FOSSIL ENERGY

DOE/BC/10830-1
(DE86000271)

Evaluation of the Storms Pool Improved Waterflood Project

Topical Report

By
Douglass K. Norton
Dwight L. Dauben

March 1986

Performed Under Contract No. AC19-85BC10830

Keplinger Technology Consultants, Inc.
Tulsa, Oklahoma

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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Printed in the United States of America. Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes
Paper copy: **A03**
Microfiche copy: **A01**

DOE/BC/10830-1
Distribution Category UC-92a

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U.S. Department of Energy
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SUMMARY

A review of the performance of the Storms Pool Improved Waterflood Project has been completed. This project was designed to evaluate the efficiency of polymer flooding in a reservoir which had been extensively waterflooded. The project was conducted in a 100-acre pattern in the Waltersburg sandstone of the Storms Pool Field, located in White County, Illinois. This field is typical of many old oil fields in the Illinois Basin. A total of 703,000 barrels of biopolymer-thickened water was injected, which represents about 23 percent of the pore volume. The project was terminated early, as expenses were greatly exceeding revenues.

The project resulted in little or no incremental oil production. The lack of response is attributed mainly to the conditions in which the polymer was injected. The project indicates that the injection of a polymer which acts dominantly to increase viscosity has little potential for increasing oil recovery under the conditions where a waterflood has been successful, the mobility ratio is favorable, and when initiated in the latter stages of the flood. The movable oil saturation is thought to have been lower than anticipated by the operators. Biodegradation of the polymer probably occurred, as evidenced by the lack of polymer in offset wells and in back-produced injection water. The lack of data collected and/or reported prevented a thorough analysis of the project.

Field equipment and procedures appeared adequate for the mixing, filtration, and injection of polymer made up in river water. Some problems occurred during those periods of the year when the river water contained a large amount of dispersed fines. The use of a river water is questioned due to the problems of removing dispersed fines and to the increased protection required to prevent biodegradation of the biopolymer.

This project, along with others, emphasizes the need for biocides which can be conveniently used and are capable of preventing the microbial degradation of biopolymers.

INTRODUCTION

The Storms Pool Improved Waterflood Project was a cost-shared enhanced oil recovery project operated by Energy Resources Company, Inc. (ERCO) and its sub-contractor, Elf-Acquitaine Oil and Gas Company, under Department of Energy Contract No. DE-AC01-78ET12065. Preparation and testing for the polymer flood began in September 1977 and polymer injection was terminated in June 1982. The objective of the cost-shared project was to evaluate the technical efficiency and economic feasibility of polymer enhanced waterflooding as a tertiary recovery process in a heterogeneous sandstone reservoir that had been successfully waterflooded.

The purpose of this report is to provide an appraisal of the project, to suggest ways in which project performance could have been improved, and to emphasize areas needing additional research. This analysis will be helpful in advancing the technology of using polymers for improving oil recovery. This review is conducted with the recognition that hindsight is better than foresight in evaluating the proper procedures. The opinions expressed in this report represent our best judgment. It is possible that other qualified persons will have differing opinions.

This review is based upon information which has been published in Department of Energy reports[1a-e].

BACKGROUND

General Field Background

The Storms Pool Field is located near Carmi, in White County, Illinois (Figures 1 and 2). The producing interval is a Waltersburg sandstone reservoir of Late Mississippian age in the center of the Illinois Basin at 1,800 to 1,900 feet below sea level. Oil was discovered in 1939 and produced by solution gas drive until 1951. In 1953, the bulk of the producing properties was unitized into the Storms Pool Unit and prepared for waterflooding by Sinclair Oil Company. Organized waterflooding was abandoned during the 1970's as wells reached their economic limit or developed mechanical difficulties and were shut-in[1-a].

Pilot Area Geology

The structure map of the Waltersburg sand (Figure 3) shows that the pilot area is over a fairly flat secondary high at a depth of about 1,860 to 1,863 feet on the flanks of the main structural high[1-a]. The original gas cap was located at 1,863 to 1,865 feet below sea level but was considered to be water filled at the time of the polymer injection. The original oil/water transition zone spanned from 1,900 to 1,920 feet below sea level and was not expected to contribute to the oil production during the pilot test. An inactive aquifer, thought to be in communication with other Waltersburg sandstone reservoirs in the area, lies below the water contact at 1,920 feet below sea level. After waterflooding, the target oil layer for the pilot polymer flood averaged 25 feet in gross thickness from 1,865 to 1,890 feet below sea level with roughly 6 to 7 feet of random discontinuous shale streaks. The effective area being flooded in this pilot project is approximately 100 acres over Tracts 9 and 10 of the Storms Pool Unit.

Pilot Area Reservoir Data

Reservoir parameters used in the design of the polymer flood pilot are summarized in Table 1. Well No. 10-5 was drilled by ERCO in July 1978, to obtain further information about the pilot area. Logs and cores from this well were useful in the support of the existing data and in the definition of current fluid saturations.

Definition of the oil saturations was considered a major goal before initiating the polymer flood project. An in-place oil saturation of 40 percent was computed from volumetric estimates and the cumulative oil recovery. An oil saturation of around 40 percent was also computed from the logs on Well No. 10-5. Residual oil saturations were assumed to be 23 percent, based upon the core analyses results shown in Table 2. Although not specified, it is assumed that the retort method was used to determine the oil saturations. The movable oil saturation was determined to be about 17 percent, as shown from the log data in Figure 4.

Relative permeability measurements were measured on two cores from Well No. 10-5. Figure 5 shows the results of a water-oil steady-state relative permeability curve, and Figure 6 shows an unsteady-state water-oil relative permeability curve. Residual oil saturations from both tests were in the range of 30 percent. Figure 5, in particular, is indicative of water-wet behavior. The procedures for handling the cores were not completely described, so it is difficult to make comparisons between the results. Figure 7 shows a fractional flow curve, computed from the data in Figure 5.

The operators considered the appropriate movable oil saturation to be 17 percent pore volume, or 679,000 barrels.

PROJECT DESIGN

Figure 8 shows the pilot area and the locations of the injectors and producers. Tracts 9 and 10 of the Storms Pool Unit were chosen for the enhanced oil recovery pilot due to the originally small gas cap and excellent production history. Injection wells on Tracts 6 and 12 were included to complete the two 5-spot patterns.

The target oil layer underlying the pilot area averaged 25 feet in gross thickness from 1,865 to 1,890 feet below sea level with roughly 6 to 7 feet of random discontinuous shale streaks. ERCO determined the average oil saturation in this oil layer to be 40 percent with a irreducible oil saturation of 23 percent, thus indicating a potential movable oil saturation of 17 percent.

The project was simulated using a two-dimensional stream-tube model provided by Elf-Acquitaine[1-b]. The objective of the simulations was to study effects of polymer slug size and to investigate the effects of a possible field-wide fluid drift. The results of the preliminary simulation efforts were as follows:

Case	Oil Recovered in Excess of Waterflood (barrels)	%OOIP
I. (no drift, 20 mg/g retention)	111,000	4
I. (no drift, 30 mg/g retention)	80,000	3
II. (drift, 20 mg/g retention)	80,000	3

Subsequently, static pressure measurements made in the pilot area indicated that field-wide drift should not significantly affect the flow of injected fluids.

The design specified the injection of 253,000 pounds of Pfizer's Flocon 1035. The polymer was selected in lab tests with six copolymers (polyacrylamides) and two biopolymers (polysaccharides), using the following criteria[1a-e]:

1. Compatibility with river and formation waters.
2. Electrochemical degradation.
3. Mechanical degradation.
4. Resistance factors, residual resistance, and retention rates.
5. Sensitivity to presence of ancillary chemicals.

All polymers tested appeared capable of decreasing the mobility of the injected water. It was decided that the sensitivity of polyacrylamides to salts and shear at the wellbore were negative factors which were difficult to overcome, whereas the microgel formation and susceptibility to microbiological degradation found in polysaccharides were mitigable. Of the polysaccharides tested, Pfizer's Flocon 1035 was judged the best candidate for injection[1-c]. It was determined that delivery of the polymer broth with 2,000 ppm formaldehyde content and treatment of the Wabash River water with 50 ppm Magnacide 480 (a biocide) would suitably prevent microbiological degradation of the dilute injected polymer. Quality control parameters for Pfizer's Flocon 1035 were established as outlined in Table 3.

A tapered polymer slug injection scenario was designed for the Storms Pool pilot by ERCO according to a method described by Claridge.[2] The objective of the design was to minimize viscous fingering by the drive water injected after the polymer slug. The slug design also included a 500 ppm retention buffer pre-flush to account for polymer that would be lost to retention between injection and producer.

PROJECT IMPLEMENTATION

The six injection wells in the pilot area were acidized, reperforated or deepened as necessary to ensure even injection of polymer throughout the formation, and then equipped with two-inch plastic coated tubing. Only one injection well, Tract 12-Well No. 4, required a light hydraulic frac to attain a sufficient injection rate of 6 barrels per minute at 225 psig.

The four original pilot-area production wells and the newly drilled Tract 10-Well No. 5 were equipped with new sucker rods, downhole pumps, and pumping units (160,000 pounds peak torque, 74-inch stroke). Perforations into the water-filled gas cap in Well No. 9-1 were squeezed with cement. All wells appeared capable of producing several hundred barrels per day of total fluid.

The original fresh water supply facility at the Wabash River was refurbished and upgraded to provide the water required for polymer dilution. A tri-filtering system, manufactured by Culligan International Corporation, was installed to filter the river water before polymer dilution. Each of the three filters was indicated to be capable of filtering 75 gallons per minute of water. As the project design only required 100 gallons per minute, the plan was to use two filters at a time while the third was cleaned by back-washing.

A detailed description of the polymer mixing and injection facility can be found in the references[1a-c]. Figure 9 is a schematic showing the facilities for injection of polymer. Separate tanks for injection water, polymer broth, and dilute polymer were installed. The tanks were epoxy coated on the inside to prevent fluid contamination and insulated with polyurethane foam on the outside to prevent freezing of the stored fluids.

Figure 10 shows a chronological flow chart of the significant events associated with the project from October 1980 to December 1982. As can be seen on the flow chart, preflush water injection began on October 21, 1980. Polymer injection at 500 ppm commenced on March 7, 1981, at a rate of about 700 barrels per day. Beginning in September 1981, the polymer broth was mixed with produced water prior to injection, rather than Wabash River water, as produced water disposal had become a problem. Polymer injection, as plotted in Figure 11, continued at 500 ppm until March 1982 and at 400 ppm from March until June 30, 1982. Lower polymer concentrations were not injected, as had been anticipated in the tapered slug design. Produced water was reinjected from July until December 1982, at which time the project was terminated. Total polymer injected was 703,199 barrels or 23.4 percent of pore volume.

Oil production associated with the injection period is plotted in Figure 12. Neither producing water cut information nor total withdrawal rates from the pilot area were published in the annual reports, so it is not known whether the increase in average daily production from a total of 7.8 barrels of oil per day to about 12 barrels of oil per day was due to polymer injection or to other factors such as workovers, injection rates, or withdrawal rates. This oil production increase, even if entirely due to polymer injection, can only be considered meager, both from a technical and an economic viewpoint.

EVALUATION OF PROJECT PERFORMANCE

This discussion addresses the performance of the project and provides our opinions on the specific aspects of the project that might have been better conducted. There appeared to be little or no additional oil recovered from the project. Although a small response is indicated from production data (Figure 12), such response can also be attributed to workovers which may have been conducted concurrently. As later discussed, the inclusion of water production data would have been helpful in determining the amount of incremental oil recovered which can be attributed to polymer. Although the project did not provide a significant amount of tertiary oil, an analysis of the contributing factors will be helpful in future projects. The discussion initially focuses on the overall strategy, and then addresses selected aspects of the project.

Project Suitability

We question the suitability of the Storms Pool as a candidate for a tertiary recovery test of polymer flooding. The favorable waterflood mobility ratio and the large volumes of prior water injection combine to produce conditions that leave little room for further improvement in sweep. The following calculation for a 5-spot geometry, based upon Craig[3], illustrates the low potential for improved oil recovery by polymer flooding for the above conditions. It is recognized that these are generalized correlations and that calculations made using the specific patterns and relative permeability for Storms Pool could produce somewhat different results.

The illustrative calculations were made using Figure 13, from Reference 3. These calculations assumed a permeability variation of 0.7, as reported for Storms Pool and a mobility ratio of 0.6.

The mobility ratio was computed using Figure 5 (steady-state test) and the definition of mobility ratio which is consistent with the correlation shown in Figure 13. It is defined as:

$$M = \frac{K_{rw}}{\mu_w} \cdot \frac{\mu_o}{K_{ro}}$$

μ_o = viscosity to oil

μ_w = viscosity to water

K_{rw} = relative permeability to water when only water is flowing

K_{ro} = relative permeability to oil when only oil is flowing

$$M = \frac{.11}{1} \cdot \frac{6}{1} = .66$$

These calculations indicate the following for initial oil saturation of 72 percent of pore volume.

Waterflood Recovery = 52.7 percent original oil-in-place

Polymer Flood Recovery = 54.7 percent original oil-in-place

(Resistance Factor = 5)

These calculation indicate an approximate 2 percent original oil-in-place incremental increase in oil production, assuming that both a waterflood and a polymer flood were initiated at the same initial oil saturation. Polymer flood recovery would actually be less than computed above, due to adsorption losses and the large volumes (4 to 5 pore volumes) of prior water injected. Also, the incremental oil production would be considerably delayed, which would decrease the present worth of the additional oil. This anticipated oil recovery is in the range of the predictions made by the operators.

The operators pointed out that the waterflood efficiency had been less than hoped. However, it appears on a field-wide basis that much of the problem was related to the loss of fluids into the gas cap and underlying aquifer. Polymer could not correct these types of problems. The pilot area itself had fewer of these types of problems, and waterflood efficiency was reported to be good. In spite of the loss of fluids to the gas cap and aquifer, the overall field-wide recovery from primary and secondary operations was reported to be 43 percent original oil-in-place. Experience, in general, indicates this recovery level is substantial. It would be difficult to obtain significantly higher oil recovery without improving displacement efficiency (as by a process which develops miscibility) or by contacting oil which had been bypassed due to large contrasts in permeability. The failure to detect tracers at offset wells indicates that there were no severe channeling problems.

The above discussion does not infer that polymer flooding is an unsuitable process. Polymer flooding is expected to show significant benefits over waterflooding where the waterflood mobility ratio is poor, oil-wet conditions are involved, and where polymer injection is initiated in the early-to-mid portion of the flood. Polyacrylamides and cross-linked polymers (polyacrylamides or biopolymers) can also be effective in reducing channeling caused by large contrasts in permeability.

Measurement of Movable Oil Saturations

Volumetric and electric log measurements made on Well 10-5 indicated that the oil saturation at the beginning of the polymer flood project was about 40 percent of pore volume. The amount of movable oil was determined by the difference of this saturation and the residual oil saturation as determined by the routine core analysis data shown in Table 2. This residual oil saturation was reported to be 23 percent of the pore volume, which resulted in a movable oil saturation of 17 percent pore volume.

We believe that a 17 percent movable oil saturation is high. First, there are uncertainties in the 40 percent oil saturation due to the known inaccuracies of using well logs for measuring intermediate-range oil saturations. Questions also exist on the saturations from volumetric estimates, due to the compounding of errors in the basic measurements which leads to a final computation, and to the uncertainties in the areal and vertical distribution of the oil. Second, and more important, we believe that the residual oil saturation as determined by the core analysis was too low. Oil is normally expulsed due to the depressurization and gas evolution that occurs as cores are moved to the surface[4]. The degree to which oil is expulsed is difficult to quantify, but is a function of coring methods, rock permeability, amount of gas in solution, and oil viscosity. We anticipate that the residual oil saturation is closer to the 30 percent level, as determined in the relative permeability tests (Figures 5 and 6). Saturations from these procedures would tend to be more accurate since cores are normally resaturated before testing. Even these procedures are subject to uncertainties, since wetting conditions can be changed by the drilling fluid chemicals or by laboratory cleaning processes.

Additional evidence of high water saturations is evidenced by the performance of Well No. 10-5, drilled in July 1978. The well was reported to produce at high water cuts, and contributed little to the oil production. Specific data were not sufficient to perform calculations which would estimate saturations.

Since the question of movable oil saturation was critical to the success of this project, we believe that additional testing should have been performed. A log-inject-log test would have helped to confirm the movable oil saturation. This procedure involves an initial short-term production period to re-establish saturations, the logging of the well using an electric or thermal neutron decay time log, the injection of controlled salinity fluids to establish a residual oil saturation, and relogging of the well with the previously used tool. Alternative procedures include the single-well tracer method, or use of a pressure core barrel or a sponge core barrel.

Data Collection Program

Evaluation of the project was made difficult due to the lack of reported data. The following are parameters, in general, which indicate that polymer is producing beneficial results. These are listed in the approximate order of importance.

1. Reduction in the water-oil ratio at offset producers. Reductions indicate that the polymer has changed the fluid flow distribution within the reservoir. Improved oil recovery is achieved mainly by extending the economic life of the flood. Increases in oil production can be a result of the polymer or of workovers that may have been performed concurrently (e.g., stimulations, recompletions, improved lift equipment). The absence of any water production data for Storms Pool makes the evaluation difficult.

2. Reduced injectivity. If polymer is effective, injection rates will decline or pressures will increase. Data were not available to make an assessment of Storms Pool. However, it was reported that pressure fall-off tests had been conducted and that the mobility of in situ fluids had been reduced.

3. Improved injection profiles. Improvements were reported, but no data were provided for analysis.

4. Other tests. Various other tests can provide indications of effectiveness. These include (1) back-production tests to establish the stability of the polymer, (2) changes in the fluid levels at offset producers, (3) salinity changes at offset producers, and (4) differences in elution profiles if interwell tracers had been injected both before and after polymer injection.

We believe that the collection and/or the reporting of data was not adequate for Storms Pool. The collection of data to evaluate most of the above parameters would have greatly improved the interpretability of the project.

Laboratory Test Program

During 1979, Energy Resources conducted a series of laboratory tests to evaluate the physical and chemical characteristics of several candidate polymers for use in Storms Pool. These tests examined the compatibility of polymers with Waltersburg formation water and Little Wabash River water, rheologic and retentive behavior of polymer solutions in reservoir cores, and polymer solution filterability. These tests, together with polymer cost estimates, provided the basis for polymer selection and slug design.

Initially, it was determined that 100 percent river water would be used for the polymer injection. Mixtures of river water and produced water were considered to be incompatible. For example, precipitation of iron sulfide could occur from the reaction of iron in the river water (from old pumps and water lines) and hydrogen sulfide in the produced water (from sulfate-reducing bacteria). Such solids could plug injection wells.

Laboratory studies were conducted using 100 percent river water and with mixtures of 80 percent river water and 20 percent formation water (to simulate a mixture which could occur in the reservoir). Laboratory tests determined that the viscosity of polyacrylamides was reduced significantly by higher salinity concentrations, whereas, biopolymers demonstrated little sensitivity. It was pointed out that polyacrylamides were shear sensitive, but no estimates were made on the degree to which polymers might be degraded during injection through the perforations into the formation. Other tests indicated that the viscosity of Pfizer's Flocon 1035 biopolymer was increased by addition of biocides, particularly formaldehyde.

A comprehensive core test program evaluated the resistance factor, the residual resistance factor, and adsorption losses for various polyacrylamides and biopolymers. The resistance factor (RF) is the ratio of the mobility to water and the mobility of polymer. The residual resistance factor (RRF) is the degree to which adsorbed polymer reduces the permeability to water. The RF, RRF, and adsorption losses are the key factors in the design of a project.

In general, the core tests indicated typical flow behavior and adsorption losses for the various polymers. These tests demonstrated that biopolymers reduce mobility principally by a viscosity increase, whereas, polyacrylamides reduce mobility both by a viscosity increase and by a permeability reduction. There appeared to be some plugging problems with both the polyacrylamides and biopolymers. Good filtration tended to reduce the plugging problems and decreased adsorption losses.

Filterability tests showed considerable variation among the biopolymers. Pfizer's Flocon 1035 had fewer injectivity problems than competing biopolymer products. It was concluded that the Pfizer product would not need to be filtered in the field through diatomaceous earth as might be required for competing polymers.

Pfizer's Flocon 1035 was selected as the preferred polymer for Storms Pool. It was recognized that this polymer had potential problems related to microgel formation and biodegradation. However, it was considered that these problems could be controlled through proper filtration and the use of biocides. The polyacrylamides were also considered suitable. There were, however, concerns expressed on their sensitivity to salinity and shear. It was indicated that a 500 ppm solution of Flocon 1035 produced an RF of 10, an RRF of 1 to 2, and an adsorption loss of 16.34 mg of polymer/g of rock (95 pounds of polymer per acre-foot of rock).

It is our opinion that the operators did a good job in the laboratory test program. The program was comprehensive and focused on the parameters which are important in the selection of a preferred polymer and in the design of a project. The test procedures appeared suitable and the results appeared typical.

We concur with the operators that the Pfizer Flocon polymer is a good product. Its use in the broth form helps overcome some of the hydration and filtration problems that can otherwise occur when using the dry product.

Having the benefit of hindsight and later industry experience, we do not believe that the biodegradation problems can be as easily controlled as may have been implied. Biodegradation has proved to be a serious problem in the use of biopolymers. We also believe that the shear degradation problems with polyacrylamides may have been overstated. We concur that shear degradation can be a serious problem with polyacrylamides. However, the extent of shear degradation can be predicted and steps taken as necessary to reduce the shearing forces. In addition, partially sheared polyacrylamides can still demonstrate properties which are beneficial in improving sweep efficiency.

As discussed elsewhere, we doubt that the polymer flood as implemented in Storms Pool could have been successful. We do not believe that the injection of a reduced mobility fluid can significantly improve sweep in a reservoir having a favorable waterflood mobility ratio, especially when injected in the latter stages of the waterflood. Polymers can be effective under such conditions if there has been considerable bypassing of oil, arising from large contrasts in permeability. However, a polyacrylamide or cross-linking procedure (using polyacrylamides or biopolymers) would be required to reduce the permeability of contacted areas to subsequently injected water.

Tracer Program

Tracers were injected into the injection wells for the purposes of determining the sweep efficiency of the injected polymer and to define the polymer inaccessible pore volume.

On May 4, 1981, Cobalt-60 was injected into Well No. 12-4 as designed and into Well No. 9-3 by mistake. The inadvertent injection of Cobalt-60 into Well No. 9-3 resulted in the termination of the original plan and a re-design of the tracer program. This was necessary since the source of tracer produced in Well No. 9-1 could not be determined.

On May 7, 1981, tracers were injected into the following wells:

Injection Well	Isotope	Quantity
6-4	CO-57	20 Ci
10-3	HTO	5 Ci
10-1	I-125	30 Ci
9-3	CO-58	100 Ci
9-2	HTO	5 Ci
12-4	CO-57	20 Ci

The injection was conducted successfully and without incident.

Fluids at offset producers were analyzed periodically for tracers. As of the last reported analysis (December 1981), no tracers had been detected at offset wells.

The design as executed on May 7, 1981, generally appears adequate, both in the selection and quantity of tracer. The design, of course, would have been improved if the mistaken injection of Cobalt-60 into Well No. 9-3 had not occurred. The relatively large amount of Cobalt-58 injected appears appropriate, in view of its short half-life (73 days). However, upon the same basis, it appears that a larger quantity of I-125 should have been injected because of its short half-life of 56 days. By comparison, Cobalt-57 has a short life of 270 days, Cobalt-60 a half-life of 5.2 years, and tritated water a half-life of 12.5 years.

The absence of tracer in produced samples over a 7-month period indicates that there were no severe channeling problems. Tracer might have been detected at a later date had the analysis program continued.

Filtration

Figure 9 is a schematic diagram showing the layout of facilities for the project. As indicated, river water was used as the source of injected water. It was used in preference to produced water since polymer properties are known to be more favorable in fresh waters. However, river water is known to create special problems arising from the bacteria in the water, entrained oxygen which is normally not practical to remove, and the presence of dispersed fines. The filtration system must be capable of removing an adequate amount of the fines and must be sufficiently flexible to handle the increased fines content brought about by flooding conditions.

As shown in Figure 9, the basic filtration system consists of (1) cyclone filters, to remove the very large particles; (2) sand filters, to remove the bulk of the solid fines; and (3) cartridge filters, as a final filtration step. Flocculants were added prior to the sand filters to promote the agglomeration of solids, thereby improving the effectiveness of the filters in removing solids.

The injection fluid quality was reported to be good during the injection of preflush water. Water quality was judged in part by turbidity measurements made using a spectrophotometer. Some mechanical modifications were made in the system as a final step before polymer injection.

Polymer injection began on March 7 at a rate of about 700 barrels per day. It was reported that the low rate was due to poor performance of the water clarification system. It was necessary to reduce the filter flow rate and to increase the frequency of the back-flow cycles. Polymer injection was shut down from mid-May through late June due to the high solids content of the river water, brought on by flooding conditions.

Changes were made to improve the performance of the filtration system. These included (1) use of 10 micron cartridge filters upstream and 5 micron filters downstream to improve fluid quality and extend filter life; (2) modifications in the backflush operation to use filtered, rather than unfiltered, water; (3) installation of an auxiliary injection pump and high pressure manifold to allow increased injection pressures; and (4) modifications in the concentration of the chemical flocculants. It was suggested (but apparently not implemented) that upflow sand filters be used to improve total throughput.

These modifications led to improved injectivity of the polymer. In September 1981, produced water was blended with the river water because of the inability to dispose of all of the produced water. Detailed injectivity data are not available for review.

We believe that the operators did a good job in handling the adverse problems encountered in the filtration of the river water. Several points are offered here for discussion.

The selection of the river water can be questioned. As earlier indicated, river water inherently introduces problems related to the bacteria, entrained oxygen, and solids content. It has some advantages arising from the low salinity. However, the biopolymer can perform acceptably well at the salinity level of the produced water (38,000 ppm). The produced water would have advantages in having reduced solids content, significantly less oxygen, and reduced biodegradation problems. The concentration of the polymer would have to be increased somewhat to compensate for the increased salinity. A further alternative would be use of fresh water from shallow zones within the area. This area is known to contain an ample supply of fresh water in various shallow zones.

It was reported that modifications in the equipment allowed for injection pressures up to 750 psi. Parting pressure was indicated to be about 750 psi. It is not clear if injection pressures had been maintained at the 700 psi range. If so, we have concerns that such pressures could exceed the parting pressure level. The resulting injection pressure gradient of 0.80 is higher than the fracture parting level of many reservoirs. Supporting step rate data (not provided in the report) would have been helpful in further assessing the safe pressure operating range. Injectivity problems would have been greatly reduced if the fracture parting pressure had been exceeded. The penalty, however, would be reduced sweep efficiency.

Filtration could have been improved by the use of diatomaceous earth filtration. This type of system is very effective in the removal of solid fines, thereby improving the polymer injectivity over that which could be otherwise obtained. Diatomaceous earth filtration is needed particularly for lower permeability rock. The major disadvantage of diatomaceous earth filtration is the complexity of the operation and the increased personnel training required for operation. For Storms Pool, there appears to be no clear choice, considering both the advantages and disadvantages of competing systems.

Polymer Stability

A major concern in the Storms Pool program has been the resistance of biopolymer to microbial degradation. The biopolymer was expected to be resistant to other potential forms of degradation (e.g., chemical, shear). The following is a discussion of the events of the project which may affect the stability of the polymer.

Preflush water injection began in October 1980. Water was taken from the Little Wabash River. During the final month of preflush injection, the injection plant was purged using a 25 ppm acrolein solution, a potent biocide. The purpose was to sterilize the injection facility so that bacteria would not be present to subsequently degrade the polymer.

Laboratory personnel determined in December 1980, that microbiological activity existed in the water being injected. This appeared to be the result of injecting 18 ppm of the Magnicide 480 (2, 2-dibromo-3-nitrilo-propionamide) instead of the designed 50 ppm. The biocide dosage was consequently increased to the recommended 50 ppm concentration level.

Another site visit was made in January 1981, to evaluate the microbiological activity as well as to make other measurements. The colony counts were unacceptably high, and the biocide concentration was boosted to 100 ppm.

Polymer injection began on March 7, 1981.

Biocide testing continued throughout the year. These tests were conducted to confirm that the proper biocide and concentration were being used. Colony counts were determined to be at very low levels. Tests made in October 1981, indicated that the colony counts were significantly reduced when measured downstream from the point of biocide injection. This indicated that the biocide was inhibiting metabolic activity. Solutions of 2 percent iso-butanol and sec-butanol also appeared to be effective in laboratory tests in preventing viscosity reductions. These, however, were not used in the injection waters. Other work conducted during this period indicated that butanols in combination with formaldehyde were particularly effective in inhibiting microbial activity[5].

In March 1982, concerns were expressed about the condition of the polymer in the reservoir. Plans were made at that time to conduct an injection profile survey, pressure fall-off tests, and a back-production test.

It is reported that the injection profile survey indicated improved fluid distribution within the vertical interval. However, no data were provided to independently assess the results.

It was further reported that the pressure fall-off tests indicated qualitatively an improved in situ viscosity. It was pointed out that such tests are difficult to assess due in part to the non-Newtonian nature of the polymer. Data were not available to make an independent assessment.

A back-production test conducted on Well No. 9-2 on May 21, 1982, indicated (with the exception of one sample) no detectable quantities of polymer. Although disappointing, it was pointed out that there can be various causes for degradation as the polymer is back-produced.

Analyses of produced waters at offset wells failed to confirm the breakthrough of biopolymer.

We believe that the operators recognized the significance of the potential biodegradation problems and took reasonable actions to protect the polymer. Initially, it was determined that biodegradation could be a major problem since river water was to be used for injection. Such waters contain a large amount of bacteria, entrained oxygen, and minerals which serve as nutrients. Introduction of the Xanthan biopolymer provides all of the ingredients for significant biological activity. Remedial actions are designed to control biological activity in the surface facilities, in the wellbore, and in the reservoir near the wellbore. It is generally agreed that significant biological activity will not occur in the interwell area since bacteria are not expected to pass through the matrix of the rock.

Significant biodegradation could have occurred. The absence of any polymer in the back-production test is strong evidence that degradation has occurred. We agree with the operators that various procedures within the test itself can promote degradation or can cloud interpretation. However, we believe that polymer should still have been detected, considering the large quantities which had been injected into the well. Without further documentation of results, we do not believe that the reported improvement in the injection profile or the reduced mobility computed from pressure fall-off tests provide concrete evidence of polymer stability.

Our assessment is that the operators did a good job in monitoring the biological activity and in adjusting the biocide program to control the colony count. The use of acrolein during the preflush stage was intended to sterilize the surface facilities and wellbore areas so that the subsequent polymer would be protected. Acrolein is known to be a very potent biocide, but can be difficult to use because of its toxicity to humans and its tendency to polymerize in the presence of air. The operators thereafter monitored the bacteria count and increased the biocide concentration as necessary.

We believe that the major problem in the program was the failure to achieve a total kill of the bacteria. It is likely that the bacteria became more concentrated at the wellbore because of their inability to propagate through reservoir matrix. Microgels would also tend to accumulate at the injection face, which would lead to a buildup of a high concentration of polymer. Although the biocide could control microbial activity in the surface facilities, the buildup of bacteria and polymer concentrations at the injection face provides conditions which could lead to biodegradation. Once started, the biodegradation process is very difficult to control.

Achieving a total kill of bacteria is very difficult with existing biocides. The acrolein has its limitations as previously discussed. Chlorinated compounds (e.g., chlorine gas, hypochlorite) are also potent biocides and could have been used for achieving a total kill in Storms Pool. However, the use of such compounds also has disadvantages arising from safety concerns and from their corrosive nature. An effective biocide program without excessive corrosiveness can be achieved by maintaining a chlorine biocide concentration slightly in excess (e.g., 1/2 ppm) of that required for a total kill. However, such a program will require a frequent and time-consuming monitoring operation.

Other biocides, such as formaldehyde and glutaraldehyde, have advantages in their ease of use. However, there does not appear to be a biocide which is sufficiently potent and yet not have some significant disadvantages in its use.

CONCLUSIONS

1. The Storms Pool project recovered little or no incremental oil over the original waterflood.

2. The anticipated incremental oil recovery was probably too high, considering that the waterflood had been successful, the waterflood mobility ratio favorable, and large volumes of water had been previously injected.

3. The anticipated movable oil saturation was also thought to be too high, based upon our analysis of log and core data and the watercut at a newly drilled infill well.

4. The laboratory program was well conducted and directed at the key parameters affecting the design and implementation of the project.

5. The field equipment and procedures appeared adequate for the mixing, filtration, and injection of polymer.

6. The choice of river water is questioned, based upon its high solids content which increases filtration difficulties, and the high bacteria count which increases the chances for microbial degradation of the polymer.

7. Biodegradation of the polymer is suspected, based upon the lack of polymer in offset wells and in back-produced samples. Biodegradation may have occurred by the inability of the biocides to achieve a total kill of the bacteria.

RECOMMENDATIONS

We believe that future projects can be improved by more critically examining the suitability of the reservoir for polymer flooding and by using the polymer and procedures that are optimum for the field. It is also very important to incorporate a program for evaluating performance and to implement a data collection program that allows for a proper evaluation of the project.

This project, along with others, has demonstrated the need for a better understanding of the many complex and interrelated factors which influence the degradation of biopolymers. Biocides are needed which can effectively protect biopolymers from microbial degradation. Our judgment is that such a biocide must be convenient to use, economically feasible, and have the capability of achieving a total kill of the bacterial colonies.

REFERENCES

1. Energy Resources Company, "Enhanced Oil Recovery By Improved Waterflooding":

   a. First Annual Report, September 1977 - September 1978, BETC/2541-12.
   b. Second Annual Report, October 1978 - September 1979, DOE/ET/12065-26.
   c. Third Annual Report, October 1979 - September 1980, DOE/ET/12065-38.
   d. Fourth Annual Report, October 1980 - September 1981, DOE/ET/12065-52.
   e. Final Report, October 1981 - December 1982, DOE/ET/12065-66.

2. Claridge, E. L., "A Method of Design of Graded Viscosity Slugs", SPE Paper 6848, 1977.

3. Craig, Forrest F. Jr., "The Reservoir Engineering Aspects of Waterflooding", SPE Monograph, Volume 3.

4. Rathmell, J. J, Braun, P. H., and Perkins, T. K., "Reservoir Waterflood Residual Oil Saturation from Laboratory Tests", Transactions, AIME, 1973, 255, pp. 175-185.

5. "Big Muddy Field Low-Tension Flood Demonstration Project", Fourth Annual Report, April 1981 - March 1982, DOE/SF/01424-45.

TABLE 1

RESERVOIR PARAMETERS - STORMS POOL
POLYMER FLOOD PILOT PROJECT

Type of Reservoir Rock	Consolidated Sandstone
Permeability Range	50 to 900 md
Porosity Range	18 to 22 percent
Wettability	Predominantly Water-Wet
Reservoir Temperature	95°F
Oil Gravity at 95°F	35.0° API
Oil Viscosity at 95°F	6.0 cp
Pilot Area	100 acres
Acre Feet of Oil Sand	2,100
Average Net Sand Thickness	60 feet
Average Oil Sand Thickness	35 feet
Initial Oil Saturation	72 percent PV
Primary Oil Recovery	16 percent PV
Waterflood Oil Recovery	15 percent PV
Present Oil Saturation	40 percent PV
Average Residual Oil Saturation	23 percent PV
Average Movable Oil Saturation	17 percent PV

TABLE 2

TRACT 10-WELL 5 CORE ANALYSIS
(SOURCE: OILFIELD RESEARCH, INC.)

Depth, Subsea	Permeability Horizontal	Permeability Vertical	Porosity, Percent	Saturation Percent Oil	Saturation Percent Water
1,860	0.10	0.10	12.5	0.0	88.2
1,862	0.10	0.10	11.3	0.0	97.8
1,864	0.44	0.10	11.5	0.0	93.5
1,866	1.8	1.8	11.3	20.2	47.8
1,867	0.10	0.10	12.3	5.4	70.4
1,868	2.1	0.10	11.8	14.0	62.5
1,869	41	23	16.7	33.8	38.0
1,870	51	33	13.6	23.3	36.8
1,871	82	20	15.3	26.6	26.2
1,872	156	111	16.9	27.8	45.8
1,873	79	7.3	20.0	23.9	33.7
1,874	115	86	17.8	10.3	32.1
1,875	0.10	0.10	8.3	0.0	48.5
1,876	0.10	0.10	7.1	0.0	42.9
1,877	28	14	18.5	9.6	19.3
1,878	596	31	17.4	27.0	52.7
1,880	277	630	20.8	23.9	47.8
1,882	913	794	21.9	20.2	35.4
1,884	403	20	18.9	25.7	34.9
1,886	311	333	22.4	26.7	50.0
1,888	820	596	21.0	18.4	39.4
1,890	340	58	19.5	28.2	42.4
1,892	307	746	20.6	22.0	47.3
1,894	389	364	22.8	19.4	48.5
1,896	353	225	20.1	22.5	42.8
1,898	280	626	20.3	19.4	52.8
1,900	71	48	18.3	30.0	28.8
1,902	102	94	17.9	25.6	32.1
1,904	89	10	19.0	20.6	35.7
1,906	87	119	16.6	20.4	26.4
1,908	199	8.5	18.5	23.1	32.1

Averages

1,866-1,878	75	40	15.9	23.7	37.2
1,878-1,909	346	294	19.8	23.3	40.6

TABLE 3

QUALITY CONTROL PARAMETERS FOR POLYSACCHARIDE INJECTION FLUID

Test	Acceptable Range	Frequency
Filterability in 1.2-Micron Filter		
Millipore Filter Ratio	1.0 - 1.3	every batch
Total Filtration Time	1,000 sec/liter max.	every batch
Viscosity at 500 ppm		
In Wabash River Water	7 - 9 cp	every batch
In Pfizer Standard Water	9 - 11 cp	every batch
Active Content		
Viscosity Methods	2.6 percent minimum	every batch
Total Carbohydrate Method	2.5 percent minimum	as needed
Formaldehyde Content	2,000 ppm	as needed

FIGURE 1

PROJECT LOCATION

STORMS POOL PROJECT
WHITE COUNTY, ILLINOIS

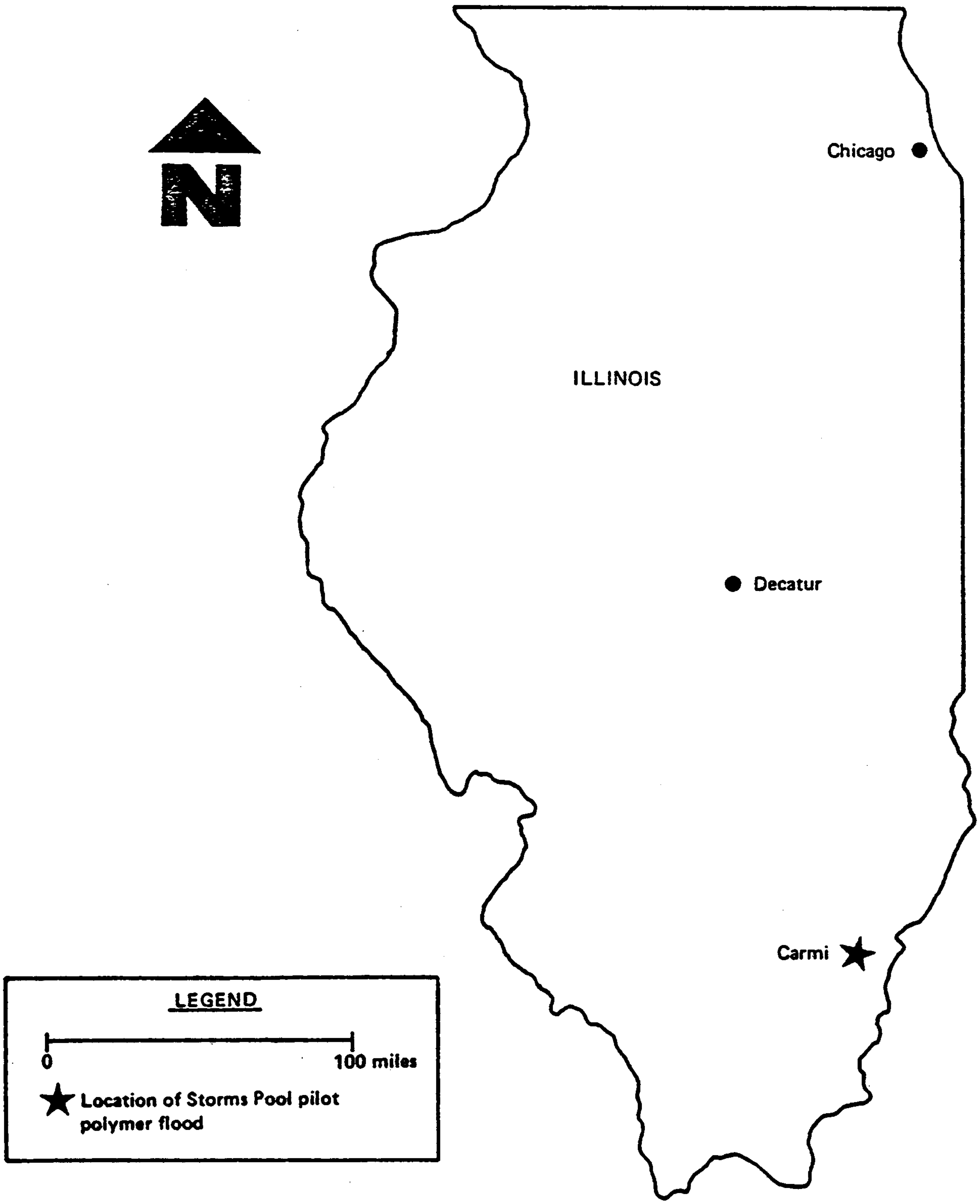


FIGURE 2

THE STORMS POOL PILOT POLYMER FLOOD
WHITE COUNTY, ILLINOIS

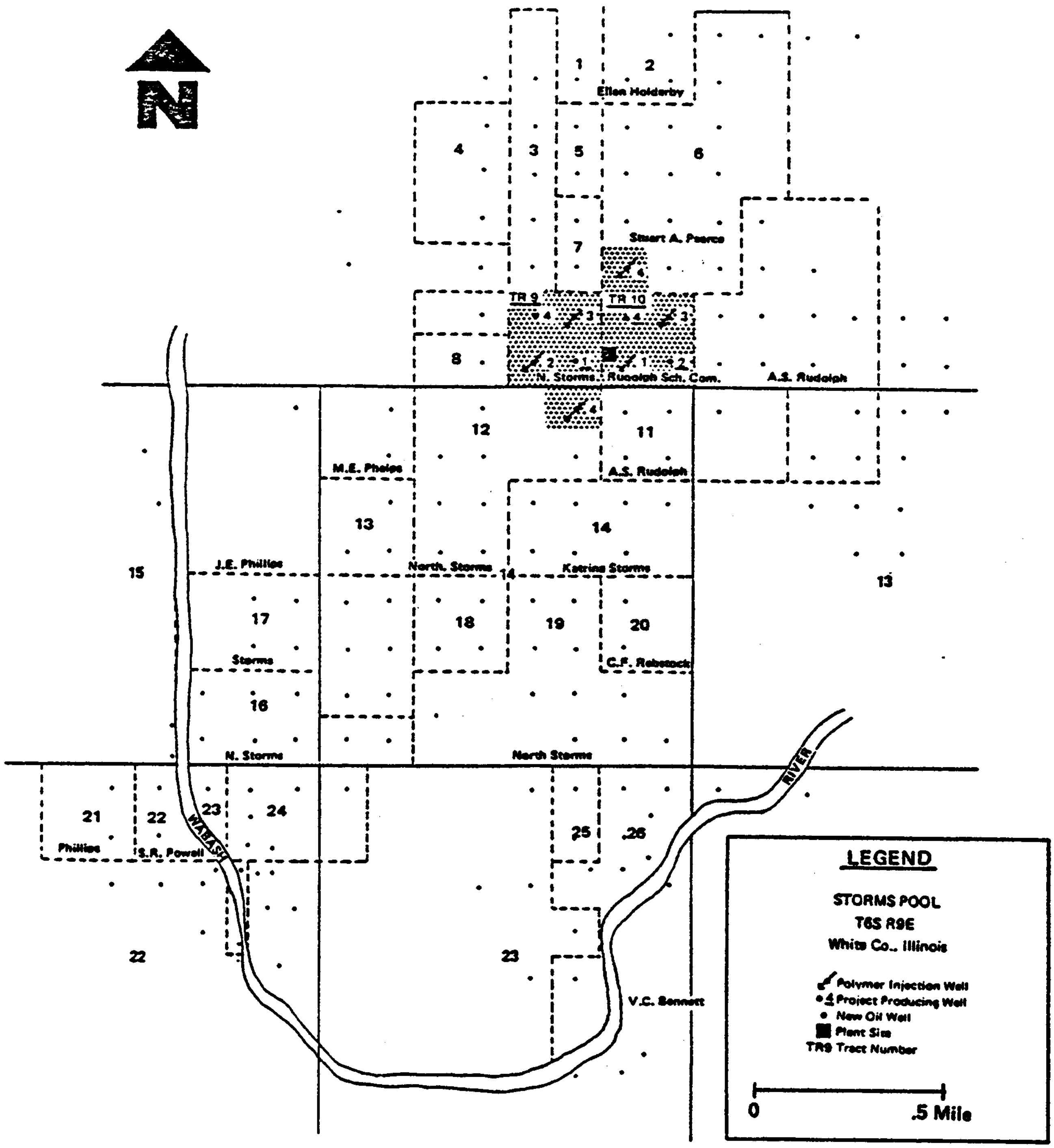


FIGURE 3

WALTERSBURG SAND STRUCTURE

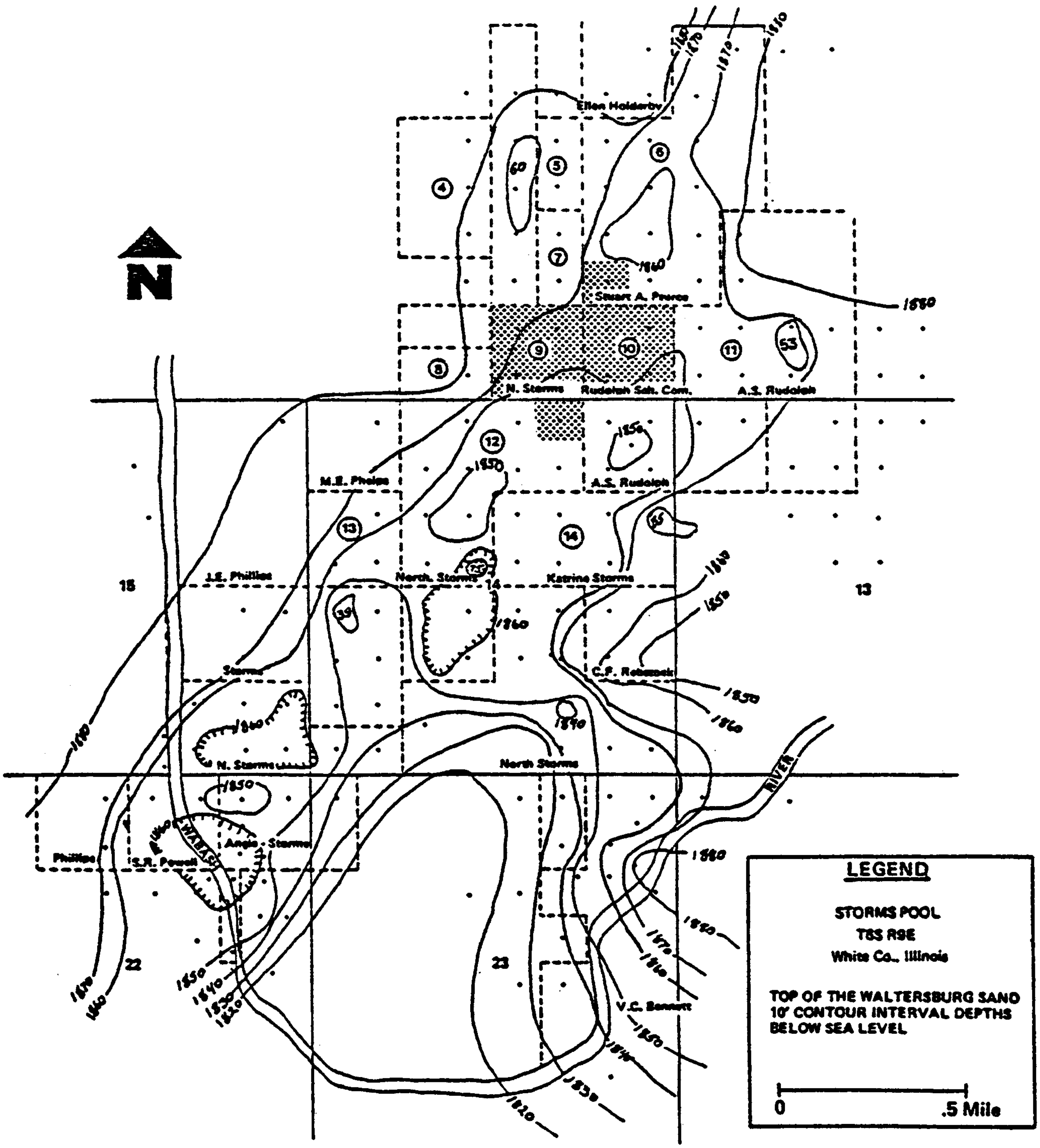


FIGURE 4

MOVABLE OIL SATURATION
(WELL NO. 10-5, DUAL INDUCTION LOGS)

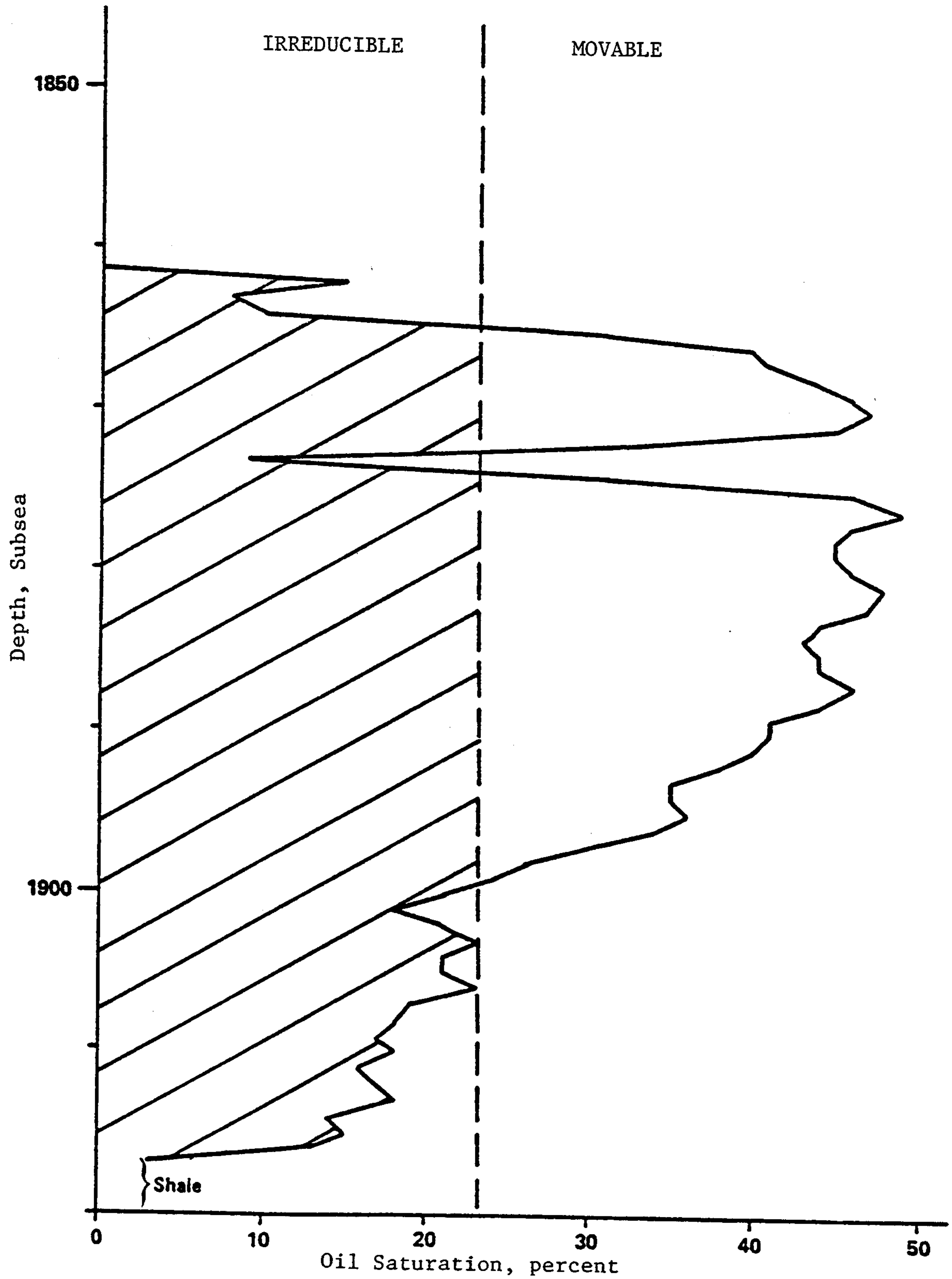


FIGURE 5

STEADY-STATE WATER-OIL RELATIVE PERMEABILITIES

RUDOLPH SCH. COM. WELL NO. 10-5
STORMS POOL FIELD
WHITE COUNTY, ILLINOIS
DEPTH: 2,293 FEET

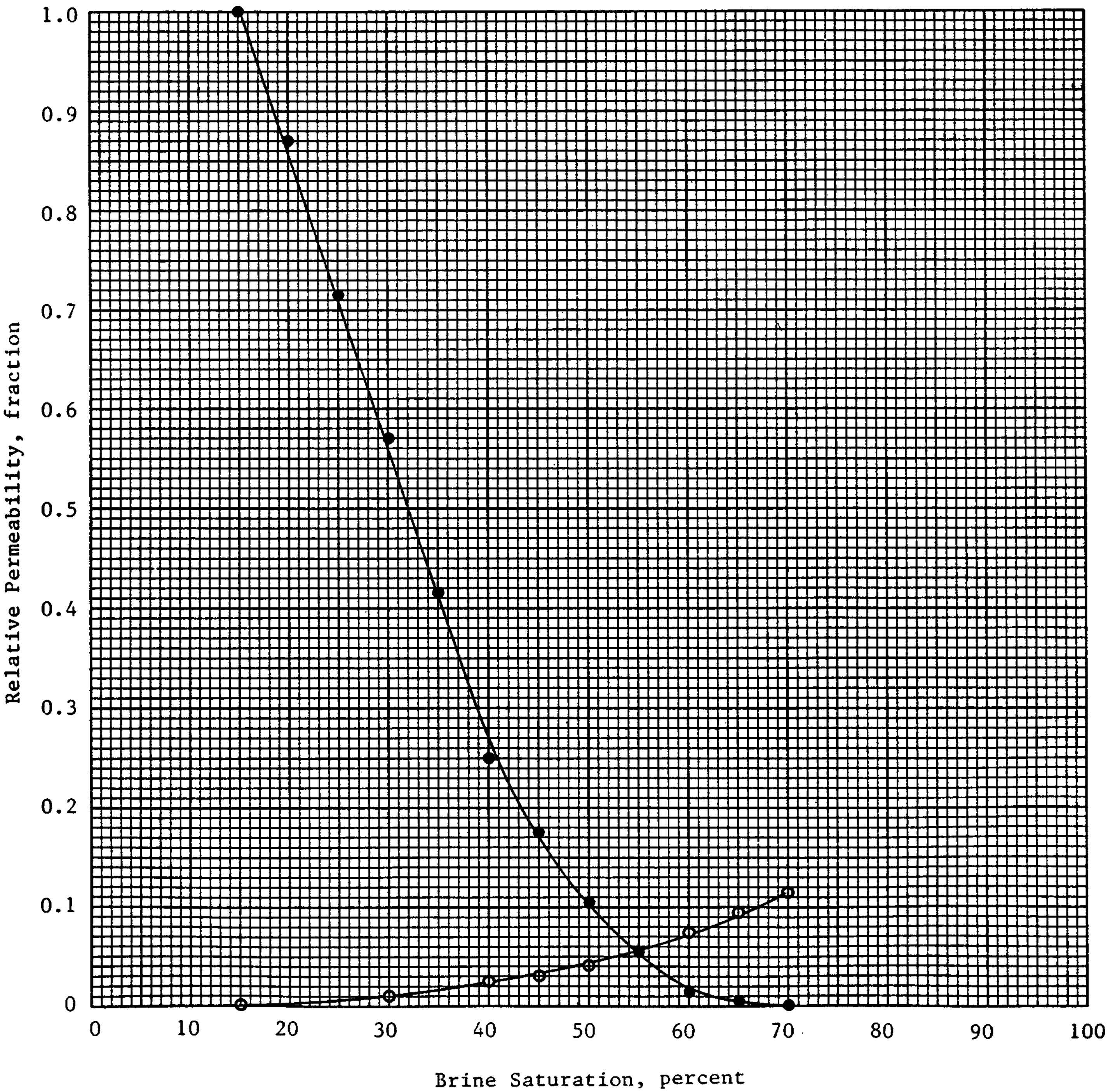


FIGURE 6

UNSTEADY-STATE WATER-OIL RELATIVE PERMEABILITIES

RUDOLPH SCH. COM. WELL NO. 10-5
STORMS POOL FIELD
WHITE COUNTY, ILLINOIS
DEPTH: 2,284 FEET

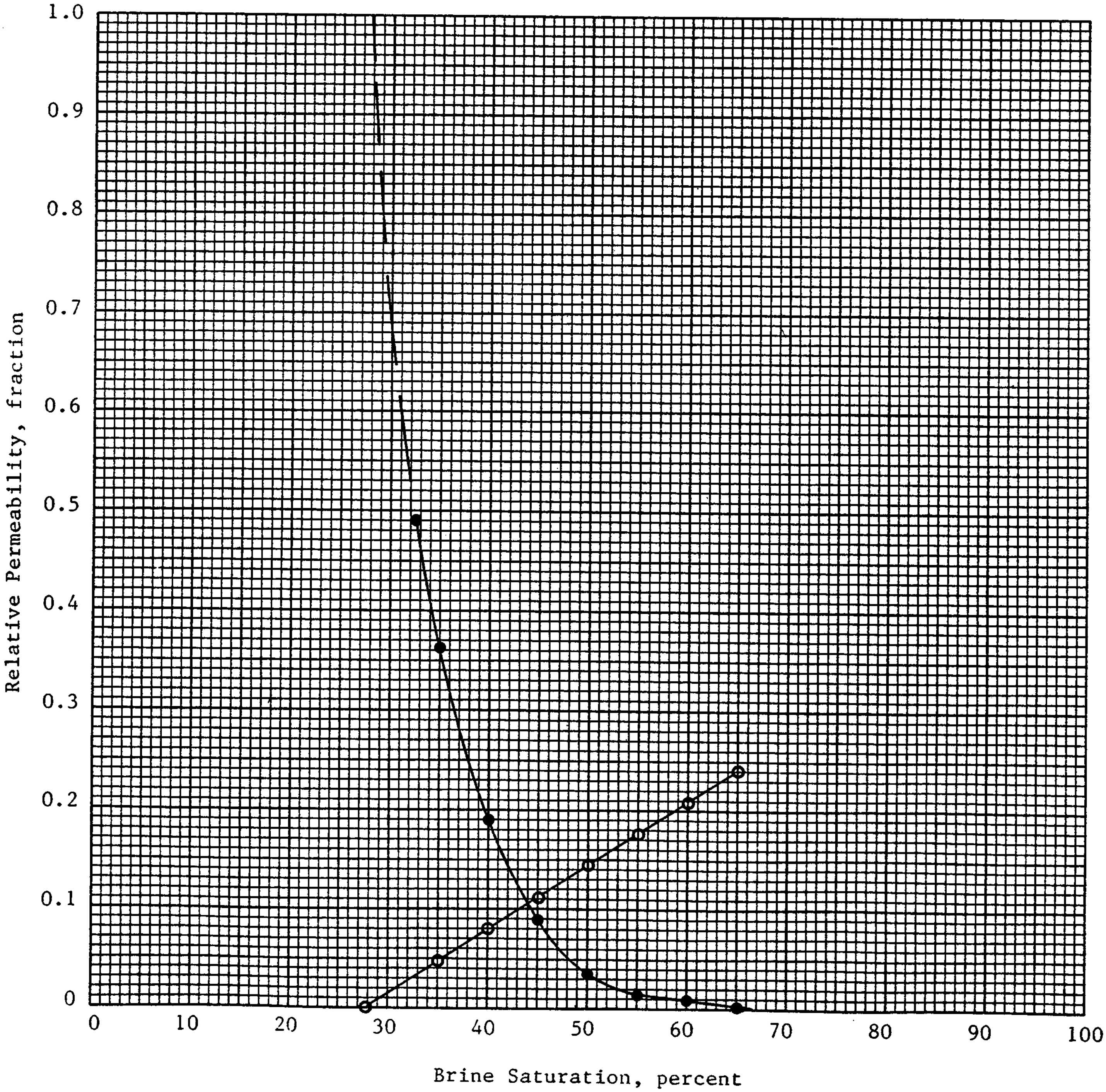
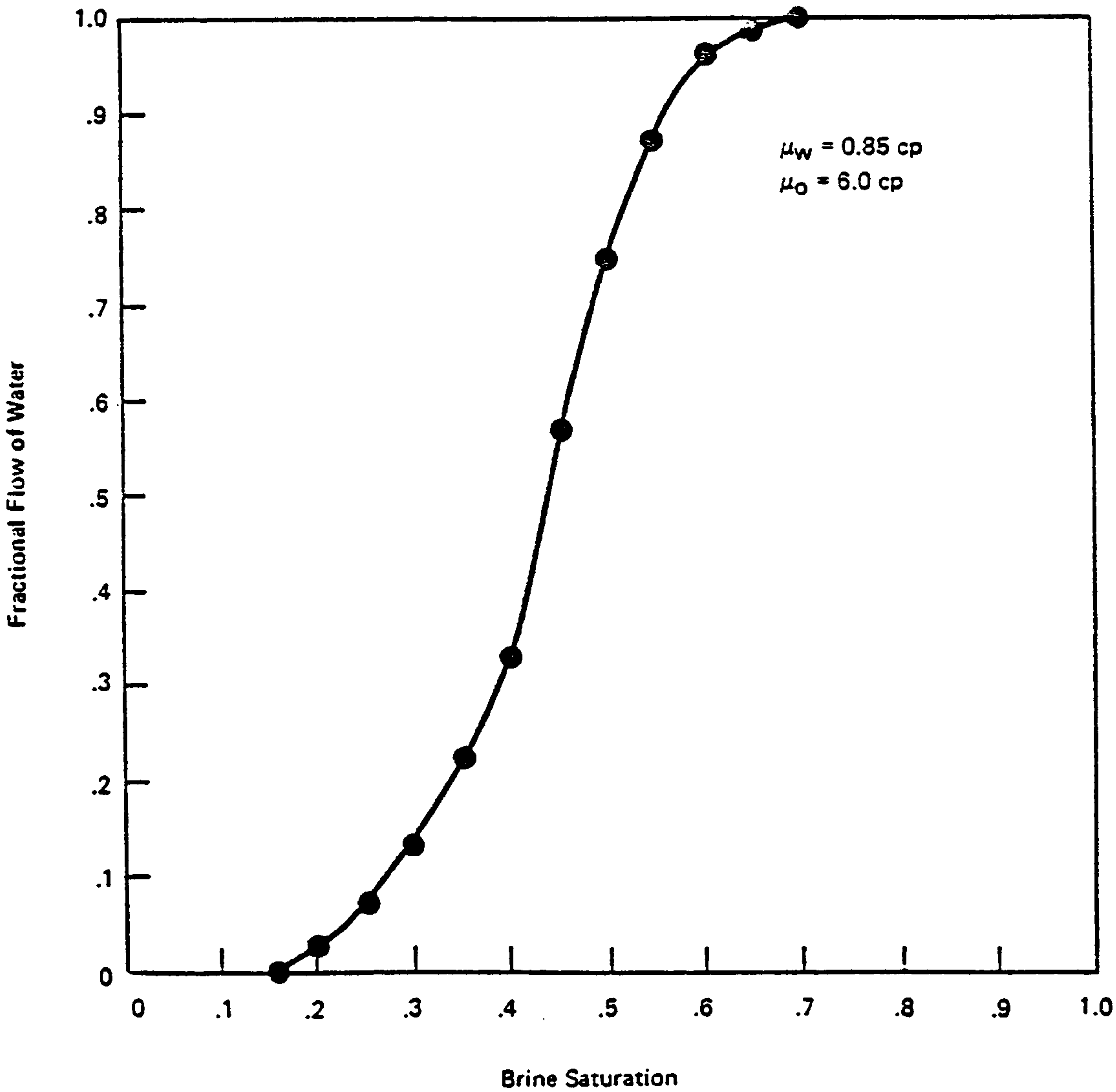


FIGURE 7

FRACTIONAL FLOW OF WATER VS. BRINE SATURATION
AT WELL NO. 10-5
(AS MEASURED BY ELF-AQUITAINE)

STORMS POOL PROJECT
WHITE COUNTY, ILLINOIS



Storms Pool, Rudolph 5
White County, Illinois
Measured by Elf-Aquitaine, Inc.
10 August 1979

FIGURE 8

PROJECT LAYOUT

STORMS POOL PROJECT
WHITE COUNTY, ILLINOIS

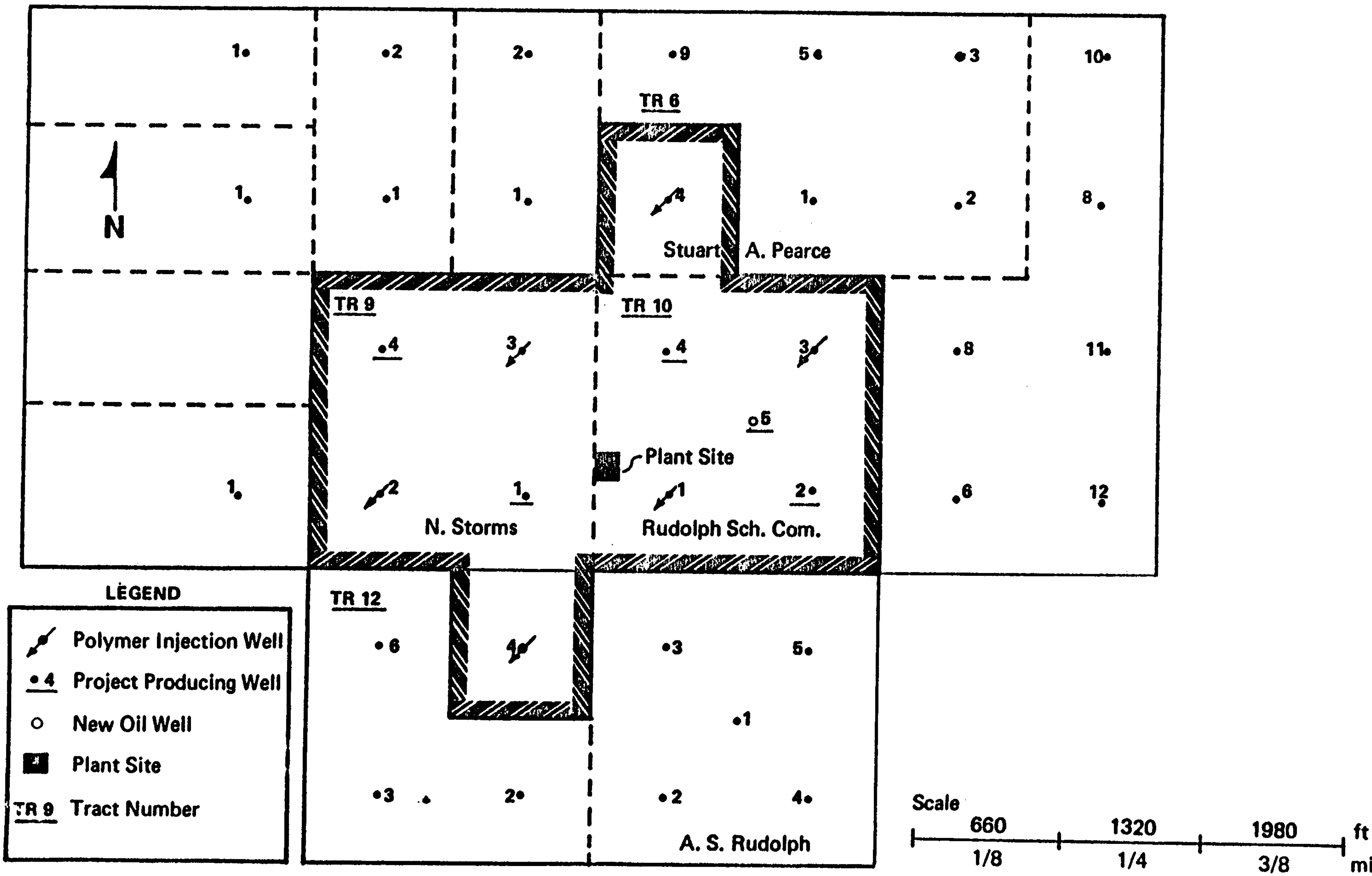


FIGURE 9

LOCATIONS OF SAMPLING STATIONS AT STORMS POOL UNIT

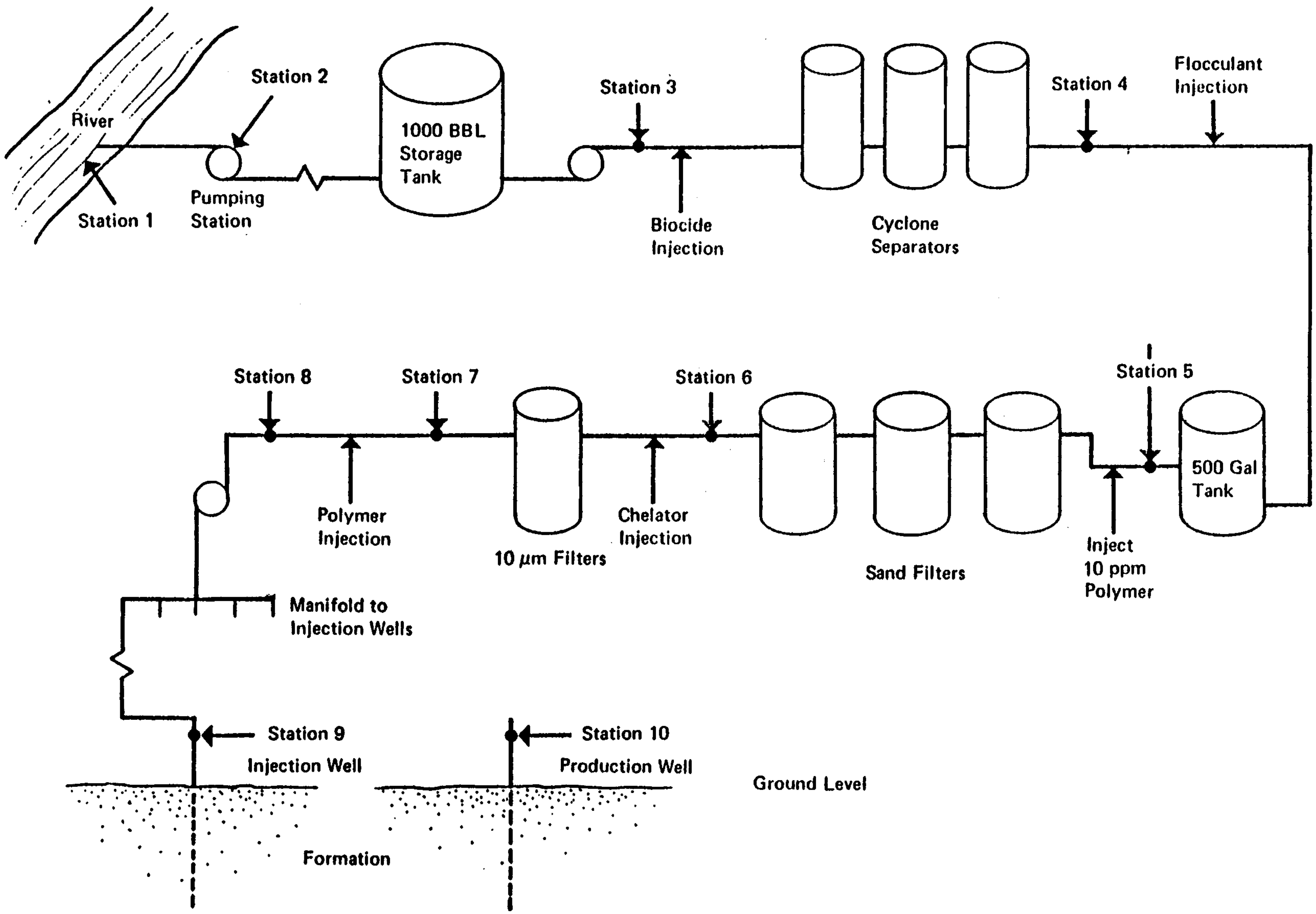


FIGURE 10

SIGNIFICANT EVENTS IN THE STORMS POOL PROJECT

```
   1980                              1981                                                   1982
10  11  12   1   2   3   4   5   6   7   8   9  10  11  12   1   2   3   4   5   6   7   8   9  10  11  12

XXXXX
Preflush injection (discontinuous)

    XXXXXXXXXXXXXXXXXXXXX
    Preflush (continuous) with 50 ppm magnacide 480

              XXXXXXXXX
              Purge System with 25 ppm Acrolein

                   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
                   1035 Injection                  Flocon 4800 Injection

                         XXXXXXXX
                         Polymer Shut-in due to Floods

                                   XXXXXXXXXXXXXXXXXX
                                   Produced Water used for Polymer

                   XXXXX
                   Solids Problems in Polymer (iron oxide, sloughed polymer)

             XXX
             Interference Test

                       XXX
                       Injection of Tracers

                                         XXX
                                         Analysis of Polymer in Producers

                                 XXXXXXX
                                 Analysis of Bacteria in Injection Water

                                                 XX
                                                 Polymer Concentration reduced
                                                 from 500 ppm to 400 ppm

                                                           XX
                                                           Elf Aquitaine Withdrew Support

                                                      XX
                                                      Back-Production Test

                                                      XX
                                                      Injection Profile

                                                        XX
                                                        Surfactant Addition to Improve Injection
                                                        (70 ppm Triton X-100)

                                                           XXXXXXXXXXXXXXXXXXXXXXXX
                                                           Water Injection
```

FIGURE 11

POLYMER INJECTION HISTORY

STORMS POOL PROJECT
WHITE COUNTY, ILLINOIS

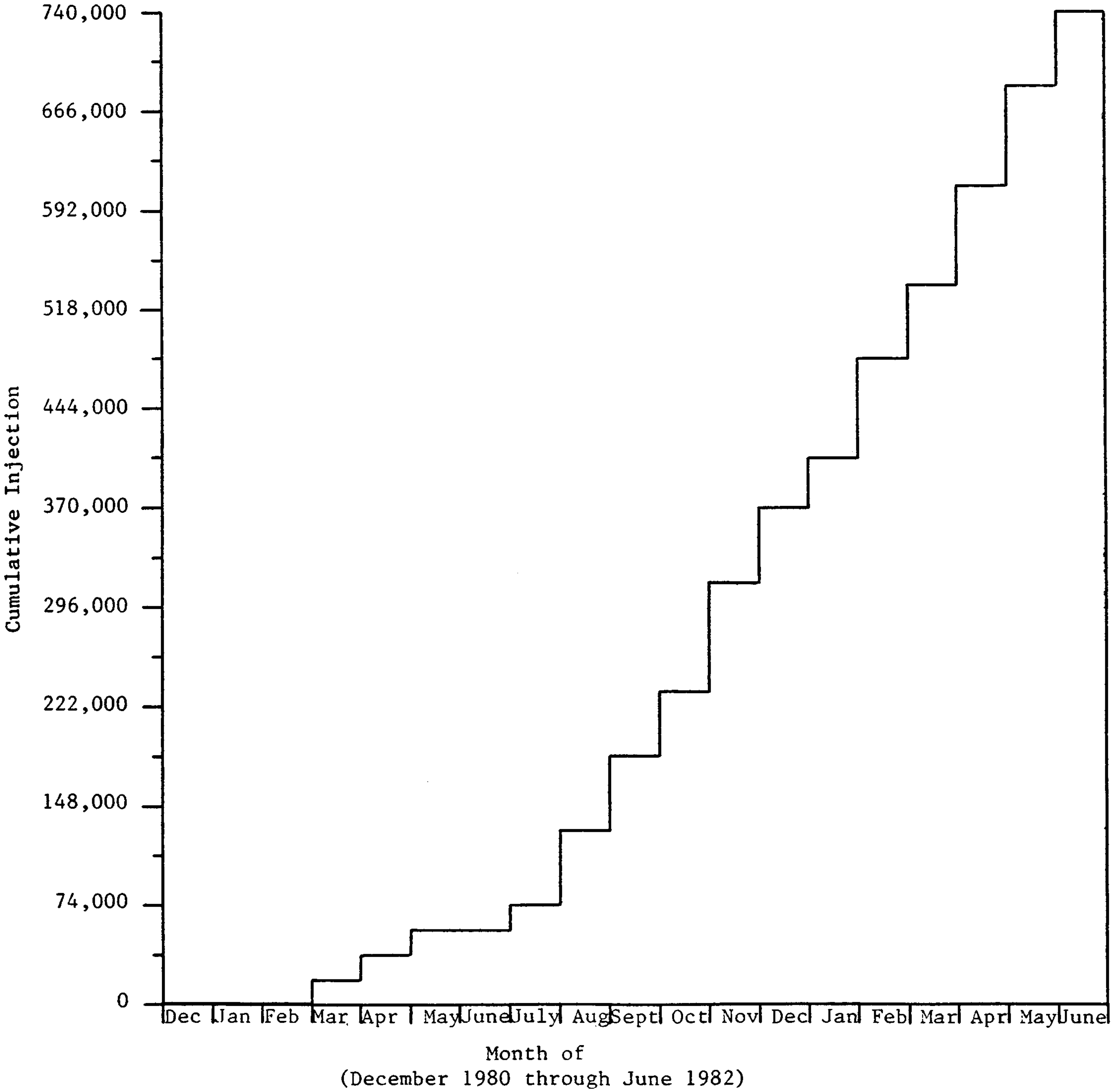


FIGURE 12

OIL PRODUCTION HISTORY
STORMS POOL IMPROVED WATERFLOOD

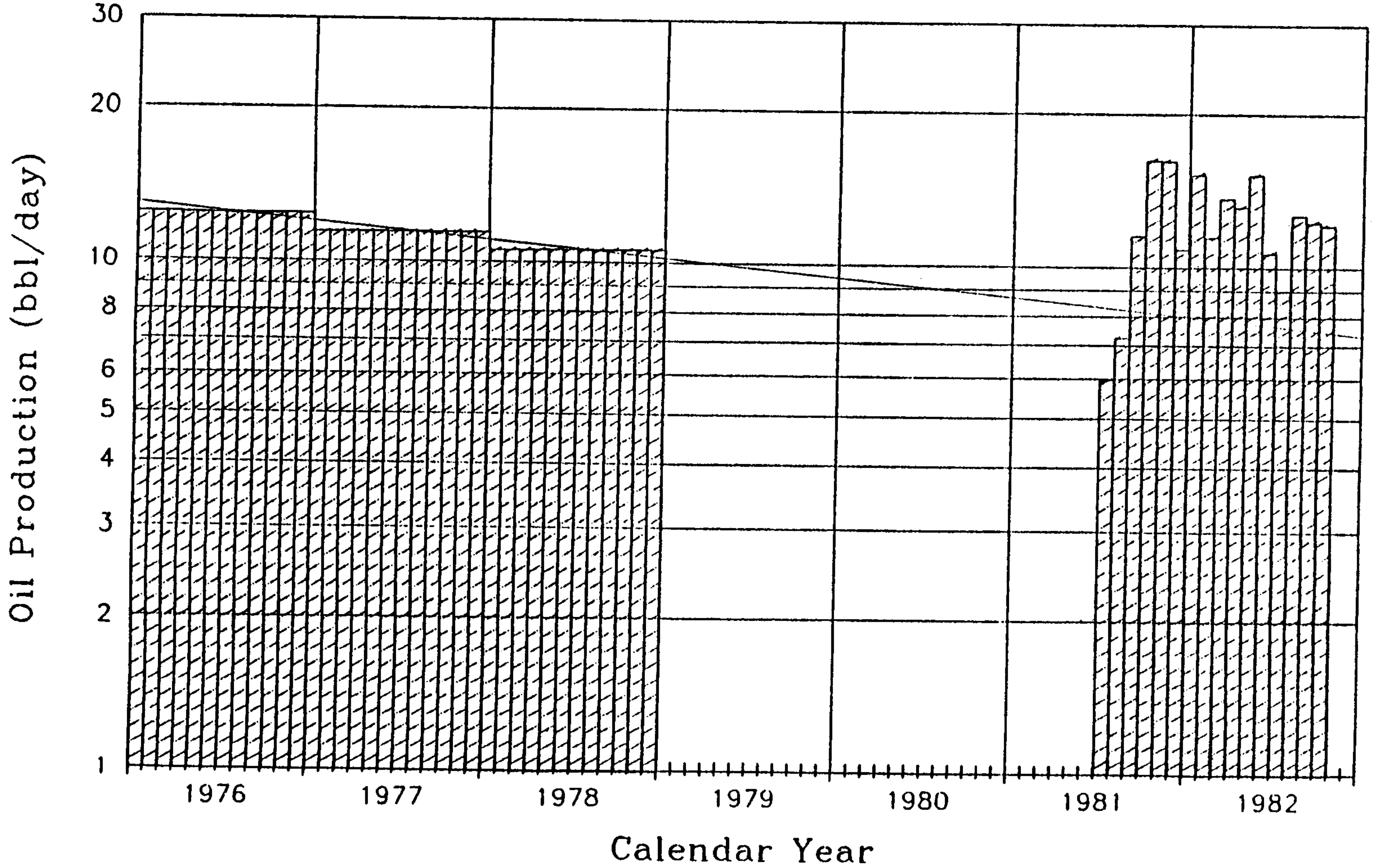
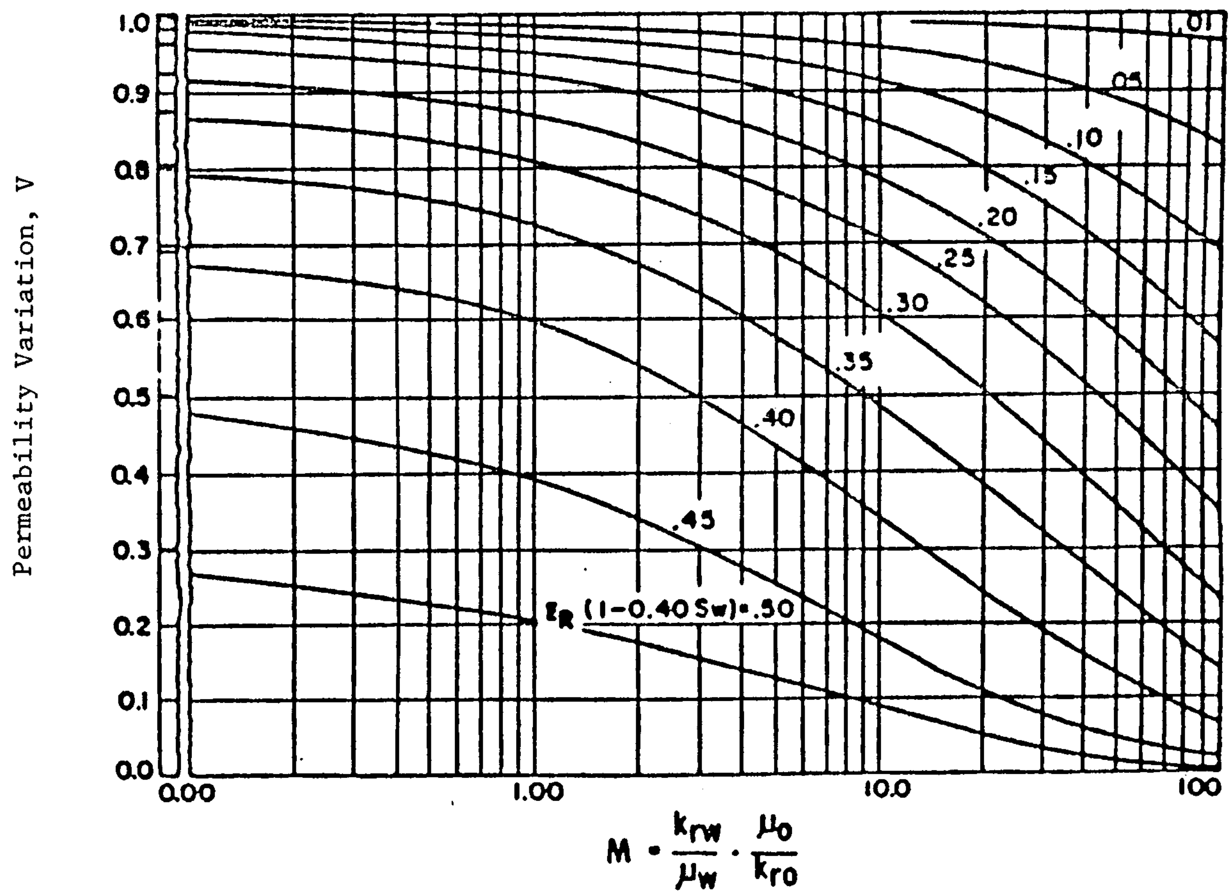


FIGURE 13

PERMEABILITY VARIATION VS. MOBILITY RATIO
SHOWING LINES OF CONSTANT E_R (1 - 0.40 Sw)
FOR A PRODUCING WOR OF 100[3]

STORMS POOL PROJECT
WHITE COUNTY, ILLINOIS



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