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ENHANCED OIL RECOVERY BY IMPROVED WATERFLOODING Second Annual Report

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Date Published—August 1980

Energy Resources Company, Inc.
Cambridge, Massachusetts

U. S. DEPARTMENT OF ENERGY

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ENHANCED OIL RECOVERY BY IMPROVED WATERFLOODING,
Second Annual Report

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POLYMER IMPROVED WATERFLOOD
STORMS POOL UNIT, WHITE CO., ILLINOIS

Abstract

Energy Resources Co. Inc. is currently operating a pilot polymer improved waterflood of the Storms Pool, a sandstone reservoir in the Illinois basin. During the second year of the project, progress was made in all phases of the project most significantly in the laboratory work, field preparation, and computer simulation. In addition, Tasks II, VII, and IX, polymer selection, workovers, and model building were completed during 1979.

The polymer selected, based on laboratory comparisons of ten different products under simulated reservoir conditions, is a xanthan type polysaccharide polymer manufactured by Pfizer Inc. Other laboratory work included preliminary testing of biocides and oxygen scavengers. Development of the pilot area continued with the completion of the well workovers and the design and initiation of construction of the injection facility.

Preliminary simulation was begun to determine the effect of polymer adsorption, fieldwide drift, and other conditions on eventual production. An injection strategy will be determined based on these results.

In support of the laboratory and field operations, discussions were opened with Pfizer concerning a polymer purchase agreement and minimum quality standards were established. A complete environmental assessment of the project was made and proper containment and disposal facilities were added to the design of the injection system.

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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 pilot polymer flood in the Storms Pool near Carmi, in White County, Illinois (see Figure 1). The project is a cost-sharing venture in which Energy Resources and the United States Department of Energy (DOE) bear equal shares in the expenditure of \$2,170,955 for equipment, chemicals, and labor. Preparation for the polymer flood began in September 1977, under DOE Contract Number DE-AC01-78ET12065, and the project is scheduled for completion in December 1982. This report reviews progress during the second year of performance. Progress during the first year is reported in DOE document BETC/2541-12, "Enhanced Oil Recovery by Improved Waterflooding: First 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 large oil companies or other outside parties knowledgeable in enhanced oil recovery 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 computerized simulation of the pilot polymer flood. The present report reviews 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, preliminary reservoir simulation, and program support activities.

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

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

The reservoir analysis presented in the first annual report gives evidence that, although oil saturations higher than 40 percent exist in the pilot area, the fluid saturations and rock properties are vertically nonuniform in the 50-foot pay zone. Since the waterflood is also characterized by an adverse mobility ratio, it is reasonable to expect that viscous fingering and water channeling have contributed to the high watercuts experienced in the past decade. Although an uneven field-wide distribution of injectors and producers led to concern over a possible fluid drift across the pilot area, static pressure measurements revealed no pressure gradient strong enough to cause such a drift. A set of transient pressure tests has been designed to help determine the degree of fluid movement between the wells in the pilot area.

Twelve polymers, including eight polyacrylamides and four polysaccharides, were chosen as candidates to be tested in the laboratory. Experiments conducted by Energy Resources, Core Laboratories of Dallas, Texas, and several polymer vendors yielded data on the compatibility of polymers with makeup water and formation brine, rheologic and retentive behavior of polymer solutions in reservoir cores, and filterability of polymer solutions. Consideration of these results along with costs and logistics led to the selection of Pfizer Chemicals Division's polysaccharide, Flocon 1035. This polymer showed a low susceptibility to degradation by saline formation brine and to permanent viscosity reduction by the high shear rates expected to prevail at injection wellbores. The data from these laboratory studies supported the design of a graded polymer slug featuring buffers against retention and viscous fingering at the upstream edge.

Further laboratory work by Energy Resources and Elf-Aquitaine yielded relative permeability and capillary pressure curves for use in reservoir engineering and simulation. These curves show that the Waltersburg sandstone in the pilot area is slightly water-wet and help explain the field's high watercuts. Energy Resources' microbiology laboratory conducted a taxonomic screen of the microbial population in the makeup and formation waters and performed a set of experiments to determine whether any species would be likely to attack the injected polymer. Based on these results, biocides have been chosen for injection with the polymer. A quality control program will help assure consistency of the chemicals delivered to the field.

Workovers at most of the 11 wells of the pilot area helped to correct several problems typically encountered

in old fields. Most of the wells were acidized; the new producer Well 10-5 was perforated, and new Gulberson pumps and rods were run in the old producers. One injector was squeezed at the gas cap and deepened to the bottom of the producing interval to give a better injection profile.

An injection plant now stands between Tracts 9 and 10. Injection lines are in place, and much of the equipment needed for polymer injection has been assembled.

Energy Resources and Elf-Aquitaine developed a plan for numerical simulation to support the design and monitoring of the polymer slug. The plan calls for three phases, including preliminary simulations using a stream-tube model to provide rough estimates of fluid flow patterns, polymer requirements, and fluid production; detailed simulation using refined laboratory and reservoir data to determine an injection strategy; and quarterly simulator runs to monitor field performance. Preliminary simulations revealed that fluid drift, if present, could cause an inefficient polymer flood and that polymer retention rates significantly higher than accepted laboratory rates could reduce oil recovery by up to 30 percent. Subsequent field and laboratory tests indicate that neither of these potential sources of inefficiency will be present.

Program support activities included the signing of a letter of intent to purchase polysaccharide from Pfizer and an environmental assessment of the polymer flood. The environmental assessment found that the project would have negligible impact on the local environment. An environmental protection plan will ensure the safe handling and disposal of fluids during the operation of the polymer flood.

SECTION TWO

RESERVOIR AND WELL TESTS

During 1979 the project team used results of the reservoir analysis to design and interpret static pressure measurements. A plan was also outlined for pressure interference tests. This section discusses these activities.

2.1 Reservoir Characteristics

To guide the design and interpretation of pressure tests, the project team established several hypotheses concerning reservoir characteristics peculiar to the pilot area. These hypotheses are based on the reservoir description presented in the first annual report and on subsequent analysis of field data. Although the hypotheses do not provide a complete definition at the producing zone in the pilot area, they help explain discrepancies between the reservoir's performance and ideal waterflood behavior.

First, there appears to exist an interval of roughly 35 feet where movable oil resides in the pilot area. The oil saturations in this interval exceed 40 percent in places, although areal variations may exist. This hypothesis is based on conservative interpretation of the dual induction laterologs taken from Well 10-5, drilled in 1978. These logs show an average oil saturation of about 40 percent in the interval 1866 to 1900 feet subsea. Material balance calculations on the production in Tracts 9 and 10 estimate that 60 percent of the original oil in-place (72 percent saturation) has been produced, corroborating the logs at Well 10-5.

Second, the oil saturation is vertically nonuniform in the pilot area, being lower in the bottom 10 to 15 feet of pay and perhaps in sand originally in the gas cap that overlay portions of the pilot area. The fluid saturations in the Schlumberger Coriband analysis at Well 10-5 show less oil saturation in the lower zone (1876 to 1910 feet subsea), in agreement with electric logs taken early in the field's drilling history and a 1958 study for Sinclair Oil Company. The existence of an extended lower zone of high water saturation (and therefore high water permeability) is consistent with the tendency, noted by early operators, of wells shot below 1890 feet subsea to produce at large watercuts. The excess in volume of fluids injected over volume produced during the waterflood suggest higher water saturations in the former gas cap.

Third, the reservoir rock in the pilot area is vertically inhomogeneous, although the heterogeneities do not seem to be areally consistent. Core analyses show two kinds of vertical variations: one comprising thin, impermeable shale streaks that have no apparent correlation from well to well and the other being irregular fluctuations in ideal-gas permeability, again having no apparent areal significance.

These three hypotheses support a fourth; namely, that the flow of oil and water in the pilot area is characterized by water channeling and consequently by injected water bypassing oil. Water channeling is a plausible explanation for high watercuts at producers despite the existence of significant mobile oil saturations in parts of the field (e.g., at Well 10-5). Also, channeling could have been promoted by vertical variations in rock and fluid properties as well as by viscous instabilities due to the unfavorable mobility ratio between injected water and oil. Injection profiles measured by Sinclair in 1958 led that company to conclude that injected water was entering the underlying zone of high water saturation. Selective plugging of injectors around Well 12-1 in 1958 (near the pilot area) back to around 1880 feet subsea resulted in improved oil recovery, supporting that conclusion. Channeling through the old gas cap may also have occurred. Well 9-1, for example, has 5 feet of gas sand and produced at the highest watercuts of Tracts 9 and 10 before being shut in; an adjacent injector, Well 12-4, was originally perforated in the gas cap. Throughout the history of the waterflood, oil cuts have been much higher at producers without a gas cap and completed above 1880 feet subsea. This project will attempt to control mobility in the gas cap and water zone by injecting polymer into them.

Fifth, the field-wide pattern of injection and production indicates the possibility of a large scale drift of fluids across the pilot area. Jim Haley Production Company currently has more injectors than producers southwest and upstructure of the pilot area and more producers than injectors northeast and downstructure. A southwest-to-northeast fluid drift could be the result, and such a drift, if large enough in magnitude, could adversely affect the confinement of fluids in the pilot pattern.

Finally, there is some possibility that zones of gas sand exist which are not liquid saturated. If this is the case, then the compressibility of fluids near these zones will be large, a circumstance that could affect the interpretation of pressure pulse tests.

2.2 Static Pressure Measurements

In October, 1979, we performed static pressure measurements in the pilot area. Static pressures at injectors were measured using Amerada bottom-hole pressure recorders, and at the same time echometer readings were taken at producers. These measurements yielded static pressures at each well in the pilot area.

The following procedure was used.

October 9 The two active producers, Wells 10-2 and 10-4, were shut in to allow reservoir pressure to stabilize. A tubing-end locator was run in each injector to check the depths of tubing ends, fluid levels, and bottoms. These results are shown schematically in Figures 3 through 8.

October 17 Otis Engineering Company of St. Elmo, Illinois, ran an Amerada bottom-hole pressure recorder in Wells 9-3 and 12-4.

October 18 Otis ran Amerada pressure recorders in Wells 9-2 and 10-1.

October 19 Otis ran Amerada pressure recorders in Wells 6-4 and 10-3.

The results of the injector surveys are shown in Tables 1 through 6. The readings in Table 1 show that the pressure in Well 6-4 had not stabilized at the time of the survey but was still falling; therefore the results for this well are not reliable.

The static pressure measurements for the six injectors and five producers are summarized in Table 7. The rightmost column lists the static pressures corrected to a datum depth of 1831 feet subsea. Two static pressure estimates are given for producers, one based on the assumption that the annulus is filled with water, the other assuming an oil-filled annulus. The assumption of a water-filled annulus is probably accurate for producers 9-1, 9-4, 10-2, and 10-4, which had recently been acidized. The presumed higher oil saturation and the high liquid level at the new Well 10-5 suggest that its annulus may be partially oil-filled.

Discounting the measurement at 6-4, there appears to be a net pressure difference of approximately 35 psig between the southwest and northeast ends of the pilot area. Since the distance between, say, Wells 12-4 (southwest edge) and 10-3 (northeast edge) is 1866 feet, the overall pressure

Figure 3. Profile of Well 6-4, October 19, 1979.

Figure 4. Profile of Well 9-2, October 18, 1979.

Figure 5. Profile of Well 9-3, October 17, 1979.

Figure 6. Profile of Well 10-1, October 18, 1979.

Figure 7. Profile of Well 10-3, October 19, 1979.

Figure 8. Profile of Well 12-4, October 17, 1979.

TABLE 1

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 6-4

DATE: October 19, 1979

DEPTH: 2270 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
1630	0	0	0.490	374.4
1730	1.0	0.130	0.4905	374.8
1830	2.0	0.260	0.4903	374.65
1930	3.0	0.390	0.4896	374.25
2030	4.0	0.520	0.489	373.7
2130	5.0	0.650	0.488	372.9
2230	6.0	0.780	0.4872	372.3
2330	7.0	0.910	0.4865	371.8
10/20/79				
0030	8.0	1.040	0.4855	371.0
0130	9.0	1.170	0.4847	370.4
0230	10.0	1.300	0.4835	369.5
0330	11.0	1.430	0.4825	368.8
0430	12.0	1.560	0.4817	368.1
0530	13.0	1.690	0.4205	367.2
0630	14.0	1.820	0.4795	368.5

TABLE 2

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 9-2

DATE: October 18, 1979

DEPTH: 2270 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
0900	0	0	0.433	331.1
0915	0.25	0.0296	0.433	331.1
0930	0.5	0.0592	0.4328	330.9
0945	0.75	0.0888	0.4325	330.75
1000	1.0	0.1185	0.432	330.1
1030	1.5	0.1777	0.4317	330.1
1100	2.0	0.2370	0.4317	330.1
1130	2.5	0.2962	0.4317	330.1
1200	3.0	0.3555	0.4317	330.1
1230	3.5	0.4147	0.4317	330.1
1300	4.0	0.4740	0.4317	330.0
1330	4.5	0.5333	0.4315	330.0
1400	5.0	0.5925	0.4312	329.85
1430	5.5	0.6517	0.4312	329.85
1500	6.0	0.7110	0.4312	329.85

TABLE 3

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 9-3

DATE: October 17, 1979

DEPTH: 2241 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
1025	0	0	0.362	277.2
1030	5 min.	0.0108	0.3635	278.35
1035	10 min.	0.0216	0.3636	278.4
1040	0.25	0.0324	0.3636	278.4
1045	20 min.	0.0433	0.3636	278.4
1050	25 min.	0.0541	0.3636	278.4
1055	0.5	0.0649	0.3636	278.4
1110	1.75	0.0973	0.3636	278.4
1125	1.0	0.1298	0.3636	278.4
1140	1.25	0.1622	0.3636	278.4
1155	1.50	0.1947	0.3636	278.4
1210	1.75	0.2271	0.3636	278.4
1225	2.0	0.2596	0.3636	278.4
1255	2.5	0.3245	0.3636	278.4
1325	3.0	0.3894	0.3636	278.4
1355	3.5	0.4245	0.3636	278.4
1425	4.0	0.5191	0.3636	278.4
1455	4.5	0.5840	0.3636	278.4
1525	5.0	0.6489	0.3636	278.4
1550	5 hrs. 25 min.	0.7030	0.3636	278.4

TABLE 4

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 10-1

DATE: October 18, 1979
 DEPTH: 2272 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
1710	0	0	0.4098	313.6
1715	5 min.	0.0110	0.4106	314.0
1720	10 min.	0.0221	0.4106	314.0
1725	15 min.	0.0331	0.4106	314.0
1730	20 min.	0.0441	0.4106	314.0
1735	25 min.	0.0552	0.4106	314.0
1740	0.5	0.0662	0.4106	314.0
1810	1.0	0.1324	0.4103	313.8
1840	1.5	0.1986	0.4102	313.75
1910	2.0	0.2648	0.410	313.0
1940	2.5	0.3311	0.410	313.0
2010	3.0	0.3973	0.410	313.0
2040	3.5	0.4635	0.4102	313.75
2110	4.0	0.5297	0.4102	313.75
	4.5	0.5959	0.4102	313.95
2210	5.0	0.6622	0.4102	313.75
2310	6.0	0.7946	0.4104	313.85

TABLE 4 (CONTINUED)

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
10/19/79				
0010	7.0	0.9270	0.4107	314.05
0110	8.0	1.0594	0.411	314.4
0210	9.0	1.1919	0.4115	314.8
0310	10.0	1.3243	0.412	315.2
0410	11.0	1.4567	0.413	315.9
0510	12.0	1.5892	0.4134	316.2
0610	13.0	1.7216	0.4138	316.5
0700	13 hrs. 50 min.	1.8320	0.414	316.7

TABLE 5

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 10-3

DATE: October 19, 1979
DEPTH: 2250 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
0900	0	0	0.3825	292.8
0915	0.25	0.0159	0.383	293.2
0930	0.5	0.0318	0.3832	293.45
0945	0.75	0.0477	0.3834	293.6
1000	1.0	0.0637	0.3834	293.6
1030	1.5	0.0955	0.3834	293.6
1100	2.0	0.1273	0.3834	293.6
1130	2.5	0.1592	0.3834	293.6
1200	3.0	0.1910	0.3834	293.6
1230	3.5	0.2228	0.3834	293.6
1300	4.0	0.2547	0.3834	293.6
1330	4.5	0.2865	0.3834	293.6
1400	5.0	0.3183	0.3834	293.6
1430	5.5	0.3502	0.3834	293.6
1500	6.0	0.3820	0.3834	293.6

TABLE 6

AMERADA BOTTOM-HOLE PRESSURE MEASUREMENTS FOR WELL 12-4

DATE: October 17, 1979

DEPTH: 2259 feet subsurface

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
1734	0	0	0.4305	329.3
1739	5 min.	0.0111	0.4306	329.35
1744	10 min.	0.0221	0.4307	329.4
1749	0.25	0.0332	0.4307	329.4
1754	20 min.	0.0442	0.4307	329.4
1759	25 min.	0.0552	0.4307	329.4
1804	0.5	0.0663	0.4307	329.4
1819	0.75	0.0995	0.4307	329.4
1834	1.0	0.1326	0.4307	329.4
1849	1.25	0.1658	0.4307	329.4
1904	1.50	0.1989	0.4307	329.4
1919	1.75	0.2322	0.4307	329.4
1934	2.0	0.2635	0.4307	329.4
2034	3.0	0.3980	0.4307	329.4
2134	4.0	0.5307	0.4307	329.4
2234	5.0	0.6634	0.4306	329.35
2334	6.0	0.7961	0.4306	239.35

TABLE 6 (CONTINUED)

TIME	HOURS FROM START	TIME DEFLECTION (INCHES)	PRESSURE DEFLECTION (INCHES)	BOTTOM-HOLE PRESSURE (psig)
10/18/79				
0034	7.0	0.9288	0.4306	329.35
0124	8.0	1.0614	0.4306	329.35
0234	9.0	1.1942	0.4306	329.35
0334	10.0	1.3268	0.4306	329.35
0434	11.0	1.4595	0.4305	329.3
0534	12.0	1.5922	0.4304	329.25
0634	13.0	1.7249	0.4304	329.25
0700	13 hrs. 26 min.	1.7825	0.4304	329.25

TABLE 7
RESULTS OF STATIC PRESSURE MEASUREMENTS

AMERADA MEASUREMENTS

INJECTION WELL NUMBER	DEPTH SUBSURFACE (ft)	GROUND LEVEL (ft)	DEPTH SUBSEA (ft)	STATIC PRESSURE (psig)	STATIC PRESSURE AT 1831 ft SUBSEA (psig)
9-2	2270	397	1873	330	314.5
10-1	2272	399	1873	313	297.5
10-3	2250	371	1879	293.6	275.5
6-4	2270	393	1877	366	348.8
12-4	2259	397	1862	329.4	318.6
9-3	2241	367	1874	278.4	262.5

ECHOMETER MEASUREMENTS

PRODUCTION WELL NUMBER	DEPTH OF LIQUID LEVEL SUBSURFACE (ft)	GROUND LEVEL (ft)	DEPTH OF LIQUID LEVEL SUBSEA (ft)	LIQUID LEVEL ABOVE 1831 ft SUBSEA (ft)	STATIC PRESSURE AT 1831 ft SUBSEA (psig)
9-1	1581	402	1179	652	299 ^a 216 ^b
9-4	1495	367	1128	703	322 ^a 236 ^b
10-1	1616	401	1215	616	283 ^a 202 ^b
10-4	1611	368	1243	588	270 ^a 191 ^b
10-5	1439	393	1046	785	359 ^a 268 ^b

^a Assuming a water-filled annulus

^b Assuming an oil-filled annulus

gradient in this direction is approximately 0.019 psig/ft. The corresponding fluid drift is less than 0.02 ft/day. This result, if accurate, indicates that field-wide drift should not significantly influence the flow of injected fluids during the pilot flood.

2.3 Interference Test Program

We outlined a program of interference tests to help determine the degree of communication between wells in the pilot area. The program consists of two tests:

Test 1: Inject water for four days at 600 bbl/day. Record pressure responses at all other wells for six days, using pressure bombs in the other injectors and echometers in the producers (since pumps and rods already in place will make it difficult to run pressure bombs there).

Test 2: Inject water for 4 days at 600 bbl/day in injector 9-3, again recording all changes in injection rate. Record pressure responses at all other wells except Well 10-1 for 6 days as in Test 1. These tests are depicted in Figure 9.

The proposed injection rate of 600 bbl/day should suffice to attain a pressure difference of at least 15 psig, which should yield an unambiguous pressure response at the observation wells. The proposed observation times are based on an estimate of pressure change using the equation for the pressure response to a single well in an infinite reservoir:

$$\Delta p = \frac{q\mu}{4\pi kh} Ei \left(-\frac{\phi\mu Cr^2}{4kt} \right) \quad (2-1)$$

where

$$Ei(-x) = - \int_x^{\infty} \frac{\exp(-u)du}{u}$$

Equation 2-1 is expressed in Darcy units; see Matthews and Russell, Pressure Buildup and Flow Tests in Wells, SPE Monograph Volume 1. Assuming the (Darcy unit) values:

$$\begin{aligned} k &= 0.2 \text{ darcies} \\ h &= 1200 \text{ cm} \\ \mu &= 10 \text{ cp} \\ C &= 1.45 \times 10^{-4} \text{ atm}^{-1} \end{aligned}$$

gives the equation

$$\Delta p = 0.2488 \text{ Ei}(3.281 \times 10^4 r^2/t)$$

in oilfield units. This estimate of pressure change is plotted against time for the four appropriate values of r in Figure 10.

Figure 9. Geometry of proposed interference tests.

Figure 10. Estimated pressure change, as a function of distance and time, for proposed interference tests.

SECTION THREE

POLYMER SELECTION AND SLUG DESIGN

During 1979 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 the Waltersburg formation and from 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 supported the final selection of polymer and the design of a graded slug for injection.

Two basic types of polymers were examined: polyacrylamides (and their salts) and polysaccharides or biopolymers. Twelve polymers from nine manufacturers were evaluated; eight of the polymers were polyacrylamides and four were polysaccharides. The polymers are identified in this report by an alphabetic index indicating manufacturer, product, state, and weight percent as listed in Table 8. In this scheme different polymers from the same manufacturer are numbered, e.g., C1 and C2 for American Cyanamid polymers with different molecular weights.

3.1 Compatibility with River and Formation Waters

The compatibility of polymers with the river and formation waters was evaluated in terms of sensitivity to salt, to mechanical shear, and to ancillary chemicals. Susceptibility to microbial attack, also an important consideration, is discussed in Section 4.3.

The analyses of the formation water and water from the Little Wabash River appear in Table 9. We decided to use 100 percent river water for dilution of either polymer type because of incompatibilities between the river and formation waters. For example, precipitation of iron sulfide could result from the reaction of iron in the river water, which is eluted or dissolved from the rusted river water pumps and from the rusted river water line to Jim Haley's injection plant, with hydrogen sulfide, which is produced by sulfate reducing bacteria in the formation water. Most of the tests were performed in an 80/20 synthetic mixture of river and formation waters based on the compositions listed in Table 9. This mixture was used to simulate conditions in the reservoir, where the injected

TABLE 8

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

	POLY- MER	MANU- FACTURER	PRODUCT	STATE	ACTIVE PRODUCT (Wt %)
P O L Y A C R Y A M I D E S	A	Amoco	Sweepaid 103	W/O ^a Emulsion	25
	B	NALCO	NAL-FLO F HMWS	W/O Emulsion	30
	C1	American	Cyanatrol 950S	W/O Emulsion	30
	C2	Cyanamid	Cyanatrol 960S	W/O Emulsion	30
	D	Allied Colloid	1100-L	W/O Emulsion	50
	E1	CORT ^b	N-Hance 335	Aqueous Log	30
	E2	CORT	N-Hance 330	Aqueous Log	27
	F	Dow	XD-30226.0	W/O Emulsion	28
P O L Y S A C C H A R I D E S	G1	Pfizer	Flocon 1035	Broth	2.7
	G2	Pfizer	Flocon 4880	Broth	5.7
	H	Abbott		Broth	2.75
	J	Rhone- Poulenc	Rhodopol	Dry	88

^aWater/oil.

^bJoint venture company of Phillips Petroleum and Hercules.

TABLE 9

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

polymer solution will probably contact significant concentrations of formation brine even after a very efficient preflush. The iron content of the formation water was neglected in the manufacture of synthetic formation water because of precipitation problems which could occur in the oxidizing environment of the laboratory. These problems will not necessarily occur in the reducing conditions of the reservoir, even though all of the iron may not be removed from the injection water. The use of oxygen scavengers in the injection system will help prevent ferrogenic precipitation.

3.1.1 Electrochemical Degradation

The extreme sensitivity of the polyacrylamides to electrolytes is demonstrated by the electrochemical degradation factors listed in Table 10. The electrochemical degradation factor is the ratio of shear viscosities of polymers in river water to the viscosities of polymers in an 80/20 mix of river and formation waters. Viscosities were measured in a Brookfield viscosometer with a UL adapter at a shear rate of 7.3 sec^{-1} and 95° F . The polyacrylamides are much more viscous than the polysaccharide at equivalent concentrations in fresh water but are less viscous than the polysaccharide in the saline water (10,000 ppm TDS). The high molecular weight of the polyacrylamides, which is responsible for their high viscosity in fresh water, results from the reactive nature of the individual polymer molecules. The diffuse double layer generated by the high charge density of the reactive monomer units is compressed in the presence of high concentrations of uni- and polyelectrolytes. The collapse of the double layer lowers the electrostatic forces of repulsion and causes the polymer chain to ball up as a result of Van der Waals forces of attraction. Thus, the viscosity of the high molecular weight polyacrylamides drops, as illustrated in Figure 11, by an order or magnitude in the presence of uni- and polyelectrolytes at approximately 10,000 ppm TDS. The viscosity of the polysaccharide G is not affected by the presence of the electrolytes because of the lower charge density on the saccharide monomers. The relative insensitivity of xanthan gum broths to salt concentration is illustrated in the viscosity-concentration curves of polysaccharide J in concentrations of brine ranging from about 1,000 ppm to roughly 40,000 ppm in Figure 12.

3.1.2 Mechanical Degradation

Figure 13 illustrates the viscous response of 500 ppm solutions of the test polymers to shear at reservoir temperatures in 100 percent river water and an 80/20 mix of river

TABLE 10

ELECTROCHEMICAL 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 FORMATION WATERS (cp)	ELECTROCHEMICAL DEGRADATION FACTOR
<u>Polyacrylamides</u>			
A	36.3	2.6	14.0
B	49.8	4.3	11.6
C	43.0	2.5	17.2
D1	64.0	3.6	17.8
D2		2.8 ^a	
D3		2.5	
E	42.4	3.8	11.2
F	62.3 ^b	4.3 ^a	14.5
<u>Polysaccharides</u>			
G1	8.9	8.3	1.1
G2	13.0	12.5	1.04
H	13.4	8.4	1.6
J ^c	12.6	10.5	1.2

^aThis measurement was made on an unfiltered solution; all other solutions were filtered with a depth filter.

^bThe electrochemical degradation factor can be used for comparative purposes although the results of these tests are at 75° F and the other tests are at 95° F .

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

Figure 11 Viscosity as a function of polymer concentration in 100% river water and in 80/20 mix of river and formation waters.

Figure 12. Viscosity as a function of concentration for biopolymer J at 95°F and 7.3 sec⁻¹ with salt concentration as a parameter.

Figure 13. Viscosity at 500 ppm as a function of shear with river water and with 80/20 mix of river and formation waters.

and formation waters. These data were measured by a Brookfield rotational viscosometer with a UL adapter. The sensitivity of the polymers to shear appears independent of the electrochemical environment. The independence of the shear-viscosity relationships and electrolyte concentration is further illustrated in Figure 14. The shear rate, τ , in the porous medium is calculated from the following equation:¹

$$\tau = \frac{1.42 \times 10^4 \times Q}{A \sqrt{\phi k}}$$

where Q is the flow rate in cc/sec; A is cross-sectional area in cm²; k is the permeability in darcies, and ϕ is porosity, expressed as a fraction. Over the range of shear studied, the viscosity of the test polymers is reduced about 40 to 50 percent. Most of this reduction will occur at the high velocities experienced at the wellbore if the surface facilities are adequately designed to minimize mechanical shear.

The shear rate at the open-hole completions in the Storms Pool is approximately 2,000 sec⁻¹ at an injection rate of 600 bbl/day; the shear rate in the reservoir is approximately 20 sec⁻¹ at a reservoir rate of 1 ft/day. The viscosity of polyacrylamide B at the wellbore shear is approximately 44 percent of the viscosity at a typical laboratory shear of 7.3 sec⁻¹, a value obtained from extrapolation along curve B for the 80/20 mix in Figure 13. Experience in the Wilmington field and in laboratory investigations² suggests that some of the polyacrylamide viscosity reduction under increased shear will be irreversible on removal of the high shear field. The viscous response of the biopolymer to shear appears to be reversible.

Table 11 lists the screen factors of the polyacrylamides in 100 percent river water and an 80/20 mix of river and formation waters at room temperature. 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 SS screens. The screen factor is a measure of the viscoelastic response of the polymer and is more sensitive than viscosity to mechanical degradation. Thus the screen factor is a better measure of mechanical degradation than viscosity; this measurement is, however, polymer specific.

¹B. Sandiford, personal communication, October; 1978,

²Maerker, J.M. (1975), Shear degradation of partially hydrolyzed polyacrylamide solutions, Soc. Pet. Eng. J. (August):311.

Figure 14. Viscosity as a function of shear for biopolymer J at 95°F and 500 and 1,000 ppm of active polymer concentration with salt concentration as a parameter.

TABLE 11

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	A	11.66
O		
L	B	25.70
Y		
A	C	6.62
C		
R	D1	31.35
Y		
L	D2	15.80 ^a
A		
M	D3	16.00
I		
D	E1	14.46
E		
S	F	55.90
		49.50
		23.00

^aUnfiltered.

3.1.3 Viscosity in the Presence of Biocides

The viscosity of Pfizer's Flocon 1035 (polysaccharide G1) at various concentrations of biocides was measured at varying shear rates. The results, plotted in Figures 15 through 17, show that viscosity tends to increase with increasing concentration of biocide, although there is no consistent pattern to the curves. Cross-linking of the polysaccharide molecules probably contributes to the viscosity increases. The cross-linking effect appears most noticeably with formaldehyde.

3.2 Rheologic and Retentive Behavior in Cores

Core-flooding tests were performed to determine the resistance factors (RF), residual resistance factors (RRF),

Figure 15. Percent change in viscosity as a function of rpm for polysaccharide G1 with formaldehyde.

Figure 16. Percent change in viscosity as a function of rpm for polysaccharide G1 with acrolein.

Figure 17. Percent change in viscosity as a function of rpm for polysaccharide G1 with Visco 3991.

and retention rates of candidate polymers. Since core flooding experiments are lengthy and costly, polymers E, B and G2 were initially selected for further testing on the basis of their compatibilities with river and formation waters. Flow tests on polymers C and D were done at the expense of their manufacturers. Table 12 summarizes the rheologic behavior measured in tests 1 through 12. Table 13 summarizes the retentive behavior measured in these tests.

3.2.1 Core Flooding Methodology

The polymer flow tests numbered 1, 4, 5, 9, 10, and 11 in Table 12 were carried out at Core Laboratories in Dallas, Texas. The other flow tests were carried out by polymer manufacturers. In the Core Labs tests, core samples were prepared by first extracting the residual oil and water using solvents. The solvent-cleaned cores were then placed under the 80/20 brine in a desiccator. The desiccator was then evacuated to 30-50 mm Hg at which pressure there was no apparent release of gas bubbles from the core or from the liquid surface. The pore volumes of the cores tested were between 13 cc and 15 cc. A difference of up to 40 percent was measured between the permeabilities to air and liquid, suggesting that in some cases these procedures may not have saturated the core samples completely. Subsequent tests in ERCO's EOR Laboratory evacuated the core before introducing liquid allowing more complete saturation.

Polymer solutions of 1 weight percent in river water were prepared according to each manufacturer's suggested mixing procedure. Each solution was then diluted to the requisite concentration in an 80/20 mix of synthetic river and formation waters. A spot check of the formation water at a recent visit to Core Laboratories indicated that its pH was 7.8, a high value compared to 6.8 as listed in Table 9. The high pH of the formation water could have caused some of the injectivity problems experienced with biopolymer G2. Each diluted polymer was filtered in a Seals No. 10 Candle Filter, a microporous porcelain filter.

The flow experiments were conducted in the vertical upflow mode with the reservoir rock held in a Hassler sleeve. A confining pressure of 300 psig was applied radially on the core and the back pressure was held to 40 psig. The pressure drop between the inlet and outlet lines of the core was recorded continuously during the run. Polymer concentrations in the effluent stream were measured by precipitation of the polymer in the 1.0 cc to 1.5 cc samples and turbidimetric evaluation of the precipitated

TABLE 12

RHEOLOGICAL BEHAVIOR OF POLYMERS
IN RESERVOIR CORES AT 95° F and ~2.0' / DAY

TEST NUMBER	POLYMER	RF TO 80/20 RIVER/ FORMATION (TDS 10,000 ppm)	RRF TO 80/20 RIVER/ FORMATION (TDS 10,000 ppm)	RRF TO 0/100 RIVER/ FORMATION (TDS 40,000 ppm)
1	B	18.0	4.5	
2	B ^a	17.9	7.1	2.3
3	B ^a	16.0	6.3	1.9
4	C	14.0	7.5	
5	D	39 @ 10 PV 19.5 @ 5 PV	13.5	
6	E1	45.6	32.2	
7	E2	41.81	9.3	
8	E2 ^a	23.0	18.1	3.6
9	E2 ^a	19.2	11.7	1.5
10	E1 ^a + Aluminum citrate	19.1 to 150.0	35.0	31.0
11	G2	15.0	9.3	
12	H	6	2	

^aCarried out with residual oil (courtesy of CORT).

TABLE 13

RETENTIVE BEHAVIOR OF POLYMERS IN
RESERVOIR CORES AT 95° F and ~2.0'/DAY
WITH AN 80/20 MIX OF RIVER AND FORMATION WATER

TEST NUMBERS	POLYMER	LB/ACRE-FT	POLYMER RETENTION	
			$\mu\text{g/g}$ ROCK	FRACTIONAL RETENTION OF POLYMER INJECTED
1	B	309	55.1	0.131
2	B ^a	385	68.6	0.163
4	C	236	40.5	0.094
6	E1	299	53.0	0.106
7	E2	227	39.8	0.084
8,9	E2 ^a	330	58.9	0.140
11	G2	321	57.3	0.136

^aCarried out with residual oil (courtesy of CORT).

amounts. The polymer retentions were evaluated from the area under the retention curve and the elution-desorption curve. These values are then the "irreversible" retentive losses of polymer recorded in Table 13.

3.2.2 Results of Core Flooding Experiments

The transient RF and effluent concentrations of polymers and tracers are plotted in Figures 18 through 28. In Figure 18 the RRF of polymer E1 dropped to 3.7 after the upstream end of the sample was trimmed. This may have been indicative of sand-face plugging but not filter-cake buildup since the transient RF curve flattens out at large pore-volume throughput. Inlet and outlet end effects could be responsible for the extremely high resistance factors; the transient pressure drops were measured across the inlet and outlet lines. Sand-face plugging is a probable cause for the high value of polymer retention. The breakthrough concentration in Figure 18 never reaches the inlet concentration. This core flooding experiment was repeated at the supplier's expense with a lower molecular weight polymer, E2. The RRF was reduced to 9.0 and the retention for this run was 227 lb/acre-ft. The transient RF and concentration curves of polymer E2 are illustrated in Figure 19.

The RRF of polymer B in Figure 20 does not indicate plugging, although the transient RF curve shows a monotonic increase with pore-volume throughput. The slight upward trend in the transient RF suggests some plugging behavior at high values of pore-volume throughput.

The transient RF and concentration curves of polysaccharide G2 are illustrated in Figure 21. The transient RF curve reflects some plugging behavior but not to the degree indicated by the high retention rate (321 lb/acre-ft). The RRF of 9.3 (very high for a polysaccharide) reflects this polymer retention. Note that the effluent polymer concentration appears stabilized at 90 percent of the injected concentration. This deviation from 100 percent could have resulted from inaccurate measurements of the polymer concentration, inaccurate pore volumes, or significant dead volume since 1/8-inch Swagelock connectors were used in the flow experiments. The large retention could have resulted from failure to filter the water properly before dilution, from reversible complexing with such divalent ions as Ca^{++} or Mg^{++} , or from the high pH.³

³McCaffery, F.G. and Edillson, F.L. (1977), An Investigation of the gelation tendencies of Pfizer's Biopolymer 1935, Petroleum Recovery Institute, Research Note RN-5 (January 1, 1977).

Figure 18. Resistance factor and concentrations of Polymer E in reservoir cores at 95°F.

Figure 19. Resistance factors and concentrations of Polymer E2 in reservoir cores at 95°F.

Figure 20. Resistance factor and concentrations of Polymer B in reservoir cores at 95°F.

Figure 21. Resistance factor and concentrations of Polymer G2 in reservoir cores at 95°F.

Polymer rheology tests on polyacrylamide E2 (Tests 8 and 9, shown in Figures 3-22 and 3-23, respectively) indicate some difference between CORT's test results and the results from Core Laboratories. Although the RF from the manufacturer's test, Test 8, is approximately half that of Test 7, the retention of Test 8 is less than the retention of Test 6. These discrepancies are also observed with the RF and RRF to 80/20 mix between Tests 7 and 8 and between Tests 1 and 2. CORT measured differential pressure drops across a slowly rotating core and measured retention by recirculating the injected solution until the concentration of the polymer injected was equal to the concentration in the effluent stream. The procedures used to mitigate capillary end effects, gravity segregation, and nonequilibrium adsorption in CORT's experiments could be reasons for the differences between their results and the results from Core Laboratories.

Test 10, illustrated in Figure 24, was carried out with polyacrylamide E1 and an aluminum citrate mixture. The high RF of 145 indicates effective permeability reduction of the aqueous phase in the core. The RRF of 35 to the 80/20 mix indicates that mobility control would be very effective during the fresh-water-drive stage of the improved waterflood. This residual permeability reduction appears irreversible since the RRF to the 100 percent brine is approximately the same as that of the 80/20 mix of fresh water and brine. This high RRF to brine indicates that mobility control by a polyacrylamide-aluminum citrate treatment would be effective during the fresh-water and subsequent brine floods which follow the polyacrylamide slug.

The transient RF and concentration profiles of polymer C2 are illustrated in Figure 25. The increase of the RF curve suggests that some plugging of the reservoir occurs. A previous test at Cyanamid's expense with a lower molecular weight polymer (C1) showed little active or residual resistance effects; Cyanamid did not release the details of this test.

The transient RF curve in Figure 26 indicates that filter cake plugging of the reservoir core was significant for polymer D. The injectivity problems could have resulted from incompatibility of this polyacrylamide with the reservoir brines. This possible incompatibility is inferred from the electrochemical degradation factor of 17.8 listed in Table 10.

The polyacrylamide and polysaccharide which performed best in the compatibility studies and core experiments were tested for rheological and retentive behavior in cores in a 100 percent brine environment. These severe tests reflect

Figure 22. Resistance factor of polymer E2 in reservoir cores at 95°F (Courtesy of CORT).

Figure 23. Resistance factor of polymer E2 in reservoir cores at 95°F (Courtesy of CORT).

Figure 24. Resistance factors of polymer E1 with aluminum citrate in reservoir cores at 95°F (Courtesy of CORT).

Figure 25. Resistance factor and concentration profile of polymer C2 in 80/20 mix with thiocyanate.

Figure 26. Resistance factor of Polymer D in reservoir cores at 95°F.

the interaction of the polymers with brines of unswept regions in the reservoir. The polymers were dissolved in distilled water and then mixed with 100 percent brine to the desired concentration of 500 ppm. The dilution was such that the brine concentration was greater than 99 percent. The results of the compatibility studies for these polymers are listed in Table 14.

The rheological and retentive behavior of these polymers is graphed in Figures 27 and 28. As indicated in the transient RF curve in Figure 28, the injectivity of polyacrylamide G2 is not severely impaired by the presence of high salinity brines. The transient RF curve of polyacrylamide E2, Figure 28, implies that a significant amount of sand-face plugging occurs in the high salinity environment. The RF, RRF and retention of these polymers in the 80/20 mix and 100 percent formation water are tabulated in Table 15. The RF and RRF of polyacrylamide E2 in 100 percent river water (a courtesy of CORT) is also listed in Table 15. The RF and RRF of the polyacrylamide is not as affected by high salinity as the viscosity. The RF and RRF of the polysaccharide is much more affected by the high salinity environment than the viscosity.

3.2.3 Further Testing of Pfizer's Flocon 1035

Energy Resources remeasured the rheologic and retentive behaviors of polysaccharide G1 (Pfizer's Flocon 1035) after

TABLE 14

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

POLYMER	VISCOSITY IN 100% RIVER WATER (cp)	VISCOSITY IN 80/20 MIX RIVER/FORMATION WATER (cp)	ELECTRO-CHEMICAL DEGRADATION FACTOR	VISCOSITY IN 100% WATER (cp)	ELECTRO-CHEMICAL DEGRADATION FACTOR
Polyacrylamide E2	42.4	3.8	11.2	1.3	32.6
Polysaccharide G2	13.0	12.5	1.04	13.5	(0.96)

Figure 27. Resistance factor and concentrations of Polymer G2 in reservoir core @95°F with 100% formation brine in the connate water and in the injected solution.

Figure 28. Resistance factors and concentrations of Polymer E2 in reservoir core @95°F with 100% formation brine in the connate water and in the injected solution.

TABLE 15

RHEOLOGICAL AND RETENTIVE BEHAVIOR OF A POLYSACCHARIDE AND
A POLYACRYLAMIDE IN RESERVOIR CORE AT 95° F AND ~ 2.0 FT/DAY

	RF	RRF	RETENTION	
			µg/g ROCK	LB/ACRE-FT
Polysaccharide G2 in 80/20 ^a	15.0	9.3	55.3	321
Polysaccharide G2 in 0/100	9.0	2.0	93.3	542
Polyacrylamide E2 in 100/0	49.0	10.0		
Polyacrylamide E2 in 80/20	41.81	9.3	39.8	227
Polyacrylamide E2 in 0/100	27.0	27.0	153.9	889

^a80/20 stands for a mixture of 80 percent river water and 20 percent formation water.

the dilute polymeric solutions were filtered. Figures 29 through 36 show the breakthrough and transient RF curves for these tests, conducted at $75 \pm 2^\circ \text{ F}$ in restored-state reservoir cores saturated with formation brine. The measurements were made with 500 ppm of active polymer dissolved in filtered and unfiltered river water and in filtered and unfiltered formation brine; solutions were filtered through a 10-micron ceramic filter under a pressure head of between 1 and 4 psig. The retentions are summarized in Table 16. These retentions compare with previously measured retentions of $55.3 \mu\text{g/g}$ rock and $93.3 \mu\text{g/g}$ rock for 500 ppm polysaccharide G2 in the filtered 80/20 mix and in filtered formation water at $95^\circ \pm 2^\circ \text{ F}$. The differences in retention between the filtered and unfiltered solutions indicate that a significant portion of the retention results from mechanical entrapment of microgels which are formed in the presence of divalent cations such as Mg^{++} and Ca^{++} . Early breakthrough of the polysaccharide (at roughly 0.3 PV throughput) occurs because of species dispersion which is accentuated by the short length of the reservoir cores. The breakthrough concentration profiles were measured by a phenol/sulphuric acid assay of the effluent stream; the calibration curve for the spectrophotometer and cell path used is plotted in Figure 37.

TABLE 16

RETENTION RATES OF PHIZER'S FLOCCON 1035 USING
FILTERED AND UNFILTERED MAKEUP WATERS

55 ppm ACTIVE POLYSACCHARIDE G1 IN:	RETENTION	
	$\mu\text{g/g}$ ROCK	LB/ACRE-FT
River water (filtered)	16.34	95
Formation water (filtered)	20.70	120
River water (unfiltered)	31.00	180
Formation water (unfiltered)	63.80	370

Figure 29. Breakthrough concentration profile of dilute polysaccharide solution from reservoir cores (Waltersburg Formation) at $75 \pm 2^\circ \text{F}$.

Figure 30. Resistance factor of dilute polysaccharide solution in reservoir cores (Waltersburg Formation) at 75+ 2° F.

Figure 31. Breakthrough concentration profile of dilute polysaccharide solution from reservoir cores (Waltersburg Formation) at $75 \pm 20^\circ \text{F}$

Figure 32. Resistance factor of dilute polysaccharide solution from reservoir cores (Waltersburg Formation) at $75 \pm 2^\circ\text{F}$.

Figure 33. Breakthrough concentration profile of dilute polysaccharide solution from reservoir cores (Waltersburg Formation) at $75 \pm 2^\circ\text{F}$.

Figure 34. Resistance factor of dilute polysaccharide solution in reservoir cores (Waltersburg Formation) at $75 \pm 2^\circ$ F.

Figure 35. Breakthrough concentration profile cores (Waltersburg Formation) at $75 \pm 2^\circ\text{F}$.

Figure 36. Resistance factor of dilute polysaccharide solution from reservoir cores at $75 \pm 2^\circ\text{F}$.

Figure 37. Calibration curve for polysaccharide concentration by the phenol/H₂SO₄ method assay.

The resistance factor of 500 ppm polysaccharide G1 in river water (filtered through a 3-5 micron filter) begins to level out at 3.1 in Figure 30. This resistance factor is specific to the flooding velocity of 16.5 ft/day. The resistance factor at field rates (e.g., 1 ft/day) can be obtained from the plot in Figure 30 since the shear rate is directly proportional to the flooding velocity and the logarithm of viscosity is directly related to the logarithm of shear rate. The shape of the resistance factor curves for the xanthan gum in formation brine indicates that some plugging occurs for the filtered case (Figure 32) but that severe plugging occurs for the unfiltered case (Figure 36).

3.3 Filterability

Tests for filterability of polysaccharides through millipore filters are similar in procedure to screen factor tests for polyacrylamides but yield different interpretations. The millipore filter ratio is defined as the ratio of the time required for the last 250 cc to the first 250 cc of 1000 cc of 500 ppm polymer solution to flow through a presaturated 1.2 micron millipore filter under a constant gas pressure of 40 psi. The millipore filter ratio is a measure of the propensity of polysaccharide molecules to plug the filter and, by inference, the oil formation. Solutions with millipore filter ratios greater than 1.5 are considered unacceptable; recent specifications of polysaccharide solutions by oil companies require that the filter ratio be no greater than 1.3. The flow time at 1000 seconds is a parameter which should be considered in conjunction with the filter ratio. Filter ratios alone could be misleading in that a high degree of constant plugging could produce a low filter ratio. Pfizer has recommended that runs with flow times greater than 1000 sec/ℓ be considered unacceptable.

Table 17 lists the millipore filter ratios and the cumulative flow times of Pfizer's polysaccharide G. The diluents used for these runs were all filtered through a 0.65-micron filter under pressure. Pfizer explained the high results of the filter ratios in runs 1 through 4 as having been caused by some resin residues from an in-line distilled water filter even though the water had been refiltered through a 0.25-micron filter. Pfizer conducted runs 5 through 14 in their research laboratories. Energy Resources' laboratory conducted runs 15 through 18. The increase in millipore filter ratio between the 100 percent river water (run 10), 80/20 mixture (runs 11, 12, and 13), and a 100 percent formation water (run 14) is consistent

TABLE 17

POLYSACCHARIDE G^a
MILLIPORE FILTER RATIOS OF 500 PPM ACTIVE
POLYSACCHARIDE PRODUCT UNDER A PRESSURE OF 40 PSI

RUN NO.	BROTH CONC. (WT %)	DILUENT (% RIVER ^b / % FORMATION ^c WATERS)	VISCOSITY (cp @ 6 rpm)	FLOW TIME (@1000 cc)	MILLIPORE FILTER RATIO
1	2.7	80/20	9.6	89.59	1.97
2	2.7	80/20	9.6	94.61	2.27
3	2.7	80/20	9.6	91.19	2.10
4	2.7	d	9.8	51.81	1.97
5	G1 2.7	80/20	9.9	40	1.14
6	2.7	80/20	9.9	43	1.17
7	2.7	80/20	9.3	35	1.32
8	2.7	80/20	9.3	31	1.30
9	G2 5.7	--	--	--	--
10	7.4	100/0	10.3	61	1.16
11	G3 7.4	80/20	10.1	83	1.37
12	7.4	80/20	9.9	80	1.30
13	7.4	80/20	9.9	75	1.30
14	7.4	0/100	10.3	285	2.9
15	8.4	100/0	10.0	51	1.60
16	G4 8.4	100/0	10.0		1.57
17	8.4	80/20	10.6	63	1.76
18	8.4	80/20	10.6		1.60

^aPolysaccharide from manufacturer G is made in four different concentrations (G1 = 2.7%, G2 = 5.7%, G3 = 7.4%, G4 = 8.4%).

^b250 ppm TDS with 2:1:: Na+:Ca++

^c38,500 ppm TDS with 19:1:: Na+:Ca++

^d500 ppm TDS with 10:1:: Na+:Ca++

with the high retention of polysaccharide G2 measured by Core Laboratories in reservoir cores in the 80/20 mixture (321 lb/acre-ft) and in 100 percent formation water (542 lb/acre-ft).

The results of filterability tests carried out by Core Laboratories are plotted in terms of filter rate (ml/sec) versus cumulative throughput (ml) in Figures 38 through 43. These representations combine the effects of incremental plugging (slope of curve) and initial plugging tendencies (initial flow rate) of dilute polysaccharide solutions. These curves indicate that biopolymer G1 has a better filterability than biopolymer H but that biopolymer G1 is much more affected by the presence of divalent and univalent electrolytes than biopolymer H. These results support the assertion that high retention of polysaccharide G1 in reservoir cores is caused by microgel formation cross-linked with polyelectrolytes. Core Laboratories stated that the quality of filterability data was poor for biopolymer G2 and did not report these results. G3 and G4 are new products from Pfizer which were not tested by Core Laboratories.

Energy Resources also measured the millipore filter ratios of candidate polysaccharides. The results, plotted in Figure 44 and summarized in Table 18, indicate that with respect to filtration time and rate the Pfizer polysaccharides performed best. Filtration of the polysaccharides in distilled water indicated that the Kelco and Abbott broths would require diatomaceous earth filtration before injection.

The compatibility of Pfizer's Flocon 1035 with different biocides at varying concentrations (10, 50 and 100 ppm) in distilled water is illustrated in Figures 45 through 52. Baseline curves of filtration time and filtration rate are plotted in Figures 45 and 49. The filterabilities of the solutions appear to decrease with increasing concentrations of biocide, although as with the viscosity measurements discussed in Section 3.1.3 there is no consistent pattern to the curves.

3.4 Conclusions of the Polymer Selection Program

The results of the compatibility studies can be summarized by the following statements:

- The polyacrylamides are much more viscous than the polysaccharides at equivalent concentrations of fresh water, but the viscosities of these polyacrylamides are much more sensitive to saline water than

Figure 38. Results of Core Laboratories' millipore filter tests for polysaccharide G1 at 1000 ppm in pure river water.

Figure 39. Results of Core Laboratories' millipore filter tests for polysaccharide G1 at 500 ppm in pure river water.

Figure 40. Results of Core Laboratories' millipore filter tests for polysaccharide G1 at 1000 ppm in an 80/20 mix of river and formation waters.

Figure 41. Results of Core Laboratories' millipore filter tests for polysaccharide G1 at 500 ppm in an 80/20 mix of river and formation waters.

Figure 42. Results of Core Laboratories' millipore filter tests for polysaccharide H at 500 ppm in pure river water.

Figure 43. Results of Core Laboratories' millipore filter tests for polysaccharide H at 500 ppm in an 80/20 mix of river and formation waters.

Figure 44. Filterability of dilute polysaccharide solutions (500 ppm active polymer) of xanthan gum broths.

Figure 45. Filtration time curves for polysaccharide G1.

500 ppm Xanthan
 Distilled Water (Filtered)
 40 psi N₂ Overpressure
 1.2 micron Filter

FORMALDEHYDE			
	10 ppm	50 ppm	100 ppm
First Pass	△	▲	▲
Second Pass	□	◻	◻

Figure 46. Filtration time curves for polysaccharide G1 with formaldehyde.

500 ppm Xanthan
Distilled Water (Filtered)
40 psi N₂ Overpressure
1.2 micron Filter

ACROLEIN

	10 ppm	50 ppm	100 ppm
First Pass	△	▲	▲
Second Pass	□	▣	■

Figure 47. Filtration time curves for polysaccharide G1 with acrolein.

Figure 48. Filtration time curves for polysaccharide G1 with Visco 3991.

Figure 49. Filtration time curves for polysaccharide G1.

Figure 50. Filtration time curves for polysaccharide G1 with acrolein.

Figure 51. Filtration time curves for polysaccharide G1 with formaldehyde.

Figure 52. Filtration time curves for polysaccharide G1 with Visco 3991.

those of the polysaccharides. The viscosity of the polyacrylamides degrades by an order of magnitude on increase of the salt concentration from 189 ppm to 7,844 ppm (see Table 9).

- Analysis of the sensitivity of these polymers to rotational shear suggests that some permanent loss of viscosity could occur at the wellbore for the polyacrylamides but not the polysaccharides.

In addition, the results of the microbiological study reported in Section Four suggest that polysaccharides may be subject to deleterious effects of microbial attack. Compatibility tests between a polysaccharide and various biocides yielded the following result:

- The viscosity of Pfizer's Flocon 1035 (polysaccharide G1) increases with increasing concentration of the biocides acrolein, formaldehyde, and Visco 3991. This increase is attributed to cross-linking among the polysaccharide chains.

The investigation of rheologic and retentive behavior in reservoir cores led to the following conclusions:

- The high RF and RRF of polyacrylamides E is consistent with their high screen factors. Some injectivity problems were encountered with polymer E1; there were no injectivity problems with polymer E2, which with a

TABLE 18

MILLIPORE FILTER RATIOS MEASURED BY ENERGY RESOURCES
FOR CANDIDATE POLYSACCHARIDES

	MILLIPORE FILTER RATIO	
	FIRST PASS	SECOND PASS
Pfizer	1.98	1.41
Kelco	7.43	1.68
Rhone-Poulenc	Terminated	2.66
Abbott	Terminated	Terminated

lower molecular weight has a lower intrinsic viscosity than E1. The high RF of polyacrylamides E and the relative ease of injection could have resulted from their extended molecular length and linearity, likely byproducts of the gamma radiation manufacturing process.

- Polyacrylamides such as C and D, which had high electrochemical degradation factors, exhibited plugging behavior and low RF in the reservoir cores.
- Polysaccharide G2 had an unusually high RRF (9.3) and retention rate (321 lb/acre-ft) in an unfiltered 80/20 mix of river and formation waters. The high retention and RRF probably resulted from mechanical entrapment of microgels (reversible complexes of divalent cations with polysaccharide molecules) formed in the 80/20 mixture. Tests in unfiltered 100 percent formation water indicated higher retention (542 lb/acre-ft) in the reservoir cores. The retention rates were significantly lower (95 lb/acre-ft in river water; 120 lb/acre-ft in formation water) when the polymer solutions were filtered.

Filterability tests showed considerable variation among the polysaccharides. Pfizer's Flocon 1035 yielded the best results; the ratios for Kelco and Abbot products indicated that these polysaccharides would need to be filtered through diatomaceous earth before injection. Addition of biocides decreased the filterability of the Pfizer polymer tested.

The costs per active pound of the candidate polymers as of mid-1979 are shown in Table 19. In general, the polyacrylamides are cheaper per active pound than the polysaccharides. These cost differences must be weighed with expected field performance and the likelihood of technical success of the flood based on the laboratory experiments.

All polymers tested appeared capable of yielding mobility ratios reliably less than 1.0 (i.e., favorable) under reservoir conditions. Therefore the higher RF 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. Table 20 summarizes the properties of this polymer which will be used in further design and simulation of the polymer flood.

TABLE 19

COSTS OF POLYMERS PER ACTIVE POUND, MID-1979

POLYMER		ACTIVE PRODUCT (WT%)	COST PER BULK LB (\$)	TRANSPORTATION COST (\$)	COST/ ACTIVE LB (\$)
P O L Y A C R Y L A M I D E S	A	25	0.54 (New Orleans)	0.03	2.28
	B	30	0.43 (Clearing, Illinois)	0.0134	1.478
	C1	30	0.385	0.0217	1.356
	C2	30			
	D1	50	0.70	f.o.b.	1.40
	D2	50		Carmi, IL	
	E1	28	0.51		
	E2	28			
P O L Y S A C C H A R I D E S	F	28	1.10		
	G1	2.7	1.90/active lb	0.43/active lb	2.33
	G2	5.7			
	G3	9.0			
	H	2.75	2.00/active lb	0.40/active lb	2.40
	J	88			

TABLE 20

SUMMARY OF CHARACTERISTICS OF PFIZER'S
FLOCON 1035 (POLYSACCHARIDE G1)

Delivered state	Broth
Injected concentration	500 ppm
Electrochemical degradation factor	1.1
Sensitivity to shear degradation	small and reversible
Susceptibility to microbial attack	sufficient to require biocides
Resistance factor	10 ^a
Residual resistance factor	approximately 1.2 ^b
Retention rate	16.34 µg/g rock ^b

^aAssumed completely attributable to viscosity increase.

^bAssuming dilute polymeric solutions are filtered through a 1.2 micron filter.

3.5 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.

The objective in the viscous buffer calculation is to design several stages of decreasing polymer concentration, each of whose volume is 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.⁴ For ease of implementation in the field, this method is applied assuming five stages V_1 , V_2 , ..., V_5 of concentration 500 ppm, 400 ppm, ..., 100 ppm, respectively. The viscosity of each stage is estimated by linear interpolation:

$$\mu(C) = 0.85 + 0.0153 C$$

where C is expressed in ppm and μ in cp. A residual resistance factor of 1.2 is assumed.

The method computes V_1 , ..., V_5 as fractions of total pore volume contacted using factors K_1 , ..., 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. Table 21 lists the results of these calculations using Claridge's equations.

TABLE 21

CALCULATION 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: $M_5 = \mu_5 / (\mu_w \cdot \text{RRF})$

⁴Claridge, E.L., A method of design of graded viscosity slugs, SPE Paper 6848, 1977.

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 = 2.189×10^{-3} lb/ft³ contacted at a concentration of 500 ppm, i.e., 3.122×10^{-3} lb/ft³. Therefore the volume of the retention buffer expressed as a fraction of pore volume contacted is

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

The actual amount of polymer required in a slug comprising segments $V_r, V_1, \dots, V_5$ (see Figure 53) is obtained from the volume of pore space that will be contacted by the slug. For each quarter five-spot having area 217,800 ft², pay thickness 50 feet, porosity 0.19, and an areal sweep efficiency E of 0.9 with $S_{or} = 0.3$ gives

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

The resulting polymer requirements are listed in Table 22 on a quarter five-spot basis. Assuming 18 quarter five-spots will be contacted, the total mass of polymer required to flood the pilot area is $18 \times 1.406 \times 10^4 \text{ lb} = 2.53 \times 10^5 \text{ lb}$ active weight.

TABLE 22
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

Figure 53. Schematic of polymer slug stages.

SECTION FOUR

LABORATORY TESTING AND EVALUATION

In addition to the polymer selection program, the project team performed a set of laboratory tests to determine such rock and fluid properties as relative permeabilities, capillary pressure, and the susceptibility of polymer to biological degradation. A quality control program was developed to ensure consistency of the chemicals used during the pilot flood.

4.1 Relative Permeabilities

Both Energy Resources and its subcontractor Elf-Aquitaine measured the relative permeabilities of cores from Well 10-5 to oil and water. Elf-Aquitaine used the steady-state method to arrive at the relative permeabilities and corresponding fractional flow listed in Table 23. These curves are plotted in Figures 54 through 56.

Energy Resources used the dynamic method of Johnson, Bossler, and Naumann.¹ These data, plotted in Figure 57, were obtained by unsteady displacement of formation fluids (crude and brine) from reservoir cores by river water at the reservoir temperature, $95^{\circ} \pm 2^{\circ}$ F. The plugs (2 inches in diameter and 3 inches in length) were taken perpendicular to the axis of the core from Well 10-5 and were therefore oriented approximately parallel to the bedding plane of the sand, whereas the plugs used by Elf-Aquitaine were perpendicular to the bedding plane. The displacement tests plotted in Figure 57 were conducted at a scaled flow rate of about 10 ft/day to ensure negligible capillary pressure gradients and end effects.

The endpoint saturation and relative permeabilities for the Elf-Aquitaine and Energy Resources measurements are compared in Table 24. The two sets of curves are consistent in several respects. First, the residual oil saturation is high - at least 30 percent in both cases. Both curves show a low relative permeability to oil at water saturations above 60 percent, a feature that may help explain the high watercuts experienced in the field to date. Both curves also show a maximum less than 50 percent, typical of water-wet sands. There are, however, two notable differences in

¹Johnson, E.F., Bossler, D.P., and Naumann, V.O. (1959), Calculation of relative permeabilities from displacement experiments, Trans. AIME 216:370.

TABLE 23

RELATIVE PERMEABILITY MEASUREMENTS ON RUDOLPH 5,
LEVEL 2293', AS MEASURED BY ELF-AQUITAINE, AUGUST 1979

s_w	k_{rw}	k_{ro}	f_w	k_{rw}/k_{ro}
0.16	0.	1.	0.	0.
0.20	0.004	0.870	0.031	0.00460
0.25	0.008	0.722	0.073	0.011
0.30	0.013	0.572	0.138	0.0227
0.35	0.017	0.413	0.225	0.412
0.40	0.022	0.250	0.333	0.0880
0.45	0.033	0.178	0.567	0.185
0.50	0.044	0.105	0.747	0.419
0.55	0.055	0.055	0.876	1.000
0.60	0.073	0.015	0.972	4.867
0.65	0.092	0.006	0.991	10.33
0.70	0.110	0.	1.	

ERCO

ENERGY RESOURCES CO. INC.
135 Alewife Brook Parkway
Cambridge, Massachusetts 02138

DATE August 10, 1979

BY Elf-Aquitaine

SAMPLE NO.

COMPANY ERCO

LEASE Rudolph Sch. Com

WELL NO 5

FIELD Storms Pool

COUNTY White

STATE Illinois

Figure 54. RELATIVE PERMEABILITIES vs. WATER SATURATION.

Method Steady-State

Permeability md

Depth from 2293 feet

Porosity

Formation Waltersburg

Residual Brine Saturation 16

Residual Oil Saturation 30

REMARKS

ERCO

ENERGY RESOURCES CO. INC.

135 Alewife Brook Parkway

Cambridge, Massachusetts 02138

UNIT _____

BY Elf-Aquitaine

SAMPLE NO. _____

COMPANY ERCO LEASE Rudolph Sch. Com. WELL NO. 5FIELD Storms Pool COUNTY White STATE Illinois

Figure 55. RELATIVE PERMEABILITY RATIO vs. SATURATION

Method Steady-State

Permeability, md _____

Depth ft. from 2293 feet

Porosity _____

to _____

Residual Brine Saturation 16Formation WaltersburgResidual Oil Saturation 30

REMARKS

-100-

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

Figure 56. Fractional flow of water vs. brine saturation at Well 10-5, as measured by Elf-Aquitaine.

ERCO

ENERGY RESOURCES CO. INC.
185 Alewife Brook Parkway
Cambridge, Massachusetts 02138

BY Energy Resources Co. Inc.
SAMPLE NO. CA62/DY7

COMPANY _____ LEASE Rudolph WELL NO. 10-5
FIELD Storms Pool COUNTY White STATE Illinois

Figure 57. Relative permeability vs. water saturation.

Method Transient Permeability, md _____
Depth ft. from 2284 ft. Porosity 19.7%
to _____ Residual Brine Saturation 24.8% %
Formation Waltersburg Residual Oil Saturation 33.6% %

REMARKS.

TABLE 24

COMPARISON OF ENDPOINT SATURATIONS AND RELATIVE PERMEABILITIES
AS MEASURED BY ENERGY RESOURCES AND ELF-AQUITAINE

LABORATORY	S_{orw}	S_{wir}	k_{ro}^{max}	k_{rw}^{max}
Energy Resources	0.336	0.248	0.495	0.250
Elf-Aquitaine	0.30	0.160	1.0	0.110

the curves. Figure 53 shows an irreducible water saturation less than 20 percent whereas that in Figure 57 is greater than 25 percent. Also, the intersection of the oil and water curves occurs to the right of 50 percent in Figure 53 but to the left in Figure 57. These features in combination indicate that the reservoir rock is slightly water-wet or of intermediate wettability.

The total relative mobilities, expressed in reciprocal centipoises, are plotted in Figure 58 for the two sets of relative permeabilities measured. The total relative mobility is defined as the sum of the relative mobilities to oil and water, i.e.,

$$\lambda_T = \frac{k_{ro}}{\mu_o} + \frac{k_{rw}}{\mu_w}$$

The values $\mu_o = 6.0$ cp, $\mu_w = 0.85$ cp are assumed. These reciprocal mobility curves are typical in that the total relative mobility of the oil-water bank decreases to a minimum immediately after breakthrough and gradually increases with an increase in water saturation. This direction is the same for a polymer flood in which, for a constant viscosity (or concentration) polymer slug, the mobility ratio increases from a lower value prior to breakthrough to a maximum in the medium saturation range.

For the pilot polymer flood in the Storms Pool, the minimum total relative mobility can be used to check the polymer slug design. The minimum total relative mobility in the lowest curve of Figure 58 is 0.057 cp^{-1} . At a water saturation of 45 percent, corresponding to this minimum total relative mobility, the mobility ratio for an

Figure 58. Comparison of total relative mobility versus saturation for curves measured by Energy Resources and Elf Aquitaine.

8.5 cp slug is 0.045. At flood-out, i.e. residual oil saturation and the end of a graded slug, the mobility ratio is still favorable at 0.046.

4.2 Capillary Pressure

Capillary pressure curves are shown in Figures 59 and 60. Figure 59 illustrates a typical air drainage curve in which the irreducible brine saturation is approximately 12 percent. This figure corresponds reasonably well with some of the residual saturations of the dynamic displacement experiments. The imbibition and drainage curves of a reservoir crude-brine system in the same core are illustrated in Figure 60.

4.3 Microbiology of the Storms Pool

Bacteria in oil reservoirs pose several potential problems in the design of a polymer flood. H_2S formed by sulfate reducing bacteria may combine with iron in water, forming a colloidal suspension which will complex with suspended particulate matter, including bacteria. This can cause clogging when the water is injected into the oil reservoir. Biopolymers are a prime nutrient source for bacteria, and microbial attack can alter the viscosity and gel properties of polymer-water solutions. Although biocides such as formaldehyde and paraformaldehyde have been used in initial concentrations as high as 10 percent, they often fail to inhibit microbial growth completely because effective concentrations may be much lower in situ. To understand the microbiological community associated with the Storms Pool, Energy Resources performed a taxonomic screen of the microflora from the site's river and formation waters. The anaerobic sulfate reducing bacteria associated with core sediments were also quantified, and the 10 most prevalent bacterial colony types from each class of sample were isolated and characterized. The ability for isolates to subsist on hydrocarbons, biopolymer, and a polyacrylamide was also determined.

4.3.1 Materials and Methods

Water samples were obtained near the intake below the river pumps on the Little Wapash River and from the Waltersburg formation at Well 6-16 during the last week of September 1978.

ERCO

ENERGY RESOURCES CO. INC.

185 Alewife Brook Parkway
Cambridge, Massachusetts 02138DATE 10/11/79BY JBESAMPLE NO. CA81/EQ05COMPANY _____ LEASE Rudolph WELL NO 10 - 5FIELD Storms Pool COUNTY White STATE Carmi, Illinois

Figure 59 CAPILLARY PRESSURE vs. SATURATION

Method Centrifugal Permeability, md 375 mdDepth from 2285 ft Abs. Porosity 23.7%

to _____ Residual Saturation _____ %

Formation Waltersburg Residual Saturation _____ %REMARKS Air Drainage

ERCO

ENERGY RESOURCES CO. INC.
185 Alewife Brook Parkway
Cambridge, Massachusetts 02138

DATE 10/18/79BY JBESAMPLE NO. CA81/EQ05

COMPANY _____ LEASE Rudolph WELL NO. 10-5
FIELD Storms Pool COUNTY White STATE Carmi, Illinois

Figure 60. CAPILLARY PRESSURE vs. SATURATION.

Method Centrifugal Permeability, md 375 md
Depth ft. from 2285 ft. Abs. Porosity 23.7% %
to _____ Residual _____ Saturation _____ %
Formation Waltersburg Residual _____ Saturation _____ %

REMARKS: Wettability Index = 0.5

Aerobic and Anaerobic Heterotrophic Population

Water samples from each source were membrane-filtered through 0.45-micron Nuclepore membranes (Nuclepore Corp., Pleasanton, California) to count the colony-forming units (CFU) per ml of sample. The following dilution series was filtered in triplicate: 100 ml of sample, 10 ml of sample, 10 ml of 1:10 dilution, 10 ml of 1:100 dilution, and 10 ml of a 1:1,000 dilution. One membrane of each dilution was then placed on each of the following nutrient media:

1. Nutrient agar on 50-mm plate.
2. API agar plate prepared according to Allred.² Sulfate reducing colonies become black on this medium.
3. Media-free 50-mm plates. Membranes were then overlaid with API agar to exclude air and therefore select anaerobes.

Nutrient agar and aerobic API plates were incubated aerobically at 20° C for 7 days. Anaerobic API plates were placed in a BBL³ Gas Pak system and incubated anaerobically in an atmosphere of H₂ and CO₂ for 6 weeks, being observed periodically during that period. At the end of the incubation period, sulfate reducing CFU/ml (black colonies) and total anaerobic CFU/ml were counted.

Anaerobic Sulfate Reducers in Core Samples

A similar procedure was followed to quantify the anaerobic sulfate reducers in the formation. Two core samples from Well 10-5 at 2,272 feet subsea were cracked open and the interior sections removed aseptically into a sterile mortar. They were ground with a mortar and pestle to a fine sandy consistency. The following procedure was performed in quadruplicate: 1 g of sample was transferred to a tube containing 9 ml API broth. This was stoppered and flowed back and forth four times to mix the inoculum. One ml from this tube was then transferred to a second tube of 9 ml API agar and mixed as before. The serial transfer was continued until a dilution of 1:10,000 was reached. The tubes were then capped and incubated at 20° C over a period of 5

²Allred, R.C. (1965), API recommended practice for biological analysis of subsurface injection waters (New York, Amer. Petrol. Institute), p. 4.

³Registered trademark of Becton, Dickinson and Company.

weeks. The tubes were checked each week for intense black colonies indicating sulfate reducing bacteria.

Isolation and Maintenance of Isolates

To isolate a representative bacterial population from the water samples, 10 representative colonies from each master plate were restreaked onto nutrient agar and API agar plates, then incubated for 3 days at 20° C. They were then transferred to 5° C for storage for 2 weeks. Single colonies from each of the nutrient and API agar plates were then streaked onto nutrient and API agar slants, respectively, and incubated for 3 more days at 20° C. A second set of nutrient agar and API plates was restreaked again from these slants to obtain pure cultures. During the experimental period, the isolates were restreaked onto fresh slants three times at 2-week intervals to maintain the freshness of the cultures. All cultures were maintained at 20° C and all microscopic and physiological tests were made with 48- to 72-hour-old cultures.

Taxonomic Identification of the Isolates

The isolates were screened taxonomically according to the procedures delineated in Energy Resources' taxonomy manual. The following tests were performed on each isolate: Gram stain, cell motility and morphology, colony morphology, physiological tests for catalase, oxidase and urease activity, carbohydrate utilization, gelatin hydrolysis, cellulose degradation, nitrate reduction, O/129 (vibriostat) sensitivity, and citrate reduction. Phase microscopy of all organisms was performed using a Zeiss universal-phase epifluorescence scope.

Screen for Nutritional Capabilities

To assess the capability of each of the isolates to grow on polyacrylamide B, biopolymer G2, and a model hydrocarbon mixture (11.1 percent each of C₁₂ - C₂₂ n-alkanes) the following procedure was used: the test polymer or model hydrocarbon mixture absorbed onto 10 percent silica gel was mixed 15 percent weight-to-volume with sterilized Makula and Finnerty's⁴ river media, plus 1.5 percent agar. Thorough mixing was accomplished by sonicating the mixture 20 minutes in sterile 1-liter polypropylene bottles and vortexing for 5

⁴Makula, R., and Finnerty, W.R. (1969), Microbial assimilation of hydrocarbons. I. Fatty acids derived from normal alkanes, J. Bacteriol. 95:2102-2107.

minutes at high speed. This procedure was required for homogenizing the medium plus the nutrient source mixture. The media were then poured into 100-mm petri plates. Each isolate was streaked in duplicate onto each of the three media. The isolates were also streaked onto Makula and Finnerty's river media and 15 percent agar without the supplemental polymer or hydrocarbon source to check for the utilization of agar as a sole carbon source. All plates were incubated at 20° C for 10 days. Isolates growing on test media were transferred from the initial test plate and restreaked onto a second set of plates to ensure that growth on the primary plate was not due to nutrient carry-over. Isolates growing on test nutrients but not on unsupplemented agar were considered confirmed utilizers of the test carbon sources.

4.3.2 Results

Quantification of Heterotrophic Bacterial Community

Quantitative data for aerobic and anaerobic heterotrophs are given in Table 25. Aerobic heterotrophs in the sampled formation water, river water, and sediment were numerically significant in all three sources. Titters ranged from 60 CFU/ml in the sediment and formation water samples to 450 CFU/ml in the river water sample. Aerobes are considered to be significant at titers greater than or equal to 9 CFU/ml. The anaerobic population was significant (at least 1,500 CFU/ml) in the sediment sample only.

TABLE 25

COLONY-FORMING UNITS OF BACTERIA IN FORMATION WATER, RIVER H₂O AND SEDIMENT

	RIVER WATER (CFU/ml)	SEDIMENT (CFU/ml)	FORMATION WATER (CFU/ml)
Aerobes	450	100 - 150	70
Facultative anaerobes	310	13,000 - 26,000	93
Strict anaerobes	0	1,000 - 19,000	7
Sulfate reducers	0	100 - 1,000	5

Taxonomy of Sampled Formation and River Water Bacteria

The taxonomy of the formation and river water samples (Table 26) showed a typical cross section of aerobic bacteria associated with soil and water. Three genera predominated: Bacillus, Pseudomonas, and Arthrobacter. Anaerobic sulfate reducers were found only in the formation water sample but constituted 40 percent of the isolates from this source. Four of the five sulfate reducing isolates were Desulfovibrio species; one was Desulfotomaculum species.

Nutritional Screen: Polymer and Hydrocarbon Utilization

Data from the nutrient screen are summarized in Table 27. Biopolymer G2 supported extensive growth but polyacrylamide B did not. Identification of each of the isolates showed a predominance of three taxa that are commonly associated with soil and water. Of the isolates from each of the three groups, Arthrobacter, Bacillus, and Pseudomonas, one-third to one-half were able to grow on biopolymer G2 with 30 ppm formaldehyde, and 60-100 percent were supported by the hydrocarbon mixture. Two other isolates, identified as Micrococcus and Citrobacter species, were able to utilize the hydrocarbon mixture only. Only one isolate was able to utilize the polyacrylamide B. The isolate has tentatively been identified as a Micrococcus species, but such nutritional flexibility is unusual with this species and the isolate's identity should be re-examined.

The testing procedure used here is subject to some variation due to the difficulty in handling the polymers in a solid form. Polyacrylamide B appeared able to degrade the agar support matrix into which it had been mixed, causing the media to turn into a sticky slime which would not adhere to the test plate after 3 or 4 days' incubation. This condition occurred erratically among the test plates and made it difficult and in some cases impossible to determine if growth occurred. Apparently this was not due to bacterial degradation, because the condition was originally discovered in uninoculated plates. After 4 weeks of incubation, fungal growth was observed on several of the polyacrylamide B plates. The fungus may have been introduced to the plates as a contaminant or may represent part of the microflora. Further investigation of this fungus is under way.

4.3.3 Discussion

The initial screen of the isolates from river and formation samples reveals a cross section of taxonomic

TABLE 26

STORMS POOL UNIT BACTERIAL TAXONOMY:
PREDOMINANCE AND DISTRIBUTION OF BACTERIAL TAXA
FROM SAMPLED RIVER AND FORMATION WATERS

A. AEROBIC HETEROTROPHS IN RIVER AND FORMATION WATER

TAXONOMIC GROUP	NUMBER OF ISOLATES FROM TOTAL OF 39	NUMBER OF RIVER WATER ISOLATES (18)	NUMBER OF FORMATION WATER ISOLATES (21)
<u>Arthrobacter</u>	3	2	1
<u>Bacillus</u>	7	5	2
<u>Pseudomonas</u>	7	3	4
<u>Micrococcus</u>	5	1	4
<u>Sporosarcina</u>	4	3	1
<u>Aerococcus</u>	2	1	1
<u>Corynebacterium</u>	3	1	2
<u>Flavobacter</u>	1	1	-
<u>Mycobacterium</u>	1	-	1
<u>Leuconostoc</u>	1	-	1
<u>Hypnomicrobium</u>	1	1	-
<u>Citrobacter</u>	1	-	1
<u>Lactobacillus</u>	1	-	1
<u>Actinobacillus</u>	1	-	1
<u>Paracoccus</u>	1	-	1

B. ANAEROBIC HETEROTROPHS IN RIVER AND FORMATION WATER

TAXONOMIC GROUP	NUMBER OF ISOLATES FROM TOTAL OF 13	NUMBER OF RIVER WATER ISOLATES (3)	NUMBER OF FORMATION WATER ISOLATES (10)	SULFATE REDUCTION
<u>Vibrio</u> (facultative)	5	3	2	0
<u>Bacillus</u> (facultative)	3	0	3	+a
<u>Desulfovibrio</u>	4	0	4	+++b
<u>Desulfotomaculum</u>	1	0	1	+++b

+a = <10 percent sulfate reduction activity.

+++b = >90 percent sulfate reduction activity.

TABLE 27

NUTRITIONAL CAPABILITIES: GROWTH OF COLONIES IN
BIOPOLYMER G2, COPOLYMER B, AND MODEL HYDROCARBON MIXTURE

	NUMBER OF COLONIES GROWING		
	BIOPOLYMER G2 ^a	POLYACRYLAMIDE	HYDROCARBON MIXTURE
<u>Arthrobacter</u>	1	0	2
<u>Bacillus</u>	4	0	7
<u>Pseudomonas</u>	2	0	6
<u>Micrococcus</u>	0	1	1
<u>Citrobacter</u>	0	0	1

^aContained 300 ppm formaldehyde.

groups comparable to previous findings on bacterial populations associated with waterflooded oil fields.^{5,6,7,8} The two water sources contain taxa which have potential to metabolize the biopolymer G2 with 300 ppm formaldehyde, cause corrosion, and plug the formation.

The predominant isolate types were able to utilize the biopolymer G2 with 300 ppm formaldehyde as a growth medium. A formaldehyde concentration of 75 to 80 ppm is considered necessary for effective biological control. However, extended polymer residence times in the reservoir, usually at least 110 days, coupled with variations in the system (such as preferential adsorption of highly active biocides)

⁵Bastin, E.S., and Gifeer, J.W. (1930), Additional data on sulfate-reducing bacteria in soils and waters of Illinois oilfields, Bull. Am. Assoc. Petrol. Geologists 14:143-159.

⁶Ginsberg-Karagicheva, T.L. (1933), Microflora of oilwaters and oil-bearing formations and biochemical processes caused by it. Bull. Am. Assoc. Petrol. Geologists 17:52-65.

⁷Issatchenko, V. (1940), J. Bacteriol. 40:379-381.

⁸Zobell, C.E. (1950), Fundamental research on occurrence and recovery of petroleum, Report of Progress for 1948-1949 (New York, Am. Petrol. Inst.).

can result in a decrease in the actual biocide concentration and a decrease in its effectiveness.⁹ Zobell¹⁰ conducted permeability studies of various bacterial species in reservoir rock. He found that pseudomonads can permeate very fine-grained sandstone and survive indefinitely. The presence of pseudomonad isolates in the formation water sample (83 percent of which are able to use biopolymer G2 with 300 ppm as sole carbon source) could reduce the efficacy of the flood if the biopolymer is not injected with sufficient concentrations of biocide.

Biopolymer-metabolizing bacteria are also present in the river water samples. Accordingly, care must be taken not to introduce these populations into the oil bearing rock where they may proliferate and become a source of similar problems.

Sulfate reducing bacteria have been found in the samples, and therefore the potential for corrosion and clogging exists. However, a smaller proportion of sulfate reducing isolates than expected was found in the two water samples. All sulfate reducing isolates were found in the formation water sample and sediments, indicating a close association with the oil formation and not the surface waters.

The next logical step in studying the microbiology of the Storms Pool is to determine whether the microbiological community does, in fact, adversely affect the polymers used in the project. Preliminary experiments are under way to determine the effect of two isolates on the viscosities of biopolymer G2 under laboratory conditions. If microbial growth adversely affects polymer viscosity in these experiments, the next task will be to ascertain whether a similar phenomenon occurs in simulated field conditions. The third phase will be used to develop corrective measures for any deleterious effects of the microbial community on the polymer solution.

4.4 Quality Control Program

Preliminary specifications to be used for polymer quality control were submitted to Pfizer in November, 1979.

⁹Myers, G.C. (1962), Paraformaldehyde resistant starch fermenting bacteria in "starch-base drilling mud," Appl. Microbiol. 10:418-421.

¹⁰Zobell, C.E. (1946), Fundamental research on occurrence and recovery of petroleum, Report of Progress for 1944-1945 (New York, Am. Petrol. Inst.).

The quality control program planned includes testing for millipore filterability, viscosity, active weight, and formaldehyde content, as indicated in Table 28. These parameters are tentative and subject to revision after the injectivity test scheduled for January, 1980. If injectivity is extremely good more latitude might be allowed in the millipore filter ratio and absolute filterability tests. An on-site quality control lab is being designed to perform these tests and other necessary lab work.

Testing of ancillary chemicals began during November, 1979 to determine the effect of various biocides, oxygen scavengers, and chelating agents on the integrity of the polymer and its ability to function under reservoir conditions. These tests are discussed in Section Three. Two biocides will be used to allow rotation.

TABLE 28

QUALITY CONTROL PARAMETERS FOR POLYSACCHARIDE

TEST	ACCEPTABLE RANGE	FREQUENCY
<u>Filterability in 1.2-micron</u>		
<u>Filter</u>		
Millipore filter ratio	1.0 - 1.3	every batch
Total Filtration time	1000 sec/liter max.	every batch
<u>Viscosity at 500 ppm</u>		
In Wabash River water	7 - 9 cp	every batch
In Pfizer standard water	9 - 11 cp	every batch
<u>Active Content</u>		
Viscosity method	2.6% minimum	every batch
Toal carbohydrate method	2.5% minimum	as needed
<u>Formaldehyde Content</u>	2000 ppm	as needed

SECTION FIVE

WELL PREPARATION

Reconditioning and restimulation of the 10 original wells in the pilot area began in November, 1978 and was completed in the period covered by this annual report. In addition the new Well 10-5, drilled in 1978, was completed and prepared for production. Three wells, one injector and two producers, were reconditioned in 1978. Well 10-3 was cleaned, acidized, and tested; Wells 9-1 and 9-4 were both cleaned and tested for production rate. These workovers are reported in the first annual report. The remaining wells were worked on in 1979.

5.1 The New Well 10-5

In 1978 an additional well was drilled in the center of Tract 10 to recover a complete fresh core from the Waltersburg sand and for logging and observation during pre-injection testing. This well is only 466 feet from the nearest injectors and producers (Figure 61), whereas normal well spacing in the pattern is 10 acres or 660 feet between injector and producer. The new well will therefore receive a stronger, more interpretable response in pressure tests and will play an important role in tracer and polymer injection to check the progress of chemicals.

From May 25 to June 1, 1979, Well 10-5 was circulated clean to 2306 feet subsurface and perforated with 60 holes (approximately two holes per foot) between 2267 and 2297 feet subsurface (1865 to 1895 feet subsea). Figure 62 is the gamma ray-neutron log which was run in conjunction with the perforation job. This well was perforated only in the top 30 feet of the Waltersburg formation in hope of avoiding the zone of high water saturation which lies just below the oil zone. The well was acidized on June 7, 1979 with 1000 gallons of Halliburton MCA and 1000 gallons of 5 percent HCl. A swab test produced 3 bbl/hr of formation water with a trace of oil. Rods and tubing were run, and the well is currently ready for production.

5.2 Injection Well Workovers

Five of the six injection wells for this pilot were reconditioned during the period covered by this report. The sixth, Well 10-3, was completed in 1978.

Figure 61. Layout of Storms Pool pilot facilities.

Snyder Logging Service GRAYVILLE, ILL.		Gamma Ray Neutron Log		
FILING NO. _____		COMPANY <u>ENERGY RESOURCES CO., INC.</u>		
WELL <u>RUDOLPH #5</u> (N10-5)		FIELD _____		
COUNTY <u>WHITE</u> STATE <u>ILLINOIS</u>		LOCATION <u>660' N 690' W SE/c</u>		
SEC <u>11</u> TWP <u>6S</u> RGE <u>9E</u>		OTHER SERVICES <u>PERFORATE</u> <u>60 HOLES</u> <u>2267'-2297'</u>		
PERMANENT DATUM _____ ELEV. _____ LOG MEASURED FROM <u>393' 8" ABY. GL</u> FT ABOVE PERM. DATUM DRILLING MEASURED FROM <u>393'</u>		ELEV. <u>88</u> D.P. _____ O.L. _____		
DATE	<u>5-30-79</u>	<u>5-30-79</u>	<u>5-30-79</u>	
RUN NO	<u>ONE</u>	<u>ONE</u>	<u>ONE</u>	
TYPE LOG	<u>GAMMA-RAY</u>	<u>NEUTRON</u>	<u>CCL</u>	
DEPTH-DRILLER	<u>5304'</u>	<u>2309'</u>	<u>2305'</u>	
DEPTH-LOGGER	<u>2301'</u>	<u>2309'</u>	<u>2305'</u>	
BOTTOM LOGGED INTERVAL	<u>2301'</u>	<u>2309'</u>	<u>2305'</u>	
TOP LOGGED INTERVAL	<u>1892'</u>	<u>1900'</u>	<u>1896'</u>	
TYPE FLUID IN HOLE	<u>WATER</u>			
SALINITY PPM CL				
DENSITY				
LEVEL				
MAX REC. TEMP. DEG F				
OPERATING RIG TIME	<u>3 HRS.</u>			
RECORDED BY	<u>W. BUNTING</u>			
WITNESSED BY	<u>A. BARODY</u>			
RUN NO	BORE HOLE RECORD		CASING RECORD	
	BIT	FROM	TO	SIZE
				<u>5 1/2"</u>
				WGT
				FROM
				<u>3309' +</u>
				TO
				<u>SURF.</u>

Figure 62. Gamma Ray Neutron Log, Well 10-5.

The reservoir engineering report for the project generated some questions regarding the thickness of the oil-saturated sand. Logs of Well 10-5 had indicated the presence of oil deeper than the originally assumed oil-water contact at 1890 feet subsea. Well 10-1 therefore was deepened to 2310 feet subsurface level (1910 feet subsea) and a Schlumberger dual induction laterolog was run. The moderately high resistivity below 2290 feet subsurface recorded by this log (Figure 63) was difficult to interpret in light of the large volumes of fresh water injected through this well during the waterflood. The low resistivity recorded in the completion interval (2272-2282 feet subsurface) suggests that the shot hole is quite large, extending off-scale of the medium-range induction log.

well 10-1 was then acidized with 500 gallons of 5 percent HCl which was allowed to stay in the shot hole, followed by 1500 gallons of 15 percent Halliburton FE acid under pressure. The acid was pumped in at 2 gal/min and was followed by 3 bbl/min of formation water at 100 psig. Two-inch plastic coated tubing and a packer were set in the hole at 2161 feet subsurface, and the well is now hooked up for injection.

Well 9-2 was circulated clean to a total depth of 2283 feet subsurface (1880 feet subsea) and acidized with 1500 gallons of 15 percent Halliburton FE acid. Plastic coated tubing was run in the well and a packer set at 2163 feet subsurface.

Well 9-3 was circulated clean to a total depth of 2248 feet subsurface (1882 feet subsea) and was drilled 6 feet deeper to increase injectivity and ensure even injection of polymer throughout the formation. Halliburton acidized the well as follows: 500 gallons 5 percent HCl at no applied pressure, 1000 gallons Halliburton MCA at 3 bbl/min at 300 psig, 1000 gallons 5 percent HCl at 2 bbl/min at 100 psig and finally formation water at 2 bbl/min at 100 psig.

well 6-4 was circulated clean to 2487 feet subsurface and plugged back to 2279 feet subsurface (1886 feet subsea). Halliburton acidized the well with the sequence used on well 9-3 and eventually flushed the well with formation water at 200 bbl/min at 500 psig. Two-inch plastic coated tubing and a packer were run into the well and set at 2187 feet subsurface.

Well 12-4 required several special operations. Heavy rotary mud and silt was circulated and drilled out of the well to the 7-inch casing shoe at 2261 feet subsurface

Schlumberger		DUAL INDUCTION LATEROLOG			
COUNTY		COMPANY ENERGY RESOURCES COMPANY			
WELL		STORMS FIELD #1			
FIELD		STORMS FIELD			
COUNTY		WHITE STATE ILLINOIS			
LOCATION		TRACT TO WELL #1		Other Services:	
API SERIAL NO		SEC	TWP	RANGE	FDC-CNL-GR BHC
Permanent Datum:		GL		Elev.: -	
Log Measured From		TOP OF 7" 1		Ft. Above Perm. Datum	
Drilling Measured From		11		D.F. -	
Date		10-17-78			
Run No.		ONE			
Depth-Driller		2327			
Depth-Logger (Schl.)		2318			
Btm. Log Interval		2315			
Top Log Interval		2267			
Casing-Driller		7" @ 2270 @ @ @			
Casing-Logger		2267			
Bit Size		6 1/4"			
Type Fluid in Hole		SALT GEL			
Dens. Visc.		- -			
pH Fluid Loss		- - ml ml ml ml			
Source of Sample		FLOWLINE			
Rm @ Meas. Temp.		277 @ 68 °F @ °F @ °F @ °F			
Rml @ Meas. Temp.		266 @ 62 °F @ °F @ °F @ °F			
Rmc @ Meas. Temp.		416 @ 68 °F @ °F @ °F @ °F			
Source: Rml Rmc		M C			
Rm @ BHT		- @ - °F @ °F @ °F @ °F			
Circulation Stopped		1400			
Logger on Bottom		1630			
Max. Rec. Temp.		- °F °F °F °F			
Equip. Location		7642 MT. VERNON			
Recorded By		HONOR & SARK			
Witnessed By Mr.		D. HALEY

Figure 63. Dual Induction Laterolog, Well 10-1.

(1864 feet subsea). The casing, which was perforated into the gas cap during primary production, was squeezed with cement and left to set. The cement was then drilled to the top of an old string of tubing which was left in the hole. This tubing was cut off about 100 feet below the target interval, and the well was cemented back to 2281 feet subsurface. After circulating clean, the well was acidized according to the program described above and was flushed with 0.5 bbl/min of formation water at 1000 psig. This was judged unsatisfactory, and when the well was entered for pressure testing the completion interval appeared to be completely blocked with heavy mud and cement debris. The well was recleaned and acidized with only marginal improvements in injection rates, eventually taking 12 bbl/hr at 300 psig. A light 10,000-gallon hydraulic fracturing of the interval with 20-40 sand at 1800 psig increased injection rates to 6 bbl/min at 225 psig.

Two-inch plastic-coated injection lines were installed and connected with each injection well. Figure 64 summarizes the current status of the six injectors.

5.3 Production Wells

Of the four original producing wells in the project, two were cleaned and fitted with rods and tubing in 1978. In 1979 the rods and downhole pumps in Wells 10-2 and 10-4 were replaced. These wells are both currently producing a total of 10 bbl/day. Pumping units for the three remaining wells are being installed. Well 9-4 required an 8-foot substructure. Three-inch PVC flowlines connect each producer to a tank battery on Tract 10.

Profile of Well 9-2, October 18, 1979.

Profile of Well 9-3, October 17, 1979.

Profile of Well 6-4, October 19, 1979.

Profile of Well 12-4, October 17, 1979

Profile of Well 10-1, October 18, 1979.

Profile of Well 10-3, October 19, 1979.

Figure 64. Profiles of Storms Pool pilot injection wells.

SECTION SIX

CONSTRUCTION OF FACILITIES

Essentially all the construction and fabrication of the polymer injection facility and connecting pipeline and electrical network completed to date was performed during the period covered by this report. In 1978 only some preliminary design and preparation was completed in conjunction with the geologic and engineering analysis of the reservoir. During 1979 detailed design of the injection facility, purchasing of required equipment items and preparation of the field progressed simultaneously throughout the first half of the year. The final design and shipment of equipment to Carmi was completed during the third quarter of 1979, and fabrication of the facility and connecting fluid network occupied the last months of 1979 in preparation for water injection.

6.1 Preparation of the Pilot Site

Construction of the injection plant required extensive preparation of the site, field access roads, and existing equipment. The injection plant site was graded and cleared of debris and 60 tons of 3/4-inch gravel was spread as a base for the polymer storage and mixing tank battery. In addition the grader distributed 30 tons of 1-inch gravel along the field roads to improve access. A trailer bed hull serving as a bridge was set over a creek that runs between the plant site and Tract 9. Figure 65 shows the field road network.

In conjunction with the preparation of the field site, much of the existing equipment in the field was upgraded. New sucker rods were purchased for each production well and existing pumps were inspected. In all, 9,200 feet of 2-inch I.D. steel pipe, tested to 10,000 psig, were bought, sand-blasted and epoxy coated for use as injection line.

This phase of construction was frequently interrupted and postponed by snow and freezing weather. However, most of the essential preparation was accomplished in the scattered periods of fair weather early in the year, and the field was ready for active construction during the summer.

6.2 Plant Design and Purchasing of Equipment

The design of the injection facility evolved through several stages of complexity. During this design phase

Figure 65. Layout of Storms Pool pilot road network.

large equipment items with long lead times were ordered wherever possible. A tri-filtering system, manufactured by Culligan International Corporation, was ordered in December 1978 to filter the injection water from the Little Wabash River. Each of the three units is capable of filtering 75 gal/min of water. Our design flow rate calls for a maximum of 110 gal/min; therefore two units will easily handle the required flow while the third is cleaned by backwashing. In addition a Gardiner Denver PT4L triplex plunger pump was purchased for use as the main injection pump. The pump was previously used at a car wash for approximately 6 months. All parts of the pump, including valves, seats, plungers, and belt drive, were inspected and showed very little wear. The pump was guaranteed to operate properly by the vendor, Simpson Brothers in Fairfield, Illinois.

During this period we chose a building contractor after receiving quotes from several contractors in the area. Plans for the injection building were finalized in January, 1979 and the metal building shell was assembled on site in February. The concrete foundation was not poured until April due to bad weather. The final structure is 30 feet wide and 36 feet long with 12-foot-high walls. The floor is 4-inch-thick concrete, with the exception of the area under the triplex pump which is 6 inches thick. A 12-foot x 15-foot office has been partitioned off. A 3-foot-wide and 3-foot-deep drainage trench runs lengthwise through the building. The layout of the building is depicted in Figure 66.

Anderson & Son Electric began work on electrification of the plant and pumping wells in January. By April three transformers were installed adjacent to the injection facility. These transformers step the primary voltage of 12,500 volts down to 400 volts.

A preliminary version of the piping and instrumentation diagram (P&ID) was produced in January and revised several times through July based on input from DOE, polymer suppliers, and other oilfield operators. The preliminary version is shown in Figure 67. By the end of July all equipment had been ordered with the exception of instrumentation. The Appendix is a list of the equipment and the vendors which supplied them.

During July and August injection and flow lines were laid in the field and connected to each well. Injection lines were brought to the east end of the injection plant for connection to the pump upon completion of the plant. PVC flow lines were linked to each production well and to

Figure 66. Injection plant layout.

Figure 67.

ENERGY RESOURCES CO INC			
NAME	DATE	APPROVED BY	DATE
DATE	1/11/80		
EQUIPMENT LAYOUT - EOR PROJECT			
CHEMICAL			
D 1700 009			

the existing tank battery on Tract 10. Existing flow lines were replaced with 3-inch PVC pipe, and an additional freewater knockout will enable us to monitor production from a single well by keeping it separate from the rest of the production. Each well will be periodically monitored in this way.

The method of fresh water supply was finalized during this period and the existing pumps at the river station were examined. A 1000-barrel tank was ordered from a local fabricator and placed at the injection plant. The fresh water supply method hinged on the ability of the river pumps to supply water the extra 3000 feet from the original waterflood plant to our facility. The manufacturer, Layne Western, indicated that the pumps could supply water against the calculated head but also discovered that one of two river station pumps was inoperable. This pump was sent to St. Louis and rebuilt.

Some revisions in this P&ID were made in September at the suggestion of our subcontractor, Elf-Aquitaine. By October 1 all equipment and instrumentation was ordered and much of it had been delivered to the site. The absence of several items, significantly the cartridge filters and PVC valves, forced us to postpone fabrication until November 1979. However, during the preceding months steady progress in construction had resulted in detailed plans of a well-designed system, enabling us to complete 90 percent of the fabrication of the injection facility in the final months of 1979.

6.3 Fabrication of the Injection Plant

The internal piping, wiring and installation of equipment in the injection facility began in November, 1979. The arrival of several key pieces of equipment in October allowed two-thirds of the internal piping to be completed in 2 weeks. In addition, the 1000-barrel water tank was completed and light and heat installed in the facility. By the end of November, all piping within the plant, with the exception of the stainless steel manifold downstream of the triplex pump, had been assembled. In December the 6-inch line linking the original waterflood plant to our facility was completed, and the river pumps were reinstalled and readied for service. The 75-horsepower motor for the triplex pump was delivered and set up on skids. An 8-foot framework base for the pumping unit at Well 9-4 was constructed to compensate for its position low in the creek bed.

6.4 Current Status

All equipment essential to the injection of water is on site and assembled awaiting the installation of some basic instrumentation and wiring. The final assembly of the stainless steel connections to the injection lines is in progress, as is the wiring of the motors in the plant. Production must begin, and insulation of all tanks and exposed lines must be checked closely before injection can be started.

SECTION SEVEN

RESERVOIR SIMULATION

During 1979 Energy Resources and Elf-Aquitaine agreed on a plan for simulating the Storms Pool pilot project and conducted simulations supporting the preliminary design of a polysaccharide slug to be injected. This section summarizes these activities.

7.1 Simulation Strategy

In February, 1979, Energy Resources' project team met with Elf-Aquitaine to plan the project's simulation work. For contractual reasons they decided not to use Energy Resources' polymer flood simulator but instead to rely on Elf-Aquitaine's two-dimensional stream-tube simulator. This model has been used with good results in the Chateaufrenard field in France's Paris Basin. The overall plan for using this simulator is as follows:

- Stage 1 - Run the simulator with preliminary data to define stream-tubes, 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.
- Stage 2 - Run the simulator using more detailed and better confirmed data to determine injection strategy.
- Stage 3 - Monitor field performance quarterly.

Stage 1 was completed during 1979.

7.2 Preliminary Simulator Runs

The preliminary simulator runs (Stage 1) modeled two cases, drawn in Figure 68. 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

Figure 68. Boundaries assumed in three preliminary simulation cases.

distribution of injectors and producers. Tables 29 and 30 list the reservoir properties assumed in the runs.

In generating the stream-tubes for both cases, boundaries were chosen to approximate the no-flux boundary conditions assumed in the model. Figure 69 shows the stream-tubes 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 70 shows the stream-tubes generated for case II using the injection and production rates listed in Table 30. 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 and that the influence of the rest of the field should be measured. Section 2.2 reports the results of these measurements.

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 71, 72, and 73 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 74 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 field-wide drift and high polymer retention can each lower the additional oil recovery by about 30 percent. As reported in previous sections of this report, pressure tests 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.

TABLE 29

RESERVOIR PROPERTIES ASSUMED IN PRELIMINARY
SIMULATOR RUNS

Pay thickness	33 ft	(uniform)	
Porosity	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		
Relative permeabilities as in Figure 4-1			
Oil viscosity	6.5 cp		
Polymer resistance factor	10.0		
Polymer residual resistance factor	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	*
Production rate (bbl/day)	755	755	*

*See Table 30.

TABLE 30

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

Figure 70. Streamtubes generated by polymer flood simulator for Case II (drift from southwest to northeast).

Figure 71. Simulator performance predictions for Case I (no drift, retention = 20 $\mu\text{g/g}$ rock).

Figure 72. Simulator performance predictions for Case I' (no drift, retention = $30 \mu\text{g/g}$ rock).

Figure 73. Simulator performance predictions for Case II (drift, retention = 20 μ g/g rock).

Figure 74. Comparison of simulator performance predictions for Cases I, I', and II.

SECTION EIGHT

PROGRAM SUPPORT

8.1 Purchase of Polymer

After deciding to use a polysaccharide, Energy Resources began negotiations with polymer manufacturers to find the best combination of product quality and price. Laboratory data (see Section Three) indicated that Pfizer's product had the best performance characteristics, and this company was willing to supply polymer from their Groton, Connecticut plant.

Pfizer's price per active pound was competitive with other manufacturers, but the shipping expenses from Groton to Carmi nearly doubled this cost. Pfizer suggested several ways of reducing this transportation cost. First, they suggested that they might move production to Terre Haute, Indiana if some fermentation capacity opened up there in time. Second, the possibility of producing a higher concentration broth (up to 9 percent) seemed likely at that stage. Finally, failing the first two, Pfizer agreed to consider paying a portion of the freight costs.

At this point Energy Resources requested price proposals from both Abbott Chemicals and Kelco. Abbott replied that no excess production capacity was available in 1979 or early 1980. Kelco on the other hand offered to supply biopolymer broth out of their Okmulgee, Oklahoma plant. Although this offer represented considerable savings in freight, Kelco was unable to match Pfizer's price for broth since the Okmulgee plant normally produces powder. In addition, the Kelco broth performed less acceptably in the laboratory tests.

Pfizer's offer to pay 25 percent of freight costs virtually eliminated Kelco's slight price advantage, but Kelco was willing to lower their price further if necessary. Still, close examination of Kelco product indicated that it might require diatomaceous earth filtration prior to injection. This would cause an unacceptable increase in our cost; therefore when Pfizer lowered their price \$0.10/lb to remain competitive with Kelco, Energy Resources sent Pfizer a letter of intent to buy up to 250,000 pounds of Flocon 1035 biopolymer.

Precise terms and agreements are being drawn up based on a meeting held in Cambridge on December 4, 1979. General

specifications of polymer quality were also drawn up in that meeting and are outlined in Section 4.3. The final agreement will be signed in January, 1980 and will include provisions for discontinuance of polymer purchases and escalation of price with raw material costs. First polymer delivery is expected in March, 1980.

8.2 Environmental Assessment and Environmental Protection Plans

In November, 1979, a draft environmental assessment¹ of the Storms Pool pilot polymer flood was completed by Energy and Environmental Analysis, Inc. of Arlington, Virginia and submitted to the DOE's Office of Fossil Energy. This assessment was prepared in accordance with the DOE's proposed guidelines for compliance with the National Environmental Policy Act (FR44, No. 139, p. 42136); the report evaluates environmental impacts of the project on the site, the existing air and water quality, the surrounding community, and the health and safety of project workers. Included is a description of proposed alternative actions to the existing project; both the "No action" and "Alternative site" options are explored.

The assessment concludes that there are no major potential long-term environment impacts associated with the construction and operation of the polymer flood in its present location. Short-term effects are expected to last only for the duration of the project. The project will probably have no appreciable impacts on surface and groundwater quality, socioeconomic, or historical and archaeological resources. The report also states that the alternative options "No action" or "Alternative site" would not necessarily be better on environmental grounds than the planned project.

The existing air quality near the project site is good, and at the nearest air quality monitoring station pollutant levels are below short-term and annual air quality standards. Air quality impacts from the project have been and will be negligible. Fugitive dust emissions during facility construction were minor, and the only significant sources of air emissions during operation will be low-level vehicle exhaust. Roads have been or will be resurfaced to reduce fugitive dust emissions.

¹Environmental Assessment of the Department of Energy/ Energy Resources Company Polymer Improved Waterflood (Draft) Energy and Environmental Analysis, Inc. for U.S. DOE Contract No. EF-77-C-01-2624, November 1979.

Water samples have been taken from the Little Wabash River and the turbidity level is extremely high. No degradation of surface water from the pilot project operations is anticipated. No process wastewater from the project will be discharged intentionally into any surface waters in the area; all wastewater will be disposed of underground via the brine reinjection well into oil-bearing formations. The EEA study concludes that there is virtually no possibility of significant groundwater contamination in the project area.

Socioeconomic impacts of the Storms Pool project will be insignificant due to its small manpower requirements. The project is not expected to cause any significant noise impact. The maximum noise level probably occurred during construction or drilling and apparently had no significant impact on humans or wildlife. Most of the noise henceforth will be contained in the injection facility. Production well operations are powered electrically, and noise is not a problem there.

No significant impacts on land use are expected. Oil production has been a major land use at the project site since 1939. The oil field is in an agricultural area, and soybeans and corn have been grown on the surface concurrently with oil production. The pilot project permits continuation of these previous land uses.

At time of the assessment the project site and surrounding area had received unusually heavy rains, and some surface areas on the site were in poor condition. Most areas were expected to dry out in the later, dryer parts of the summer. Project funds were used to resurface the injection plant access road with gravel to prevent run-off problems. Cleanup efforts have been planned for the oil storage tank and production well areas, where previous activities of another operator had left debris and oil standing on the surface.

Environmental Protection Plan

Three types of potential pollutants will be of concern at the project facility:

1. Filtration wastes from filtering of river water for injection.
2. Polymer storage tank residues and filtration wastes from pre-injection polymer solution filters.
3. Above-surface hydrocarbon leaks or spills at the project site, as addressed in federal regulation 40 CFR 112 and amendments.

The methods used to dispose of these wastes are regulated by various state and federal regulations. The following waste disposal practices have been outlined in ERCO's Environmental Protection Plan.

The filtered wastes from the river water cleanup system will be composed of sediment and debris and are not considered hazardous wastes. Any liquid wastes from the system, such as that from the four hydrocyclones, will be piped directly to the brine disposal well which also will be used for disposal of produced water. The pipes conveying liquid wastes to the disposal well will be kept in adequate repair and inspected regularly. Liquid waste which is not in proper form to be reinjected will be disposed of by evaporation in an excavated lined pit in conformance with Rule IX, "Avoidance of Fresh Water Pollution and Disposal of Salt Water or Other Liquids to Prevent Waste," of the State of Illinois Act in Relation to Oil, Gas, Coal and Other Surface and Underground Resources. Solid wastes which result from the filtering of river water or evaporation of waste liquids will be collected and disposed of by shipment to the properly classed landfill.

The same disposal options, with the additional possibility of removal by pump truck, exist for the polymer filtration and tank residue wastes. Liquid wastes of low viscosity will be piped to the reinjection well for disposal. Viscous wastes such as polymer residue will be collected by a hired waste tank truck. Samples of the waste will be analyzed bimonthly.

In the event of a chemical leak or spill around the project's surface facilities, the field manager will be immediately notified. Facilities are being built at the injection plant to handle such spills. A concrete-lined pit will be constructed at the polymer loading area. The cement loading area surface will be so constructed that all surfaces will drain into the pit. The pit will be equipped with a submersible pump so that any waste material collected can be pumped into disposal vessels and transported for proper disposal. This pit will also serve as an emergency sump for the injection plant. The plant area will have drains leading to the pit so any spilled material or water from backwashing filters can be collected and contained.

The two 8,860-gallon oil storage tanks will be located inside a dike high enough to retain 19,400 gallons of leaked oil (two tanks' capacities, plus 10 percent). The bermed area will be graded to direct the flow into a containment area from which it will be pumped into a tank truck and

shipped to a reprocessing plant or other suitable facility. In the event of a rupture, the oil will flow into an impermeable bermed or diked area. It will then be pumped out to a holding tank, and the area will be cleaned. Oil-absorbent material will be kept at the separation facility for routine cleanup and small spills; this supply of absorbent will be replaced as it is used.

Inspection and Records

The surface facility will be inspected in the last week of each operating month and the results recorded in the field operations log. Production facilities will have a flowline maintenance program to prevent spills from this source. The program will include monthly examinations of the production equipment and record keeping on all such activities.

Emergency telephone numbers as well as those of ERCO managers, the field manager, the waste tank truck removal service, and the local EPA inspector will be posted in several places in the injection facilities. Field personnel will be trained in the operation and maintenance of equipment and instructed in applicable pollution control regulations.

INSTRUMENTATION LIST

CLIENT: DOE
CONTRACT NO.:

UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

PAGE 1 of 9
DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PSH 5-1	Pressure Switch/Indicator	293.00	12165	Pilgrim Instruments, ordered 9/11/79
PI 5-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 7/25/79, shipped 10/1/79
PI 5-2	Pressure Indicator	17.60	11932	same as above
FI 10-1	Flow Indicator	280.96	12263	McMaster Corp., ordered 9/21/79, shipped 10/7/79
LSH 10-1	Level Switch High	58.00	10969	Delaval Turbine Inc., ordered 7/25/79
LSL 10-1	Level Switch Low	58.00	10469	Delaval Turbine Inc., ordered 7/26/79
TI 10-1	Temperature Indicator	69.85	11932	Kenett Corp., ordered 7/25/79, shipped 9/27/79
I 12	Motor Starter	259.74	11934	Sandman Electric w/inter- lock and heater, ordered 8/1/79
PI 13-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 7/25/79, shipped 10/1/79
PI 13-2	Pressure Indicator	17.60	11932	same as above
PI 14-1	Pressure Indicator	17.60	11932	same as above
I 14a	Motor Starter	46.80	11935	Sandman Electric, ordered 8/1/79
FI 16-1	Flow Indicator (Rotometer)	258.71	12263	McMaster, ordered 9/21/79, shipped 10/7/79

LIST OF INSTRUMENTATION AND EQUIPMENT FOR PILOT INJECTION FACILITIES

APPENDIX

INSTRUMENTATION LISTCLIENT: DOE
CONTRACT NO.:UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

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DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PT 16-1	Pressure Transmitter	704.00	12167	Pilgrim, electronic gage, ordered 9/11/79
PIC 16-1	Pressure Indicating Controller	1255.00	12167	Pilgrim, electronic w/power supply, ordered 9/11/79
PY 16-1	Current to Pressure Transducer	314.00	12167	Pilgrim, ordered 9/11/79
PI 18-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
FE 16-3(OP)	Orifice Plate	44.00	12014	Carr Bros., ordered 8/28/79
FE 16-3(OF)	Orifice Flanges (2)	240.00	12014	same as above
FT 16-3	Flow Transmitter w/Manifold	832.00	12011	Pilgrim, electronic DP w/B valve manifold, ordered 8/9/79
FIC 16-3	Flow Indicating Controlloer	1,345.00	12165	Pilgrim electronic indicating controller w/FSL and FSL 16-3, ordered 10/1/79
PI 18-2	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
PI 20-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
I 20a	Motor Starter	46.80	11935	Sandman Electric, ordered 8/1/79

INSTRUMENTATION LIST

CLIENT: DOE
CONTRACT NO.:

UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

PAGE 3 of 9
DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PI 22-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
PI 24-1	Pressure Indicator	17.60	11932	same as above
I 22a	Motor Starter	46.80	11935	Sandman Electric, ordered 8/1/79
I 24a	Motor Starter	46.80	11935	same as above
TI 22-1	Temperature Indicator	69.85	11932	Kenett Corp.
TI 33-1	Temperature Indicator	69.85	11932	Kenett Corp., ordered 7/25/79, shipped 9/27/79
BRV 32-1	Breather Vent	148.00	11933	Protectoseal, ordered 9/30/79
BRV 33-1	Breather Vent	148.00	11933	Protectoseal, ordered 9/30/79
LSH 32-1	Level Switch (high)	58.00	10469	Delaval Turbine, ordered 7/25/79
LSL 32-1	Level Switch (low)	58.00	10469	Delaval Turbine ordered 7/25/79
LSH 33-1	Level Switch (high)	58.00	10469	same as above
LSL 33-1	Level Switch (low)	58.00	10469	same as above

INSTRUMENTATION LIST

CLIENT: DOE
CONTRACT NO.:

UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

PAGE 4 of 9
DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PI 34-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
I 36	Motor Starter	163.02	11935	Sandman, ordered 8/1/79
FE 36-1(OP)	Orifice Plate	42.00	12014	Carr Brothers, 3/4" plate w/bore calculation, ordered 8/28/79
FE 36-1 (OF)	Orifice Flange	131.00	12014	Carr Brothers, 3/4" PVC 15016 flange, ordered 8/28/79
FI 36-1 (M)	3-Valve Manifold	95.00	10214	Carr Brothers, SS manifold, ordered 8/28/79
FI 36-1	Flow Indicator	345.00	10214	Carr Brothers, DPP Flow- meter w/3" dial, ordered 8/28/79
FE 40-1 (OP)	Orifice Plate	44.00	10214	Carr Brothers, 2 1/2 SS plate w/bore calculation, ordered 8/28/79
FE 40-1 (OF)	Orifice Flange (2)	240.00	10214	Carr Brothers, 2 1/2" PVC 15016 flange, ordered 8/28/79

INSTRUMENTATION LIST

CLIENT: DOE
CONTRACT NO.:

UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

PAGE 5 of 9
DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
FI 40-1 (M)	3-Valve Manifold	95.00	10214	Carr Brothers, SS manifold, ordered 8/28/79
FI 40-1	Flow Indicator	345.00	10214	Carr Brothers, DP flowmeter w/3" dial, ordered 8/28/79
RIC 36-1	Ratio Indicating Controller	805.00	12168	Pilgrim Instruments, electronic station w/cable and resistor, ordered, 9/11/79
FY 36-1	Current-to-Pressure Transducer	314.00	12167	Pilgrim Instruments, transducer w/booster, ordered 9/11/79
FY 40-1	Current-to-Pressure Transducer	314.00	12167	same as above
LIC 40-1	Load Indicating Controller	1,321.00	12168	Pilgrim Instruments, electronic controller w/power supply, cable resister, ordered 9/11/79
LE 40-1	Level Element	819.00	12169	Pierce Associates, level lance w/cable and probe, ordered 9/11/79
LT 40-1				
TI 40-1	Temperature Indicator	69.85	11932	Kenett Corp., ordered 7/25/79, shipped 9/25/79

INSTRUMENTATION LIST

CLIENT: DOE
CONTRACT NO.:

UNIT NAME: Waterflooding
UNIT NO.:

PROJ. MGR.: D.B.

PAGE 6 of 9
DATE: 10/15/79

ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
BRV 40-1	Breather Vent	148.00	11933	Protectoseal, ordered 9/30/79
LSH 40-1	Level Switch (high)	58.00	10469	Delaval, ordered 7/25/79
LSL 40-1	Level Switch (low)	58.00	10469	same as above
I 39	Motor Starter	163.02	11935	Sandman, ordered 8/1/79
PI 41-1	Pressure Indicator	17.60	11932	Kenett Corp., ordered 9/11/79, shipped 10/1/79
PI 41-2	Pressure Indicator	17.60	11932	same as above
FI 44-1	Flow Indicator (Rotometer)	251.06	12263	McMasters, ordered 9/21/79, due for shipment 11/19/79
I 42	Motor Starter	2,150.46	11934	Sandman, ordered 9/11/79
PY 42-1	Current to Pressure Transducer	314.00	12167	Pilgrim, ordered 9/11/79
PIC 42-1	Pressure Indicating Controller	1,427.00	12167	Pilgrim, electronic con- troller w/pressure switch, cable, resister, ordered 9/11/79
PCH 42-1	Pressure Switch (high)			

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PT 50-1	Pressure Transmitter	774.00	12014	Carr Brothers, transmitter w/power supply, ordered 9/28/79
PRV 50-1	Pressure Relief Valve	845.00	12266	OCV, control valves, ordered 9/28/79
FR 50-1	Flow Recorder	1,745.00	12168	Pilgrim Instruments, multi scan potentiometer recorder, ordered 9/11/79
FI 50-1	Flow Indicator	5,590.00	10372	Controlotron, display computer w/multiplex switch
FY 50	Flow Transducer	3,030.00	10372	Controlotron, transducer w/cable, ordered 6/5/79
PR 50-1	Pressure Recorder	1,185.00	12011/ 12012	Pilgrim Instrument, electronic recorder chart w/resistor, mounting tray and filter plates, ordered 8/9/79
PSL 50-1	Pressure Switch (low)			
PR 50 tray	Mounting Tray	108.00	12165	Pilgrim, slide mounting tray, ordered 9/11/79
I 5a	Motor Starter	259.74	12016	Sandman, size 2, ordered 9/7/79

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
PRV 50-1	Pressure Relief Valve	845.00	12266	OCV, control valves, ordered 9/28/79
FR 50-1	Flow Recorder	1,745.00	12168	Pilgrim Instruments, multi scan potentiometer recorder, ordered 9/11/79
FI 50-1	Flow Indicator	5,590.00	10372	Controlotron, display com- puter w/multiplex switch
FY 50	Flow Transducer	3,030.00	10372	Controlotron, transducer w/cable, ordered 6/5/79
PR 50-1	Pressure Recorder	1,185.00	12011/ 12012	Pilgrim Instrument, elec- tronic recorder chart w/ resistor, mounting tray and filter plates, ordered 8/9/79
PSL 50-1	Pressure Switch (low)			
PR 50 tray	Mounting Tray	108.00	12165	Pilgrim, slide mounting tray, ordered 9/11/79
I 5a	Motor Starter	259.74	12016	Sandman, size 2, ordered 9/7/79
I 5b	Motor Starter	2,421.00	12016	Anderson, size 5 control box, ordered 3/19/79, shipped 9/15/79

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
I 39b	Motor Starter	86.50	11934	Sandman, manual safety starter, ordered 8/1/79
I 11	Motor Starter	197.34	11935	Sandman, magnetic starter, ordered 8/1/79, on site 10/1/79
Total Estimated Cost		33,049.95		

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 5	Water Pump at Pumping Station	-	-	Operating at Haley's Plant
E 6a	10 mesh S.S. Basket Strainer	837.00	#10436	Industrial Filters. In line 2 1/2" filter w/ cleaning gasket
E 6b	10 mesh S.S. Basket Strainer	837.00	#10436	same as above
E 10	Water Storage Tank (210 bbl)	2,150.00	#10351	Norris City Supply. Cost does not include internal coating nor insulation
E 11	Centrifugal Pump for Water	740.00	#10262	Tapco Pump Company. Cost includes 10 hp Motor w/o Starter
E 12	Centrifugal Pump for Backwash	852.00	#10262	Tapco Pump Company. Cost includes 15 hp Motor w/o Starter
E 13a	Hydrocyclone (Normal Flow)	240.00	# 8904	P.O. to Culligan on 11/6/78. Part of Order w/Filtration System
E 13b	Hydrocyclone (Normal Flow)	240.00	# 8904	same as above
E 13c	Hydrocyclone (Backwash)	371.00	#10435	Industrial Filters. Part of Order w/Filters and Strainers

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 13d	Hydrocyclone (Backwash)	371.00	#10435	Industrial Filters. Part of Order w/Filters and Strainers
	Hydrocyclone (spare)	240.00	# 8904	Part of Order given to Culligan for Water Filtration System.
E 14	Coagulant Chemical System	499.00	#10396	Acusan Co. Cost includes Pump (M14b) Tank, Liquid Level Switch (LI 14-1) + Agitator (m 14a)
E 15	None	-	-	
E 16	Water Filtration System	11,608.00	#10434	P.O. Issued to Koch. Delivery expected August 1, 1979
E 18a	Cartridge Filter (w/16 extra cartridges)	606.00	#10435	P.O. to Industrial Filters (6/18/79) Polypropylene type replaceable cartridges to remove particulates
E 19	None	-	-	
E 20	Oxygen Scavenger System	499.00	#10396	Acusan Co. Cost includes Pump (M 20 by Tank, Level Switch (LI 20-1) and Agitator

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 21	Static Mixer	378.00	#10434	Koch Industries. Delivery expected August 1, 1979
E 22	Chelating Agent System	499.00	#10396	Acusan Co. Cost includes Pump (M 22b Tank, Level Switch (LI 2201) and Agitator
E 23	Oxygen Scavenger Sampler	1,395.00	#10373	Barclay Chemical Co. System includes Sensor and Analyzer
E 24	Biocide Chemical System	499	#10396	Acusan Cost includes Pump (M 24b Tank, Level Switch (LI 24-1) and Agitator
E 25	Sampling Cylinder	135.00	#10395	Joseph Bertram Company. Cost includes 150 ml cylinder & needle valve and ball valve
E 26	Static Mixer	378.00	#10434	Koch Industries. Delivery expected August 1, 1979
E 27	None	-	-	
E 28	Sampling Cylinder	135.00	#10395	Bertram Company. Cost includes 150 ml & needle valve and toggle valve

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 29	none	-	-	
E 30	Rotary Valve Pump	(\$2,650.00)		Received Quotation from Tapco. No order placed yet
E 31	Plastic Basket Strainer	395.00	#10466	PO to Industrial Filters. Polypropy in-line basket filters polymer from truck to storage tank
E 68	Plastic Basket Strainer	395.00	#10466	
E 32	Polymer Storage Tank (210 bbl)	2,150.00	#10351	Norris City Supply. Cost does not include internal coating or insulation
E 33	Polymer Storage Tank	2,150.00	#10351	same as above
E 34	Chemical Metering Pump	2,282.00	#10151	Robbins & Myers. Meyno with variable special drive. Delivery expected Mid-August
E 35	none	-	-	
E 36	Dynamic Mixer	4,170.00	#10261	Greerco. Tandem Shear Mixer P.O. to Peter Kahn 6/31/79. Delivery expected August 1, 1979, inc. 2 HP motor

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 37	none	-	-	
E 38	none	-	-	
E 39	Agitator	2,753.00	#10436	Cleveland Mixer. Top mounted w/1 1/2 HP to operate @ 45 M.
E 40	Final Dilution Tank (210 BBL.)	2,150.00	#10351	Norris City Supply. Cost does not include Internal Coating or insulation
E 41a	S.S. Filter (100 mesh)	713	#10435	Industrial Filters. Replacement cloth cartridges. Remove particles down to 100 microns
E 41b	S.S. Filter (100 mesh)	713	#10435	
E 42	Triplex Plunger Pump	4,000.00	# 8864	Gardner Denver Triplex Pump PT 4L w/o Motor
E 43	Sampling Cyclinder	135.00	#10395	150 ml cyclinder w/toggle valve and needle valve
E 44	Viscometer	3,072.00	#10371	In-line w/solenoid valve for operation control
E 45	Compressor	(\$3,000.00)		To operate @ 100 psi; 32 ACFM estimate from McMasters

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ITEM NO.	DESCRIPTION	COST	PO NO.	REMARKS
E 46	none	-	-	
E 47	none	-	-	
TOTAL ESTIMATED COST		\$55,221.00		

UNITED STATES DEPARTMENT OF ENERGY
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