

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (P*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
105	507	2.0	2.0	5.7
106	861	5.0	5.0	14.3
103	1173	8.0	8.0	22.8
100	1360	10.0	10.0	28.6
96	1610	13.0	13.0	37.1
94	1920	17.0	15.0	42.9
93	2465	24.0	16.5	47.1
93	3447	37.0	18.5	52.9
92	4425	50.0	19.0	54.3
91.5	5950	70.0	20.5	58.6
91.0	6900	82.0	21.5	61.43
90.5	8242	100.0	21.5	61.43

Run No. 2.4

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (B*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
118	906	2.0	2.0	5.9
116	1370	4.0	4.0	11.8
114	1958	7.5	7.5	22.1
113	2363	10.0	10.0	29.4
109	3866	22.0	15.0	44.1
107.5	5586	38.0	16.5	48.5
107.5	7097	50.0	17.0	50.0
107.5	9299	70.0	17.5	51.5
106.5	10774	82.0	17.5	51.5
105.5	12654	100.0	17.5	51.5

TABLE B-2

Run No. 2.5

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Brine Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
43	2124	3.0	3.0	9.7
40	4917	6.5	6.5	21.0
40	6420	9.0	9.0	29.0
40	7708	12.0	12.0	38.7
40	8980	14.5	13.0	42.0
40	10360	18.0	13.5	43.5
40	14690	30.0	15.0	48.4
40	16742	35.0	15.25	49.2
38	23078	53.5	15.50	50.0
38	38049	92.5	20.15	65.0

TABLE B-3

RUN NO. 3

Run No. 3.1

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Brine Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
38	916	3.5	3.5	9.9
38	1710	6.5	6.5	18.3
38	2380	10.0	10.0	27.2
38	2519	11.0	11.0	30.99
34	3300	17.0	14.0	39.4
31	3850	23.5	15.0	42.3
31	4845	36.0	15.5	43.6
28	8650	102.0	16.0	45.1

Run No. 3.2

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative Polymer Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
103.5	1600	5.0	5.0	16.1
103.5	2120	7.0	7.0	22.6
103.0	2566	9.0	9.0	29.03
103.0	2722	9.5	9.5	30.7
101.5	4156	17.0	12.0	38.7
105.5	6680	30.0	13.5	43.6
110.0	15560	57.0	14.5	46.8
112.0	21320	74.5	14.8	47.7
118.0	30170	98.0	15.6	50.3

TABLE B-3

Run No. 3.3

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (P*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
118.0	1777	2.0	2.0	9.3
117.0	2473	4.0	4.0	18.6
116.5	2956	6.0	6.0	27.9
116.0	3228	8.0	8.0	37.2
113.0	4599	14.0	11.0	51.2
110.0	9427	36.5	12.5	58.14
110.0	11598	45.5	13.0	60.47
110.0	15080	58.0	13.2	61.4
100.0	17790	66.0	13.2	61.4
109.0	20101	72.0	13.2	61.4
108.0	25669	87.0	13.5	62.8
108.0	31350	100.5	13.5	62.8

Run No. 3.4

Pressure (ΔP) p.s.i.	Cumulative Time sec.	Cumulative (B*S) Injected c.c.	Cumulative Oil Produced c.c.	Cumulative Oil Produced (% I.O.I.P.)
98	2344	2.25	2.25	12.5
98	4724	5.00	5.0	27.8
98	5423	6.50	6.5	36.1
97	6610	10.00	8.0	44.4
96	8995	15.00	9.5	52.8
96	11605	20.00	10.0	55.6
95.5	17947	34.00	10.50	58.3
98.0	28322	56.50	11.25	62.5
98.0	35798	74.50	11.75	65.3
98.0	45840	100.00	11.75	65.3

APPENDIX C

RELATIVE PERMEABILITY DATA

TABLE C-1

RUN NO. 5

$S_w^* = (S_w - S_{wi})/(1 - S_{wi})$ P.V. = 50 cc

$k_{rB} = (S_w^*)^4$ $k_{ro} = (1 - S_w^*)^2(1 - S_w^{*2})$

5.1 Conventional waterflood

$S_{wi} = \frac{50 - 34}{50} * 100 = \underline{32\%}$ $S_w^* = \frac{S_w - 0.32}{0.68}$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.853	.728	.530	.022	.272	.0059	.0111
80	.706	.498	.248	.086	.502	.0434	.175
70	.559	.312	.097	.1945	.688	.1338	1.379
60	.412	.170	.029	.3457	.830	.2869	9.895
50	.265	.070	.005	.540	.93	.5024	100.482
40	.118	.014	.0002	.7779	.986	.7663	3831.275

5.2 Polymer waterflood

$S_{wi} = \frac{50 - 28.5}{50} * 100 = \underline{43\%}$ $S_w^* = \frac{S_w - .43}{.57}$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.825	.680	.463	.0306	.32	.0098	.021
80	.649	.421	.177	.123	.579	.0713	.403
70	.474	.225	.051	.2767	.775	.2144	4.204
60	.298	.0889	.0079	.4928	.9111	.4489	56.835
50	.123	.0150	.00023	.769	.985	.7576	3293.88

5.3 Polymer-Surfactant Waterflood and Surfactant Waterflood

$S_{wi} = \frac{50 - 17}{50} * 100 = \underline{66\%}$ $S_w^* = \frac{S_w - .66}{.34}$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
100	1.0	1.0	1.0	zero	zero	zero	zero
90	.706	.498	.248	.0864	.502	.043	.175
80	.412	.170	.0288	.346	.83	.287	9.964
70	.118	.014	.0002	.7779	.986	.767	3835.165

5'th Brine run will be very close to this (3) & (4) since $S_{wi} = \underline{67\%}$.

TABLE C-2

RUN NO. 2

$$S_w^* = \frac{S_w - S_{wi}}{1 - S_{wi}}$$

$$k_{rB} = (S_w^*)^4 \qquad k_{ro} = (1 - S_w^*)^2(1 - S_w^{*2})$$

2.1. Conventional waterflood

$$S_{wi} = 27.388\% \qquad S_w^* = \frac{S_w - .2739}{.7261}$$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.8623	.7436	.5529	.01896	.2564	.00486	.00879
80	.7246	.5250	.2757	.0758	.475	.036	.13067
70	.5868	.3443	.1186	.1707	.6557	.11195	.9439
60	.4491	.2017	.0407	.3035	.7982	.242	5.952
50	.3114	.0970	.0094	.4742	.903	.4282	45.551
40	.1737	.0301	.00091	.6828	.9699	.6622	747.715
30	.0359	.00129	.0000017	.9295	.99871	.92829	546052.8

2.2. Polymer waterflood

$$S_{wi} = 31.532\% \qquad S_w^* = \frac{S_w - .3153}{.6847}$$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.8538	.7290	.5314	.0214	.271	.00579	.0109
80	.70776	.5009	.2509	.0854	.4991	.0426	.16989
70	.56171	.3155	.0996	.1921	.6846	.1315	1.3202
60	.41566	.1728	.0299	.3414	.8272	.2824	9.4465
50	.26961	.0727	.00528	.5335	.9273	.4947	93.69
40	.12356	.0153	.00023	.7681	.9847	.7564	3288.67

2.3. Polymer-Surfactant waterflood

$$S_{wi} = 36.937\% \qquad S_w^* = \frac{S_w - .3694}{.6306}$$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.84142	.7080	.5012	.025	.292	.0073	.0147
80	.68284	.4663	.2174	.1006	.5337	.0537	.2469
70	.52426	.2748	.0755	.226	.7252	.164	2.174
60	.36568	.1337	.0179	.4024	.8663	.348	19.47
50	.20710	.0429	.00184	.628	.9571	.6017	327.02
40	.04852	.0024	.000006	.905	.9976	.903	150523.0

TABLE C-2

2.4. Surfactant waterflood

$$S_{wi} = 38.739\% \qquad S_w^* = \frac{S_w - .3874}{.6126}$$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.83676	.7002	.4902	.026	.2998	.00798	.0163
80	.67352	.4536	.2058	.106	.5464	.05824	.2829
70	.51028	.2604	.0678	.2398	.7396	.1774	2.616
60	.34704	.1204	.0145	.426	.8796	.3750	25.86
50	.18381	.0338	.00114	.666	.9662	.644	564.6
40	.02057	.004	.0000002	.9593	.9996	.9588	4794497.05

2.5. Conventional waterflood

$$S_{wi} = \frac{55.5 - 31}{55.5} = 44.144\% \qquad S_w^* = \frac{S_w - .4414}{.5586}$$

S_w	S_w^*	S_w^{*2}	S_w^{*4}	$(1-S_w^*)^2$	$(1-S_w^{*2})$	k_{ro}	k_{ro}/k_{rB}
90	.82098	.674	.4543	.032	.326	.0104	.02299
80	.64196	.4121	.1698	.1282	.5879	.0754	.4438
70	.46294	.2143	.0459	.2884	.7857	.2266	4.937
60	.28392	.0806	.0065	.5128	.9194	.47144	72.529
50	.10491	.011	.00012	.8011	.989	.7924	6603.108

APPENDIX D

OIL DISPLACEMENT TESTS

DATA AND CALCULATIONS

TABLE D-1

RUN NO. 1

Run No. 1.1

Core Pore Volume = 50.0 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 37.0 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	5.41
2.0	4.0	--	2.0	4.0	0.08	10.81
2.0	6.0	--	2.0	6.0	0.12	16.22
1.0	7.0	--	1.0	7.0	0.14	18.92
3.0	10.0	0.5	2.50	9.50	0.20	25.68
12.0	22.0	0.8	4.50	14.0	0.44	37.84
10.0	32.0	17.0	1.00	15.0	0.64	40.54
9.0	41.0	25.75	0.25	15.25	0.82	41.22
22.0	63.0	47.0	0.75	16.00	1.26	43.24
17.0	80.0	63.0	1.00	17.00	1.60	45.95
20.0	100.0	83.0	--	17.00	2.00	45.95

TABLE D-1

Run No. 1.2

Core Pore Volume = 50.0 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.13 cp
Initial oil in Place (I.O.I.P.) = 23.5 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P)
2.0	2.0	--	2.0	2.0	0.04	8.51
2.0	4.0	--	2.0	4.0	0.08	17.02
3.0	7.0	--	3.0	7.0	0.14	29.79
2.0	9.0	--	1.0	8.0	0.18	34.04
1.0	10.0	0.5	1.5	9.5	0.20	40.43
4.0	14.0	4.0	0.5	10.0	0.28	42.55
11.0	25.0	14.0	1.0	11.0	0.50	46.81
10.0	35.0	23.0	1.0	12.0	0.70	51.06
5.0	40.0	27.0	1.0	13.0	0.80	55.32
16.0	56.0	32.0	0.5	18.5	1.12	57.45
18.0	74.0	60.0	0.5	14.0	1.48	59.57
13.0	87.0	73.0	--	14.0	1.74	59.57
13.0	100.0	86.0	--	14.0	2.00	59.57

TABLE D-1

Run No. 1.3

Core Pore Volume = 50.0 cc
Oil Viscosity = 1.51 cp
Polymer + Surfactant (P*S) Viscosity = 1.13 cp
Initial Oil in Place (I.O.I.P.) = 22.0 cc

(P*S) Injected (cc)	Cumulative (P*S) Injected (cc)	Cumulative (P*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	9.09
2.0	4.0	--	2.0	4.0	0.08	18.18
2.0	6.0	--	2.0	6.0	0.12	27.27
3.0	9.0	--	3.0	9.0	0.18	40.91
4.0	13.0	2.0	2.0	11.0	0.26	50.00
7.0	20.0	8.0	1.0	12.0	0.40	54.55
10.0	30.0	17.5	0.5	12.5	0.60	56.82
14.0	44.0	31.0	0.5	13.0	0.88	59.09
26.0	70.0	56.5	0.5	13.50	1.40	61.36
30.0	100.0	86.5	--	13.50	2.00	61.36

TABLE D-1

Run No. 1.4

Core Pore Volume = 50.0 cc
Oil Viscosity = 1.51 cp
Surfactant + Brine (B*S) Viscosity = 0.907 cp
Initial Oil in Place (I.O.I.P.) = 21.50 cc

(B*S) Injected (cc)	Cumulative (B*S) Injected (cc)	Cumulative (B*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0	--	3.0	3.0	0.06	13.95
2.0	5.0	--	2.0	5.0	0.10	23.26
2.0	7.0	--	2.0	7.0	0.14	32.56
1.5	8.5	--	1.5	8.5	0.17	39.53
0.5	9.0	--	0.5	9.0	0.18	41.86
3.5	12.5	2.5	1.0	10.0	0.25	46.51
10.5	23.0	12.5	0.5	10.5	0.46	48.84
9.5	32.5	21.5	0.5	11.0	0.65	51.16
46.5	79.0	66.75	1.25	12.25	1.58	58.14
21.0	100.0	87.00	0.75	13.00	2.00	60.47

TABLE D-1

Run No. 1.5

Core Pore Volume = 50.0 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 20.0 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0	--	3.0	3.0	0.06	15.00
2.0	5.0	--	2.0	5.0	0.10	25.00
1.0	6.0	--	1.0	6.0	0.12	30.00
3.5	9.5	--	3.5	9.5	0.19	47.50
1.5	11.0	--	1.5	11.0	0.22	55.00
5.0	16.0	4.0	1.0	12.0	0.32	60.00
5.0	21.0	7.75	0.25	12.25	0.42	61.25
6.25	27.25	14.75	0.25	12.50	0.55	62.50
9.75	37.0	24.25	0.25	12.75	0.74	63.75
3.00	40.0	27.25	--	12.75	0.80	63.75
20.50	60.5	47.45	0.50	13.25	1.21	66.25

TABLE D-2

RUN NO. 2

Run No. 2.1

Core Pore Volume = 55.5 cc
Brine Viscosity = 1.1 cp
Oil Viscosity = 1.51 cp
Initial Oil In Place (I.O.I.P.) = 40.3 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.5	2.5		2.5	2.5	0.045	6.204
2.5	5.0		2.5	5.0	0.090	12.407
4.0	9.0		4.0	9.0	0.162	22.333
1.5	10.5		1.5	10.5	0.189	26.055
2.5	13.0		2.5	13.0	0.234	32.258
8.5	21.5	6.0	2.5	15.5	0.387	38.462
9.5	30.0	13.5	1.0	16.5	0.541	40.943
20.0	50.0	32.0	1.5	18.0	0.901	44.665
28.0	78.0	59.5	0.5	18.5	1.405	45.906
22.0	100.0	81.0	0.5	19.0	1.802	47.146

TABLE D-2

Run No. 2.2

Core Pore Volume = 55.5 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.72 cp
Initial Oil In Place (I.O.I.P.) = 38.0 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0		3.0	3.0	0.054	7.895
2.0	5.0		2.0	5.0	0.090	13.158
2.0	7.0		2.0	7.0	0.162	18.421
3.0	10.0		3.0	10.0	0.180	26.316
9.0	19.0	5.0	4.0	14.0	0.342	36.842
6.0	25.0	8.5	2.5	16.5	0.450	43.421
10.0	35.0	17.5	1.0	17.5	0.631	46.053
15.0	50.0	31.0	1.5	19.0	0.901	50.00
32.5	82.5	63.0	0.5	19.5	1.486	51.316
17.5	100.0	80.5	--	19.5	1.802	51.316

TABLE D-2

Run No. 2.3

Core Pore Volume = 55.5 cc
Oil Viscosity = 1.51 cp
Polymer + Surfactant (P*S) Viscosity = 1.76 cp
Initial Oil in Place (I.O.I.P.) = 35.00 cc

(P*S) Injected (cc)	Cumulative (P*S) Injected (cc)	Cumulative (P*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0		2.0	2.0	0.036	5.714
3.0	5.0		3.0	5.0	0.090	14.286
3.0	8.0		3.0	8.0	0.144	22.857
2.0	10.0	2.0	10.0	0.180	28.571	
3.0	13.0		3.0	13.0	0.234	37.143
4.0	17.0	2.0	2.0	15.0	0.306	42.857
7.0	24.0	7.5	1.5	16.5	0.432	47.143
13.0	37.0	18.5	2.0	18.5	0.667	52.857
13.0	50.0	31.0	0.5	19.0	0.901	54.286
20.0	70.0	49.5	1.5	20.5	1.261	58.571
12.0	82.0	60.5	1.0	21.5	1.477	61.429
18.0	100.0	78.5	--	21.5	1.802	61.429

TABLE D-2

Run No. 2.4

Core Pore Volume = 55.5 cc
Oil Viscosity = 1.51 cp
Surfactant + Brine Viscosity (B*S) = 0.932 cp
Initial Oil in Place (I.O.I.P.) = 34.0 cc

(B*S) Injected (cc)	Cumulative (B*S) Injected (cc)	Cumulative (B*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0		2.0	2.0	0.036	5.882
2.0	4.0	2.0	4.0	0.072	11.765	
3.5	7.5		3.5	7.5	0.135	22.059
2.5	10.0		2.5	10.0	0.180	29.412
12.0	22.0	7.0	5.0	15.0	0.396	44.118
16.0	38.0	21.5	1.5	16.5	0.685	48.529
12.0	50.0	33.0	0.5	17.0	0.901	50.000
20.0	70.0	42.5	0.5	17.5	1.261	51.471
12.0	82.0	64.5	--	17.5	1.477	51.471
18.0	100.0	62.5	--	17.5	1.802	51.471

TABLE D-2

Run No. 2.5

Core Pore Volume = 55.5 cc
Oil Viscosity = 1.51 cp
Brine Viscisoty = 1.01 cp
Initial Oil in Place (I.O.I.P.) = 31.0 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0		3.0	3.0	0.05	9.68
3.5	6.5		3.5	6.5	0.12	21.00
2.5	9.0		2.5	9.0	0.16	29.00
3.0	12.0		3.0	12.0	0.16	38.7
2.5	14.5	1.5	1.0	13.0	0.26	42.0
3.5	18.0	4.5	0.5	13.5	0.32	43.5
12.0	30.0	15.0	1.5	15.0	0.54	48.4
5.0	35.0	38.0	0.5	15.5	0.63	--
18.5	53.5	--	--	--	0.96	--
39.0	92.5	--	--	16.0	1.67	51.61

TABLE D-3

RUN NO. 3

Run No. 3.1

Core Pore Volume = 48.2 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 35.5 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.5	3.50	--	3.5	3.5	0.073	9.86
3.0	6.50	--	3.0	6.5	0.135	18.31
3.5	10.0	--	3.5	10.0	0.207	28.17
1.0	11.0	--	1.0	11.0	0.228	30.99
6.0	17.0	3.0	3.0	14.0	0.353	39.44
6.5	23.5	8.5	1.0	15.0	0.488	42.25
12.5	36.0	20.5	0.5	15.5	0.747	43.66
66.0	102.0	86.0	1.0	16.5	2.116	45.07

TABLE D-3

Run No. 3.2

Core Pore Viscosity = 48.2 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.901 cp
Initial Oil in Place (I.O.I.P.) = 31.0 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
5.0	5.0	--	5.0	5.0	0.104	16.13
2.0	7.0	--	2.0	7.0	0.145	22.58
2.0	9.0	--	2.0	9.0	0.187	29.03
0.5	9.5	--	0.5	9.5	0.197	36.65
7.5	17.0	5.0	2.5	12.0	0.353	38.71
13.0	30.0	16.5	1.5	13.5	0.622	43.55
27.5	57.5	43.0	1.0	14.5	1.193	46.77
17.0	74.5	59.0	0.3	14.8	1.546	47.74
23.5	98.0	82.4	0.8	15.6	2.033	50.32

TABLE D-3

Run No. 3.3

Core Pore Volume = 48.2 cc
Oil Viscosity = 1.51 cp
Polymer + Surfactant (P*S) Viscosity = 1.536 cp
Initial Oil in Place (I.O.I.P.) = 21.5 cc

(P*S) Injected (cc)	Cumulative (P*S) Injected (cc)	Cumulative (P*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.041	9.30
2.0	4.0	--	2.0	4.0	0.083	18.60
2.0	6.0	--	2.0	6.0	0.124	27.91
2.0	8.0	--	2.0	8.0	0.166	37.21
6.0	14.0	3.0	3.0	11.0	0.290	51.16
22.5	36.5	24.0	1.5	12.5	0.575	58.14
9.0	45.5	32.5	0.5	13.0	0.944	60.47
12.5	58.0	44.8	0.2	13.2	1.203	61.40
8.0	6 .0	52.8	--	13.2	1.369	61.40
6.5	72.5	59.3	--	13.2	1.504	61.40
14.5	87.5	73.5	0.3	13.5	1.805	62.79
13.5	100.5	87.0	--	13.5	2.085	62.79

TABLE D-3

Run No. 3.4

Core Pore Volume = 48.2 cc
Oil Viscosity = 1.51 cp
Surfactant + Brine (B*S) Viscosity = 0.9144 cp
Initial Oil in Place (I.O.I.P.) = 18.0 cc

(B*S) Injected (cc)	Cumulative (B*S) Injected (cc)	Cumulative (B*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.25	2.25	--	2.25	2.25	0.047	12.50
2.75	5.00	--	2.75	5.00	0.104	27.78
1.50	6.50	--	1.50	6.50	0.135	36.11
3.50	10.00,	2.0	1.50	8.00	0.207	44.4
5.0	15.00	5.5	0.5	9.50	0.312	52.78
5.0	20.00	10.0	0.5	10.00	0.415	55.56
14.0	34.00	23.5	0.5	10.50	0.705	58.33
22.5	56.50	45.25	0.75	11.25	1.172	62.50
18.0	74.50	62.75	0.50	11.75	1.546	65.278
25.5	100.00	88.25	--	11.75	2.075	65.278

TABLE D-4

RUN NO. 4

Run No. 4.1

Core Pore Volume = 53.0 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 29.0 cc

Brine Injected (cc)	Cumulative Brine Injected (cc)	Cumulative Brine Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Brine Produced (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.7	2.7		2.7	2.7	0.05	9.3
1.4	4.1		1.4	4.1	0.08	14.1
1.8	5.9		1.8	5.9	0.11	20.3
7.6	13.5		7.6	13.5	0.25	46.6
7.5	21.0	6.0	1.5	15.0	0.40	51.7
5.0	26.0	16.0	1.0	16.0	0.49	55.1
14.0	40.0	30.0	--	16.0	0.75	55.1

TABLE D-4

Run No. 4.2

Core Pore Volume = 53.0 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.72 cp
Initial Oil in Place (I.O.I.P.) = 27.00 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumlative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0		2.0	2.0	0.04	7.4
3.1	5.1		3.1	5.1	0.10	18.9
3.4	8.5		3.4	8.5	0.16	31.5
2.0	10.5	0.5	1.5	10.0	0.20	37.0
2.5	13.0	2.0	0.5	10.5	0.25	38.9
⋮	⋮	⋮		⋮		
	200.0	186.5		15.39	3.77	57.00

TABLE D-4

Run No. 4.3

Core Pore Volume = 53.0 cc
Oil Viscosity = 1.51 cp
Surfactant + Brine (B*S) Viscosity = 0.907 cp
Initial Oil in Place (I.O.I.P.) = 29.00 cp

Cumulative (B*S) Injected (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
142.4	17.95	2.68	61.7

Run No. 4.4

Core Pore Volume = 53.0 cc
Oil Viscosity = 1.51 cp
Polymer + Surfactant (P*S) Viscosity = 1.79 cp
Initial Oil in Place (I.O.I.P.) = 20.00 cp

Cumulative (P*S) Injected (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
79.77	13.5	1.51	67.5

TABLE D-5

RUN NO. 5

Run No. 5.1

Core Pore Volume = 50.0 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 34.00 cc

Brine Injected (cc)	Cumulative Brine Injected (cc)	Cumulative Brine Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Brine Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
10.0	10.0	--	10.0	10.0	0.20	29.41
11.0	21.0	9.0	2.0	12.0	0.42	35.29
2.0	23.0	10.0	1.0	13.0	0.46	38.24
1.0	24.0	10.50	0.50	13.50	0.48	39.71
2.0	26.0	12.0	1.0	14.50	0.52	42.65
3.0	29.0	14.50	0.00	14.50	0.58	42.65
3.50	33.50	18.50	0.50	15.0	0.67	44.12
7.75	41.25	25.50	0.75	15.75	0.826	46.32
6.75	48.00	32.25	0.00	15.75	0.96	46.32
9.00	57.00	39.50	1.75	17.50	1.14	51.47
9.50	66.50	49.00	--	17.50	1.33	51.47
5.00	71.50	54.00	--	17.50	1.43	51.47
40.00	111.50	92.50	1.50	19.00	2.23	55.88
70.00	181.50	162.50	--	19.00	3.63	55.88

TABLE D-5

Run No. 5.2

Core Pore Volume = 50.0 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.72 cp
Initial Oil in Place (I.O.I.P.) = 28.50 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
1.0	1.0	--	1.0	1.00	0.02	3.5
2.0	3.0	--	2.0	3.00	0.06	10.5
2.0	5.0	--	2.0	5.00	0.10	17.5
2.5	8.5	--	3.5	8.50	0.17	29.8
1.5	10.0	--	1.5	10.0	0.20	35.1
0.5	10.50	--	0.50	10.50	0.21	36.84
0.25	10.75	--	0.25	10.75	0.215	37.7
0.25	11.00	--	0.25	11.00	0.22	38.59
0.75	11.75	0.25	0.50	11.50	0.235	40.35
0.75	12.50	0.50	0.50	12.00	0.250	42.10
1.00	13.50	1.00	0.50	12.50	0.27	43.85
1.3	14.80	2.00	0.30	12.80	0.296	44.91
0.95	15.75	2.50	0.45	13.25	0.315	46.49
1.25	17.00	3.00	0.75	14.00	0.34	49.12
1.0	18.00	3.50	0.50	14.50	0.36	50.87
1.0	19.00	4.50	--	14.50	0.38	50.87
2.00	21.00	6.00	0.50	15.00	0.42	52.63
1.00	22.00	7.00	0.50	15.50	0.44	54.38
2.50	24.50	8.50	0.50	16.00	0.49	56.14
4.60	29.10	13.00	0.10	16.10	0.582	56.49
6.4	35.50	19.00	0.40	16.50	0.710	57.89
3.0	38.50	21.50	0.50	17.00	0.77	59.65
5.0	43.50	26.00	0.50	17.50	0.87	61.4
3.5	47.00	29.50	--	--	0.94	61.4
2.5	50.50	33.00	--	--	1.01	61.4
5.0	55.50	38.00	--	--	1.11	61.4
9.0	64.50	47.00	--	--	1.29	61.4

TABLE D-5

Run No. 5.3

Core Pore Volume = 50.00 cc
Oil Viscosity = 1.51 cp
Polymer + Surfactant (P*S) Viscosity = 1.79 cp
Initial Oil in Place = 17.00 cc

(P*S) Injected (cc)	Cumulative (P*S) Injected (cc)	Cumulative (P*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.00	3.0	--	3.0	3.0	0.06	17.64
1.0	4.0	--	1.0	4.0	0.08	23.53
1.0	5.0	--	1.0	5.0	0.10	29.41
1.0	6.0	--	1.0	6.0	0.12	35.29
1.0	7.0	--	1.0	7.0	0.14	41.17
1.0	8.0	--	1.0	8.0	0.16	47.05
1.0	9.0	--	1.0	9.0	0.18	52.94
1.0	10.0	--	1.0	10.0	0.2	58.82
1.0	11.0	--	1.0	11.0	0.22	64.70
1.0	12.0	--	1.0	12.0	0.24	70.58
0.3	12.3	--	0.3	12.3	0.246	72.35
0.7	13.0	0.2	0.5	12.8	0.26	75.29
2.0	15.0	2.0	0.2	13.0	0.30	76.47
14.0	29.0	15.0	1.0	14.0	0.58	82.35
10.0	39.0	24.50	0.5	14.50	0.78	85.29
11.0	50.0	35.2	0.3	14.80	1.00	87.05
46.0	96.0	79.0	2.2	17.0	1.92	100.
12.00	108.0	90.7	--	17.0	2.16	100.
10.50	118.5	101.0	--	17.00	2.37	100.

TABLE D-5

Run No. 5.4

Core Pore Volume = 50.0 cc
Oil Viscosity = 1.51 cp
Brine + Surfactant (B*S) Viscosity = 0.907 cp
Initial Oil in Place (I.O.I.P.) = 17.0 cc

(B*S) Injected (cc)	Cumulative (B*S) Injected (cc)	Cumulative (B*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	11.76
0.5	2.50	--	0.5	2.50	0.05	14.70
0.5	3.0	--	0.5	3.0	0.06	17.64
4.0	7.0	--	4.0	7.0	0.14	41.17
2.50	9.50	--	2.5	9.50	0.19	55.88
1.0	10.50	--	1.0	10.50	0.21	61.76
0.5	11.00	--	0.5	11.00	0.22	64.70
1.0	12.00	0.50	0.5	11.50	0.24	67.64
2.0	14.00	2.00	0.5	12.00	0.28	70.58
11.00	25.00	12.50	0.5	12.50	0.50	73.52
2.6	27.6	14.50	0.6	13.10	0.552	77.05
1.1	28.7	15.50	0.1	13.20	0.574	77.65
0.1	28.8	15.50	0.1	13.30	0.576	78.23
10.2	49.0	21.70	3.7	17.00	0.980	100.
99.0	138.0	119.7	--	17.00	2.76	100.
23.3	161.3	142.3	--	17.00	3.226	100.

TABLE D-6

RUN NO. 6

Run No. 6.1

Core Pore Volume = 51.0 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 38.0 cc

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0	--	3.0	3.0	0.06	7.89
1.0	4.0	--	1.0	4.0	0.08	10.53
3.0	7.0	--	3.0	7.0	0.14	18.42
4.0	11.0	1.0	3.0	10.0	0.22	26.32
3.0	14.0	2.0	2.0	12.0	0.27	31.58
4.0	18.0	4.5	1.5	13.5	0.35	35.53
17.0	35.0	19.5	2.5	15.5	0.69	40.79
15.0	50.0	34.0	0.5	16.0	0.98	42.11
60.0	110.0	92.5	1.5	17.50	2.16	46.05
40.0	150.0	131.5	1.0	18.50	2.94	48.68
75.0	225.0	205.5	1.0	19.50	4.41	51.32

TABLE D-6

Run No. 6.2

Core Pore Volume = 51.0 cc
Oil Viscosity = 1.51 cp
Surfactant + Brine (B*S) Viscosity = 0.9072 cp
Initial Oil in Place (I.O.I.P.) = 23.5 cc

(B*S) Injected (cc)	Cumulative (B*S) Injected (cc)	Cumulative (B*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (B*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	8.51
3.0	5.0	--	3.0	5.0	0.10	21.28
2.0	7.0	--	2.0	7.0	0.14	29.79
1.0	8.0	--	1.0	8.0	0.16	34.04
2.0	10.0	0.5	1.5	9.5	0.20	40.43
2.0	12.0	2.0	0.5	10.0	0.24	42.55
3.0	15.0	3.5	1.5	11.5	0.29	48.94
5.0	20.0	7.5	1.0	12.5	0.39	53.19
30.0	50.0	36.0	1.5	14.0	0.98	59.57
50.0	100.0	84.0	2.0	16.0	1.96	68.09
25.0	125.0	108.0	1.0	17.0	2.45	72.34
25.0	150.0	133.0	--	17.0	2.94	72.34

TABLE D-6

Run No. 63

Core Pore Volume = 51.00 cc
Oil Viscosity = 1.51 cp
Polymer Viscosity = 1.72 cp
Initial Oil in Place (I.O.I.P.) = 21.00 cc

Polymer Injected (cc)	Cumulative Polymer Injected (cc)	Cumulative Polymer Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Polymer Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	9.52
2.0	4.0	--	2.0	4.0	0.08	19.05
2.5	6.5	--	2.5	6.5	0.13	30.95
1.5	8.0	--	1.5	8.0	0.16	38.10
2.0	10.0	1.0	1.0	9.0	0.20	42.86
10.0	20.0	4.70	3.3	12.3	0.39	58.57
42.0	62.0	48.0	1.7	14.0	1.22	66.67
38.0	100.0	84.7	1.3	15.3	1.96	72.86
37.0	137.0	120.7	1.0	16.3	2.69	77.62
26.0	163.0	146.2	0.5	16.8	3.20	80.00
17.0	180.0	163.0	0.2	17.0	3.53	85.71
20.0	200.0	183.0	--	17.0	3.92	85.71

TABLE D-6

Run No. 64

Core Pore Volume = 51.00 cc
Oil Viscosity = 1.72 cp
Polymer + Surfactant (P*S) Viscosity = 1.77 cp
Initial Oil in Place (I.O.I.P.) = 19.50 cc

(P*S) Injected (cc)	Cumulative (P*S) Injected (cc)	Cumulative (P*S) Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative (P*S) Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
3.0	3.0	--	3.0	3.0	0.06	15.38
2.0	5.0	--	2.0	5.0	0.10	25.64
2.0	7.0	--	2.0	7.0	0.14	35.90
3.0	10.0	--	3.0	10.0	0.20	51.28
4.0	14.0	3.0	1.0	11.0	0.27	56.41
4.0	18.0	6.0	1.0	12.0	0.35	64.54
32.5	50.5	36.5	2.0	14.0	0.99	71.79
9.5	60.0	45.0	1.0	15.0	1.18	76.92
12.0	72.0	56.75	0.25	15.25	1.41	78.21
27.5	99.5	83.00	1.25	16.50	1.95	84.62
50.5	150.0	133.5	--	16.50	2.94	84.62

TABLE D-6

Run No. 65

Core Pore Viscosity = 51.00 cc
Brine Viscosity = 1.01 cp
Oil Viscosity = 1.51 cp
Initial Oil in Place (I.O.I.P.) = 15.00

Water Injected (cc)	Cumulative Water Injected (cc)	Cumulative Water Produced (cc)	Oil Produced (cc)	Cumulative Oil Produced (cc)	Cumulative Water Injected (PV)	Cumulative Oil Produced (% I.O.I.P.)
2.0	2.0	--	2.0	2.0	0.04	13.33
1.0	3.0	--	1.0	3.0	0.06	20.00
2.0	5.0	--	2.0	5.0	0.10	33.33
1.0	6.0	--	1.0	6.0	0.12	40.00
1.0	7.0	--	1.0	7.0	0.14	46.67
15.3	22.3	10.5	4.8	11.8	0.44	78.67
13.7	36.0	23.5	0.7	12.5	0.71	83.33
39.0	75.0	60.0	2.5	15.00	1.47	100.0
12.8	87.8	72.2	0.6	15.60	1.72	100.0