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ENHANCED OIL RECOVERY BY IMPROVED WATERFLOODING

Third Annual Report
October 1979 - September 1980

Work Performed for the Department of Energy
Under Contract DE-AC19-78ET12065

Date Published—April 1981

Energy Resources Co. Inc.
Houston, Texas

U. S. DEPARTMENT OF ENERGY

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ENHANCED OIL RECOVERY BY IMPROVED WATERFLOODING

**Third Annual Report
October 1979 - September 1980**

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Date Submitted—November 1980

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SECTION ONE

INTRODUCTION AND SUMMARY

Energy Resources Co. Inc. and its subcontractor Elf-Aquitaine Oil and Gas Company are conducting a 100-acre pilot polymer flood in the Storms Pool Field near Carmi, in White County, Illinois (see Figure 1). The project is a cost-sharing venture in which the United States Department of Energy (DOE) bears \$1,579,189 of the \$3,750,144 project costs. Preparation for the polymer flood began in September 1977, under DOE Contract Number DE-AC19-78ET12065, and the project is scheduled for completion in December 1983. This report reviews progress during the third year of performance (October 1979 through September 1980). Progress during the first year is reported in DOE document BETC/2541-12, "Enhanced Oil Recovery by Improved Waterflooding: First Annual Report," while progress during the second year is reported in DOE document DOE/ET/12065-26, "Enhanced Oil Recovery by Improved Waterflooding: Second Annual Report."

The Storms Pool is typical of many old fields in the Illinois Basin which are candidates for enhanced oil recovery. Once highly productive, the field has yielded over 12 million barrels of oil from the Waltersburg formation since its discovery in 1939. The field has been waterflooded for over 20 years and is now largely in stripper production with high watercuts at most producing wells. Material balance and recent electric logs indicate, however, that there is a substantial volume of movable oil still in place, presumably bypassed by the inefficient waterflood. The polymer flood is intended to improve the sweep efficiency, showing that the engineering, management, and financial resources required for such tertiary techniques can be applied to similar fields that might otherwise be abandoned for lack of investment by parties knowledgeable in enhanced oil technology.

The first annual report reviewed the groundwork upon which much of the second year's work was based. That report included a geologic analysis of the Storms Pool and its production potential, the rationale for the selection of a pilot site (shown in Figure 2), some preparation of wells and facilities, an extensive plan for testing candidate polymers in the laboratory, and a proposed approach to the computerized simulation of the pilot polymer flood. The second annual report reviewed a year of intensive laboratory, design and field work, including a reservoir and well test program, the results of the polymer selection and additional laboratory testing, workovers and construction of facilities,

Figure 1. Location of the Storms Pool pilot polymer flood.

Figure 2a. The Storms Pool and location of the pilot area.

Figure 2b. Layout of Storms Pool pilot facilities.

preliminary reservoir simulation, and program support activities. This report discusses the final polymer selection, design of the graded polymer banks, results of reservoir pressure tests and plans for continued testing, and completion of basic plant construction. An updated milestone chart is also presented which takes into account the unexpected delays encountered to date. Because the second report actually covered a 15-month period, this report will overlap somewhat with information contained in the second report.

Pfizer Chemicals Division's Flocon 1035 polysaccharide was selected for use in this project over 11 other polymer candidates. These other candidates included eight polyacrylamides and three polysaccharides in dry and liquid forms. Experimental laboratory studies by Energy Resources, Core Laboratories of Dallas, and several polymer vendors provided considerable information on polymer compatibility with injection and formation brines, rheologic and retentive behavior of the polymer in reservoir cores, and filterability (or injectability) of the polymers. The Pfizer Flocon 1035 biopolymer broth showed the expected low susceptibility to shear degradation at the anticipated wellbore injection rates and also presented a high tolerance to the saline formation brine. An agreement has been signed with Pfizer to provide the polymer required for the Storms Pool Project.

The laboratory data obtained using the Pfizer biopolymer were utilized to aid in the design of the graded polymer slug. The purpose of this graded slug is to prevent viscous fingering at the trailing edge of the polymer slug from collapsing the slug. This graded slug also features buffers against polymer retention and viscous fingering at the upstream edge.

Static pressure tests were made to determine the reservoir drift to be encountered in the Waltersburg formation. This drift was found to be insignificant, which suggests that the polymer flood will be easily contained within the pilot pattern. Interference tests are planned to begin soon.

Plant construction is now completed. Numerous delays were experienced including unauthorized substitution of equipment, faulty equipment, and delivery schedule revisions. Most management difficulties have now been solved and smoother, more timely operation of the project is anticipated. A milestone chart, updated to account for these delays, is presented in the Program Support section.

Water injection for preflush will be initiated by November 1. After about 2 months of preflush (representing about 10 percent pore volume) and plant shakedown operation, polymer injection will be initiated. Initial oil production due to polymer is expected after about 120 days of polymer injection. Reservoir simulation studies predict that about 100,000 barrels of additional oil will be recovered by this improved waterflood.

SECTION TWO

POLYMER SELECTION AND SLUG DESIGN

During the second and third years of this project, Energy Resources conducted a series of laboratory tests to determine the physical and chemical characteristics of several polymers chosen as candidates for field use. These tests examined the compatibility of polymers with waters from both the Waltersburg formation and the Little Wabash River, rheologic and retentive behavior of polymer solutions in reservoir cores, and polymer solution filterability. Data from this program and cost estimates were used to determine the final selection of polymer and to aid in the design of a graded slug for injection.

Two basic types of polymers have been examined: polyacrylamides and polysaccharides. Twelve polymers from nine manufacturers were evaluated; eight of the polymers were polyacrylamides and four were polysaccharides. The polymers investigated are listed in Table 1.

2.1 Compatibility with River and Formation Waters

Table 2 presents the analyses of both the Waltersburg formation water and the Little Wabash River water. Due to incompatibilities between the formation and river waters, it was decided early in these studies that only river water would be used for injection. If a mixture were used, the hydrogen sulfide present in the formation water would react with iron picked up by the river water as it was transported through the water pump and water line to the injection facility. Synthetic water solutions were prepared in the laboratory to simulate the formation and injection water ion compositions. Iron and hydrogen sulfide were not included in these synthetic mixtures in order to prevent reaction in the oxidizing environment of the laboratory. Most tests were performed in a synthetic solution representing 80 parts river water to 20 parts formation water in order to simulate the conditions in a preflushed reservoir where mixing occurs between the injection and connate waters.

The compatibility of the polymers with river and formation waters can be evaluated in terms of three different sensitivities: sensitivity to the ionic composition of the water, sensitivity to mechanical shear forces, and sensitivity to the presence of ancillary chemicals.

TABLE 1
IDENTIFICATION OF POLYMERS BY MANUFACTURERS, PRODUCT
TYPE, STATE AND WEIGHT PERCENT

	MANUFACTURER	PRODUCT	STATE	ACTIVE PRODUCT (WT %)
P O L Y A C R Y L A M I D E S	Amoco	Sweepaid 103	W/O ^a Emulsion	25
	NALCO	NAL-FLO F HMWS	W/O Emulsion	30
	American Cyanamid	Cyanatrol 950S	W/O Emulsion	30
		Cyanatrol 960S	W/O Emulsion	30
	Allied Colloid	1100-L	W/O Emulsion	50
	CORT ^b CORT	N-Hance 335	Aqueous Log ^c	30
		N-Hance 330	Aqueous Log	27
	Dow	XD-30226.0	W/O Emulsion	28
P O L Y S A C C H A R I D E S	Pfizer	Flocon 1035	Broth	2.7
	Pfizer	Flocon 4880	Broth	5.7
	Abbott		Broth	2.75
	Rhone- Poulenc	Rhodopol	Dry	88

^aWater/oil.

^bJoint venture company of Phillips Petroleum and Hercules.

^cPolymer material is provided as a resilient gel, shaped like a log.

TABLE 2
COMPOSITION OF FORMATION AND RIVER WATER
IN STORMS POOL PROJECT

CONSTITUENT	WALTERSBURG FORMATION WATER (ppm)	LITTLE WABASH RIVER WATER (ppm)
Sodium	13,715	18
Calcium	732	23
Magnesium	358	8
Chloride	23,250	25
Sulfate	7	5
Iron	1	0
Bicarbonate	403	110
Carbonate	0	0
Total	38,466	189
Total Iron	1	9
Barium	18	0
H ₂ S	2.4	0
pH at 24° C	6.8	7.1
Specific gravity at 24° C	1.03	1.0
Resistivity at 24° C (ohm-m)	0.2	43.0
Turbidity (Nephelometric Turbidity Units)	54	77

2.1.1 Sensitivity to Ionic Composition of Water

The sensitivity of each polymer to the ionic composition of the solution water was measured using the viscosity degradation factor. This viscosity degradation factor is the ratio of the viscosity of the polymer when prepared in river water (a very low ionic, or salt, concentration) to the viscosity of the polymer when prepared in the 80/20 mixture of river and formation water (a high ionic, or salt, concentration). The viscosities were measured using a Brookfield viscometer with the UL adaptor at a shear rate of 7.3 reciprocal seconds (6 rpm) and at a temperature of 95° F, and are shown in Table 3.

The presence of electrolytes in the saline 80/20 mixture causes the polyacrylamides to display much lower viscosities than when using the fresh river water, as indicated by viscosity degradation factors ranging from 11 to 18. The relative insensitivity of the polysaccharides to salt concentration is indicated by the low viscosity degradation factors which range from 1.04 to 1.6.

Polysaccharides are clearly superior to polyacrylamides in terms of their sensitivity to the ionic composition of the water contacted. This viscosity stability will enable one to use less polymer to achieve the viscosity required at expected reservoir conditions.

2.1.2 Sensitivity to Mechanical Shear Forces

Mechanical shear forces will be encountered at the sand face during polymer injection. The shear rate expected for the shot-hole completions in the Storms Pool project is approximately 2,000 reciprocal seconds at the planned injection rate of 600 barrels per day, compared with a shear rate of 20 reciprocal seconds for an in situ flow rate of 1 foot per day. Other mechanical shear forces will be present in the surface mixing and injection facilities. Upon removal of the high shear forces encountered, some of the observed polyacrylamide viscosity reduction will be irreversible, while the viscous response of the polysaccharides is nearly totally reversible.

Figure 3 presents the shear rate versus viscosity curve for the Pfizer Flocon 1035 polysaccharide. This plot, typical of those for most polysaccharides, shows that the solution becomes less viscous as the shear forces on the polymer are increased. These characteristics indicate that polysaccharides exhibit non-Newtonian behavior. The effect

TABLE 3

VISCOSITY DEGRADATION OF 500 ppm ACTIVE
POLYMER AT A SHEAR RATE OF 7.3 sec⁻¹ and 95° F

POLYMER	VISCOSITY IN RIVER WATER (cp)	VISCOSITY IN 80/20 MIX OF RIVER FORMA- TION WATERS (cp)	VISCOSITY DEGRADATION FACTOR
<u>Polyacrylamides</u>			
Sweepaid 103	36.3	2.6	14.0
NAL-FLO F HMWS	49.8	4.3	11.6
Cyanatrol 950S	43.0	2.5	17.2
1100-L	64.0	3.6	17.8
1100-L		2.8 ^a	
N-Hance 335	42.4	3.8	11.2
XD-30226.0	62.3 ^b	4.3 ^a	14.5
<u>Polysaccharides</u>			
Flocon 1035	8.9	8.3	1.1
Flocon 4880	13.0	12.5	1.04
Abbott	13.4	8.4	1.6
Rhodopol ^c	12.6	10.5	1.2

^aThese measurements were made on an unfiltered solution; all other solutions were filtered with a depth (cartridge-type) filter.

^bThe viscosity degradation factor can be used for comparative purposes although the results of these tests are at 75° F rather than at 95° F.

^cDry polymer (all others are liquids or gels).

Figure 3. Viscosity as a function of shear for Pfizer 1035 polymer at 95°F and 500 and 1,000 ppm of active polymer concentration with salt concentration as a parameter.

of these shear forces on the solution viscosity is almost totally reversible. The obvious advantage of this type of behavior is that the solution viscosity near the wellbore is much lower than that displayed in the interwell area. This means that fluid injection can be more easily accomplished by lowering the resistance near the wellbore, while simultaneously maintaining the desired viscosity level in the interwell area.

For polyacrylamides, the screen factor is a better measure of mechanical degradation than is viscosity. Because the screen factor is a measure of the viscoelastic response of the polymer, it is more sensitive than viscosity to mechanical degradation. The screen factor is defined as the ratio of the flow time for the polymer solution to the flow time of the appropriate solvent (water or brine) through a random stack of five 200-mesh stainless steel screens. Table 4 presents the polyacrylamide screen factors for both river water and the 80/20 mixture of river and formation waters at room temperature.

2.1.3 Sensitivity to the Presence of Ancillary Chemicals

Laboratory studies have been performed by ERCO's Houston facility and by Pfizer, Inc. to investigate the effects of chemical additives on the injection fluid. The additives studied include biocides, oxygen scavengers, chelating agents, and coagulants, all of which are capable of exerting adverse as well as beneficial effects on this improved waterflood. The data are presented in greater detail in Section Three, Laboratory Testing and Evaluation. The following conclusions have been made:

1. The use of oxygen scavenger provides only minimal benefit at best. Corrosion inhibition by oxygen scavenging is not necessary in this plastic and fiberglass injection plant. Oxygen elimination in order to prevent microbiological growth of aerobic organisms is generally of only minor benefit and does threaten the more beneficial maintenance of effective biocide levels due to biocide destruction by excess oxygen scavenger.
2. Polymer injectivity and transport through the formation can be improved by the addition of 150 ppm sodium citrate dihydrate. This is accomplished by utilizing the sodium citrate to chelate iron (III), magnesium (II), and calcium (II).

TABLE 4

VISCOELASTIC RESPONSE OF POLYMERS AS MEASURED
BY SCREEN FACTOR

POLYMER		SCREEN FACTOR IN RIVER WATER AT 75° F	SCREEN FACTOR IN 80/20 MIX OF RIVER/FORMATION WATERS AT 75° F
P			
O	Sweepaid 103	11.66	7.01
L			
Y	NAL-FLO F HMWS	25.70	18.10
A			
C	Cynatrol 950-S	6.62	2.84
R			
Y	1100-L	31.35	15.80 ^a
L			
A	1100-L		16.00
M			
I	N-Hance 335	55.90	49.50
D			
E	XD-30226.0		23.00
S			

^aUnfiltered.

3. Cationic flocculant is required to thoroughly process the river water through the sand filter prior to polymer mixing and injection. Excess coagulant passing through the sand filter bed must be prevented to eliminate an unfavorable reaction with the xanthan polysaccharide. Failure to do so can result in an insoluble anionic-cationic polymer complex which will interfere with injectivity and mobility.
4. Biocide protection is necessary to ensure the delivery of an effective polymer solution to the reservoir. Numerous biocides and combinations of biocides have been studied to determine the most effective biocides and doses for this project. The selection of two biocides will permit the alternating of biocide types on a regular basis to prevent any immunity development by the xanthan degraders which may be present in the injection brine. The two biocides chosen were Magnacide 480 (2,2-dibromo-3-nitrilopropionamide) at 10 ppm and Kathon WT (isothiazolines) at 50 ppm. Although Magnacide 480 is relatively short-lived, surface hold-up time is even shorter. Reservoir contamination is usually a result of insufficient surface protection. The primary utility of improved waterflooding biocides is to prevent surface microbiological contamination.

2.2 Polymer Selection

All polymers tested appear capable of reliably yielding mobility ratios less than 1.0 (i.e., favorable) under reservoir conditions. Therefore the higher resistance factor of polyacrylamides in fresh water poses no great advantage over polysaccharides, since marginal improvement in areal sweep efficiency is small for decreasing mobility ratios lower than unity. The sensitivity of polyacrylamides to salts and shear at the wellbore are negative factors which are difficult to overcome, whereas the microgel formation and possible susceptibility to microbiological degradation found in polysaccharides are probably mitigable. Among the polysaccharides, Pfizer's Flocon 1035 was judged the best candidate for injection.

2.3 Slug Design

The concentration of the injected polysaccharide slug will be tapered at its trailing edge to mitigate viscous

fingering by the drive water injected after it. The slug will also include a buffer of full-strength (500 ppm) polymer solution sacrificed to retention. The tapered trailing edge, or viscous buffer, and the retention buffer together are intended to ensure the integrity of the slug as it flows from injectors to producers, thereby optimizing the flood's areal sweep efficiency.

2.3.1 Viscous Buffer Design

The objective in the viscous buffer calculation is to design several stages of decreasing polymer concentration with each volume just large enough to withstand viscous fingering from the upstream stage over the length of the flood. Ideally, then, viscous fingering at the trailing edge will destroy the slug's integrity just as the leading edge reaches the producers. A method for designing such a tapered slug is described by Claridge.¹ For ease of implementation in the field, this method is applied assuming five stages $V_1, V_2, \dots, V_5$ of concentration 500 ppm, 400 ppm, $\dots$, 100 ppm, respectively. The viscosity of each stage was determined from laboratory data.

The method computes $V_1, \dots, V_5$ as fractions of total pore volume contacted using factors $K_1, \dots, K_5$ describing the mixing zones in the stages:

$$K_i = [0.78 + 0.22 (M_i)^{1/4}]^4$$

Here M_i is the mobility ratio between stage i and the fluid upstream of it. The fractions of contacted pore volume required by each stage as a buffer against viscous fingering are determined using the following equations:

$$V_1 = 1 - 1/K_1$$

$$V_2 = 1/K_1 - 1/K_1^2 K_2$$

$$V_3 = 1/K_1^2 K_2 - 1/K_1^2 K_2^2 K_3$$

$$V_4 = 1/K_1^2 K_2^2 K_3 - 1/K_1^2 K_2^2 K_3^2 K_4$$

$$V_5 = 1/K_1^2 K_2^2 K_3^2 K_4 - 1/K_1^2 K_2^2 K_3^2 K_4^2 K_5$$

¹Claridge, E.L., A method of design of graded viscosity slugs, SPE Paper 6848, 1977.

Table 5 lists the results of these calculations using Claridge's equations.

2.3.2 Retention Buffer Design

The objective in the retention buffer calculation is to determine the amount of polymer that will be lost to retention between injector and producer. Laboratory measurements indicate a polymer retention rate of $16.34 \mu\text{g/g rock} = 2.189 \times 10^{-3} \text{ lb/ft}^3$ for a polymer concentration of $3.122 \times 10^{-2} \text{ lb/ft}^3$ solution (500 ppm). Therefore the volume of the retention buffer expressed as a fraction of pore volume contacted is

$$V_r = \frac{2.189 \times 10^{-3} \text{ lb/ft}^3 \text{ contacted}}{3.122 \times 10^{-2} \text{ lb/ft}^3 \text{ solution}} = 0.070 \frac{\text{ft}^3 \text{ solution}}{\text{ft}^3 \text{ contacted}}$$

The actual amount of polymer required in a slug comprising segments $V_r, V_1, \dots, V_5$ (see Figure 4) is obtained from the volume of pore space that will be contacted by the slug. For each quarter five-spot having an area of $217,800 \text{ ft}^2$, a pay thickness of 50 feet, a porosity of 0.19, and an areal sweep efficiency E of 0.9 with a final oil saturation of 0.3 gives

$$\begin{aligned} V_{\text{contact}} &= 217,800 \text{ ft}^2 \times 50 \text{ ft} \times 0.19 \times E \times (1 - S_{or}) \\ &= 1.304 \times 10^6 \text{ ft}^3 \end{aligned}$$

$$V_r = (1.304 \times 10^6 \text{ ft}^3 \text{ contacted}) (0.070 \frac{\text{ft}^3 \text{ solution}}{\text{ft}^3 \text{ contacted}})$$

$$V_r = 91,247 \text{ ft}^3 \text{ solution}$$

2.3.3 Polymer Requirements

The resulting polymer requirements for the viscous and retention buffers are listed in Table 6 on a quarter five-spot basis. With six injection wells, the project will transfer fluids into 24 quarter five-spots (assuming negligible fieldwide fluid drift). Production rates in the pilot producers will tend to restrict fluid movements to the interior of the project (12 quarter five-spots); therefore, the volumes of the other 12 are weighted by 0.5 to give a total influenced area of 18 quarter five-spots.

Assuming 18 quarter five-spots will be contacted, the total mass of polymer required to flood the pilot area is 18×1406 pounds or 253,000 pounds of active polymer.

TABLE 5

CALCULATIONS OF GRADED POLYMER SLUG STAGES FOR VISCOUS BUFFER

STAGE I	POLYSACCHARIDE CONCENTRATION C_i (ppm)	MOBILITY RATIO M_i	MIXING FACTOR K_i	FRACTION OF CONTACTED PORE VOLUME V_i
1	500	1.22	1.05	0.048
2	400	1.28	1.06	0.097
3	300	1.39	1.08	0.108
4	200	1.64	1.12	0.130
5	100	2.33*	1.22	0.166

Note: $M_5 = \mu_5 / (\mu_w \cdot RRF)$. A Residual Resistance Factor of 1.2 is assumed from laboratory data.

Figure 4. Schematic of polymer slug stages (bar widths proportional to slug size).

TABLE 6

POLYMER REQUIREMENTS FOR EACH STAGE IN A QUARTER FIVE-SPOT

SEGMENT	FRACTION OF V_{CONTACT}	VOLUME (ft ³)	CONCENTRATION (ppm)	MASS OF POLYMER (lb)
V_r	.070	91,247	500	2.849×10^3
V_1	.048	62,570	500	1.953×10^3
V_2	.097	126,443	400	3.159×10^3
V_3	.108	140,782	300	2.637×10^3
V_4	.130	169,459	200	2.117×10^3
V_5	.166	216,386	100	1.351×10^3
TOTAL	.619	806,887	-	1.406×10^4

SECTION THREE

LABORATORY TESTING AND EVALUATION

Laboratory work during the period of this annual report focused primarily on the establishment of specifications for the Pfizer polysaccharide broth and selection of suitable ancillary chemicals. The selection of the suitable ancillary chemicals is based on two criteria: the effectiveness of the chemical's performance under reservoir conditions and the chemical's effect upon the polymer. The work presented here was done by both ERCO's Houston Laboratory and Pfizer, Inc.

3.1 Selection of Ancillary Chemicals

The need for four different ancillary chemicals was suggested. The study of these chemicals (oxygen scavengers, coagulants, chelating agents, and biocides), although performed simultaneously, will be discussed individually. The testing of these chemicals sought to determine not only the effectiveness of each chemical in protecting the polymer, but also to insure that the chemical did not significantly affect the viscosity or filterability of the solution. Any significant difference in viscosity or filterability after ancillary chemical addition would suggest detrimental chemical interaction with the polymer.

3.1.1 Oxygen Scavengers

The use of oxygen scavengers to insure against aerobic bacteria growth was postulated for the Storms Pool Pilot. It is known, however, that typical oxygen scavengers rapidly degrade Magnacide 480 at concentrations typical of enhanced oil recovery operations [Exner, Buck, and Kyriacou, J. Agr. Food Chem. 21, 838 (1973)]. Sulfite and hydrosulfite are also known to react readily with formaldehyde. Studies have also indicated that oxygen scavengers react with Kathon WT.

It was concluded that the use of oxygen scavengers to minimize bacteriological growth is of only marginal benefit due to interferences with the biocides. Oxygen scavenging is not required for corrosion protection in the injection system, which is constructed of plastic and fiberglass piping and coated steel goods. Accurate control of the oxygen scavenger to prevent over- or under-dosing the system is very difficult to achieve. For these reasons, oxygen scavengers will not be used in the injection fluid.

3.1.2 Coagulants

A flocculating agent is required to aid in removing the heavy load of particulates present in the Wabash River water. The sand filters to be used were manufactured by Culligan USA, Inc. It was their recommendation that F-86, a cationic polyacrylamide polymer, be used to coagulate the dirt particles contained in the water. The effectiveness of this coagulant has been visually established in tests of the filter system. Water clarity can be improved, from approximately 53 percent for the river water to about 95 percent for the sand filtered water.

The possibility of unfavorable reactions between the cationic coagulant and the anionic polysaccharide was of major concern. As shown in Figure 5, if more than 0.5 ppm coagulant is carried through the sand filters, reaction with the Flocon biopolymer will result in a rapid increase in the solution filter ratio, indicating that there is an increased likelihood of sand face or formation plugging. To eliminate the possibility of coagulant bleeding through the filter, a modified operating procedure has been proposed. Coagulant will be added considerably upstream of the sand filters. Polysaccharide polymer will be added immediately upstream of the sand filter after the coagulant has had sufficient time to function. If any unfavorable reaction is to occur, it will be upstream of the sand filters and the unfavorable product will be easily removed. Any possible excess of coagulant will be replaced by an excess of polysaccharide at the sand filter outlet.

3.1.3 Chelating Agent

Sodium citrate has been studied as a means to stabilizing the injection fluid in the presence of various cations. As shown in Figure 6, the use of 150 ppm sodium citrate dihydrate significantly improves and maintains 1.2-micron filterability in the presence of iron (III), magnesium (II), and calcium (II). The improvement seen in the 1.2-micron Millipore test suggests that reservoir injectivity and transport through the formation will also be improved.

3.1.4 Biocides

Numerous biocides have been studied as candidates for use in the Storms Pool Project. Of these biocides, three have been chosen as the favored candidates due to their high level of effectiveness in the prevention of microbiological growth resulting in the degradation of the polymer solution.

Figure 5. Effect of flocculant on Flocon 1035 solutions.

Figure 6. Effect of Sodium Citrate on Filter Ratio.

The three favored biocides are Magnacide 480 (2,2-dibromo-3-nitrilopropionamide), Tretolite XC-401 (a chlorinated phenol), and Kathon WT (isothiazolines).

Some questions have been raised concerning the applicability of the Tretolite XC-401 biocide to oilfield use. The presence of the chlorinated phenol in oil tends to poison some of the catalysts used in refining. Although the injected concentration of Tretolite XC-401 would be quite low (less than 50 ppm) and little, if any, would partition into the oil, crude oil purchasers are very hesitant to accept oil which might pose a threat to the refining process. The use of chlorinated phenols as biocides is thus fairly successfully discouraged in enhanced oil recovery operations. Magnacide 480 and Kathon WT were chosen as the most effective biocides with no undesirable characteristics.

Magnacide 480 is an effective, although short-lived, biocide. The polymer solution will only have a 2- to 3-hour residence time in the surface facility, which is well within the life of Magnacide 480. It is thought that adequate surface protection will ensure adequate downhole protection as xanthan degrading bacteria are generally not native to petroleum reservoirs. By alternating biocides weekly, some in-depth protection can be achieved by using Kathon WT, which was effective for as long as 5 weeks in laboratory tests.

3.2 Quality Control Specifications for Polysaccharide Broth

Prior to signing the agreement with Pfizer to purchase their Flocon 1035 broth for use in the Storms Pool Project, specifications were determined to ensure the delivery of good quality broth. It was determined that the minimum biopolymer assay must be 2.5 percent active xanthan concentration, and that this broth must contain 2000 ppm formaldehyde at delivery to insure microbiological protection. Using the standard tests as outlined in Pfizer's sales brochure, a 500-ppm polymer solution prepared in a 500-ppm TDS brine must have not more than a 1.5 filter ratio with 1000 seconds flow time maximum, and the viscosity must be between 9 and 11 centipoises at 25 degrees Centigrade (77 degrees Fahrenheit) in a 6-rpm Brookfield viscometer with UL adapter. Because the effect of the chosen ancillary chemicals upon the viscosity and filterability is minimal, these additives are not included in the brine used for quality control tests. These specifications are a part of the purchase agreement with Pfizer, Inc.

SECTION FOUR

CONSTRUCTION OF FACILITIES

Construction of the pilot plant facility has continued during the past year. Numerous unanticipated delays have been encountered, primarily because this high-technology plant requires construction support beyond the capabilities of many local suppliers and contractors in the area.

4.1 Fabrication of the Injection Plant

The fresh-water supply system has been installed and seems to be working as designed. This systems pumps fresh water from the Little Wabash River to the 1000-barrel storage tank at the injection plant. This supply system has been almost entirely rebuilt with a new priming and siphoning system, new pipe from the river to the plant, and automatic controls to maintain the storage tank fluid level.

Two 210-barrel and two 300-barrel storage tanks have been installed for polymer broth storage. Installation of the pipes to the two 210-barrel tanks is complete. Pipe installation is in progress to the two 300-barrel tanks. These tanks will provide more than ample storage for the expected polymer broth demand for the pilot.

A third 210-barrel storage tank is in place to store dilute polymer solution. This tank serves as a buffer between the polymer mixing system and the polymer injection system to ensure continuous injection during short periods of mixing system downtime.

All of the injection facility tanks have been epoxy coated on the inside and insulated with polyurethane foam on the outside. The tank exteriors were painted to complete their appearance.

Construction work on the polymer mixing system and the injection system is completed except for minor modifications which will probably be made after studying the results of plant start-up. The hydrocyclone manifold system must be replaced because of cracking and leaking resulting from vibrations of the system. The injection manifold also requires replacement. Through an error during construction, 300-psi fittings were used rather than the required 600-psi fittings.

Wiring of the injection plant is essentially completed, although not all of the automatic controls have been thoroughly checked out. Numerous delays were encountered during the wiring of the control systems, primarily due to poor sub-contractor performance. After replacing the original electrical contractor, performance has improved considerably.

With the completion of the construction of the injection facility, water injection is now scheduled to begin by November 1. Minor modifications will undoubtedly be required during the plant start-up and preflush stages of this project and should be completed by early January.

4.2 Production Equipment Installation

A considerable effort during the past year has gone into installing and maintaining the production facilities. Five production pumps have been received and installed in the five production wells. Pumping units of this size (160,000 pounds peak torque, 74-inch stroke) have been in very short supply and are difficult to obtain. Acquisition of these units and their installation on an 8-foot sub-structure, required on some of the production wells during the flooding season, required considerably more time than originally anticipated.

Numerous problems have been encountered with the sucker rods for the pumping units. Due to the severe shortage of oilfield equipment, timely delivery of sucker rods could be achieved only by purchasing used rods. Many of these used rods have had sufficiently worn threads to allow for unscrewing during operation, resulting in a great deal of rig time being required until the worn rods are culled out. While few rod problems are currently being encountered, delays and intermittent production were experienced in the early stages of production start-up. Dynamometer tests have been performed on all production units to indicate the operational changes required for most efficient pump operation. The appropriate changes have been made.

An additional tank has been installed at the production battery to provide sufficient storage for the expected oil production rate. A new free water knockout has been ordered for the pilot project but has not yet been received. Its installation will complete the planned modifications to the production battery.

SECTION FIVE

RESERVOIR SIMULATION

The required simulation work for the Storms Pool Pilot is to be performed by Elf Aquitaine Oil and Gas Company.

5.1 Simulation Strategy

The simulation effort utilizes a two-dimensional streamtube model which has previously been used with good results in the Chateaufrenard field in France's Paris Basin. The plan for utilizing this simulator involves three steps:

Step 1 - Run the simulator with preliminary data to define streamtubes, investigate the effects of a possible field-wide drift on fluid flow, and estimate the size of the polymer slug needed to flood the pilot area.

Step 2 - Run the simulator using more detailed and better confirmed data to determine injection strategy.

Step 3 - Monitor field performance quarterly.

Step 1 was completed during this annual reporting period. Steps 2 and 3 will be performed as additional field data become available.

5.2 Preliminary Simulator Runs

The preliminary simulator runs (Stage 1) modeled two cases, drawn in Figure 7. Case I includes six injectors and five producers, approximating the influence of the rest of the field by the choice of boundary. No field-wide drift is assumed. Case I includes a subcase I' in which a higher value of polymer retention is assumed. Case II includes the 11 wells of the pilot area plus four artificial injectors and four artificial producers to simulate a hypothetical fluid drift possibly resulting from uneven field-wide distribution of injectors and producers. Tables 7 and 8 list the reservoir properties assumed in the runs.

In generating the streamtubes for both cases, boundaries were chosen to approximate the no-flux boundary conditions assumed in the model. Figure 8 shows the streamtubes

Figure 7. Boundaries assumed in three preliminary simulation cases.

TABLE 7

RESERVOIR PROPERTIES ASSUMED IN PRELIMINARY SIMULATOR RUNS

Pay thickness ^a	33 ft	(uniform)		
Porosity ^a	0.20	(uniform)		
Permeability	200 md	(uniform and isotropic)		
Initial oil saturation	0.40	(uniform)		
Pore volume	3.06 x 10 ⁶ bbl			
Formation volume factor	1.0 for all fluids			
Oil viscosity	6.5 cp			
Polymer resistance factor	10.0			
Polymer residual resistance factor ^a	1.0			
	<u>Case I</u>	<u>Case I'</u>	<u>Case II</u>	
Polymer retention (μg/g rock)	20	30	20	
Injection rate (bbl/day)	630	630	b	
Production rate (bbl/day)	755	755	b	

^aThese data differ slightly from those used in the graded slug design due to later refinements. These values represent the most reliable data available.

^bSee Table 8.

TABLE 8

INJECTION AND PRODUCTION RATES ASSUMED, MODEL CASE II

WELL	RATE (bbl/day)
All pilot injectors (polymer followed by water)	630
Pilot producers	
9-4	855
10-4	905
10-5	630
9-1	630
10-2	630
Artificial injectors (water only)	
I1	380
I2	630
I3	315
I4	380
Artificial producers	
P1	410
P2	440
P3	600
P4	380

Figure 8. Streamtubes generated by polymer flood simulator for Cases I and I' (no drift).

generated for cases I and I'. Notice that streamlines leaving project injectors terminate at project producers, so that the pilot pattern is well confined. Figure 9 shows the streamtubes generated for case II using the injection and production rates listed in Table 8. Here the flow from project injectors is not confined to the pilot pattern; in particular a large portion of the fluid injected at Wells 6-4, 9-3, and 10-3 is lost along with mobilized reservoir fluids to the north and east. We judged that this potential loss of fluids from the pilot area could have important implications for the polymer injection strategy. The influence of the rest of the field has been measured and been found to be insignificant.

Each case was simulated assuming 1500 days of operation and a 189,000-barrel slug of 500 ppm polymer followed by water at each pilot injector. Figures 10, 11, and 12 show the performance predictions for cases I, I', and II, respectively. The initial oil cut is approximately 2.8 percent, compared with the present observed value of about 2.0 percent. Figure 13 compares the cases side by side. After injection of 1.25 pore volumes the gains in oil production over waterflood predictions are as follows:

<u>Case</u>	<u>Oil recovered in excess of waterflood</u>
I (no drift, 20 $\mu\text{g/g}$ retention)	111,000 bbl
I' (no drift, 30 $\mu\text{g/g}$ retention)	80,000 bbl
II (drift 20 $\mu\text{g/g}$ retention)	80,000 bbl

These results indicate that the field-wide drift and high polymer retention can each lower the additional oil recovery by about 30 percent. Static pressure tests have revealed no strong field-wide fluid drift and core floods using filtered polysaccharide solution gave a value of 16.34 $\mu\text{g/g}$ rock for polymer retention.

Figure 9. Streamtubes generated by polymer flood simulator for Case II (drift from southwest to northeast).

Figure 10. Simulator performance predictions for Case I (no drift, retention = $20 \mu\text{g/g}$ rock).

Figure 11. Simulator performance predictions for Case I' (no drift, retention = 30 μ g/g rock).

Figure 12. Simulator performance predictions for Case II (drift, retention = $20 \mu\text{g/g}$ rock).

Figure 13. Comparison of simulator performance predictions for Cases I, I', and II.

SECTION SIX

PROGRAM SUPPORT

Program support for this project has encompassed numerous items in addition to management of day-to-day operations. These areas include polymer purchase, polymer transportation, technical decisions, reporting, and general program management.

6.1 Purchase of Polymer

Upon deciding to use polysaccharide polymer for the Storms Pool improved waterflood, negotiations were begun with the various polymer manufacturers to determine the optimum biopolymer in terms of product quality and price. Laboratory data, as discussed previously, have indicated that Pfizer Flocon 1035 provides the best performance. Pfizer's price per active pound is competitive with other suppliers, but transportation from the point of manufacture (Groton, Connecticut) to Carmi, Illinois nearly doubles this cost.

Agreement has been reached with Pfizer that they will pay a portion of the freight costs for polymer transportation. This portion will decrease as broth activity increases. In addition, efforts will be made to move production to Terre Haute, Indiana which would decrease transportation costs by about 80 percent.

A purchase agreement was signed with Pfizer, Inc. on August 7, 1980. This agreement specifies that any and all polymer required for the Storms Pool pilot project will be obtained from Pfizer. This agreement also provides that Pfizer will pay a pro-rated portion of the freight charges.

6.2 Transportation of Polymer

Additional efforts have been made to decrease the cost of polymer transportation. Options studied include leasing or purchasing a tank trailer and tractor unit and leasing or hiring drivers. Costs for polymer transportation were based on a 2,000-mile round trip to Groton from Carmi and 2 years of operation (two trips per week the first year and one trip per week the second year). Effects of inflation are not considered. Utilizing common carrier will cost about \$450,000. Leasing a tractor and drivers will cost about

\$195,000 plus a capital investment of \$22,000 for the tank trailer. Resale value of the trailer is estimated to be \$15,000.

The optimum means of transportation in terms of both logistics and cost is to purchase the required tank trailer and lease drivers and the tractor unit. The savings realized over common carrier will offset some of the unanticipated inflation effects on polymer costs that have occurred since the original budget was prepared for this project.

6.3 Technical Decisions

This area of program support has involved the technical evaluation of laboratory data and field work. The evaluation of these data also involved technical decisions on the operations and design features to be incorporated as well as the chemicals to be used. These plans and decisions have been discussed in the appropriate sections, although they are a part of the engineering and management required for program support.

6.4 Reporting

Reporting is always a vital part of any project. This area includes not only the monthly and annual technical reporting (both written and verbal) required for the Department of Energy, but also internal company technical and financial reporting. Report preparation requires a significant amount of time under the heading of program support.

6.5 General Program Management

This area encompasses budget and milestone management as well as personnel management. This project, while significantly behind schedule, is substantially on budget. Personnel management of the various subcontractors has also required significant amounts of time. As a result of insufficient supervision early in the year, many problems developed which have required additional management time and resulted in delays to achieving the stated milestones as specified. These personnel problems have now been largely solved and are being closely supervised to insure a timely progression of work on this project.

An updated milestone chart for this project is shown in Figure 14.

Figure 14. Enhanced Oil Recovery by Improved Waterflooding, Milestone Chart.

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