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R+D 83-31-11

CLEANUP OF LOCALIZED GROUNDWATER CONTAMINATION USING POLYMER INJECTION

A Dissertation Presented
by
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Submitted to the Graduate School of the
University of Massachusetts in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

September 1987

Department of Civil Engineering

ACKNOWLEDGEMENTS

I acknowledge my research advisor Dr. Richard R. Noss and my research committee members Dr. James W. Male, Dr. David W. Ostendorf, and Dr. Ka M. Ng, for their continued help and guidance throughout this research study. The financial support extended by Massachusetts Division of Water Pollution Control, Project Number 83-31, is gratefully acknowledged.

I would like to thank Dr. Lawrence L. Ambs and Mr. Richard Garbarino respectively professor and former graduate student of Mechanical Engineering Department for their help in the selection of Data Translation instrumentation. In addition, I would like to thank Dr. Charles Dickinson of Polymer Science and Engineering Department for his help and advise in the viscosity analysis of polymers. My thanks are also due to Mr. Daniel J. Wagner for his help and advise in the experimental setup. I thank all my friends and colleagues who have in one way or other, assisted and supported me in achieving this goal.

My family has encouraged me in all my endeavors, both academic and otherwise. I would like to extend my special thanks to them. And, last but not the least, my profound thanks go to my wife for her continued support and understanding during the course of this study at the University of Massachusetts.

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CHAPTER I

INTRODUCTION

Background and Importance

Groundwater is an essential natural resource and is one of the most widely distributed natural resources of the Earth. It constitutes more than ninety-five percent of all the fresh water available at any instant in the world (Lvovitch, 1970). The use of groundwater has escalated significantly worldwide since 1960. About fifty percent of the United States population relies on groundwater as its primary source of water (Carter, 1984), and ninety-five percent of the drinking water in the rural areas comes from the groundwater (Solley et al., 1984). In addition, groundwater supplies about twenty-five percent of the nation's domestic, agricultural, and industrial water (Driscoll, 1986).

Demand for groundwater has increased greatly over the past 35 years because of population shifts to areas where surface water resources are limited. In the recent past, the public has become more aware of the importance of groundwater, and is now taking action to protect the groundwater.

In Massachusetts, about one-third of the 6 million people obtain their water supply from wells. In 1980, on an average, 320 million gallons per day of fresh groundwater was withdrawn for public, rural, industrial, and irrigation supplies. Of this, about sixty percent was for public supply, thirty percent for industrial use, and ten percent for rural domestic supply. Although major urban areas in Massachusetts use surface-water supplies, groundwater is the primary source for about 165 public supplies and secondary source for another 33 public supplies (U.S.G.S., 1984).

There is ample evidence to show that the contamination (as well as droughts) have affected the groundwater resources significantly in the last decade. Degradation of groundwater quality by wastes and chemicals has caused water shortages in Massachusetts. Between 1978 and 1981, about 25 public-supply wells with a combined capacity of 23 million gallons per day were closed because of groundwater contamination (U.S.G.S., 1984).

Both at the State level as well as at the National level, groundwater has become the much needed valuable resource of the future, and therefore, groundwater quality protection measures should be strongly encouraged and supported by the State and Federal programs.

Problem Overview

Groundwater is a very valuable resource and the vulnerability of groundwater to overuse and the consequent water-quality degradation was not widely understood until recently. Significant advances have been made in almost all phases of groundwater technology in recent years. The focus on groundwater quality in the United States has taken an expected shift from problem recognition to problem prevention. This had led to an emphasis in the water resource management profession on taking the necessary preventive measures today to protect the nation's aquifers before they become contaminated in the future.

Protection of an aquifer is environmentally and economically more desirable than cleaning up an already existing groundwater contamination problem. However, such preventive measures need a significant investment of funds, effort, and coordination. In addition, local, state, and federal support is generally easier to obtain to resolve an existing problem than to develop a program that prevents the contamination of groundwater.

Once a portion of an aquifer has been contaminated, groundwater quality management efforts shift from prevention, to either removal, or isolation of the contaminated groundwater. In either case, it is important to be able to understand the effect of changes of certain parameters on the movement of contaminated groundwater in the aquifer. Some of the remedial technologies that can be used for controlling the groundwater contamination problems include: (1) groundwater pumping techniques involving injection and withdrawal wells to capture a plume or change the direction of groundwater movement; (2) subsurface drains consisting of gravity collection systems designed to intercept groundwater; (3) impermeable subsurface barriers to minimize the plume movement or to divert groundwater flow; and (4) in-situ biological or chemical treatment methods to remove or attenuate the contaminants in the groundwater (U.S.E.P.A., 1985a).

The purpose of this research is to investigate a new technique using polymers capable of increasing the viscosity of water, to assist in the removal of contaminated groundwater. The oil industry has been using a series of such polymers in Enhanced Oil Recovery (hereafter referred to as EOR) operations. These same polymers have significant potential for use in the cleanup of localized groundwater contamination problems.

Engineering Relevance

Groundwater moves slowly, usually about a few feet per year to a few feet per day, and therefore residence times are usually very large. This suggests that once an aquifer is contaminated, it remains so for many years. This makes it imperative that groundwater be protected from contaminants, and the long term needs of groundwater usage be taken into consideration. If groundwater is to play an important role in developing the world's water resource potential, then it needs to be protected from the increasing threat of subsurface contamination.

Control of groundwater contamination involves one or more of the following options: (1) containment of a plume; (2) removal of a plume after measures have been taken to halt the source of contamination; and (3) diversion of groundwater to prevent clean water from flowing through contaminated areas.

The cleanup of groundwater is very different from the cleanup of surface water. The most obvious difference is that the body of water is actually being cleaned in groundwater cleanups, while in surface water cleanups, we control and treat the wastewater that is entering a body of water. The body of surface water (a lake or river), can become clean once the inflow of pollutants is controlled, whereas the groundwater is not able to clean itself at a rapid rate. Therefore, in a groundwater cleanup, one must clean up the source of pollutants and also clean up the contaminated aquifer itself.

The oil recovery technology cannot be directly applied to the groundwater cleanup operations, as there are some very significant differences between these two applications. Oil recovery applications typically involve very deep and highly confined sandstone aquifers with high salt concentrations. The confined nature of these aquifers makes it possible to use high operating pressures at the injection wells. In contrast, groundwater contamination incidents are more likely to involve unconfined (phreatic) aquifers of unconsolidated materials where high operating pressure gradients can not be achieved. It is very important to be able to understand the effect of changes of certain parameters on the movement of contaminated groundwater and/or polymer solution during the cleanup operation. Therefore, the research presented here is aimed at understanding the polymer flow behavior as applied to groundwater contamination cleanup operations.

The pattern of water and polymer velocities which control the gross movement of the polymer front depends on the properties of the porous media, the location of injection and withdrawal points, the rate of injection and withdrawal, the viscosities (or mobilities) of the two fluids, i.e., polymer and water, as well as the thickness and position of the polymer front. Thus, it is to be expected that only a procedure which includes an adequate description of the above mentioned factors can be successful in completely understanding the polymer flow behavior in the porous media.

Polymer Injection

The oil industry uses several polymers such as polyacrylamides, xanthan gums, and surfactants in their Enhanced Oil Recovery (EOR) operations. Synthetically produced polyacrylamides are among the most commonly used polymers in the oil recovery operations. Polyacrylamide polymers are produced by the combination of carbon, hydrogen, nitrogen, and oxygen into basic acrylamide monomer units. These monomers are then polymerized to form a long chain polymer molecule called polyacrylamide, which can be represented as $-(CH_2CH\text{-}CONH_2)_{\overline{n}}$. These polymers, when used in concentrations of 100 ppm, can increase the viscosity of water by approximately 25 times. (The actual increase depends on the specific polymer formulation used).

In EOR operations, the process of injecting polymer-water (often called polymer flooding) involves the addition of polymers to the injection water to increase the viscosity, resulting in a more efficient recovery of residual oil. When water (without polymer) is injected into an oil reservoir, in an effort to maintain the pressure and facilitate the removal of the remaining oil, the injected water often "short circuits" through the porous medium by finding the path of least resistance from the injection well to the withdrawal (production) well. Figure 1 illustrates this short-circuiting effect. This can be controlled by the use of polymers, which, due to their viscous nature, build a plug of low mobility water (both due to increased viscosity and decreased apparent permeability). This is illustrated in Figure 2. When water is injected behind the polymer plug, the entire front advances more or less uniformly, thereby providing a better sweep efficiency. The polymer plug moves gradually towards the withdrawal (production) well, driven by the pressure

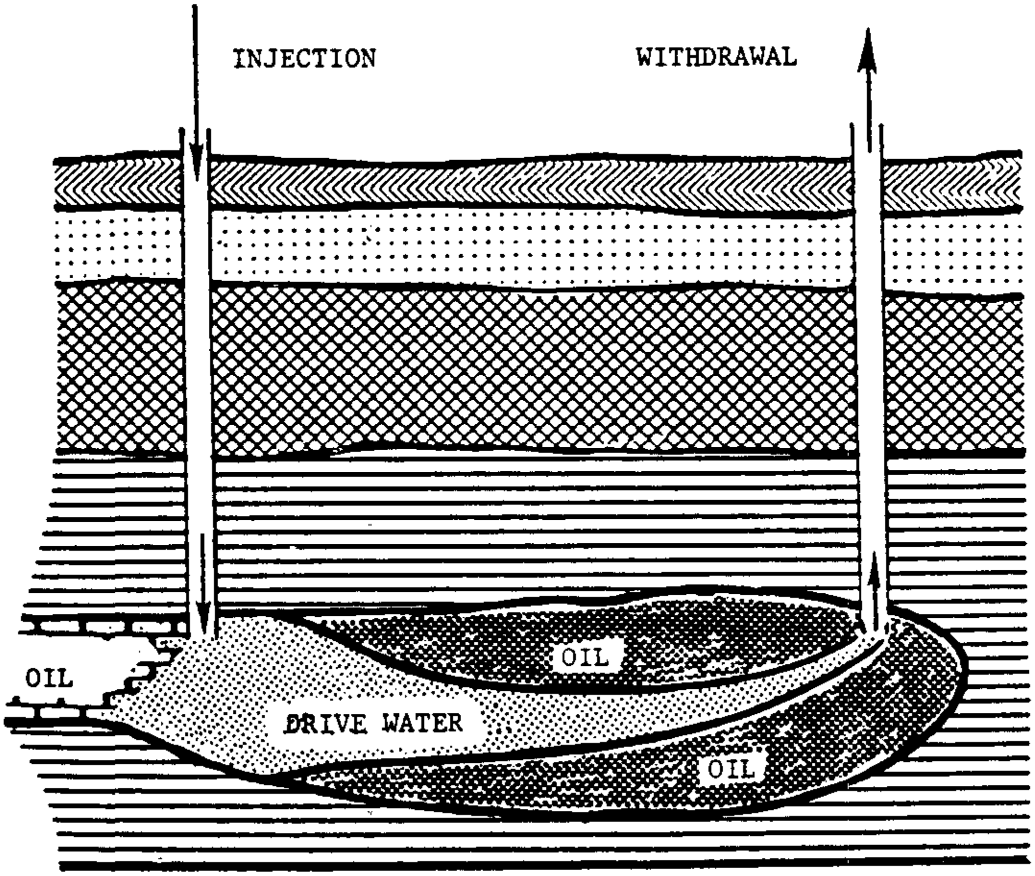


Figure 1. Short Circuiting Effect in Oil Recovery Operations Without the Use of Polymers.

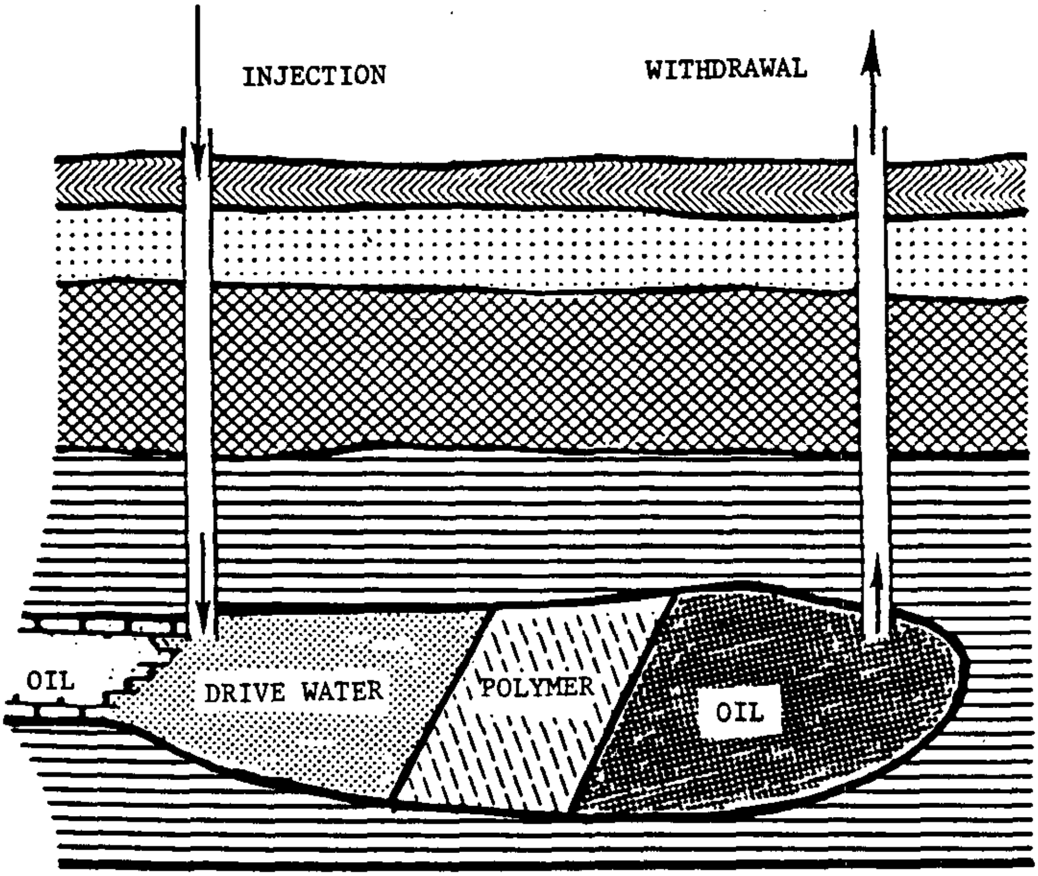


Figure 2. Controlling Short Circuiting Effect in Oil Recovery Operations by the Use of Polymers.

maintained behind it, and providing a better sweep of the residual oil in the porous media.

Scope and Objective

The use of water-soluble polymers in secondary and tertiary oil recovery operations was studied extensively by many researchers during the 1970s. However, no published literature has been found on the performance of these polymers in phreatic conditions, or on their use in dealing with groundwater contamination problems. Therefore, the purpose of this research is to develop an understanding of the flow behavior of polyacrylamide polymers in the porous media, and to discuss the suitability of using these polymers in the management of groundwater contamination incidents. The research is designed as a laboratory scale experimental study aimed at investigating the possibility of using polyacrylamide polymers in dealing with groundwater contamination cleanup operations. The primary focus of this research is to obtain as much information as possible from the experimental studies.

Thus, the overall objectives of this research are:

1. to develop a relationship between polymer concentration and viscosity, and to study the effect of polymer concentration and/or viscosity on the injection of polymer solutions.

2. to study the effect of shear rate on the viscosity of polymer solutions and its relation to the groundwater cleanup applications.

3. to investigate the effect of polymer concentration and polymer slug size (thickness of slug) on the flow properties of polymer solutions in porous media.

4. to study the effect of polymer concentration and slug size on the stability of the slug as it moves away from the injection port to the withdrawal port.

5. to develop a mathematical model that would incorporate the effects of polymer concentration and slug size to predict the position of the polymer front as a function of time.

The first objective is aimed at developing a viscosity relationship as a function of polymer concentration so that the viscosity relationship can then be incorporated into a mathematical model of groundwater/polymer flow. The second objective is meant to give an understanding of the effect of shear rate on the polymer solution viscosity, and it's relation to groundwater applications. The third objective, i.e., the effect of concentration and thickness of the slug on the flow field, will investigate the changes induced in the hydraulic head distribution, and its subsequent effect on groundwater velocity. The fourth objective addresses the integrity of the slug at various concentrations and polymer slug thickness as the polymer solution flows through the porous matrix. Thus, the third and fourth objectives are qualitative, and are meant to yield an understanding of the behavior of polymer slug using the data from various experiments. And, the final objective looks at the modeling aspects of polymer flow, which could then be tested using the experimental data.

CHAPTER II

LITERATURE REVIEW

Cleanup Methodologies

Methods which prevent groundwater contamination are undoubtedly the most effective techniques for aquifer protection. However, contamination has occurred and continues to occur in many locations due to leaching from waste disposal areas, waste spills, and illegal dumping. Once contamination occurs, there are various techniques that may be used to either contain the polluted groundwater, or treat the groundwater and clean up the aquifer, at least partially. These techniques range from removal of the polluted water with subsequent physical, chemical, or biological treatment, to physical containment and in-situ treatment with chemicals or microorganisms.

This section presents a review of the current literature pertinent to the groundwater cleanup and related methodologies. Specifically, this section will review the literature available on the different types of groundwater cleanup technologies such as, (1) groundwater cleanup techniques, (2) impermeable subsurface barrier methods including grout curtains and slurry walls, and (3) in-situ biological treatment methods.

Groundwater Pumping Methods

Various groundwater pumping techniques can be used to abate aquifer pollution problems. Groundwater pumping involves the active manipulation and management of groundwater in order to contain or remove the contaminated water. This approach has traditionally been used in dealing with salt or brackish water intrusion problems. The pumping methods are most effective in aquifers with high permeability (or hydraulic conductivity).

Withdrawal wells alone or a combination of injection and withdrawal wells can be used to either contain or remove a contaminated plume. A line of withdrawal wells can be used to halt the advance of the leading edge of a contaminant plume, for instance, to prevent the contamination of drinking water supply (U.S.E.P.A., 1985b). Use of withdrawal wells alone is best suited where the hydraulic gradient is steep and hydraulic conductivity high, and where quick removal of contaminated groundwater is not necessary. Neely, et al. (1981) reported some applications of withdrawal wells in aquifer cleanup, including the subsequent treatment and/or disposal.

In cases where the hydraulic gradient is relatively flat and hydraulic conductivity is moderate, a combination of injection and withdrawal wells can be used. The injection wells act to direct the contaminants to the withdrawal wells. This method has been used with some success for contaminants not miscible with water (U.S.E.P.A., 1985b).

Groundwater pressure ridges, another form of groundwater pumping technique, can be created using a series of injection wells around a contaminant plume or site, thereby restricting the movement of contaminated water or changing the rate of groundwater movement. By creating an area with a higher hydraulic head, the plume can be forced to change direction. "Barrier wells" which continuously pump water to prevent spreading of spent solvents and acid sludge have been installed at Woodbury Village, Minnesota surface impoundment (Neely et al. 1981). This method (of pressure ridges) has found wide application in coastal areas to prevent salt water intrusion.

Subsurface Barrier Methods

The subsurface barrier methods consist of a variety of techniques. In these methods, low permeability cut-off walls are installed below the ground to contain, capture, or redirect groundwater flow near a contaminated site. The most commonly used subsurface barrier methods include (a) Grout curtains, and (b) Slurry walls. These two subsurface barrier methods are presented in the following sections.

(a) Grout Curtains: Grouting is a process of injecting a liquid, or slurry into the porous matrix, whereby the injected fluid will move away from the point of injection to occupy the available pore space. The injected fluid, in due course of time, will solidify or form a gel resulting in a decrease in the permeability of the soil. There are basically two types of grouts, namely; Particulate grouts, and Chemical grouts.

Particulate grouts consist of water and particulate material which will solidify in the porous matrix, while chemical grouts usually consist of two or more liquids which will form a gel. Some of the commonly used grout materials are listed in Table 1. Cement grouts have been very widely used in the construction industry (especially in building tunnels) and the properties of cement grout additives are presented in Table 2.

At present there are no policy measures aimed at grouting technologies. Many industries associated with the grouting technologies are not taking a "lead" primarily because of the possible toxicity considerations associated with the chemicals. The use of chemical grouts might need to be analyzed for compliance with the Underground Injection Control Program by the United States Environmental Protection Agency (U.S.E.P.A.).

One of the major considerations in the design of the grouting system is the composition of the grout. In general, chemical grouts are used in fine-grained soils, while particulate grouts are used in

Table 1. Commonly Used Grout Materials.

Cement, Water
Cement, Rock Flour, Water
Cement, Clay, Water
Cement, Clay, Sand, Water
Clay, Water
Various Chemicals
Asphalt

Table 2. Properties of Cement Grout Additives (Source: Knox, 1983).

Additive	Property
Clay Ground Shale Rock Flour	Reduces Cost of Grout Reduces Strength of Grout
Finely Ground Bentonite	Increases Plasticity Reduces Grout Shrinkage
Calcium Chloride Sodium Hydroxide Sodium Silicate	Accelerates Setting Time
Gypsum Lime Sugar Sodium Tannate	Retards Setting Time

coarse or gravel soils. The composition of a grout will depend upon several factors, such as; type of porous media, the nature and concentration of pollutant, the time since contamination started, etc. Jones (1963) reports that the amount of cement or bentonite in a particulate grout varies widely and depends on the "workability" of the mixture: increased bentonite concentrations increase the stiffness of the slurry; adding bentonite to cement slurries decreases their compressive strength; increased bentonite concentrations decrease the specific gravity of slurries (showing a reduced tendency to migrate through the soil after injection). A general guide for the selection of grouts is presented in Figure 3. Given the soil type, one can determine the applicable types of grouts. The range of soil types to which a particular grout is applicable is represented in the figure by the white horizontal bar.

Another major consideration in the design of a grout system is the pressure at which the grout is to be injected. As mentioned earlier, much of the design basis for grouts is adapted from the construction industry. Morgenstern and Vaughan (1963) report that the grouting pressure must be determined by conducting hydraulic fracture tests in the field. This may be true for construction industry grouting practice, but, for the groundwater applications, the pressure in general, should be kept sufficiently high to ensure injection of grout and decrease the time required for grouting. Bowen (1981) discussed the several problems that might arise during the grouting operation.

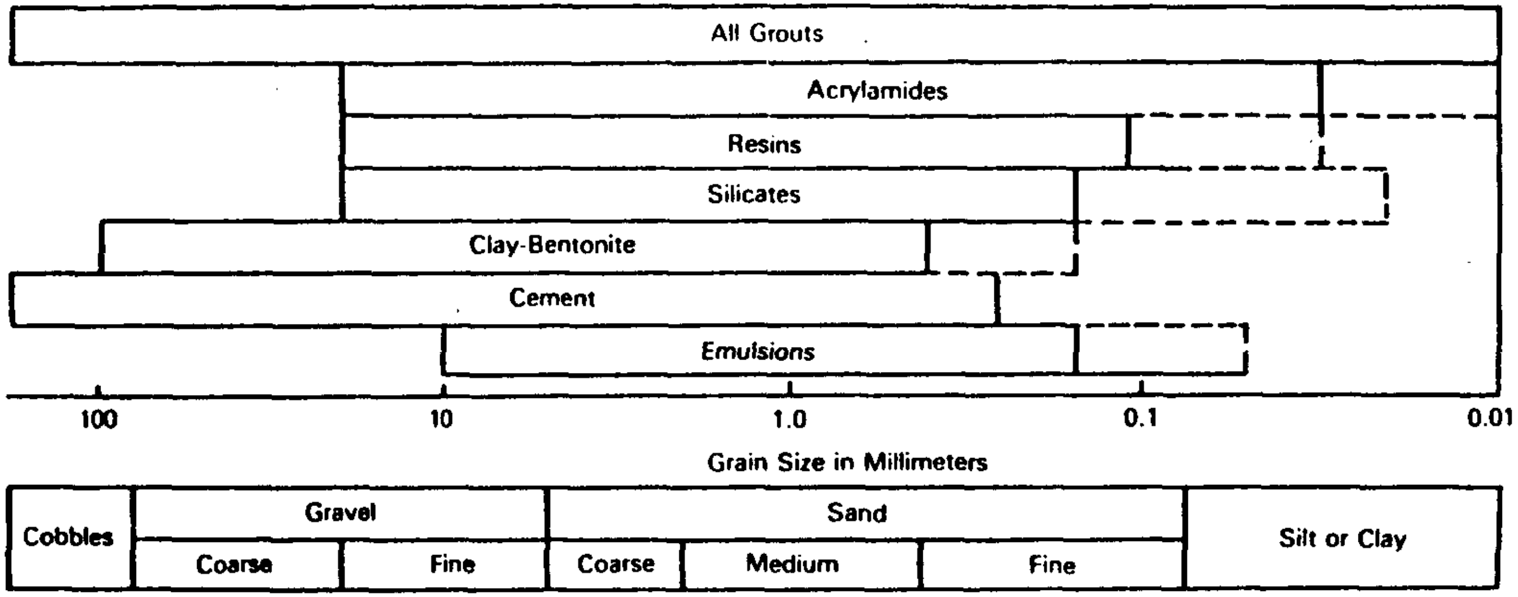


Figure 3. General Soil Type/Grain Size Guide for the Selection of Grouts (Source: Bowen, 1981).

(b) Slurry Walls: Slurry walls are the most commonly used subsurface barriers to reduce the groundwater flow. Slurry walls represent a technology for encapsulating an area to either prevent groundwater contamination or restrict the movement of previously contaminated groundwater. Basically, the technology involves digging a trench around an area and backfilling with an impermeable material. Slurry walls can be placed upgradient, downgradient, or completely surrounding the contaminated area.

Upgradient placement of a slurry wall could be used to divert clean groundwater around a contaminated area. Downgradient placement, although not common, can be employed as a partially penetrating barrier to contain and capture floating contaminants and methane. Since the contaminants come in direct contact with the slurry wall, extensive compatibility testing is required. Circumferential installations are by far the most common and offer several advantages. This type of installation greatly reduces the amount of uncontaminated groundwater entering the site from upgradient, thus reducing the volume of contaminated groundwater.

Slurry wall types are differentiated by on the materials used to backfill the slurry trench. Most commonly, a soil mixture is blended with bentonite slurry and placed in the trench. This is called a Soil-Bentonite (SB) slurry wall. In some cases the slurry trench is hardened by incorporating cement in the original slurry, and this is called a Cement-Bentonite (CB) slurry wall. Some of the characteristic features of cement-bentonite and soil-bentonite slurry walls are summarized in Table 3 (Ryan, 1980).

The advantages of Soil-Bentonite slurry walls are their low installation costs, wide range of chemical compatibilities, and low permeabilities. However, the disadvantage is that the soil-bentonite slurry walls require a large work area.

A major concern in the application of soil-bentonite walls is the compatibility of the backfill material with the contaminants present in the groundwater. D'Appolonia (1980) reported that soil-bentonite backfills are not able to withstand attack by strong acids, bases, and salt solutions. Exposure of a soil-bentonite slurry wall to certain contaminants can lead to increased permeability through (a) pore fluid substitution or (b) the increased solubility of barrier minerals in the contaminant fluid.

Although the soil-bentonite slurry walls offer the lowest cost technology, the lack of long-term performance data is a limiting factor in the use of this technology for pollution migration control. The ability of these slurry walls to withstand long-term permeation by many contaminants is in question.

Table 3. Characteristics of Cement-Bentonite and Soil-Bentonite Slurry Walls (Source: Ryan, 1980).

Cement-Bentonite	Soil-Bentonite
More suitable for limited access areas.	Lower material costs.
Independent of backfilling soil quality or availibility.	Can achieve lower permeability than cement-bentonite walls.
Cement-bentonite walls set quickly. Can cut trenches or allow traffic over slurry walls in just a few days.	Requires continuous trenching in one direction.
Can be constructed in sections.	

Cement-Bentonite slurry walls have many characteristics in common with soil-bentonite slurry walls. Therefore, to avoid duplication, the following discussion will highlight the factors that distinguish cement-bentonite slurry walls from soil-bentonite slurry walls. The principal difference between the two is the backfill, and this produces the differences in application and compatibilities.

The design and construction of a cement-bentonite slurry wall is very similar to that of a soil-bentonite slurry wall. Typical composition of cement-bentonite slurry is presented in Table 4 (Jefferis, 1981). Accelerators, retardants, and various other additives may also be used but are not common practice.

Cement-bentonite slurry walls are limited in their use by their higher costs, somewhat higher permeability, and their narrower range of chemical compatibilities. The permeability of cement-bentonite slurry wall is normally around 1 X 10^{-6}cm/sec, while that of a soil-bentonite wall is around 1 X 10^{-8}cm/sec (Spooner et al., 1984a). Cement-bentonite backfills are more susceptible to chemical attack than most soil-bentonite mixtures (Spooner et al., 1984b). Cement-bentonite is susceptible to attack by sulfates, strong acids and bases (pH ≤ 4 and ≥ 7), and other highly ionic substances.

Like soil-bentonite slurry walls, cement-bentonite slurry walls can be effective and are a relatively inexpensive means of controlling

Table 4. Typical Composition of Cement-Bentonite Slurry Mixture (Source: Jefferis, 1981).

Constituent	Percent in Slurry
Bentonite	4-7
Water	68-88
Cement	
without replacements	8-25
when blast furnace slag added, minimums	1-3
when fly ash added, minimums	2-7
Blast furnace slag, maximums, if used	7-22
Fly ash, maximums, if used	6-18

groundwater flow. As with any barrier installation, thorough compatibility testing is essential.

There has been very little information provided on the performance of slurry walls as applied to groundwater pollution control problems. However, this does not mean that the technology has not been applied. Slurry walls are common components of recommended remedial action plans at Superfund sites. Very little post construction monitoring information is available to date.

In-Situ Treatment Methods

The emphasis of this section is to present an overview of the state of knowledge of in-situ biological treatment (Biorestoration) which can be used in groundwater cleanup operations. In-situ biorestoration is a relatively new technology that is receiving increased attention as a cleanup method. Recent research has shown that a wide variety of organic contaminants can be degraded by subsurface microbial populations. In-situ biorestoration techniques are not well developed, and the current research is seeking to better define the environmental conditions that control the biodegradation.

Recent studies by Ghiorse and Balkwill (1983) indicated that the deeper subsurface environment is not sterile. Bacterial densities of around 1 X 10^6 organisms/gram of dry soil were found in several non-contaminated aquifers. Although not clearly defined at this time, several environmental factors such as dissolved oxygen, pH, temperature, nutrients, salinity, and concentration of pollutant are known to influence the capacity of microorganisms to degrade contaminants.

Water-table aquifers contain oxygen, and a wide variety of organic compounds have been shown to biodegrade aerobically. Wilson et al. (1986), and Lee et al. (1984) have reported the biodegradation of certain chemicals found in gasoline spills, and the biodegradability of organic compounds found in diesel spills were reported by Wilson et al. (1985). Several other researchers (Kuhn et al. (1985), Sulfita and Miller (1985), Lokke (1984), and Novak et al. (1984) also reported the biodegradation of other organic compounds including synthetic organic compounds.

When the concentration of organic contaminants is high, the dissolved oxygen in groundwater will be depleted and further biodegradation is possible due to anaerobic bacteria. Anaerobes that metabolize certain organic compounds and produce methane are called methanogens.

Recently, Wilson and Rees (1985) have demonstrated the anaerobic biodegradation of benzene, toluene, and xylenes in methanogenic river alluvium that has been contaminated with landfill leachate. Other related works in this area include Sulfita and Miller (1985), Wood et al. (1985), and Parsons et al. (1984).

Another approach that is of interest is the addition of microorganisms that have been especially acclimated to biodegrade a particular pollutant. Such microorganisms can be selected by enrichment culturing or genetic engineering techniques. Although there is some evidence of case histories of the use of acclimated microrganisms in the reduction of contaminants, it is noteworthy to point out that such case studies have not been managed under controlled conditions.

EOR Polymer Technology

The petroleum industry recognized the problem of inefficient oil recovery by conventional (primary and secondary) recovery methods in the early 1900's. Since then, extensive research has been done on methods of improving the displacement and sweep efficiency in petroleum recovery. Polymer flooding is one of the many methods developed to improve sweep efficiency by improving the mobility ratio.

This section presents a review of the current literature pertaining to the use of polymers in Enhanced Oil Recovery (EOR) operations. The primary focus is on the use of synthetically produced polyacrylamide polymers, but, wherever applicable, biologically produced xanthan gum biopolymers are also addressed briefly. A review of modeling aspects of polymer flow through porous media, as applied to (confined) petroleum reservoirs is presented. Finally, and most important of all to eventual application of this technique, the stability aspects and toxicity aspects are also discussed.

Enhanced Oil Recovery

Polymer flooding is an enhanced oil recovery (EOR) process that uses polymeric additives in injected water. Polymer solutions improve the water-oil mobility ratio, which results in the reservoir being swept more uniformly and completely than if flooded with water not containing polymeric additives. Currently, two types of polymers are used: (1) a synthetic polymer called polyacrylamide; and (2) a biologically produced polymer known as Xanthan gum (Jeanes, 1961).

Muskat (1949) was the first to point out that fluid mobilities would affect waterflood performance. Dykstra and Parsons (1950) showed the effect of permeability variation and mobility ratio on the recovery of oil. Aronofsky (1952) discussed the mobility ratio and its influence on flood patterns during water encroachment, while Aronofsky and Ramey (1956) reported the effect of mobility ratio on injection and production histories in a five-spot waterflood experiment. Later, Caudle and Witte (1959), also, by using a five-spot pattern, demonstrated that waterflood sweep efficiency can be improved by increasing water viscosity.

It was only in 1964 that Pye (1964) and Sandiford (1964) were able to establish that the mobility of water used in waterflooding can be reduced efficiently by adding small amounts of a water soluble polymer. Since then, many laboratory studies have been conducted to further research the use of polymeric materials to improve the sweep efficiency of the oil reservoir, thereby increasing the amount of oil recovered. Although this is by no means a complete list of such studies, some of the important findings on various aspects of polymeric materials were reported by Mungan (1966), Gogarty (1967), Dauben and Menzie (1967), Jennings et al., (1971), Knight (1973), Knight and Rhudy (1975), Szabo (1975), Sandiford (1976), Dominguez (1977), and Seright (1983). In addition, some of the detailed summaries of field test results can be found in Jewett and Schurtz (1970), Agnew (1972), and Herbeck et al., (1976).

Polymer Flow

As described earlier, petroleum reservoirs are usually several thousands of feet below the surface, and are under highly confined conditions. The polymer flow models described below, although not stated explicitly, were developed for the ideally confined conditions that exist in the petroleum reservoirs.

Different types of models are used to describe different oil-recovery mechanisms. The most widely used types are black oil, compositional, thermal, and chemical flood models. The four basic recovery mechanisms are: (1) fluid expansion, (2) displacement, (3) gravity drainage, and (4) capillary imbibition. The use of chemical flooding, and recovering oil by the displacement mechanism are most relevant to this research. Chemical flood models include polymer, micellar (surfactant), and alkaline (caustic) floods. Polymer waterflooding improves oil recovery by lowering the oil-water mobility ratio (by increasing the viscosity of water, and/or by reducing the effective permeability of the porous media to the fluids under consideration).

Patton et al., (1971) conducted an experimental and numerical study to estimate the incremental oil recovery by polymer flooding. The numerical model described simulates linear or five-spot polymer floods in a single-sand reservoir, or in a stratified reservoir. They assumed that there was no dispersion at the leading edge of polymer slug, and complete displacement of connate water by the injected polymer water. The model basically utilizes the "stream tube" approach given by Higgins and Leighton (1962). Each sand layer is divided into a number of tubes connecting the injection well to the production well. The equations of conservation of mass of water, and of polymer are solved numerically for each tube. The results indicated that a 42 percent increase in oil recovery was obtained when 1.0 pore volume (PV) of 270 ppm Kelzan polymer was injected.

Yanosik and McCracken (1979) developed and tested a nine-point finite difference simulation model. They compared the nine-spot pattern results with five-spot pattern results for adverse mobility ratio displacements. They reported that the nine-spot model predicted better results and were also able to show that the results obtained with nine-spot simulator are less sensitive to grid orientation (such as parallel grid or diagonal grid). Such adverse mobility ratio conditions are unlikely in phreatic aquifer contamination problems, so the grid orientation effects will not be addressed further.

A mathematical model for simulating chemical transport in porous media, taking into consideration dispersion and adsorption was presented by Satter et al., (1980). Chemical transport equations characterizing dispersion and adsorption of a chemical solution flowing through porous media were derived using mass balance. The accuracy of the numerical results was verified by comparison with the calculated results obtained by analytical solutions. Effects of dimensionless dispersion, adsorptive capacity, flow rate and kinetic groups were investigated.

Kazemi and MacMillan (1982) presented a numerical simulation comparison of five-spot versus line-drive using micellar/polymer flooding in a field scale operation. The patterns studied were five-spot and 4x1 line-drive. They used the simulator developed by Marathon Oil Co., which can simulate up to nine components in two phases. The partial differential equations were discretized using a standard finite difference scheme, and the resulting equations were solved by an iterative sequence scheme. Their results indicate that the line-drive produced slightly more oil than the five-spot pattern under identical conditions. Line-drive may not be practical in the removal of localized groundwater contamination, due to the fact that the curtain type polymer ring does not form around the contaminated water in a line-drive.

In addition to these, various aspects of modeling and simulation of polymer floods have been presented by Chaudhari (1971), Harvey and Menzie (1970), Todd et al., (1972), and Kazemi et al., (1978). Coats (1982) described the current level of development in the simulation of petroleum reservoirs.

Stability of Polymer Solutions

Polyacrylamide polymers control mobility both by increasing the viscosity of injected water as well as by reducing the permeability of the porous medium. Often, due to slow groundwater movement, residence times for polymer solutions in the porous media are long, and therefore polymer solution stability under various conditions becomes a very important consideration in using a polymer flood to clean up any localized groundwater contamination. Specifically, conditions that may degrade polymer solutions injected into a porous matrix must be determined and evaluated.

Polymer solutions may be degraded by mechanical, chemical, and microbial processes, but degradation can be prevented or at least minimized by using special equipment and techniques. A comprehensive study on the chemical stability of polyacrylamide polymers was conducted by Shupe (1981), using Dow Pusher^{TM} 500 (polyacrylamide polymer manufactured by Dow Chemical USA, and presently marketed as Dowell J333). This study presents data which show the effect of metals, ferrous and ferric salts, pH, oxygen, and other chemical additives on the chemical stability of polyacrylamide polymers.

Mechanical degradation of polyacrylamides presents practical problems in field operations. Maerker (1975 and 1976) conducted a comprehensive study on shear degradation of polyacrylamide solutions at low concentrations (300-600 ppm). These experiments were carried out in unconsolidated sand packs. The results indicate that shear degradation has a moderate effect on reduction of viscosity (less than 5 percent loss in most cases), with a slightly higher viscosity reduction at higher fluxes. Furthermore, shear degradation is more severe in low permeability porous media and at high salinities. Some of the similar works done in this area include Mungan (1969 and 1972), Hill et al., (1974), and Tinker and Bowman (1976).

Viscosity building properties of 34 polymers, representing 12 chemically different molecular structures or functional groups, and a large variation in molecular weights have been evaluated by Szabo (1979). Using wide ranges of salinity (NaCl), polymer concentration, and shear rate, he compared the degree of shear degradation of individual polymers. Typical results obtained with 0.1 percent NaCl at 12.5/s and 70.0/s shear rates are presented in Table 5. In general, it can be said that the viscosity decreased slightly at higher shear rates.

The presence of dissolved oxygen may reduce the viscosity of a polymer solution. The dissolved oxygen in polymer solution is believed to serve as some type of initiator for a free radical reaction between oxygen-derived radicals and traces of various reducing agents which are present in solution.

The effect of oxygen on polymer solution stability was reported by Knight (1973). Viscosity, screen factor, and pH were measured at various times in both oxygen-free and ordinary air environments. He found that the viscosity and pH of the solution were not materially affected by dissolved oxygen. It was also reported that only oxygen dissolved in the makeup water (used to make polymer solutions) appears to affect the stability of polymer solutions, and that the atmospheric oxygen that dissolves into aqueous polymer solutions does not appear to do so at a rapid enough rate to warrant any concern.

Table 5. Viscosities of Various Polymers in 0.1 % NaCl Brine Solution (Source: Szabo, 1979).

Polymer	Type	Supplier	η at 300 ppm		η at 600 ppm	
			12.5/s	70.0/s	12.5/s	70.0/s
Cyn 960	Copolymer[1]	Am. Cyan.	7.90	5.80	25.0	14.30
Q-41-F	HPAM	Nalco	7.00	4.80	16.0	9.20
Cyn 950	Copolymer[1]	Am. Cyan.	6.50	5.30	16.3	10.80
825	HPAM	Calgon	6.20	4.21	14.1	8.60
835	HPAM	Calgon	5.25	3.88	14.0	8.60
340,10% hydr.	AM AMPS	Calgon	6.60	3.80	14.1	7.62
259	HPAM	Am. Cyan.	4.50	3.70	10.5	7.70
XF-4084.2	HPAM	Dow	4.72	3.30	10.2	7.02
815	HPAM	Calgon	4.85	3.50	10.8	7.20
Cyn. 940	Copolymer[1]	Am. Cyan.	5.50	4.50	12.3	8.80
700	HPAM	Dow	4.55	3.20	10.0	6.80
340,20% hydr.	AM/AMPS	Calgon	6.00	3.30	11.6	6.80
226	HPAM	Am. Cyan.	4.50	3.15	9.50	6.40
Homopolymer	AMPS	Lubrizol	5.40	2.65	12.2	5.80
Cyn. 930	Copolymer	Am. Cyan.	4.00	3.38	10.0	7.57
500	HPAM	Dow	3.95	3.00	8.10	6.09
3060	HPAM[2]	ICI.Am.	4.00	2.91	8.30	5.95
CMC 9H4	CMC	Hercules	-	-	5.21	3.65
Experimental	Bioplolymer	Lubrizol	5.00	3.31	13.9	7.62
454 (71)	HPAM	Calgon	3.38	2.71	6.00	4.61
454 (74)	HPAM	Calgon	3.00	2.40	5.10	3.90
Kelzan MF	Biopolymer	Xanco	3.15	2.27	8.60	5.20
340	AM/AMPS	Calgon	2.89	2.41	4.90	4.00
106	Copolymer	Amoco	2.53	1.95	4.70	3.55
104	Biopolymer	Amoco	3.70	2.40	7.40	4.65
SPX 5338	CMHEC	Hercules	2.03	1.91	3.04	2.80
Natr 250 HHR	HEC	Hercules	-	-	2.75	2.60
VX 92	Cationic	Nalco	2.10	1.65	3.40	2.75
Klucel HF	Hyd.Prop.Cell.	Hercules	1.75	1.59	2.62	2.27
470	PAM	Calgon	1.43	1.25	1.86	1.62
Klucel MF	Hyd.Prop.Cell.	Hercules	1.34	1.29	1.67	1.58

1 Copolymer of acrylic acid and acrylamide, molecule structure is similar to HPAM.

2 Discontinued.

A recent study by Shupe (1981) showed that polyacrylamide polymers were affected by metals and ferrous iron salts (>5.0 ppm), in the presence of oxygen (see Table 6). As can be seen, ferrous iron salts caused severe degradation in solutions that contained oxygen. Although the exact mechanism is not completely known, Shupe points out that an oxygen-anion radical (O_2^-) is formed when a metal or metal ion is oxidized. The highly reactive oxygen-anion radical may then attack the polymer chain, which would result in a scission of the polymer chain. Shupe also reported 200-400 ppm of formaldehyde to be an optimum level to stabilize polyacrylamide polymer solutions containing oxygen.

Loss of polymer solution viscosity in water of increasing ionic strength is a concern, especially when partially hydrolyzed polyacrylamide polymers are used. Adding salts (cations) to polymer solutions primarily results in alteration of the molecule, changing from a somewhat distended to a more nearly spherical shape. This in turn may reduce the viscosity. Jennings et al., (1971), showed that a reduction in viscosity occured when 3.0 percent NaCl was added to the solution. The viscosity reduction in xanthan gums was not that adverse. Divalent cations (such as calcium) have a more pronounced effect than do monovalent cations (such as sodium). Smith (1970) also reported similar findings. Ward and Martin (1981) showed the fractional loss in viscosity to be a function of the fraction of

Table 6. Effect of Metals on Polyacrylamide Stability (Source: Shupe, 1981).

	Viscosity Loss, %		
	Solution A[1]	Solution B[2]	
Metal	2 Days	2 Days	2 Weeks
None	4	5	4
Brass	57	4	8
Copper	41	-	-
Carbon steel	76	23	54
Stainless steel	10	4	6
Monel steel	16	-	-
Fe^{++}(1 ppm)[3]	26	7	9
Fe^{++}(5 ppm)	-	20	23
Fe^{++}(10 ppm)	67	36	38

[1] No biocide; 1,000 ppm P-500; pH 8.0; 115°F (46°C).

[2] No biocide; 2,000 ppm P-500; pH 9.0; 115°F (46°C).

[3] Ferrous iron was added to polymer solution from a 100 ppm stock solution of Fe^{++} (from $FeCl_2 \cdot 4H_2O$) in Sundance brine.

multivalent cations, and independent of total ionic strength. Calcium ions caused greater viscosity reduction than magnesium ions.

Mungan (1972) has shown that the viscosities of two polyacrylamide polymers Pusher 500^{TM} and Pusher 700^{TM} (manufactured by Dow Chemical USA) were practically unaffected by pH in the range of 7.0 to 9.8. Decreasing the pH below 7.0 produced a drastic reduction in viscosity. This suggests that for groundwater applications, more polymer may have to be used to get an equivalent increase in the viscosity (since the groundwater pH is around 5.0).

Shupe (1981) studied the long term effect of pH on polyacrylamide polymer solutions at 46^{o}C (115^{o}F). Two solutions adjusted to pH 8.0 and 12.0 were studied for 21 months in the presence of oxygen. Viscosity losses of 27.0 percent and 51.0 percent respectively were reported. In addition, the pH of the solutions decreased to 7.7 and 10.2 respectively.

Toxicity of Polymers

The purpose of this section is to present the toxicity and health effects associated with compounds like polyacrylamides and polysaccharides that are used to improve the sweep efficiency in an aquifer. It should be noted that the toxicological effects can be drastically altered by the presence of other compounds, physical conditions such as temperature, pressure, and oxygen concentration, and the susceptibility of exposed individuals. Therefore, data obtained in laboratory experiments are sometimes difficult to apply to field conditions. This is especially true when long term effects have not been studied in great detail.

Both polyacrylamide and polysaccharide polymers used as mobility control agents can be considered to be essentially non-toxic (Enhanced Recovery of Residual and Heavy Oils, 1980). Some health effects, however, are reported to occur due to the physical nature (broth or powder) of the compounds used. Therefore, contact with polymer broths and exposure to polymer powders should be avoided.

Silvestro and Crocker (1980) reported that, in general these chemicals are of low toxicity. Several of these chemicals are used as food additives (e.g. xanthan gum), and others are permitted by Food and Drug Administration (FDA) to be used as constituents of food packaging or pharmaceutical drug coatings. However, the group's potential as a health hazard to personnel working with these chemicals, cannot be discounted.

Polyacrylamide polymer is synthesized from its acrylamide monomer units. It should be noted that, while the polyacrylamide polymer is considered non toxic the acrylamide monomer is highly toxic. Acrylamide monomer is considered to be a neurotoxin, and therefore the potential presence of the monomer represents the main toxicological concern. The Environmental Protection Agency (EPA) also lists the acrylamide monomer as a toxic compound. In general, because of the cross linked nature of polyacrylamide polymer, it is very unlikely that acrylamide monomer will leach from polymer. Degradation is not a major concern toxicologically since the evidence suggests that the polyacrylamide polymer breaks up into small polymer chains, and not into the monomer units. Therefore, polyacrylamide polymer may be considered to be reasonably safe enough to be injected into an aquifer to remove the more dangerous contaminants.

Polyacrylamide is non-irritating to skin under most conditions, but is irritating to eyes and mucous membranes. Technical polyacrylamide should contain no more than 0.05% acrylamide monomer by weight. Although these polymers are suspected to have local carcinogenic ability when implanted in the skin of laboratory animals, there is no evidence that polyacrylamide is a carcinogenic hazard in man. The American Conference of Governmental and Industrial Hygienists (ACGIH) recommended a maximum of one ppm of monomer by weight in potable water.

Xanthan gum (polysaccharide polymer), derived from the microorganism Xanthomonas campestris by bacterial fermentation, was approved by FDA as a food additive in 1969. Woodward et al., (1973), reported that in their laboratory studies, xanthan gum has been shown to have no systemic toxic effects (see Appendix for definition) on rats or dogs which received xanthan gum in their diet. In addition, xanthan gum does not appear to be a dermal contact hazard in man. In another study by McNeely and Kovacs (1975), the following acute toxicity (see Appendix for definition) data have been reported for xanthan gum:

Oral LD_{50} for rats ----- 5,000 mg/kg
Oral LD_{50} for dogs ----- 20,000 mg/kg
Oral LD_{50} for mice ----- 1,000 mg/kg

Degradation products of polyacrylamide and polysaccharide polymers are generally smaller fragments of the respective polymer. Polyacrylamides tend to hydrolyze at the amide linkage and form a low viscosity polymer (not monomer) with reduced mobility control properties, while polysaccharides degrade ultimately into monomer units (simple sugars). It is unlikely that toxic hazards should be expected from any of these degradation products.

In addition to the general toxicity information of this group of polymers, companies that are involved in manufacturing and/or marketing the polymers have reported some toxicity data with respect to those specific polymers. American Cyanamid reports that the single oral LD_{50} of CYANATROL polymers for young male albino rats is greater than 5.0 ml/kg, and the LD_{50} by 24 hour contact with the clipped skin of male albino rats is greater than 10.0 ml/kg (American Cyanamid Company, 1981). Dow Chemical USA, reports a low acute oral toxicity for Dowell J333 polymer (previously known as Dow Pusher 500): a LD_{50} of greater than 4,000 mg/kg (Dow Chemical USA, No Date). Custom Oil Recovery Technology (CORT) reported the toxicity of their N-Hance polymers to be "very low" (CORT Technical Data, No Date).

A recent comprehensive study by King and Noss (1987) has summarized the general physical characteristics and the possible toxic nature of polyacrylamide polymers. The authors have also included a discussion of properties and toxicity of acrylamide monomer. This extensive study was conducted to explore the potential use of polyacrylamide polymers in the cleanup of groundwater contamination.

CHAPTER III

EXPERIMENTAL INVESTIGATION

This research, as mentioned in the earlier sections, is primarily designed as a laboratory scale experimental study aimed at investigating the possibility of using viscous polyacrylamide polymers in dealing with the groundwater contamination cleanup operations. The various experimental aspects of this research are broadly discussed under three sections: (1) General Considerations; (2) Experimental Design; and (3) Experimental Methods.

General Considerations

Presented in this section are the general concepts of polymer molecules, their orientation, and their contribution to the viscosity property of polymer solutions. Also included are the general properties of Dowell J333 polyacrylamide polymer. Finally, with particular reference to this research, the effects of the viscosity ratio on the efficiency of displacement process are also presented.

Polymer Molecules and Viscosity

The polymer molecule dissolves in water by means of hydrogen bonding, but retains some of its own structural identity while in solution. These polymers are generally considered to have a random coiling configuration. This type of polymer molecule has the ability to hold a large volume of solvent (water) within its coils in a manner similar to that of sponge. Under an applied stress, the random coil is easily deformed, and changes from its generally spherical orientation to elongated ellipsoids. The coils are extensively entangled with each other, and when a coil moves it must drag along other coils too.

The presence of such extensively entangled polymer molecules in a particular solvent can give rise to a dramatic increase in viscosity which is very much greater than that found for equivalent concentrations of low molar-mass solutes. This is because of the enormous difference in dimensions between the polymer molecules and solvent molecules, and in good solvents the polymer coils are expanded even further. In general the increase in viscosity depends upon a number of factors (Young, 1981): (i) the type of polymer; (ii) the concentration of polymer; (iii) the molar mass of polymer; and (iv) the nature of solvent.

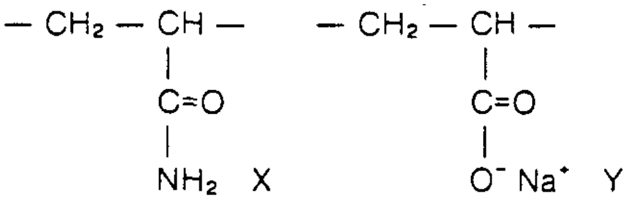
Dowell J333 Polyacrylamide Polymer

Developed from the pioneering research initiated in the early 1960s, Dow (Dowell) polymers have been used widely in major oil recovery projects since that time. Dowell polymers are available as dry, free-flowing powders, or in liquid emulsion forms. The choice of a specific product will depend upon the properties of the porous media including permeability, pore size, and lithology.

The Dowell mobility control polymers, both dry and liquid emulsion forms, are polyacrylamide polymers modified by substitution of carboxyl groups for a portion of the amide groups. The degree of substitution, sometimes called "hydrolysis level," is controlled to optimize the solubility characteristics and to minimize the adsorption of polymer on the solid surfaces. A typical chemical structure of Dowell polyacrylamide polymer is shown in Figure 4, with the major differences between the Dowell products being the molecular weight specifications. These polymers have extremely low content of insoluble materials.

Displacement Efficiency

One of the variables that affects the efficiency of a displacement process is the viscosity ratio of the displaced fluid (in this case, it would be contaminated water) and the displacing fluid (polymer-water, followed by water). The effect of viscosity can be best understood by reference to a single capillary, wherein, by the principles of viscous flow it is well known that the fluid velocity is maximum at the center of the capillary and zero at the wall. Thus,



$$-CH_2-CH(C{=}O)(NH_2)- \; X \qquad -CH_2-CH(C{=}O)(O^- Na^+)- \; Y$$

Figure 4. Typical Chemical Structure of the Dowell Polyacrylamide Polymer.

when attempting to displace a viscous fluid by one that is less viscous, the tendency is for the displacing fluid to take the path of least resistance and penetrate through the central portion of the capillary. The greater the viscosity difference between the displaced and displacing fluids, the more pronounced this effect would be.

On the other hand, if one considers the situation where the viscosity of the displaced fluid is less than that of the displacing fluid (for example, viscosity of contaminated water being less than the viscosity of injected polymer-water), the displaced fluid is more mobile and therefore does not permit the center penetration of displacing fluid. This will be the case at the leading edge of the polymer front. As the viscosity ratio increases, the trailing edge of the polymer front may experience some "fingering effect." Therefore, the determination of the integrity of the polymer slug is a part of this research study.

Experimental Design

The main experimental apparatus used in this study consisted of (1) Sand Column, and (2) Wedge Apparatus. The sand column was designed to simulate the linear flow, while the wedge apparatus was designed to simulate the radial flow. The sand column and wedge apparatus were connected to the analog to digital computer interface system via a set of pressure transducers. An engineering design of both the apparatus, as well as a brief description of the apparatus are presented below.

Sand Column Apparatus

A schematic illustration of the sand column used in this research study is shown in Figure 5. The sand column is of circular cross section with an inside diameter of 3.81 cm (1.5 in) and a total length of 100.0 cm (39.5 in). The actual diameter of the sand column was determined experimentally by the volumetric method, and is described in detail in Chapter IV, Methodology and Procedures as well as in Appendix. The experimentally determined diameter of the sand column was 3.72 cm (1.47 in).

The sand column apparatus was constructed using polyvinyl chloride (PVC) material, and was used to determine parameters such as porosity, hydraulic conductivity (and subsequently permeability), polymer adsorption, and dispersion. The flow in this column is governed by a constant head tank at the inlet end (or a constant flow rate pump), and another constant head tank at the outlet end. The discharge through the column was measured with a graduated volumetric cylinder.

Ten taps were spaced uniformly at every 10.0 cm (4.0 inch) interval along the length of the column to allow the measurement of the

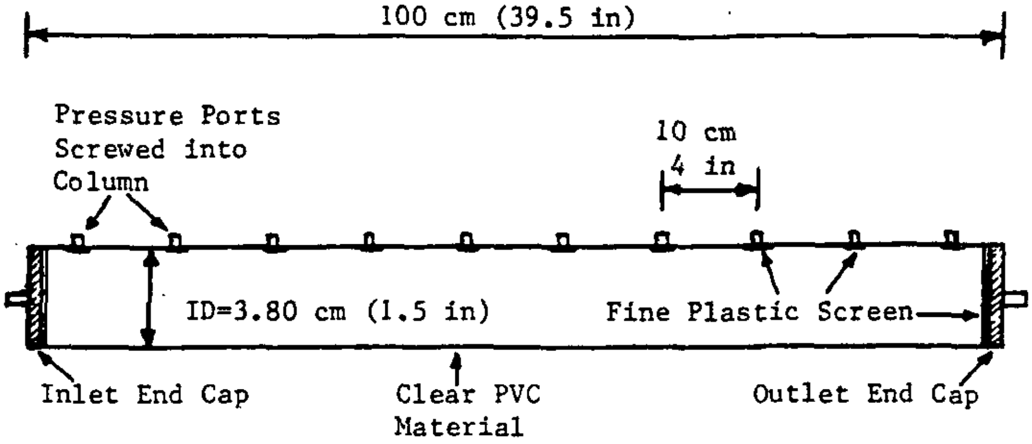


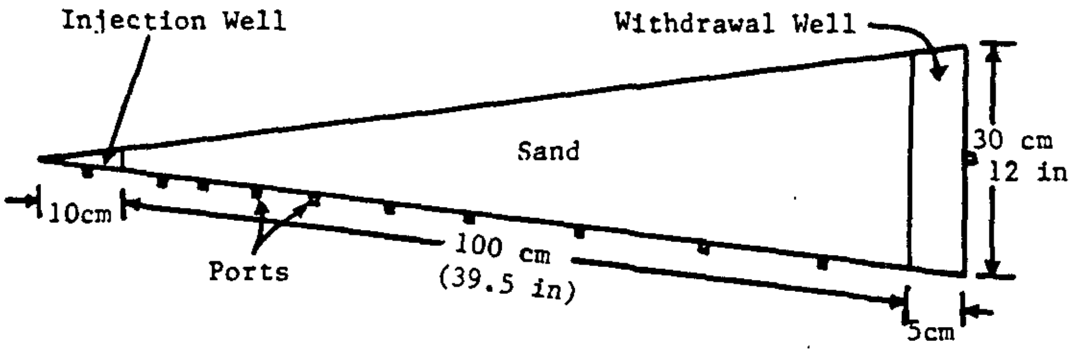
Figure 5. Design of Linear Flow Sand Column Apparatus.

pressure distribution. The taps were made of polystyrene material and had an internal diameter of 3.175 mm (0.125 inch). Fine plastic screens were used at all the ten pressure measurement ports to prevent the sand particles from entering into the pressure measurement ports. Screens made of non-corrosive polyvinyl chloride materials were used to separate the entrance and exit chambers from the sand.

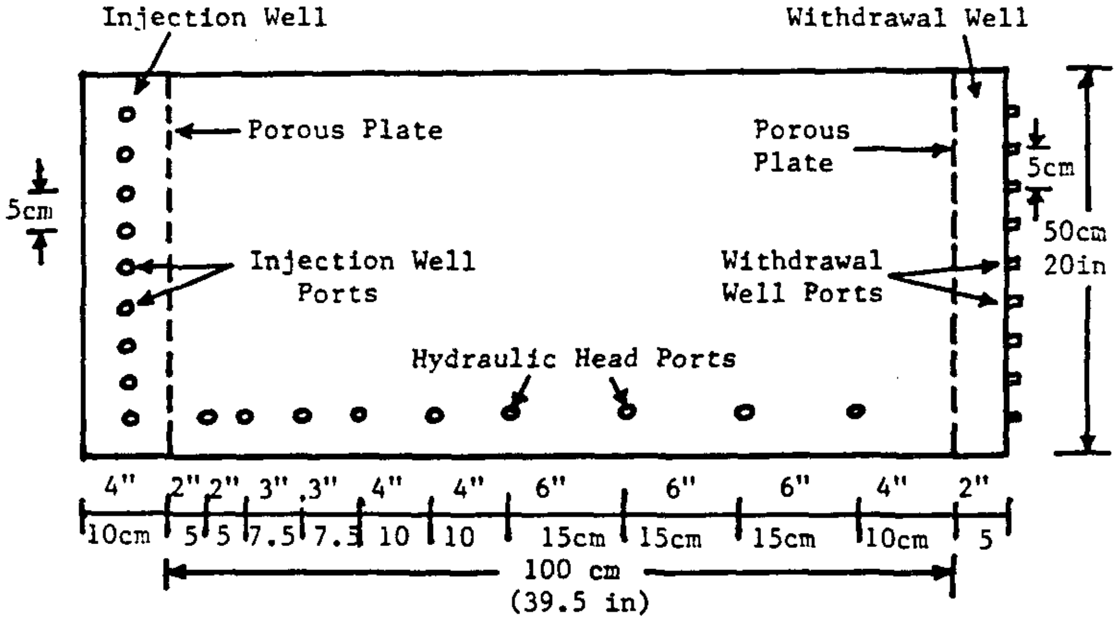
Radial Flow Wedge Apparatus

A schematic illustration of the design of the radial flow wedge apparatus is presented in Figure 6. This apparatus was used to simulate radial flow, by taking into consideration only a small segment of the whole radial flow field. The flow in the radial flow wedge apparatus is governed by a constant head tank (or a constant flow rate pump) at the inlet end and another constant head tank at the outlet end; the distance between these two points being the radius, r.

The wedge apparatus was made of one-half inch thick clear polyvinyl chloride (PVC) sheets. The apparatus was 51 cm (20 in) in height with a radial distance of 117 cm (46 in) including the injection well and withdrawal well. The actual portion occupied by sand was about 100 cm (40 in). Several ports were installed on the front PVC plate of the wedge apparatus, at predetermined radial distances, to facilitate the measurement of the pressure distribution. This is



TOP VIEW



FRONT VIEW

Figure 6. Design of Radial Flow Wedge Apparatus.

schematically illustrated in the Front-View of the design of the radial flow wedge apparatus.

The injection well and the withdrawal well are separated from the sand portion by porous PVC plates. A fine plastic screen was also placed on the porous plates to hold the sand in the sand compartment. Taps were installed at every two inches along the height of both the injection well and withdrawal well. These taps would serve to maintain a constant head in the respective wells, and thus create the required head differential. The height of the sand in the wedge apparatus was about 46 cm (18 in).

Sampling of the flowing liquids from the wedge apparatus was made possible by means of a small diameter (Cole-Parmer) reinforced teflon tubing. A schematic diagram of the design of a sampling device is shown in Figure 7. In all, 14 such sampling devices were installed in the wedge apparatus, of which nine were installed about two inches from the bottom of the apparatus along the radial distance, coinciding with the location of pressure ports. The design of both horizontal as well as vertical placement of sampling port devices in the wedge apparatus is illustrated in Figure 8. The remaining five sampling points were located between the eighth and ninth ports (about 6 inches from the withdrawal well), along the circumferential arc of the Wedge apparatus. These are placed at two inch vertical intervals to sample the vertical distribution.

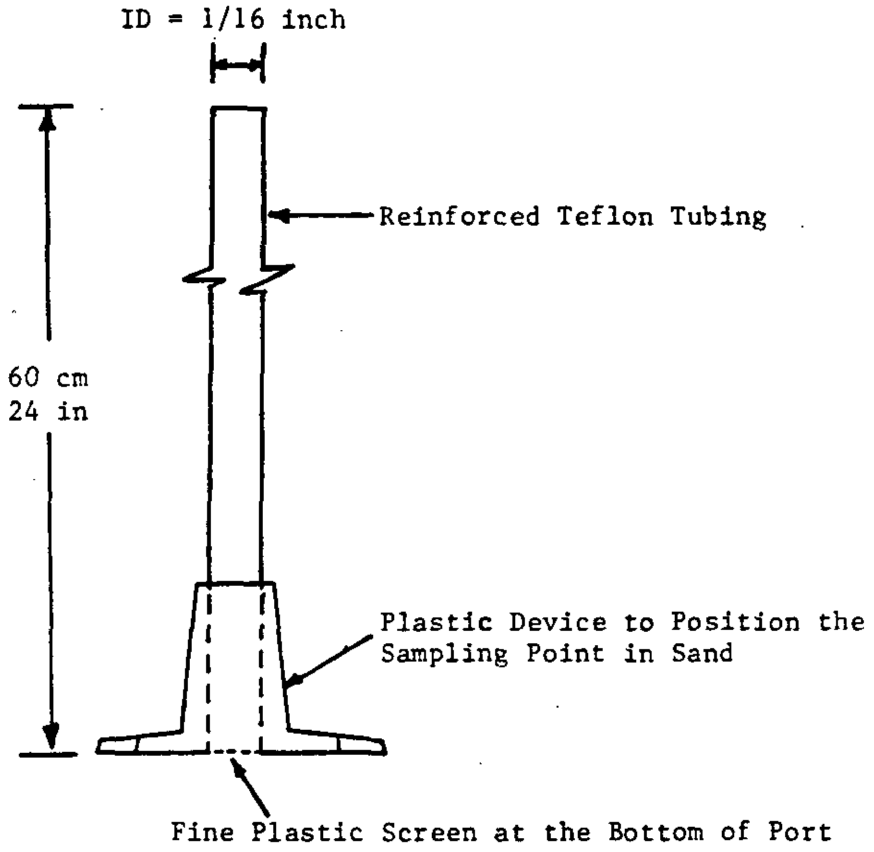


Figure 7. Design of a Typical Sampling Port Device for the Radial Flow Wedge Apparatus (Not to Scale).

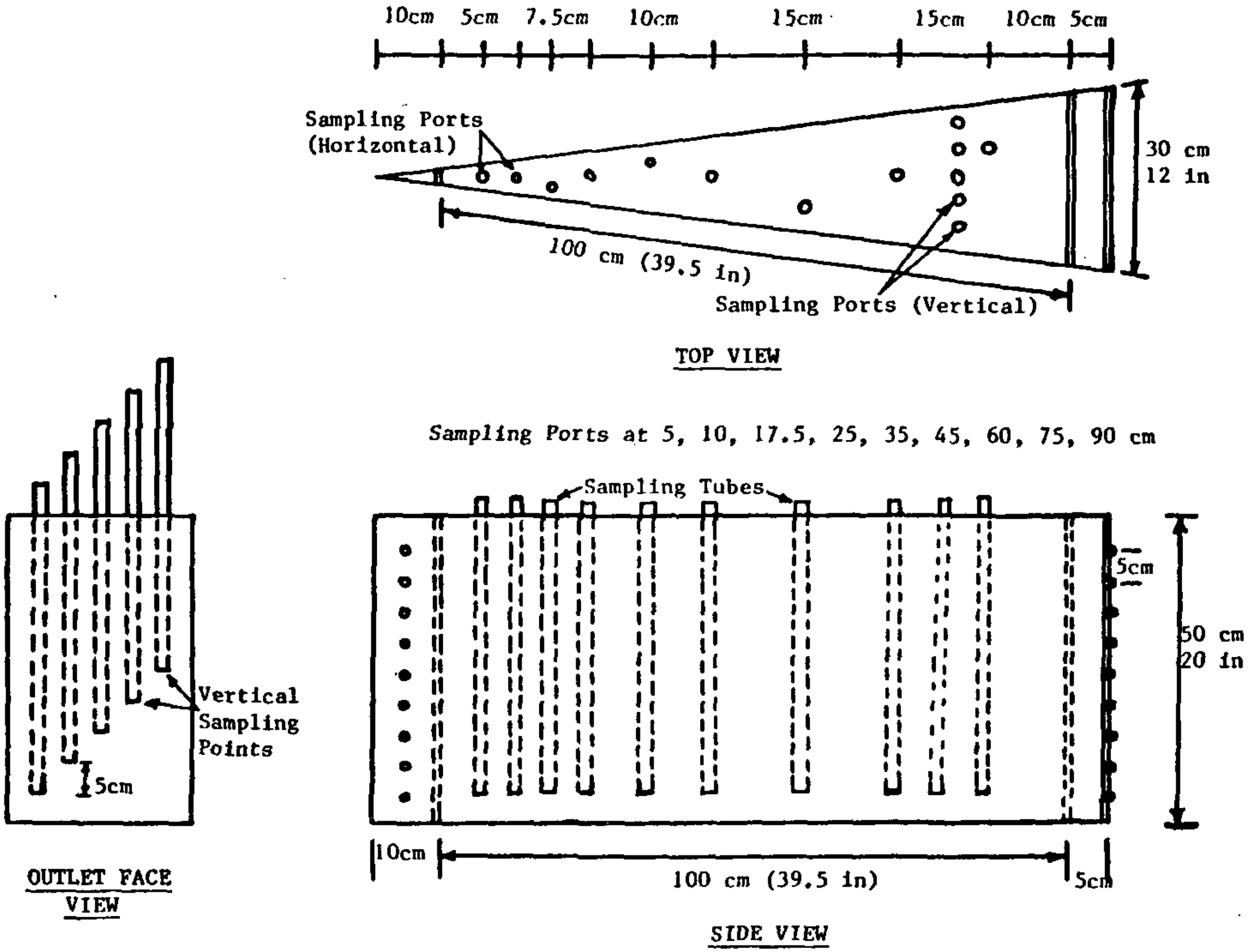


Figure 8. Design of the Placement of Sampling Port Devices in the Radial Flow Wedge Apparatus.

Experimental Methods

The laboratory analytical methods to determine the polymer concentration and polymer viscosity are described in this section. The experimental methods to do the grain-size analysis, and to determine the parameters such as porosity, and hydraulic conductivity (and subsequently permeability) are also presented below.

Polymer Concentration

Polymer solutions were prepared according to the instructions provided by the manufacturer. A detailed procedure for the preparation of Dowell J333 polyacrylamide polymer solutions is given in the Appendix.

Foshee et al., (1976), have developed a general purpose analytical method for the determination of polyacrylamide polymer concentrations. In this method, polyacrylamide reacts in an acid solution with sodium hypochlorite (bleach) to produce an insoluble chloramide, which forms a colloidal suspension. The turbidity produced by this reaction can be measured by a spectrophotometer or a turbidimeter. The procedure described for 0-500 ppm concentration range was used in the experiments.

Viscosity Measurement

Most polyacrylamide solutions used for mobility reduction are highly viscous fluids and it is not easy to obtain meaningful viscosity measurements. Foshee et al., (1976), reported that a Brookfield LVT viscometer is satisfactory in obtaining reliable viscosity measurements.

The Brookfield viscometer is based on the principle of measurement of the drag produced upon a spindle rotating at a definite constant speed while immersed in the fluid (material) under test. This drag is indicated on a rotating dial by a pointer, and the dial reading can then be converted to viscosity units in centipoise (mPa.s). The UL adapter (an additional attachment to the Brookfield Viscometer), in addition to using small samples of about 18.0 ml, aids in increasing the accuracy and precision of viscosity measurements in the range of 0-100 cp (centipoise).

Grain-Size Analysis

Permeability is a property of the porous media, and varies not only with the porosity but also with the size, distribution, and continuity of pores. The degree of uniformity of a mixture of fine to coarse material has an important effect on permeability. From an engineering point of view, when a sample contains similar size particles, the material is said to be uniformly graded. Grain-size distribution is determined by passing the sand sample through a series of sieves.

Grain-size analysis is a process in which the proportion of material of each grain size present in a given soil (grain-size distribution) is determined. The grain-size distribution of coarse-grained soils is determined directly by sieve analysis, while that of fine-grained soils is determined indirectly by hydrometer analysis. A detailed procedure for determining the grain-size distribution by sieve analysis method (U. S. Department of Army, 1980) is given below.

Sieve analysis consists of passing a sample through a set of sieves and weighing the amount of material retained on each sieve. The sieve analysis is performed on material retained on a U.S. Standard No. 200 sieve, i.e., with a sieve opening of of 0.074 mm (0.0029 inch).

The Ottawa sand was cleaned first with tap water, and then with distilled water, to remove any fines, and also to give a representative grain-size distribution of the sand that was used in the experimental setup. The sand sample was air-dried and then oven-dried at $110^{o}C \pm 5^{o}C$. The sample was allowed to cool and the weight recorded. The sample was then placed on the top sieve of a nest of sieves, and the shaking machine was operated for about 10 minutes (or until additional shaking does not produce appreciable changes in the amounts of material on each sieve). The nest of sieves was then removed from the machanical shaker and the contents retained on each sieve were transferred into weighing pans. The weights of the respective portions of sand retained on each sieve were recorded. The percentage of material by weight retained on the various sieves was computed as follows;

$$\text{Percent Retained} = \frac{\text{Weight of sand retained on a given sieve}}{\text{Total wieght of oven-dry sand}} \text{ X } 100$$

Porosity Determination

Porosity, n, is the ratio (usually expressed as a percentage or fraction) of the volume of voids of a given soil mass to the total volume of the soil mass. Porosity of the Ottawa sand was determined using the Volumetric method described in Engineer Manual (U. S. Department of the Army, 1980). The fundamental relations of the weights and volumes of the various components of a soil mass are presented in the above reference. The basic quantities which must be known to compute the void ratio and thus the porosity are, the weight and volume of the wet specimen, the weight of same specimen after oven-drying ($110^{o}C \pm 5^{o}C$ for a minimum of 4 hours), and the specific gravity of solids.

Void ratio, e, is the ratio of the volume of voids to the volume of solid particles in a given soil mass, and is given by;

$$e = \frac{V_t - V_s}{V_s} \qquad \text{(Eq. 3.1)}$$

where;

V_t = total volume of the wet specimen (sand + water), L^3

V_s = volume of solids, L^3

The volume of solids, V_s, is given by ;

$$V_s = \frac{W_s}{G_s} \qquad \text{(Eq. 3.2)}$$

where;

W_s = weight of dry soil, M

G_s = specific gravity of solids

Porosity, n, can then be computed using the equation;

$$n = \frac{e}{1 + e} \qquad \text{(Eq. 3.3)}$$

which can be simplified and rewritten as,

$$n = \frac{V_t - V_s}{V_t} \qquad \text{(Eq. 3.4)}$$

Hydraulic Conductivity

Hydraulic conductivity, K, was determined experimentally by using a constant head permeameter (Klute, 1965), in which a constant volumetric flow rate (Q), is maintained through porous media of length ΔX, and cross sectional area A. This results in a constant head differential ΔH across the sample. The hydraulic conductivity, K, can be determined by applying Darcy's law;

$$K = \frac{Q\Delta X}{A\Delta H} \qquad \text{(Eq. 3.5)}$$

The permeability of the porous media can then be computed by using the relationship;

$$k = \frac{K\eta}{\rho g} \qquad \text{(Eq. 3.6)}$$

where; η = dynamic viscosity, M/LT

ρ = density of fluid, M/L^3

g = acceleration due to gravity, L/T^2

The sand column apparatus was used as a constant head permeameter to determine the hydraulic conductivity, and subsequently to compute the permeability of the Ottawa silica sand.

CHAPTER IV

METHODOLOGY AND PROCEDURES

This section presents the methodology and detailed procedures of the experimental studies, and describes the conditions under which such experiments were carried out. The purpose of each of these experiments as well as the use of information obtained from such experiments to understand the flow behavior of polymers is outlined.

Experimental Procedures

The experimental procedures section consists of the following sub-sections, namely: (1) Viscosity experiments, (2) Shear Rate experiments, (3) Adsorption experiments, (4) Sand column experiments, and (5) Radial flow experiments. A brief background of each of the experimental processes, the importance of such experiments to this research study, as well as a brief description of the procedures for each of the above mentioned experiments is presented in the following paragraphs.

Viscosity Experiments

The presence of polymer molecules in a particular solvent can give rise to a dramatic increase in viscosity which is very much greater than that found for equivalent concentrations of low molar-mass solutes. With particular reference to this research study, viscosity is the most important property of polymers that would be investigated. Viscous fluids offer more resistance to flow, and when these viscous fluids are introduced into the porous matrix, they are bound to induce some changes in the existing hydraulic gradient as well as the flow rate.

The purpose of the viscosity experiments was to establish a relationship between polymer concentration and viscosity. It should however be noted that the viscosity of different lots of the same polymer may vary slightly. Several batches of polymer solutions were prepared at several times during the course of this research study. Polymer solutions in the concentration range of 0 ppm to 500 ppm were made following the procedures described by the manufacturer (see Appendix for the detailed procedure). Viscosity measurements of all the polymer solutions were made using the Brookfield Synchro Lectric Viscometer at 6 rpm and room temperature (usually around $20^{o}C$). The Brookfield Viscometer measures the viscosity in centipoise (0.01 poise) units, (one poise equals 1.0 dyne-second/cm). Viscosity of water at $20^{o}C$ is 1.0 centipoise.

From the data obtained in these viscosity experiments, a valid relationship between polymer concentration and viscosity can be established. This relationship can be useful in understanding the polymer flow through porous media. Viscosity relationships were developed individually for each batch of polymer solution, and then an overall viscosity relationship was developed using the experimental data of all the viscosity experiments.

Shear Rate Experiments

Viscosity is the property of a fluid or semifluid that enables it to develop and maintain an amount of shearing stress dependent upon the velocity of flow. Viscosity characterizes the resistance of a system to shear or internal friction. Depending upon the nature of substances and the temperature, the viscosity of polymers varies significantly.

At constant temperature and constant pressure, the viscosity (i.e., the ratio of shear stress to shear rate) may not depend on deformation conditions. Such fluids are referred to as Newtonian fluids, and exhibit ideal flow behavior. At ordinary shear stresses and shear rates, they do not undergo any structural change.

However, some deviations from Newtonian flow are commonly observed in polymer solutions and melts (Bauer, 1967). One such deviation is "Shear Thinning," which is a reversible decrease in viscosity with increasing shear rate. The opposite effect "Shear Thickening," an increase in viscosity with increasing shear rate, is rarely observed in polymer solutions.

Several experimental studies were conducted to study the effect of shear rate on viscosity of Dowell J333 polymer solutions. The spindle speed (rpm) of the Brookfield viscometer was used as the pseudo-shear rate, and the viscosity of polymer solutions of various concentrations was measured at four spindle speeds (6, 12, 30, and 60 rpm).

Adsorption Experiments

Adsorption studies are an essential part of the laboratory evaluation process involving the use of adsorbable materials. Primarily, the concerns regarding the polymer adsorption on the Ottawa sand particles are two fold. First, the magnitude of adsorption will determine the amount of polymer to be added to injection water. Therefore, this will have a direct effect on the overall economics of polymer use in groundwater contamination cleanups. Secondly, as polymer is adsorbed, the injected polymer solution is depleted of its polymer and moves ahead as ordinary water, or as a solution with far less polymer concentration than that of the injected solution. This would in turn affect the flow of polymer in porous media.

Adsorption of polymer on sand particles could be an important aspect in understanding the polymer movement through the porous media. While propagating through the porous matrix, the leading edge of a polymer slug gradually gets depleted of polymer by retention in the soil matrix (Patton et al., 1971). Polymer retention takes the form of adsorption, entrapment, and plugging in a porous media. It is generally believed that all three forms are operative to some degree: however, their relative importance depends on a number of factors such as type, concentration, molecular weight, flow rate, temperature, pH, solid matrix properties, etc.

High losses of polymer by adsorption would obviously be undesirable in contaminant cleanup oriented polymer injection. At the same time, it is important to note that the polymers with good adsorption characteristics could be used as a barrier technology to contain contaminated groundwater. It should be pointed out that results obtained from controlled experiments in laboratories cannot always be used to predict polymer adsorption in field situations. In many cases, the variation in the nature of soil properties and the presence of certain salts in the field may alter the surface properties of soils to either increase or decrease the adsorption.

The effect of adsorption of polymer is illustrated in Figure 9. By this process, adsorption would reduce the thickness of polymer slug, and increase the travel time required for the polymer front to

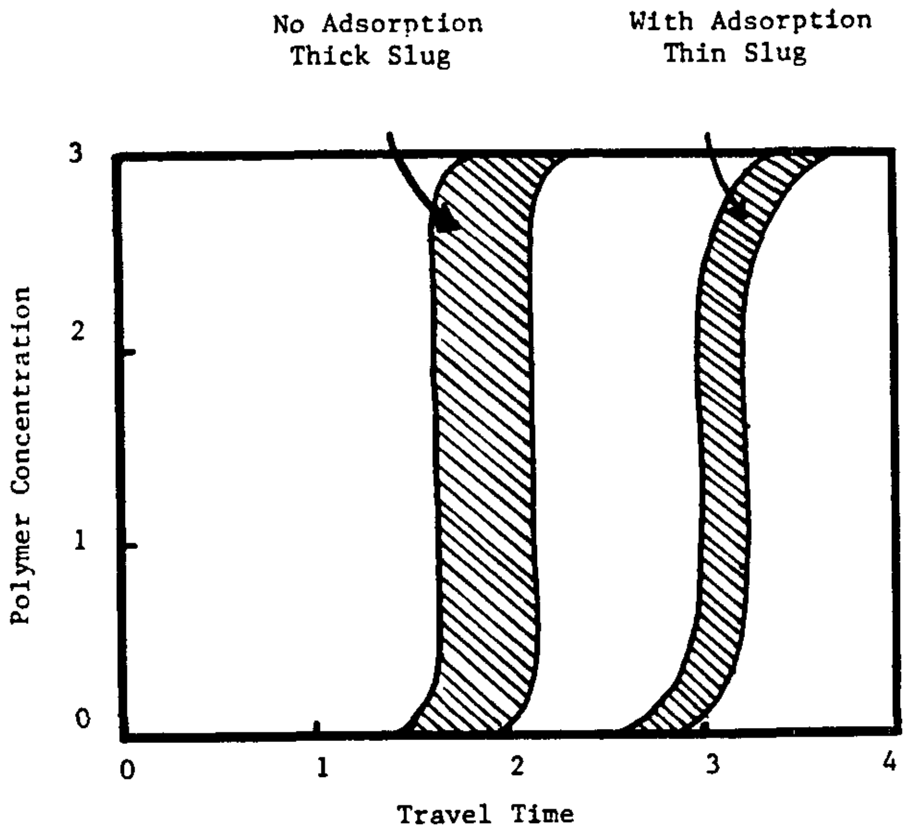


Figure 9. Effect of Polymer Adsorption on Polymer Slug Size and Travel Time.

arrive at a given point. It is also possible that adsorption would decrease the concentration of polymer throughout the slug. This would reduce the viscosity of the polymer slug, and consequently the travel time would be decreased. Thus it is very important to characterize the nature and extent of polymer adsorption on sand.

In our efforts to quantify the effects of adsorption of polymer, two types of adsorption experiments were conducted, namely Batch adsorption experiments, and Once-flow-through adsorption experiments. In batch studies, preweighed Ottawa sand samples were allowed to equilibrate for at least 48 hours in Dowell J333 polyacrylamide polymer solutions ranging from 0 ppm to 500 ppm concentration. Polymer solutions were analyzed for concentration both before adsorption and after adsorption. Then, by using conservation of mass of polymer, the adsorbed polymer can be computed using the following equation:

$$X_e = \frac{C_o - C_e}{W} \qquad \text{(Eq. 4.1)}$$

where; X_e = the equilibrium solid phase loading of polymer per unit mass of sand (mg polymer/g sand), M/M

C_o = the initial polymer concentration in solution, (mg/l), M/L^3

C_e = the equilibrium liquid phase concentration of polymer, (mg/l), M/L^3

W = the mass of sand in polymer solution, (g/l), M/L^3

In the second set of experiments, i.e., Once-flow-through studies, a known volume of polymer of known concentration was pumped through the sand column apparatus. Water as well as polymer samples were then collected at the outlet end of sand column and, once again, the mass of polymer adsorbed was computed using the mass balance approach. Once-flow-through adsorption experiments, although not so common in adsorption studies, represent the system of polymer injection more closely than the batch adsorption experiments. This was one of the main reasons for including the Once-flow-through experiments in this research study.

Sand Column Experiments

The sand column was designed to study the flow of polymer solutions through the porous media. In addition, the same sand column was also used to conduct the porosity, permeability, adsorption, and dispersion experiments.

The clear PVC pipe used to construct the sand column was supposed to have a uniform inside diameter of 3.81 cm (1.5 in). The preliminary experiments yielded erroneous results, and accurate diameter measurements were taken at both ends of the sand column. These two values differed by about 1.5 mm. Therefore, to get a more representative diameter of the sand column, the volumetric method was used. The column was filled with water and the volume of water was measured using a graduated cylinder. The details of this method as well as the calculations are presented in Appendix. The average diameter of the sand column according to the volumetric method was found to be 3.72 cm (1.47 in). This diameter was used in all the calculations. Some of the useful parameters and data pertaining to the sand column experimental study are presented in Table 7.

A typical polymer injection procedure for the sand column experiment consisted of achieving a steady state flow rate using the flow regulated pump. Polymer solution was then injected by switching the "T-connector" to the polymer reservoir. After a predetermined volume of polymer solution had been injected, the "T-connector" was switched back to water reservoir, and the injection of fresh water continued.

As the polymer slug moved along the length of the sand column, hydraulic head readings were taken at known intervals of time, fluid samples were collected at the outlet end, the movement of polymer slug was observed visually, and the times recorded. At the end of each experimental run, several pore volumes of water were pumped through the sand column until the permeability was back to the original value.

Two sets of experiments were conducted using the sand column. The first set of experiments were of constant slug size (constant volume of polymer) with varying polymer concentration, and the second set was of constant concentration with varying slug size.

Table 7. Particulars of the Sand Column Apparatus.

Cross sectional area = 10.87 cm^2 (1.685 in^2)

Inner diameter = 3.72 cm (1.47 in) based on volume.

Outer diameter = 5.08 cm (2.0 in)

Inner radius = 1.86 cm (0.73 in) based on volume.

Volume of column (excluding volume of end caps, i.e. l=96.5 cm)
= 1049.0 ml

Porosity = 0.35 (Ottawa sand specific gravity = 2.65)

Pore volume = 367.0 ml

Distance between each port = 10.2 cm (4.0 in)

Distance between the two extreme end ports = 91.5 cm (36.0 in)

1 cm pore volume = 3.80 ml; or 10.0 ml = 2.63 cm thick slug.

1 in pore volume = 9.66 ml; or 10.0 ml = 1.04 in thick slug.

Radial Flow Wedge Experiments

The experimental study involved injection wells and withdrawal wells. Therefore, it is convenient to look at the flow using radial flow apparatus. Since it would be very difficult to build an experimental apparatus with large radius, efforts were made to simulate the radial flow by using only a small segment of the otherwise complete radial flow field. This small segment is referred to as the "Wedge Apparatus" (see Figure 6).

A typical polymer injection procedure can be described as follows. To start with, a steady state flow in the wedge apparatus was achieved by maintaining a constant head, both at the injection well and at the outlet end; the difference between these two free water surfaces being the driving force for the water and/or polymer movement. Hydraulic head readings were recorded at various ports located along the radial distance of the wedge apparatus from time to time. Then a certain known volume of polymer solution was injected through the injection well (by replacing the water with polymer solution). After the required amount of polymer had been injected, injection of fresh water was resumed.

As the polymer slug moved along the radial distance of the wedge apparatus, hydraulic head, visual movement of the polymer slug, concentration of the polymer solution, and distribution of the polymer slug (both vertical and radial) were monitored both in space and time. At the end of each experimental run, several pore volumes of water were allowed to flow through the wedge apparatus to clean out any traces of polymer that may have been left inside.

Two sets of experiments were conducted using the radial flow wedge apparatus. The first of these used a constant polymer slug size, i.e., a constant volume of polymer injection in each run, with varying polymer concentration, in the range of 0 ppm to 200 ppm. These experimental runs were conducted to give an understanding of the effect of polymer concentration and viscosity on polymer flow. The second set of experiments looked into the effect of polymer slug size (thickness) by varying the volume of the polymer injected while keeping the polymer concentration constant.

CHAPTER V

DATA AQUISITION AND MANAGEMENT

The data aquisition and data management were an integral part of the experimentation, primarily designed to record the pressure readings. The data aquisition and data management system consisted of (a) hardware parts such as pressure transducers and PCDAX interface, and (b) a menu driven software program developed specifically for the single ended pressure transducers to aquire the pressure data as well as to manage such data incorporating the many operational variables.

Pressure Measurement/Analog to Digital System

The pressure measurement/analog to digital system consisted of basically two parts; (1) the pressure transducers to measure the physical quantity pressure, and (2) the PCDAX Data Translation analog to digital output computer interface system. The particulars of these two systems as well as the connections required to connect the system to the computer are described in the foregoing paragraphs.

Pressure Transducers

Omega^R PX140 series pressure transducers marketed by Omega Engineering, Inc., were used as the pressure sensing devices. These transducers are solid state piezoresistive devices that convert the physical quantity pressure into a proportionate analog (voltage) output. Specifically, the guage type transducers used in this experimental study (Model # PX 142-005G 5V) had the capability to record pressure readings in the range of 0 to 5 psi, with a sensitivity of 1.0 volt/psi. A screw terminal style Omega power supply unit (Model # PST-8, 8 Volt, 300 mA) provided the power supply to all the pressure transducers through the three pin push connector terminals.

Analog to Digital Output System

The PCDAX analog to digital interface system supplied by Data Translation, Inc., provided multifunction data aquisition and control capabilities. The complete analog to digital input/output data aquisition system was made up of the following components:

(a) DT 311:PCDAX enclosure with interface to Digital's Rainbow 100 personal computer.
(b) LDT 2801 series analog to digital output board.
(c) DT 707 companion screw terminal panel.

The LDT 2801 series boards are high performance analog and digital input/output boards which are compatible with the Digital

Equipment Corporation's Rainbow 100 personal computers. The capabilities of LDT 2801 series analog to digital board include analog inputs with programmable gain and digital outputs for 16 single ended or 8 differential input/output channels. A schematic representation of the pressure measurement analog to digital conversion data system is shown in Figure 10.

The LDT 2801 series board was connected to the Rainbow 100 personal computer input/output bus by means of a DT 311 backplane board through a 25 pin D-Shell connector (J2) and 9 pin D-Shell connector (J4). The DT 707 screw terminal panel provided the connection between the pressure transducers and the analog to digital conversion system. The screw terminal panel was connected to the LDT 2801 series board through a 50 pin ribbon cable connector (J1). The DT 707 consists of circuit board with barrier screw terminals, and an integral cable assembly and connector.

Overall Experimental System

The overall experimental system consisted of connecting the main experimental apparatus, i.e., sand column or wedge apparatus, to the various other systems like pressure sensing transducers, analog to digital data aquisition system, and other necessary experimental systems. A schematic representation of the overall experimental setup with particular reference to the pressure measurement as well as the

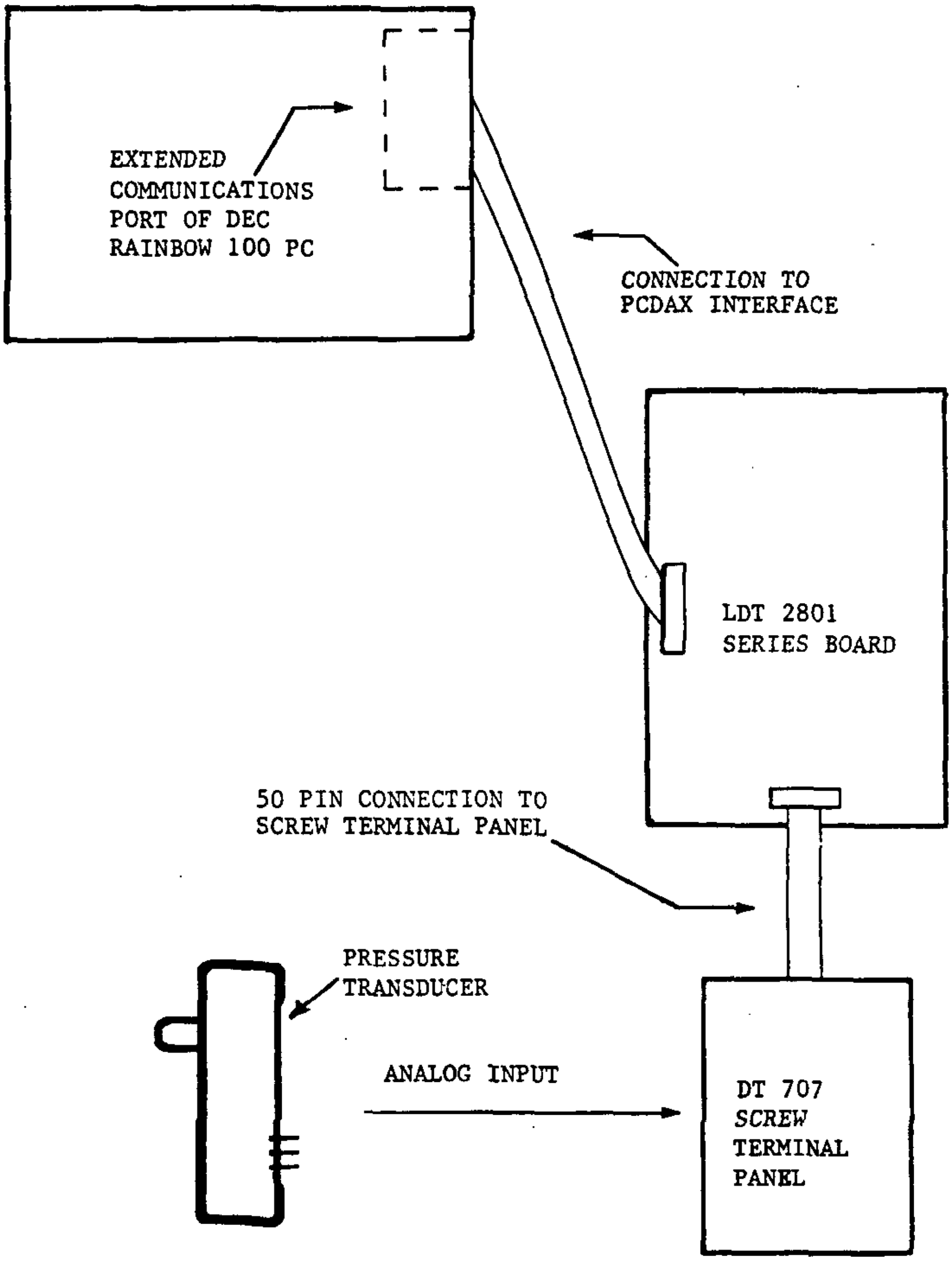


Figure 10. Schematic Representation of the Pressure Measurement/ Analog to Digital System.

data aquisition system is shown in Figure 11. A detail description of the working of the system is described below.

The intake of the flow-regulated pump is separately connected to two different reservoirs containing distilled water and polymer solution, via a "T-connector." With the help of this regulated "T-connector," only polymer solution or only water can be pumped into the experimental apparatus. The pressure taps of the apparatus (sand column or wedge) are connected to the pressure transducers via pressure tight plastic tubing. The pressure transducers obtain the required power from the power supply unit via the connectors.

The pressure transducers accept the physical quantity pressure as input and convert it into a proportionate analog (voltage) output. The analog output is then transmitted to the Analog to digital conversion board via the Screw terminal panel. The Analog to digital board converts the analog input to digital output, in conjunction with the Interface board. This final digital output is transmitted to the host computer (Digital Rainbow 100) for display and data storage.

As the liquid exits at the outlet end of the experimental apparatus, fixed volumes of samples were collected at known intervels of time. The samples were then analysed for polymer concentration.

Data Aquisition/Data Management

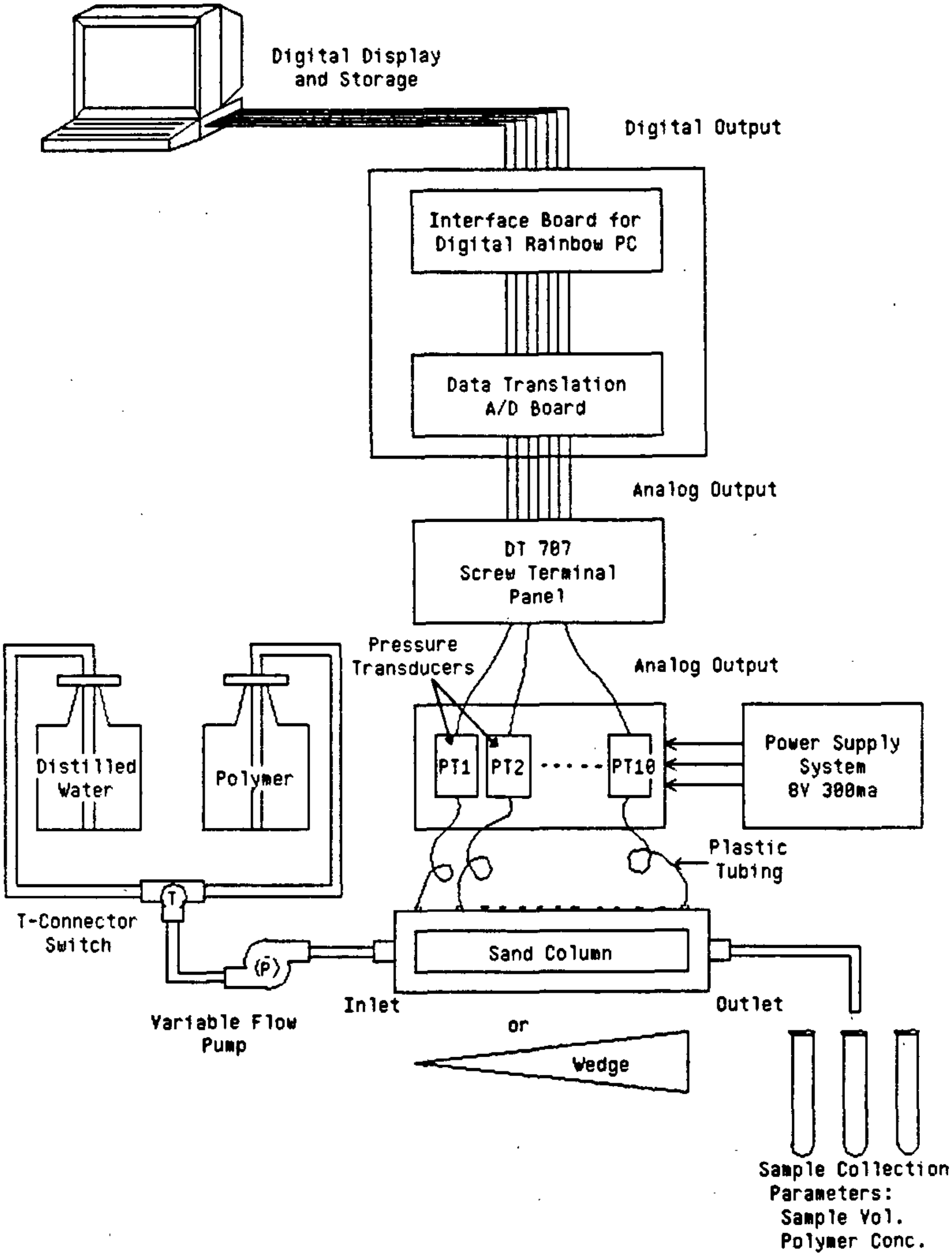


Figure 11. Schematic Representation of the Overall Experimental Setup and Data Aquisition System.

The data aquisition and data management involved the development of the menu-driven software programs written in MBASIC (Microsoft Basic) language. The LDT 2801 series board is controlled by various commands using the command language supplied by the Data Translation, Inc. These commands specify the board operation, and cause the board to perform a variety of functions. Extensive menu-driven programs were developed to take into consideration the various operational variables. The overall schematic representation of the working of the data aquisition and management system is presented in Figure 12. The complete MBASIC program developed for the data aquisition, as well as the other data management programs can be found in the Appendix.

The data aquisition and management software system consisted of the Main Menu with four options: (1) Test, (2) Reset, (3) A/D Conversion, and (4) Print Data File. Selecting the "(1) Test" option performs testing of the Data Translation board and returns to the Main Menu. Selection of "(2) Reset" option resets the system (and clears any of the previous settings) and returns to the Main Menu. Selection of "(3) A/D Conversion" displays the Sub-Menu of A/D Conversion with three Sub-Menu options: (1) Single Conversion, (2) Multiple Conversions, and (3) Calibration Conversion. Under each of these options, the user will be prompted for the selection of gain, channels, clock frequency or period, number of conversions, etc., and the data would be recorded according to the specific selections made. After recording the data, the control is returned to the Operation

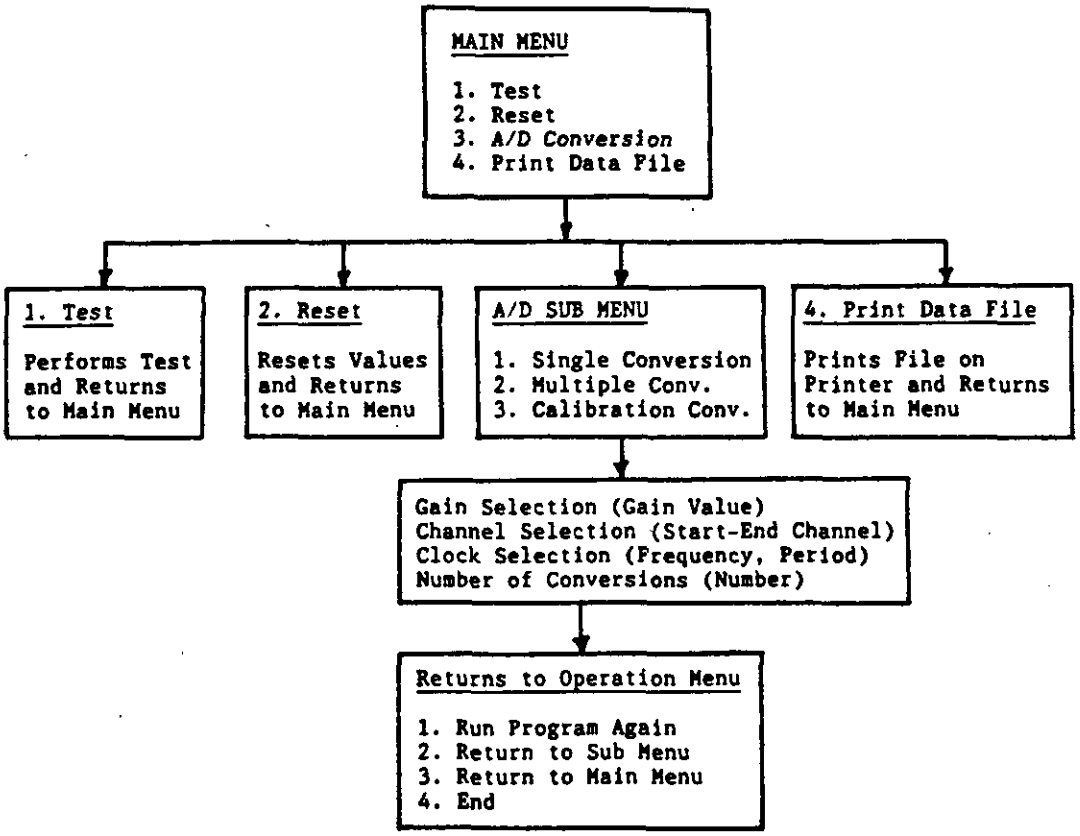


Figure 12. Schematic Representation of the Working of Data Aquisition and Data Management System.

Menu. The Operation Menu has the following options of going back to repeat the same operation again, or transfer the control to A/D Sub-Menu, or Main Menu, or to end the data aquisition and exit the program. Finally, selection of "(4) Print Data File" option prompts for the name of the data file to be printed, prints the data file on the attached printer, and returns the control to the Operation Menu.

Transducer/Channel Calibration

All the (ten) Omega guage pressure transducers were calibrated for their respective analog (voltage) output against known free water surface elevations using a long column of water. The calibration data for the transducers is presented in Table 8. Separate calibration equations that would give the hydraulic head in terms of inches of water were developed for each pressure transducer. The linear regression equations thus developed were of the form "ax + b", with the slope "a" and intercept "b". A summary of the linear regression coefficients for the calibration equations are presented in Table 9.

A typical calibration curve for pressure transducer # 5 is shown in Figure 13. The corresponding calibration equation is;

$$e_t = 1.0 + (3.3214 \times 10^{-2}) (h) \qquad \text{(Eq. 5.1)}$$

where; e_t = output from the pressure transducer, volt

Table 8. Transducer Output/Channel Calibration Experimental Data Using Sand Column Apparatus (Output Values at Gain = 2.0)

Head	Volt Output From Transducer/Channel#									
inch	0	1	2	3	4	5	6	7	8	9
0	0.98633	1.04126	1.01196	1.00464	1.00586	1.00220	0.99731	1.00952	1.00586	0.98511
0	0.98389	1.04126	1.01440	1.00586	1.00586	1.00464	0.99976	1.00952	1.00586	1.00342
10	1.34644	1.39282	1.36963	1.39771	1.38428	1.36108	1.34643	1.38428	1.38184	1.36353
20	1.69312	1.75171	1.71021	1.79077	1.75415	1.69556	1.65894	1.73950	1.71753	1.68945
30	2.01782	2.09839	2.04102	2.16797	2.11914	2.02148	1.98364	2.09351	2.05933	2.02148
40	2.34009	2.41577	2.37671	2.48535	2.48535	2.34741	2.31445	2.43164	2.39624	2.34375
50	2.66724	2.74536	2.71240	2.83447	2.84668	2.67212	2.66235	2.76367	2.74292	2.67700
60	2.99927	3.07495	3.05298	3.17505	3.19946	2.99683	3.01758	3.09204	3.08594	3.00049
70	3.33496	3.40332	3.38989	3.51196	3.54858	3.32520	3.37524	3.41797	3.43018	3.32764
0	0.98389	1.04370	1.01318	1.00586	1.00464	0.99976	0.99854	1.01074	1.00708	1.00586

Table 9. Linear Regression Coefficients for the Transducer/Channel Calibration Equations using Sand Column Apparatus.

Channel #	Slope	Intercept
0	29.83690	-29.73350
1	29.55420	-31.12370
2	29.47690	-30.03710
3	27.74920	-28.54180
4	27.40230	-27.76460
5	30.13610	-30.53320
6	29.70620	-29.48550
7	28.89700	-29.64640
8	28.92270	-29.35180
9	30.04230	-30.32520

The linear regression equations are of the form "$y = ax + b$" with "a" the slope and "b" the intercept. In terms of pressure and volt output, the equations can be written as,

$$\text{Pressure(inch } H_2O) = (\text{Slope})\ (\text{Volt Output}) - \text{Intercept}$$

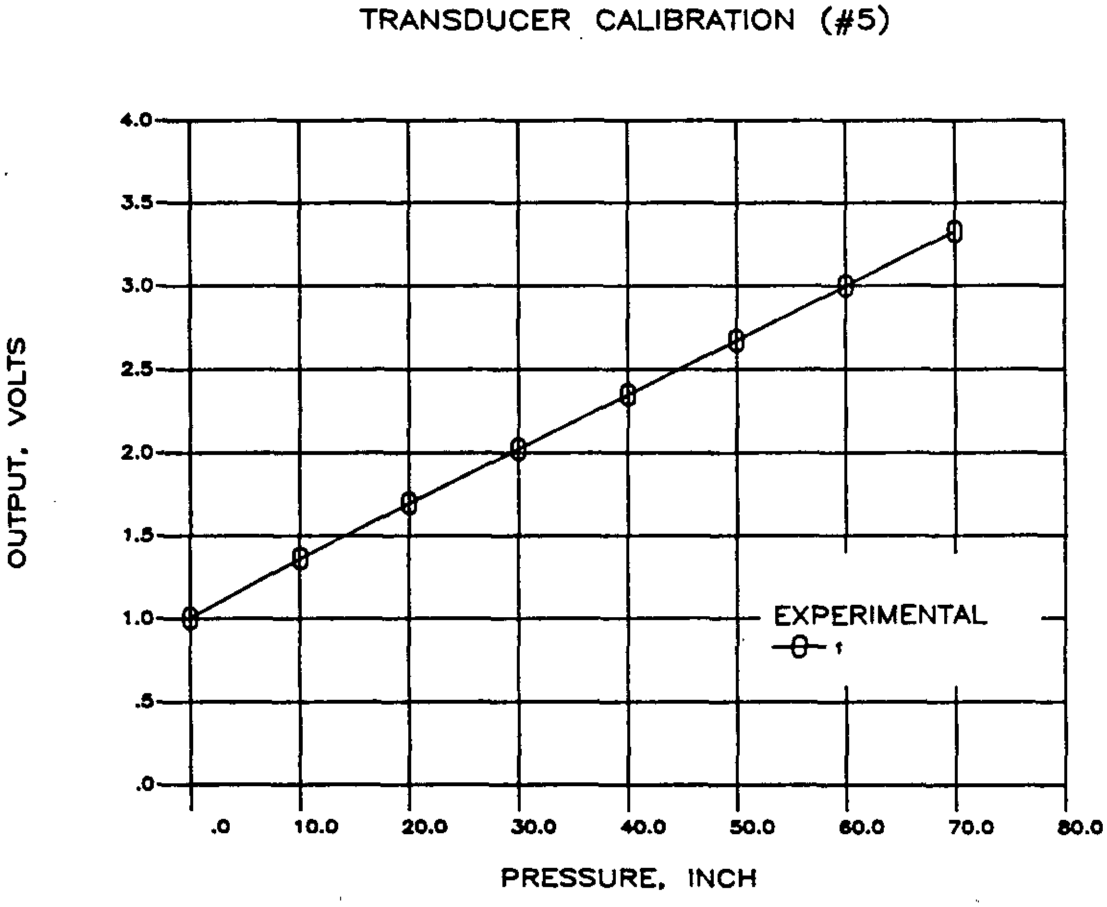


Figure 13. Typical Calibration Curve for Pressure Transducer #5; $e_t = 1.0 + (3.3214 \times 10^{-2})\ (h)$.

h = pressure (free water surface elevation), inches of water, L

At zero free water surface elevation, the transducer output corresponds to one volt. This output is commonly referred as "null" output. The sensitivity of the transducers was close to 1.0 volt/psi as claimed by Omega Engineering, Inc.

CHAPTER VI

MATHEMATICAL MODEL

The main emphasis of this research study was experimental oriented, and thus to obtain experimental data that would give an understanding of the flow of polymer solutions in porous media, and the possibility of using polymers in grounmdwater cleanup operations. Therefore, simple mathematical formulations were developed and easy to use analytical solutions were derived for the polymer flow through porous media.

The basic approach used in developing the mathematical model and deriving the analytical solution to predict the movement of the polymer slug through the porous media is presented in this section. Various assumptions were made to make the analytical model simple and easy to use. The governing equations were derived based on the principles of conservation of mass and conservation of momentum. The analytical models were tested and calibrated using the data obtained in the experimental studies, and then the model was used to predict the polymer movement in the porous media.

Hydraulic Model

Assumptions

Some of the basic assumptions used in formulating the mathematical model and deriving the analytical solution for polymer flow in one dimensional horizontal flow are presented below.

- The porous media is homogeneous (in permeability and porosity) and isotropic.
- The flow is saturated and at steady state.
- Vertical flow component is negligible.
- Darcy's law applies, with linear head loss across the polymer slug in the porous media.
- The density of polymer is same as that of water.

Model Development

A schematic representation of the linear flow modeling system and the various parameters used in developing the mathematical model are illustrated in Figure 14. The illustrated system represents the sand column apparatus that was used in most of the experimental studies.

Conservation of mass for the general one dimensional horizontal flow with a volumetric flow rate, Q, through a cross sectional area, A, and specific discharge, V, can be written as;

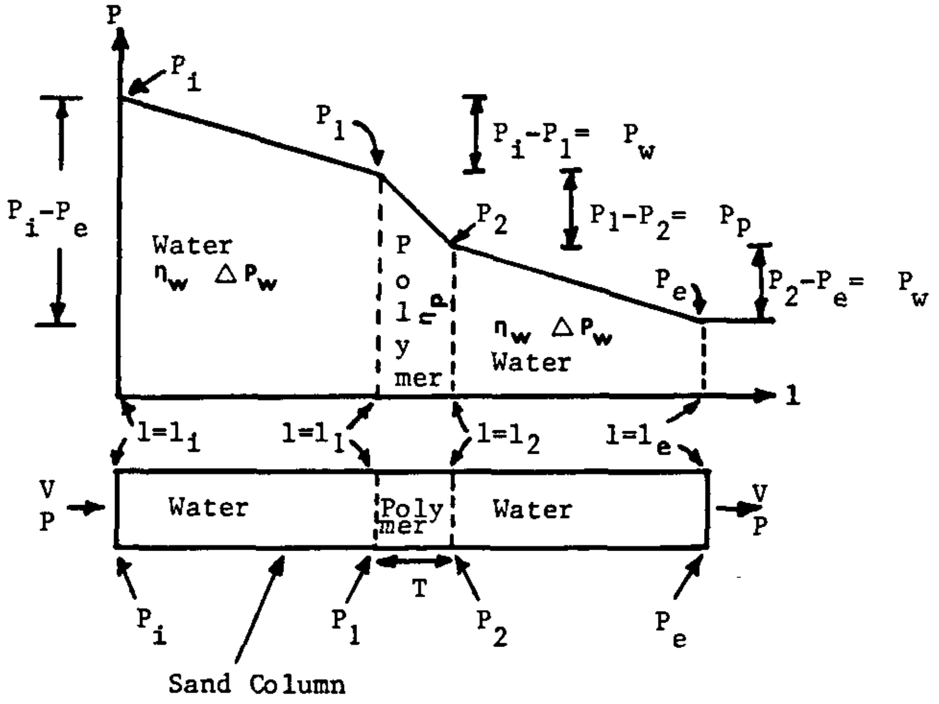


Figure 14. Schematic Representation of Linear Flow Modeling System.

$$Q = A \, . \, V = \text{Constant} \qquad \text{(Eq. 6.1)}$$

$$\text{or,} \quad V = \frac{Q}{A} \qquad \text{(Eq. 6.2)}$$

Conservation of momentum yields the well known Darcy's equation for horizontal flow;

$$V = - \frac{kg}{\upsilon} \frac{dh}{dl} \qquad \text{(Eq. 6.3)}$$

where; k = permeability of porous media, L^2

g = gravitational acceleration, L/T^2

υ = kinematic viscosity, L^2/T

h = hydraulic head, L

l = distance in the direction of flow, L

The above equation can be written in terms of pressure, p, as follows;

$$V = - \frac{k}{\eta} \frac{dp}{dl} \qquad \text{(Eq. 6.4)}$$

where; η = dyanamic viscosity, M/LT

Combining conservation of mass (Eq. 6.2) and conservation of momentum (Darcy's equation, Eq. 6.4);

$$\frac{Q}{A} = - \frac{k}{\eta} \frac{dp}{dl} \qquad \text{(Eq. 6.5)}$$

Separating the variables, the above equation can be rewritten as;

$$\frac{Q}{A} \cdot \frac{\eta}{k} \cdot \int dl = - \int dp \qquad \text{(Eq. 6.6)}$$

Equation 6.6 is the general form of horizontal flow equation for the sand column and can be integrated using the appropriate boundary conditions to give the pressure loss equations applicable to the respective (water and polymer) portions of the linear flow sand column apparatus.

For the inner (water) portion with viscosity of water, η_w, Eq. 6.6 can be written using the appropriate boundary conditions;

$$\frac{Q}{A} \frac{\eta_w}{k} \int_{l_i}^{l_1} dl' = - \int_{P_i}^{P_1} dp' \qquad \text{(Eq. 6.7)}$$

where; l_i = linear distance upto first pressure tap, L

l_1 = linear distance upto the interface separating the inner portion and polymer, L

P_i = pressure at length l_i, M/LT^2

P_1 = pressure at length l_1, M/LT^2

Integration of the above equation yields the following equation for the inner water portion;

$$\frac{Q}{A}\frac{\eta_w}{k}\,(l_1 - l_i) = P_i - P_1 \qquad \text{(Eq. 6.8)}$$

For polymer portion, with viscosity of polymer solution, η_p, Equation 6.6 becomes;

$$\frac{Q}{A}\frac{\eta_p}{k}\int_{l_1}^{l_2} dl' = -\int_{P_1}^{P_2} dp' \qquad \text{(Eq. 6.9)}$$

where; l_2 = linear distance upto the interface separating the polymer and outer portion, L

P_2 = pressure at length l_2, M/LT^2

and the solution to Equation 6.9 gives the pressure equation for the polymer portion;

$$\frac{Q}{A}\frac{\eta_p}{k}\,(l_2 - l_1) = P_1 - P_2 \qquad \text{(Eq. 6.10)}$$

Corresponding equation (Eq. 6.6) for the outer portion with water can be written as;

$$\frac{Q}{A}\frac{\eta_w}{k}\int_{l_2}^{l_e} dl' = -\int_{P_2}^{P_e} dp' \qquad \text{(Eq. 6.11)}$$

where; l_e = linear distance upto the last pressure tap, L

P_e = pressure at length l_e, M/LT^2

and integration of the above equation yields;

$$\frac{Q}{A}\frac{\eta_w}{k}\ (l_e - l_2) = P_2 - P_1 \qquad \text{(Eq. 6.12)}$$

Thus we have Equations 6.8, 6.10 and 6.12 respectively describing the pressure relationships in the inner (water) portion, polymer portion, and outer (water) portion of the sand column apparatus.

These three equations can be further simplified to give the total pressure change ($P_i - P_e$) in the sand column system. The two equations representing the inner portion (Eq. 6.8) and outer portion (Eq. 6.12) can be combined to get an expression for ($P_1 - P_2$) as follows;

$$(P_2 - P_1) + (P_i - P_e) = \frac{Q}{A} \cdot \frac{\eta_w}{k}\ [(l_1 - l_i) + (l_e - l_2)] \qquad \text{(Eq. 6.13)}$$

Rewriting the above equation in terms of $P_1 - P_2$ yields the relationship describing the pressure in the water portion;

$$P_1 - P_2 = (P_i - P_e) - \frac{Q}{A} \cdot \frac{\eta_w}{k}\ [(l_1 - l_i) + (l_e - l_2)] \qquad \text{(Eq. 6.14)}$$

Substituting Eq. 6.14 for $P_1 - P_2$ in Eq. 6.10;

$$\frac{Q}{A}\frac{\eta_p}{k}\ (l_2 - l_1) = (P_i - P_e) - \frac{Q}{A} \cdot \frac{\eta_w}{k}\ [(l_1 - l_i) + (l_e - l_2)]$$

(Eq. 6.15)

Rearranging the terms, the final expression for the total pressure in the system $(P_i - P_e)$ can be obtained as follows;

$$P_i - P_e = \frac{Q}{A.k}\left[\eta_p\ (l_2 - l_1) + \eta_w\ \{(l_1 - l_i) + (l_e - l_2)\}\right] \quad \text{(Eq. 6.16)}$$

The above equation can be rewritten for the Darcy velocity (specific discharge);

$$\frac{Q}{A} = V = \frac{(P_i - P_e)\ k}{\eta_p\ (l_2 - l_1) + \eta_w\ \{(l_1 - l_i) + (l_e - l_2)\}} \qquad \text{(Eq. 6.17)}$$

Polymer Transport Model

This section presents the development of polymer transport model that incorporates the advective transport, dispersive transport, and a "pseudo-adsorptive" retardation factor. While the batch equilibrium adsorption experimental studies clearly demonstrated that the adsorption of polymer was negligible, the polymer concentration peaks in the sand column experiments showed a "retardation" effect. Therefore, the effect of retardation factor, R_d, has been incorporated in the modeling of polymer transport.

Assumptions

The basic assumptions used in the formulation of the one dimensional horizontal flow hydraulic model remain valid for the polymer transport model. Under the Darcy assumption, the flow is described by the average linear velocity, V/n, which carries the dissolved substances by advection.

Model Development

Conservation of the flow of a non-reactive constituent with the mass balance of storage, advection, dispersion and "pseudo-adsorptive" retardation gives the following differential equation;

$$\frac{\partial C}{\partial t} + \frac{V}{nR_d}\cdot\frac{\partial C}{\partial x} - \frac{\alpha_l V}{nR_d}\cdot\frac{\partial^2 C}{\partial x^2} = 0 \qquad \text{(Eq. 6.18)}$$

where;

C = concentration of polymer solution, M/L^3

V = Darcy velocity $\equiv$ specific discharge = $\frac{Q}{A}$, L/T

x = length of sand column, L

n = porosity

R_d = retardation factor

t = time, T

α_l = longitudinal dispersivity ($\alpha_l = \frac{D}{V}$), L

The retardation, R_d, in the above equation simply retards the effectiveness of advective transport and dispersive transport by a constant factor. It is required that the retardation factor be a constant for a given experiment.

A schematic representation of the influent polymer concentration and the appropriate boundary conditions are presented in Figure 15. A constant strength polymer solution of $C = C_o$ is injected at $t = 0$, and continued upto $t = t_p$ (i.e. $C = 0$ for $t \geq t_p$). Once the polymer injection is completed, water injection is resumed.

Ogata and Banks (1961) presented the analytical solution to Equation 6.18 for a continuous influent concentration of C_o (see below, Case 1 for $t < t_p$). The influent polymer concentration

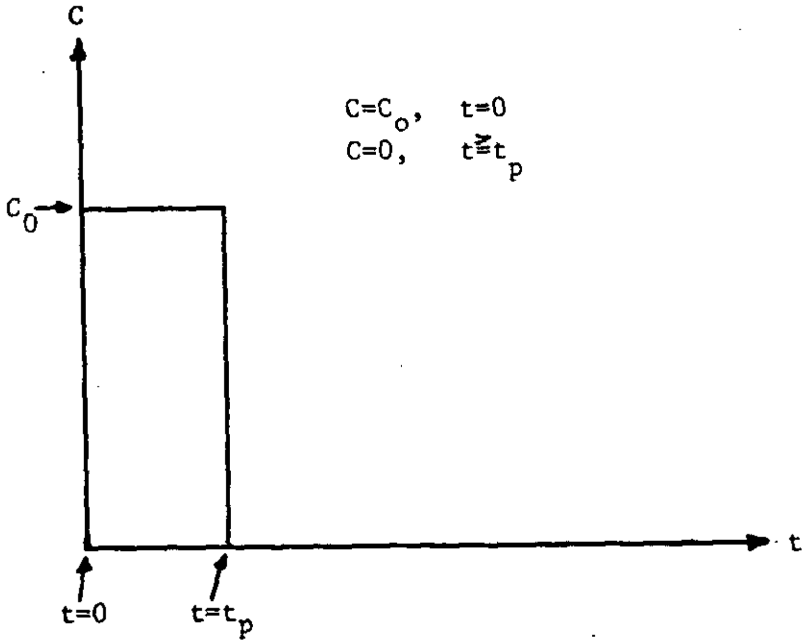


Figure 15. Schematic Representation of Polymer Injection for the Polymer Concentration Model.

described in Figure 15 can be viewed as a problem in which a continuous source of C_o is applied at $t = 0$ plus another continuous source of $-C_o$ is applied at $t = t_p$. Therefore, the principle of superposition (or time shift) can be used to determine the polymer concentration anywhere in the column (see below, Case 2 for $t > t_p$). The analytical solution thus developed is presented below.

Case 1: For $t < t_p$

$$\frac{C}{C_0} = \frac{1}{2}\left[\operatorname{erfc}\left\{\frac{x - \frac{Vt}{n\,R_d}}{2\left[\alpha_1\,\frac{Vt}{n\,R_d}\right]^{0.5}}\right\} + \exp\left(\frac{x}{\alpha_1}\right)\operatorname{erfc}\left\{\frac{x + \frac{Vt}{n\,R_d}}{2\left[\alpha_1\,\frac{Vt}{n\,R_d}\right]^{0.5}}\right\}\right]$$

(Eq. 6.19)

Case 2: For $t > t_p$

$$\frac{C}{C_0} = \frac{1}{2}\left[\operatorname{erfc}\left\{\frac{x - \frac{Vt}{n\,R_d}}{2\left[\alpha_1\,\frac{Vt}{n\,R_d}\right]^{0.5}}\right\} + \exp\left(\frac{x}{\alpha_1}\right)\operatorname{erfc}\left\{\frac{x + \frac{Vt}{n\,R_d}}{2\left[\alpha_1\,\frac{Vt}{n\,R_d}\right]^{0.5}}\right\}\right]$$

$$- \frac{1}{2}\left[\operatorname{erfc}\left\{\frac{x - \frac{V(t-t_p)}{n\,R_d}}{2\left[\alpha_1\,\frac{V(t-t_p)}{n\,R_d}\right]^{0.5}}\right\}\right]$$

$$+ \exp\left(\frac{x}{\alpha_1}\right) \quad \mathrm{erfc}\left\{\frac{x + \frac{V(t-t_p)}{n\ R_d}}{2\left[\alpha_1 \frac{V(t-t_p)}{n\ R_d}\right]^{0.5}}\right\} \Bigg] \qquad \text{(Eq. 6.20)}$$

where;

C_o = influent polymer concentration, $\frac{M}{L^3}$

t_p = time polymer injection completed, T

erfc = complementary error function

CHAPTER VII

RESULTS AND DISCUSSION

Characterization of Dowell J333 Polymer

This section describes the physical and chemical characteristics of the Dowell J333 polyacrylamide polymer, and their relation to this research study. The development of absorbance versus polymer concentration relationship as a preliminary step to the development of polymer viscosity relationship is also discussed in the foregoing paragraphs.

Characteristics of Polymer

The physical and chemical characteristics of Dowell J333 polyacrylamide polymer are summarized in Table 10. The J333 polymer was a white granular polymer with an average molecular weight of about 7 million. Polyacrylamide polymers of this molecular weight are generally considered to be high molecular weight polymers. They are anionic polymers and are rapidly soluble in water. The anionic nature of these polmers is believed to provide better sweep efficiency in the porous media. The density of the free flowing white granular polymer was about 737 kg/m^3 (46 lb/ft^3).

Table 10. Physical and Chemical Characteristics of Dowell J333 Polyacrylamide Polymers.

Physical Form	White, granular
Ionic Character	Anionic
Molecular Weight	High ($\approx 7 \times 10^6$)
Density	737 kg/m^3
	46 lb/ft^3
Solubility in water	Rapid
Molecular Formula	$-(CH_2-CH-CONH_2)_{\overline{n}}$

Absorbance versus Polymer Concentration

The first step in the development of a polymer concentration viscosity relationship was to develop a standard curve for Absorbance versus Polymer concentration. Details of the analytical method are described by Foshee et al., (1976). Presented herein is the discussion of a typical polymer concentration standard curve.

Absorbance data of Batch 5 polymer solutions ranging from 0 ppm to 500 ppm concentrations is summarized in Table 11. A typical standard curve for Absorbance versus Polymer Concentration is shown in Figure 17. Absorbance data and standard curve plots for other batches of polymer solutions can be found in Appendix. Linear Regression analysis was used to best fit the experimental data. A typical linear regression equation developed specifically for Batch 5 polymer solution can be written as;

$$C = (768.64)\ (Ab) \qquad \text{(Eq. 7.1)}$$

where; C = polymer concentration, ppm

Ab = absorbance at 470 nm

As can be seen from Figure 17, the experimental data and the polymer concentration values predicted by the equation are in close agreement with each other. The graphs presented in the Appendix would

Table 11. Absorbance Data for Polymer Concentration Analysis (Batch 5).

Polymer Concentration ppm	Absorbance[1]
0.0	0.0
0.0	0.0
100.0	0.106
100.0	0.107
200.0	0.232
200.0	0.232
300.0	0.380
300.0	0.381
400.0	0.534
400.0	0.534
500.0	0.661
500.0	0.662

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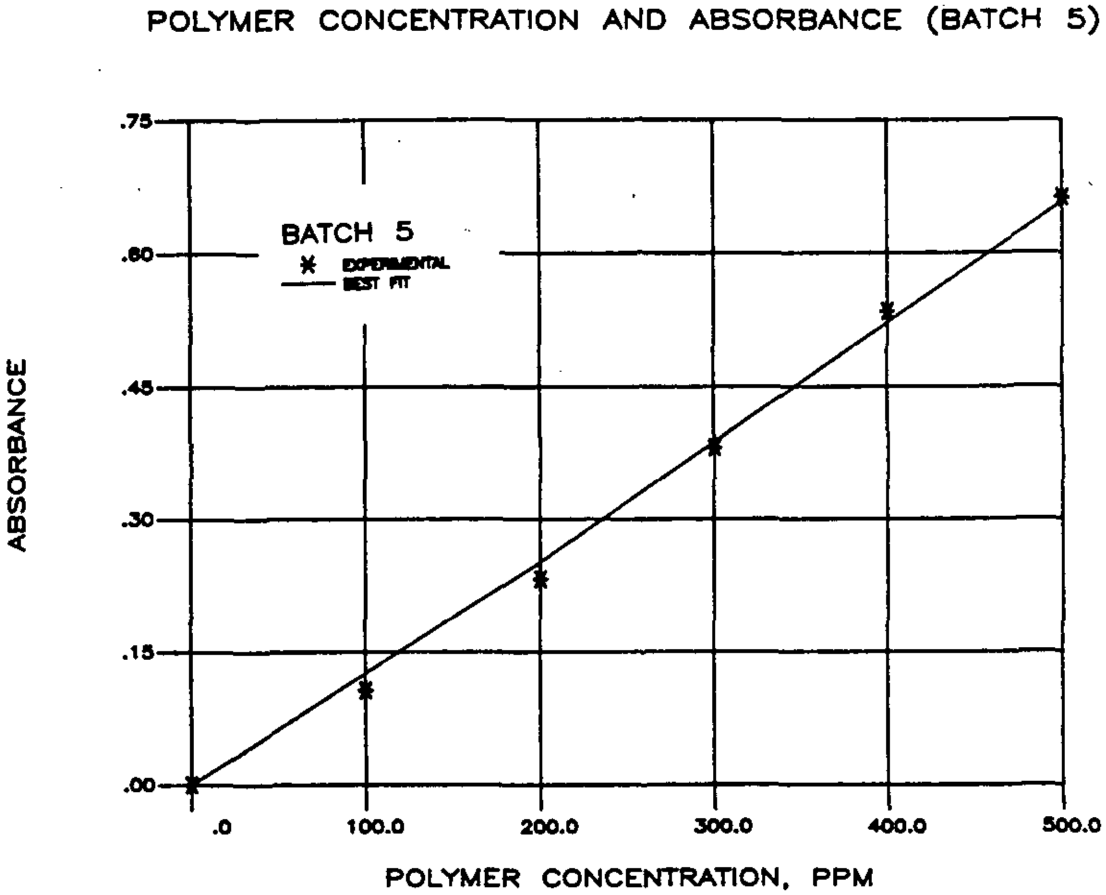
[1] Absorbance at 470 nm measured on Perkin-Elmer UV/VIS Spectrophotometer, Lambda-3B



POLYMER CONCENTRATION AND ABSORBANCE (BATCH 5)

Figure 17. Standard Curve for Polymer Concentration (Batch 5) Absorbance at 470 nm; C = (768.64) (Ab).

also lead to the same conclusion of an excellent agreement with the experimental data.

Characterization of Ottawa Silica Sand

Presented in this section are the physical characteristics of the Ottawa silica sand, followed by a discussion of the results obtained in the grain-size distribution analysis experiments.

Physical Characteristics

The physical characteristics of Ottawa silica sand are presented in Table 12. The sand was basically a clean flint shot sand, white in color with spherical grain particles. The specific gravity of the sand was 2.65 with a Hardness of 7.0 (Moh's scale). Even from the visual observations, the sand appeared to be uniform. The porosity of the sand determined from the experiments was found to be 0.35.

Grain-Size Distribution

Experimental data obtained for the sieve analysis of the Ottawa sand, including the cumulative percent retained on each sieve is summarized in Table 13. The cumulative percent retained on each test sieve is plotted against the sieve opening (or grain size), and the curve thus obtained is known as Grain-Size-Distribution curve. The

Table 12. Physical Properties of Ottawa Silica Sand.

Appearance	White, Granular
Grain shape	Rounded
Mode millimeter size	0.371 to 0.346
Specific Gravity	2.65
Hardness (Moh's scale)	7.0
Sand Type	Flint shot sand
Porosity	0.35

Table 13. Experimental Data of Sieve Analysis of Ottawa Sand.

SIEVE ANALYSIS

Date Jan 22' 87

Project Ottawa Sand Sieve Analysis (Washed and Dried)

Boring No. ____ Sample No. OS-1

Total wt in grams of sample, W_s = 366.1 | Wt in grams of material > No. 4 sieve =

Sieve Openings		U. S. Standard Sieve Size or Number	Weight Retained in grams	Percent Retained		Percent Finer by Weight
Inches	Millimeters			Partial	Total	
0.132	3.36	No. 6				
0.094	2.38	No. 8				
0.079	2.00	No. 10				
0.047	1.19	No. 16	0.0	0.0	0.0	100.0
0.033	0.84	No. 20	10.1	2.76	2.76	97.24
0.023	0.59	No. 30	24.3	6.64	9.40	90.60
0.0165	0.42	No. 40	262.9	71.81	81.21	18.79
0.0117	0.297	No. 50	55.2	15.08	96.29	3.72
0.0083	0.210	No. 70				
0.0059	0.149	No. 100				
0.0041	0.105	No. 140				
0.0029	0.074	No. 200				
		Pan	13.6	3.71	100.00	0.0
Total weight in grams						

$$\text{Partial percent retained} = \frac{\text{wt in grams retained on a sieve}}{\text{wt in grams of sample used for a given series of sieves}} \times 100$$

$$\text{Total percent retained} = \frac{\text{wt in grams retained on a sieve}}{\text{total wt in grams of oven-dry sample}} \times 100$$

For an individual sieve, the percent finer by weight = percent finer than next larger sieve - percent retained on individual sieve

Remarks The sand was washed in distilled water several times to remove any fine material it might have.

Technician ____ Computed by ____ Checked by ____ grain-size distribution of Ottawa sand is illustrated in Figure 18. This is a classic grain-size distribution curve for medium sand. The grain-size distribution curve shows at a glance how much of the sample material is smaller or larger than a given particle size. There are basically three elements essential to a complete description of this grain-size distribution curve: (1) particle size (fineness or coarseness); (2) slope of the curve; and (3) shape of the curve. Any of these elements can change independently of others.

The particle size of the Ottawa sand ranged from 0.2 mm to 1.0 mm (0.008 to 0.040 inch). Often, a specific point on a grain-size distribution curve is used as a general index of fineness. The term "Effective Size" defined as the particle size where 10 percent of the sand is finer and 90 percent is coarser, is one such often used index. The effective size of the Ottawa sand was found to be 0.360 mm (0.0142 inch). Another index of fineness is the 50 percent size, which is also referred to as the mean particle size or the average particle size. The mean particle size is a good index especially when the grain-size distribution is in a narrow range. The mean particle size of the Ottawa sand was 0.408 mm (0.0192 inch). And finally, the slope of a major portion of the grain-size distribution curve can be best described by a term called "Uniformity Coefficient" (UC).

$$U_c = \frac{\text{40-percent retained size}}{\text{90-percent retained size}} \quad \text{(Eq. 7.2)}$$

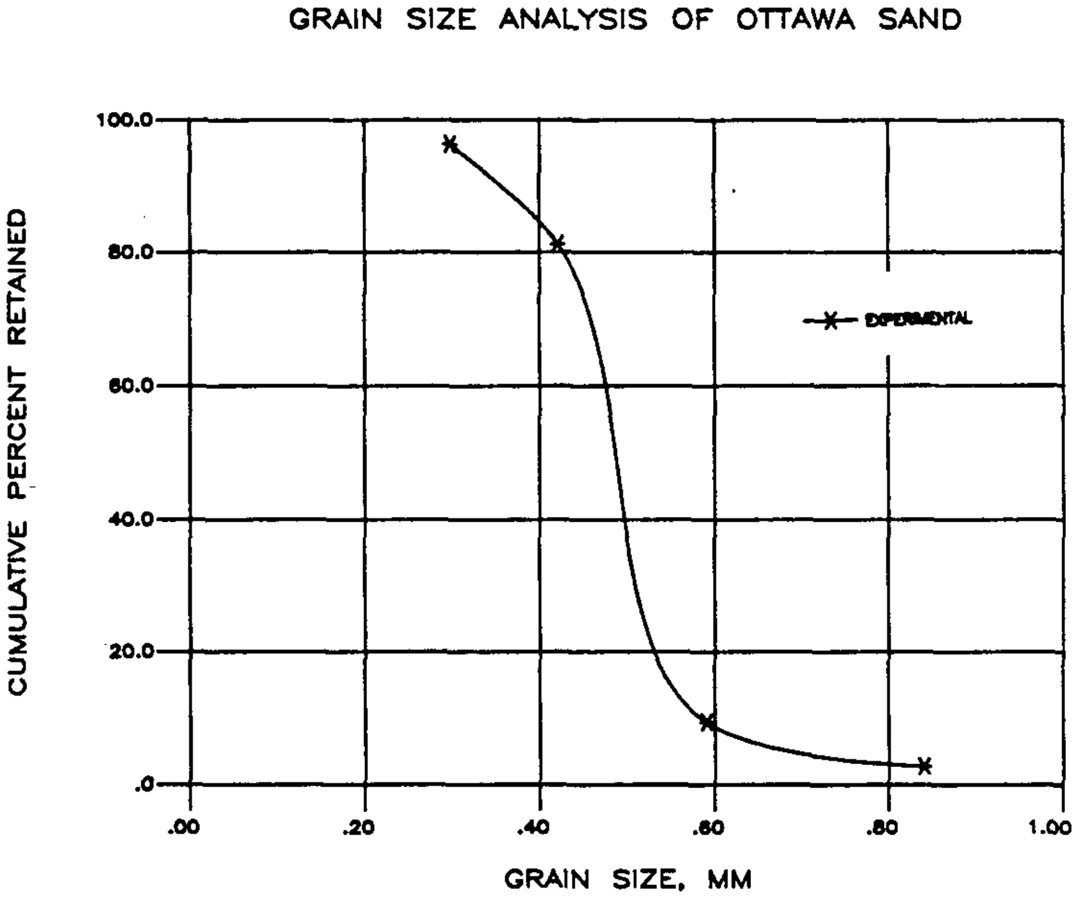


Figure 18. Grain-Size Distribution Curve for Ottawa Sand.

The closer the value of Uniformity Coefficient to unity, the more uniform is the grading of the sample between these limits. The uniformity coefficient of the Ottawa sand used in the experimental study was found to be 1.389. Therefore, this Ottawa sand can be considered to be a uniformly graded sample. It should be noted that the uniformity coefficient is limited in practical applications to materials that are rather uniformly graded, and therefore serves as a meaningful parameter only when its value is less than 5.

It is also quite clear from the grain-size distribution curve that the grain size of more than 75 percent of the Ottawa sand is between 0.40 mm and 0.60 mm.

Polymer Concentration and Viscosity

Batch Viscosity Relationships

Experimental data of polymer concentration and viscosity for five batches of polymer solutions is summarized in Table 14. Duplicate samples were analyzed for viscosity for the first two batches. Since the duplicate sample viscosity values were not significantly different, only one sample per analysis was used in the later experiments. Experimental data for each individual batch of polymer solutions can be found in Appendix.

Table 14. Polymer Concentration and Viscosity Experimental Data (Batch 1-5).

Polymer Concentration, ppm	Viscosity, cp
100.0	35.0
100.0	33.0
200.0	65.0
200.0	63.0
300.0	91.0
300.0	94.0
400.0	125.0
400.0	127.0
500.0	160.0
500.0	158.0
100.0	41.0
100.0	40.0
200.0	70.0
200.0	72.0
300.0	104.0
300.0	104.0
400.0	141.0
400.0	140.0
500.0	179.0
500.0	181.0
100.0	40.0
200.0	71.0
300.0	103.0
400.0	140.0
500.0	180.0
100.0	45.0
200.0	75.0
300.0	105.0
400.0	143.0
500.0	180.0
100.0	43.0
200.0	74.0
300.0	105.0
400.0	141.0
500.0	178.0

Viscosity relationships were developed independently for each batch of polymer solution using Linear Regression analysis. The regression coefficients as well as the related statistical parameters for each individual batch of polymer solutions are presented in Table 15, and the graphical illustration of the respective equations can be found in Appendix. In general, the viscosity data obtained was consistent, and yielded excellent polymer concentration-viscosity relationships. The viscosity was found to vary linearly with the polymer concentration, within the range of 0 ppm to 500 ppm concentrations investigated in this research study. The individual viscosity equations thus developed for each batch of polymer solutions were able to predict the viscosities that agreed very well with the experimental viscosity data. This is evident from the respective viscosity graphs as well as their "R-squared" regression coefficient statistical parameters presented in Table 15.

An analysis of the regression coefficients (see Table 15) as well as the polymer concentration versus viscosity graphs (see Appendix) clearly demonstrates that the viscosity of Batch 1 polymer solution was slightly lower compared to the viscosity of other batches of polymer solutions. This shows that the viscosities of the same polymer prepared at different times could vary slightly.

Overall Viscosity Relationship

Table 15. Linear Regression Analysis of the Polymer Concentration and Viscosity Data (for Graphs).

	Slope	F-Value	Sig. Level	R^2	Std.Dev. Regr.
Batch 1	0.3134	28630	0.0001	0.9997	1.9594
Batch 2	0.3530	16460	0.0001	0.9995	2.9078
Batch 3	0.3542	7921	0.0001	0.9995	2.9741
Batch 4	0.3544	3066	0.0001	0.9987	4.7835
Batch 5	0.3536	5014	0.0001	0.9992	3.7325
All Five	0.3423	9795	0.0001	0.9965	6.8404

Note: Forced intercept for all Batches is 1.0 (i.e., at 0.0 ppm, the viscosity is 1.0 cp).

An overall relationship was developed for polymer concentration versus viscosity using the data obtained from five batches of viscosity experiments. The overall polymer concentration versus viscosity relationship is illustrated in Figure 19. Once again, the overall concentration-viscosity relationship was found to vary linearly with the polymer concentration. At 200 ppm polymer concentration, the viscosity was found to be about 70.0 cp, and at 500 ppm it was about 172.0 cp. It should however be noted that at very high concentrations, the polymer concentration-viscosity relationship may be non-linear.

Although the viscosities of polymer solutions prepared at different times varied slightly, the polymer concentration-viscosity relationship developed using the experimental data seems to predict viscosity values that are in close agreement with the experimental values. The overall viscosity relationship equation thus developed can be written as follows;

$$\eta \text{ (cp)} = 1.0 + (0.3423)\,(C) \qquad \text{(Eq. 7.3)}$$

where; η = viscosity of polymer solution, cp

C = concentration of polymer solution, ppm

The polymer concentrations used in this research study are considered to be "dilute" solutions. For such dilute solutions, the

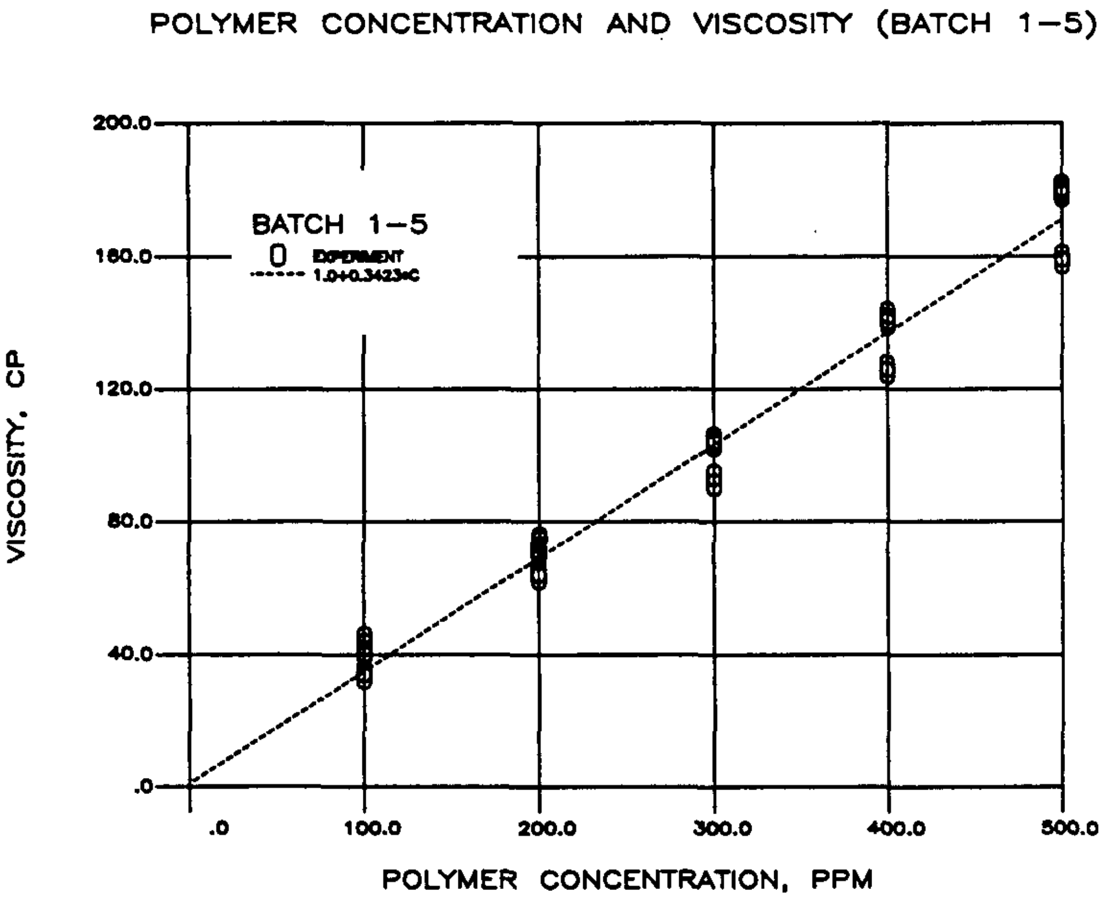


Figure 19. Overall Polymer Concentration and Viscosity Relationship (Batch 1-5); η (cp) = 1.0 + (0.3423) (C).

polymer molecules are on an average so far apart that they have negligible influence on each other. Alternatively, it leads to the conclusion that in dilute polymer solutions, the viscosity contributions of the individual polymer molecules are additive, and therefore it is this property that results in the linear relationship between polymer concentration and viscosity. For highly concentrated polymer solutions, on the other hand, the dependence of viscosity on concentration may be nonlinear. The range of concentrations that are used for groundwater applications fall in the category of "dilute" solutions, and therefore, the non-linear dependence of polymer viscosity on polymer concentration has not been a part of this research study.

The overall polymer concentration-viscosity relationship thus developed (Eq. 7.3) can be used to predict the viscosity of polymer solutions, given the polymer concentration.

Polymer Adsorption on Ottawa Sand

Summary of the polymer adsorption data obtained from Batch equilibrium experimental studies is presented in Table 16. Further details of this data can be found in Appendix. The equilibrium liquid phase concentration refers to the polymer mass remaining in the liquid, and the equilibrium solid phase concentration refers to the polymer mass adsorbed on the Ottawa sand. The equilibrium data thus obtained is graphically illustrated in Figure 20, as liquid phase concentration

Table 16. Polymer Adsorption on Ottawa Silica Sand (Equilibrium Experiment) Data.

Equilibrium Liquid Phase Conc., mg/l	Equilibrium Solid Phase Conc., mg/kg
86.5	67.5
85.7	35.8
81.6	30.7
75.9	30.1
196.7	16.5
195.9	10.3
195.9	6.8
187.8	15.3
293.9	30.5
298.0	5.0
293.9	10.2
286.5	16.9
395.9	20.5
397.5	6.3
396.7	4.1
394.3	7.1

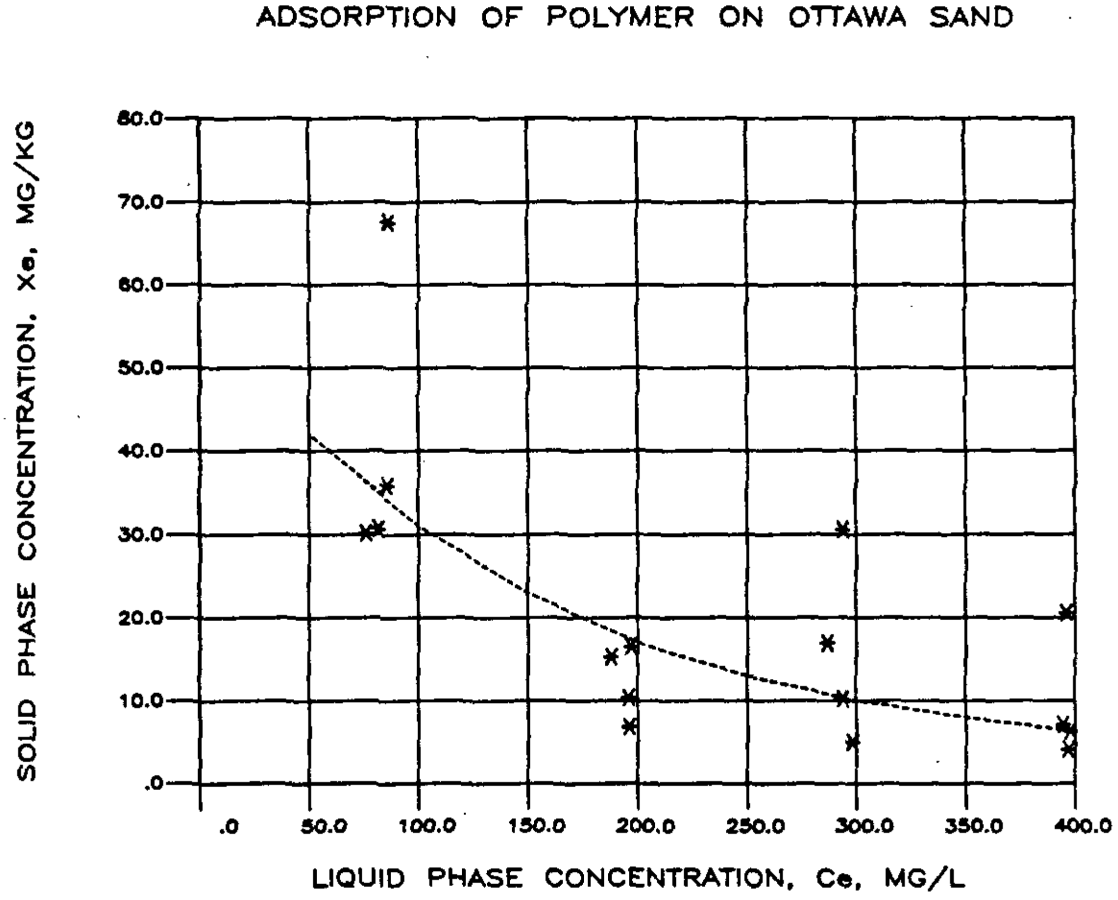


Figure 20. Adsorption of Polymer on Ottawa Silica Sand (Batch Experiments).

versus solid phase concentration to yield what is known as "Adsorption Isotherm."

A typical adsorption isotherm is illustrated in Figure 21. In a typical adsorption process, the equilibrium solid phase concentration increases with increasing liquid phase concentration. The adsorption of Dowell J333 polymer on Ottawa silica sand does not appear to follow the typical adsorption process. The equilibrium solid phase concentration of Dowell J333 polymer decreased with increasing liquid phase concentration. While the mass of polymer adsorbed seems to be negligible, the phenomenon of decreasing polymer adsorption could be explained as follows.

These polymers are generally considered to have a random coiling configuration. The coils are extensively entangled with each other, and there are more number of entanglements per unit volume of solution at higher concentrations than at lower concentrations. Therefore, at low polymer concentrations, a single polymer coil behaves more or less as an independent coil, and perhaps adsorbs easily on a sand particle. Whereas at higher concentrations, when a single polymer coil adsorbs on a sand particle, it is not able to drag along all the other coils that are entangled with it, thereby reducing the mass of polymer adsorption at higher concentrations.

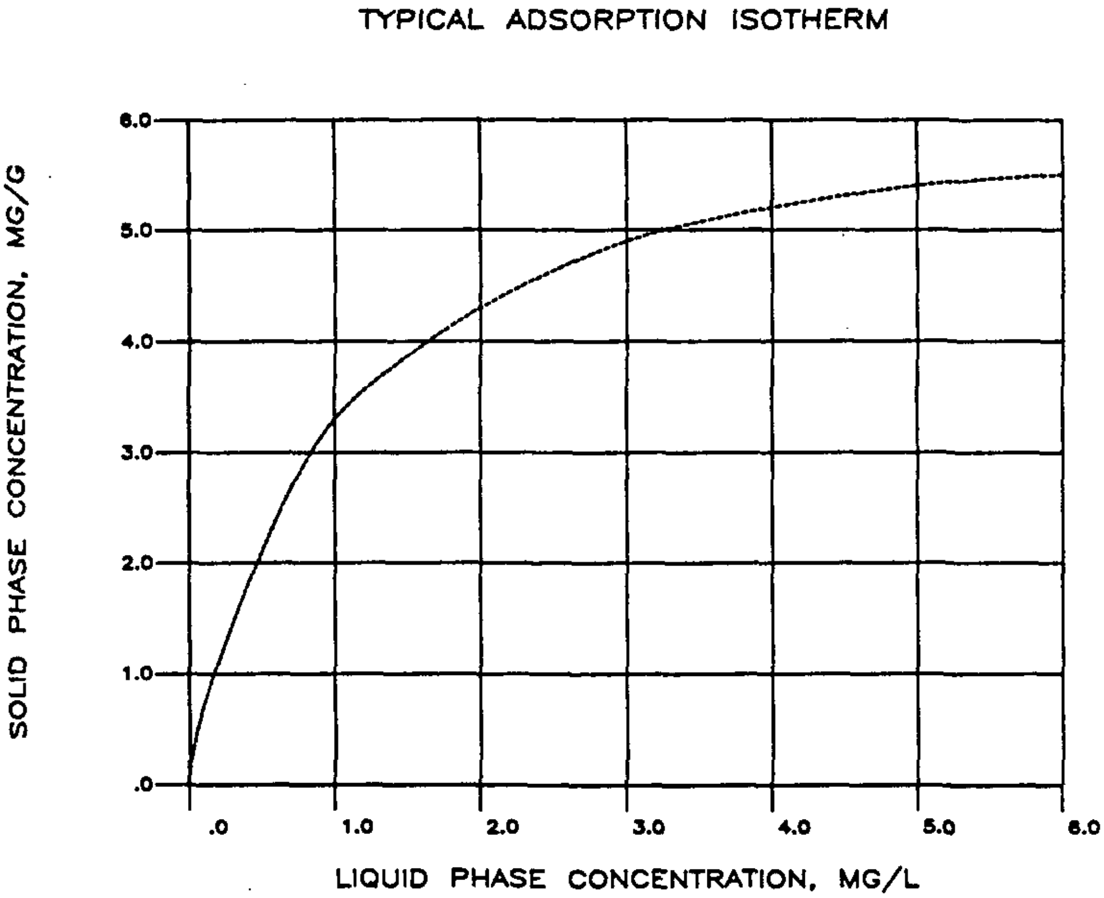


Figure 21. Typical Adsorption Isotherm.

The polymer adsorption results obtained in the Batch adsorption experiments clearly demonstrate that there was very little (or no) polymer adsorption on Ottawa silica sand. At equilibrium liquid phase concentrations in the range of 200 to 300 mg/l, the mass of polymer adsorption was found to be about 14 milligrams of polymer/kilogram of sand (or 14 micrograms of polymer/gram of sand). Mungan (1968) reported typical laboratory adsorption values for polymers in the range of thirty to several hundred micrograms of polymer/gram of adsorbent. Therefore, based on the adsorption values reported in the literature, the adsorption of Dowell J333 polymer on Ottawa silica sand can be considered to be negligible. For groundwater applications, this translates into the complete removal of polymer solutions from the porous media after the intended purpose has been served.

It has been widely reported in the literature that the laboratory results often cannot be extrapolated to predict polymer adsorption in the field scale operations. Therefore, caution should be exercised when using the laboratory adsorption data directly to field scale operations, as the conditions in the field are so different from the enclosed environmental conditions observed in the laboratory scale experiments. This is especially true in the case of groundwater applications.

Viscosity and Shear Rate

Effect of Shear Rate on Viscosity

Several experimental studies were conducted to study the effect of shear rate on viscosity of Dowell J333 polymer solutions. The spindle speed (rpm) of the Brookfield viscometer was used as the pseudo-shear rate, and the viscosity of polymer solutions of various concentrations was measured at four spindle speeds (6, 12, 30, and 60 rpm). The experimental data obtained in the Shear rate experiments is summarized in Table 17. This data is plotted in Figure 22 as pseudo-shear rate versus viscosity, illustrating the effect of shear rate on viscosity for five polymer solution concentrations.

The viscosity decreased with increasing shear rate, for all the five polymer solutions (100, 200, 300, 400, and 500 ppm). Although the trend is similar for all the five polymer concentrations studied, the decrease in viscosity was greater at higher concentrations, and relatively smaller at lower concentrations. The viscosity of a 500 ppm polymer solution decreased by 132 cp (from 178 cp at 6 rpm to 46 cp at 60 rpm), while that of a 100 ppm solution decreased by 31 cp (from 43 cp at 6 rpm to 12 cp at 60 rpm). One can also notice that the viscosity decreased much more rapidly at lower shear rates than at higher shear rates, and this was consistent for all the five polymer concentrations. Overall, there was about 70 to 75 percent reduction in viscosity over the entire range of shear rates experimented, and about

Table 17. Shear Rate and Viscosity Experimental Data (Batch 5).

Pseudo Shear	Viscosity[2], cp				
Rate[1], rpm	100 ppm	200 ppm	300 ppm	400 ppm	500 ppm
6.0	43.0	74.0	105.0	141.0	178.0
12.0	28.0	49.0	70.0	92.5	114.5
30.0	16.6	28.4	40.2	50.4	61.4
60.0	12.0	19.8	27.5	36.5	46.0

[1] Pseudo-Shear Rate = Spindle speed of Brookfield Viscometer (in revolutions per minute)

[2] Viscosity measurements were taken at room temperature, 20° C

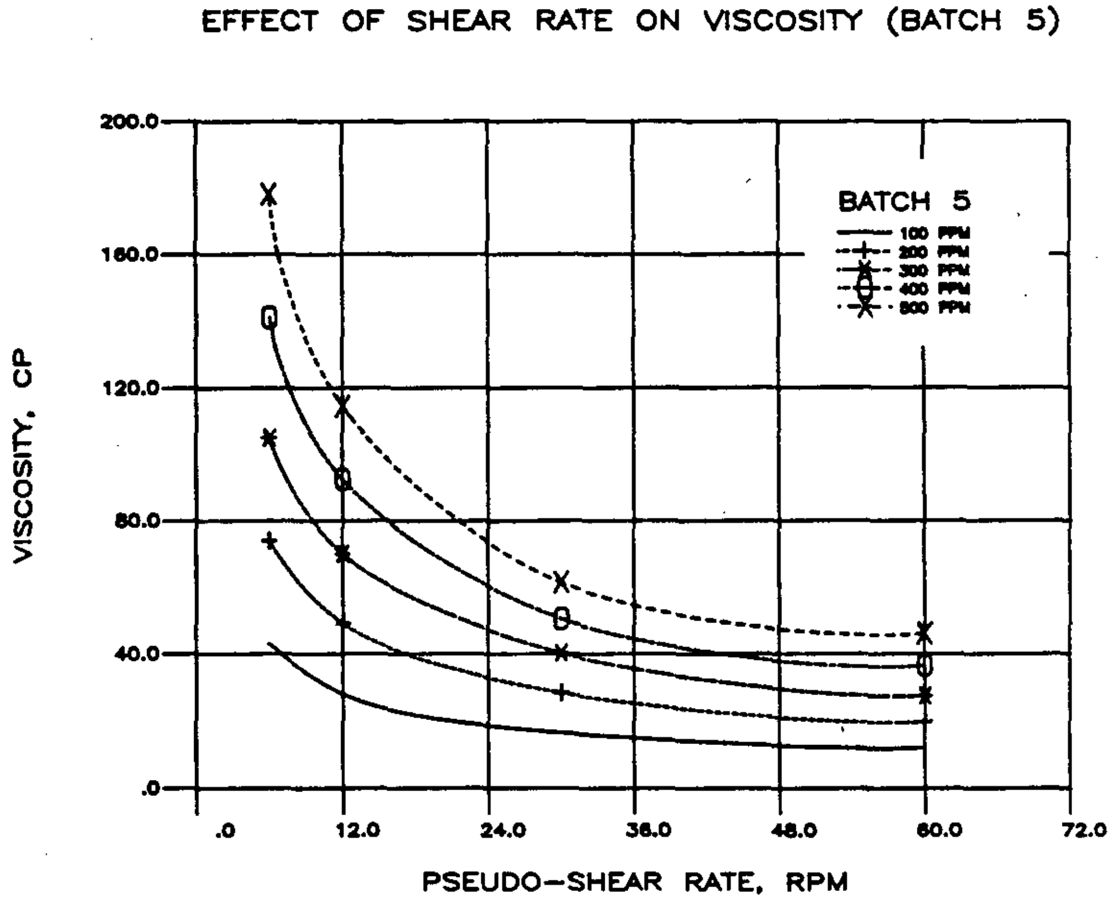


Figure 22. Effect of Shear Rate on Viscosity at Different Polymer Concentrations (Batch 5).

50 percent of this change was observed between 6 rpm and 12 rpm shear rates.

The effect of the decrease in viscosity with increasing shear rate was reversible, i.e., as the shear rate increased the viscosity decreased, and while still maintaining the same experimental conditions, as the shear rate decreased the viscosity increased to its original values. This effect of reversible decrease in viscosity with increasing shear rate is called "shear thinning," and the Dowell J333 polyacrylamide polymers that exhibited this reversible shear thinning property are considered to be pseudo-plastic fluids. The decrease in viscosity is believed to be caused by shear induced changes in the networks of entanglement chains of polymers. Thus, the shear thinning results from the tendency of the applied force to disturb the long polymer chains from their favored equilibrium conformations, causing elongation in the direction of shear.

Shear Rate/Concentration Dependence

Based upon the results obtained in the pseudo-shear rate and viscosity experiments at five different polymer concentrations, it can be concluded that the dependence of polymer viscosity on pseudo-shear rate increased with the polymer concentration. If the polymer molecules were compact, non-interacting spheres, the viscosity of polymer solution of a given molecular weight would be almost independent of its concentration. The polyacrylamide polymer molecules however, tend to expand in good solvents and offer more resistance to flow. This effect becomes greater as the polymer concentration increases, thus showing a larger decrease in viscosity at higher polymer concentrations (see Figure 22). Alternatively, it can also be reported that the shear sensitivity is less obvious at low polymer concentrations, i.e., smaller decrease in viscosity at lower polymer concentrations. This can be attributed to the fact that the molecular interactions are much less in dilute solutions.

Relevance to Groundwater Applications

The shear thinning properties of Dowell J333 polyacrylamide polymers were quantified in the laboratory using Brookfield Viscometer. However, the determination of viscometric behavior of polymer solutions in the porous matrix is much more complex, and therefore, the shear rates are not well defined in the subsurface environment. In terms of groundwater cleanup operations, the pseudo-shear rate used in the shear rate experiments corresponds to the groundwater flow velocity. The decreasing viscosity with increasing shear rate observed in the laboratory experiments can be correlated to the decrease in viscosity with an increase in the groundwater flow velocity. Alternatively, the "apparent viscosity" may be low at high injection rates.

Polymer Slug Size and Stability

Experimental studies were conducted to study the effect of polymer slug size (the thickness of polymer slug) on the integrity of the slug and its flow through the porous media. In these experiments, the polymer concentration was kept constant at 100 ppm and the thickness of polymer slug was varied from 5 cm (2 inch) upto 20 cm (8 inch), by varying the volumetric injection of polymer into the sand column apparatus.

The polymer concentration profiles observed at the outlet end of the sand column, for a constant polymer concentration of 100 ppm and slug sizes of 5 cm, 15 cm, and 20 cm (2 inch, 6 inch, and 8 inch) are presented in Figure 23, Figure 24, and Figure 25 respectively. In general, the shape of the polymer concentration curves of different slug sizes was consistent. As can be seen from the shape of the curves, it is not a "true dispersion" phenomenon, since the leading edge of the polymer front is sharp, leaving a relatively long trailing edge.

In terms of the specific behavior of each of the three slugs, the normalized polymer concentration peak, C/C_o, of the 5 cm (2 inch) slug reached a maximum of 0.08, and the concentration peaks increased slightly with increasing slug size (see Figure 24 and Figure 25). In all the three cases, the concentration peaks were observed at about 42 minutes after the start of polymer injection. This time was approximately equal to the time of 1 pore volume injection. As the slug size increased, the leading edge of the polymer front was relatively sharp. However, contrary to the expected behavior, it appears that the polymer slug did not maintain its integrity. This is apparent from the sharp peaks of all the three curves, as well as the long trailing edge of the polymer slug.

As the polymer slug advanced through the porous media, the more viscous polymer solution displaced the less viscous water. The polymer solution, by virtue of its viscosity, is less mobile than that of the water; therefore this resulted in the sharp leading edge.

At the trailing edge of the polymer front, the less viscous water is displacing the more viscous polymer solution. The water, because of its high mobility, perhaps creates small "finger effects," thereby dispersing the otherwise sharp trailing edge of the polymer front. This may be the reason for the long trailing edge of the polymer front. In all the three cases, at the end of 120 minutes, i.e. 3 pore volumes of injection, the normalized concentration, C/C_0, of the trailing edge of the polymer front was about 0.018. Several pore volumes of water was injected beyond the 120 minutes time shown on the graphs to remove any traces of polymer from the sand column.

Polymer Concentration

This set of experimental studies were conducted to study the effect of polymer concentration on the stability and integrity of the polymer slug. The thickness of polymer slug (or the volume of polymer injection) was kept constant at 15 cm (6 inches) and the concentration of polymer was varied from 100 ppm to 400 ppm.

Effect of Concentration on Polymer Slug

The concentration profiles of polymer solutions of 200 ppm and 400 ppm for a constant polymer slug size of 15 cm (6 inches) are illustrated in Figure 26 and Figure 27 respectively. (Also see Figure 24 for the concentration profile of 100 ppm polymer solution).

In general, the normalized polymer concentration peaks were observed at about 42 minutes from the time of start of polymer injection. Once again, it is quite clear from the concentration profile graphs that as the polymer concentration increased, the leading edge of the polymer front was sharp. The peak concentration of 400 ppm curve was slightly lower compared to the 100 ppm and 200 ppm curves. An analysis of the mass balance of the polymer that entered and exited tha sand column showed that the mass balance values of the lower concentrations matched better with the experimental values, than that of higher concentrations. While 90 percent of the polymer mass was accounted at 100 ppm concentration, only about 50 percent of the polymer mass was accounted for at 400 ppm concentration.

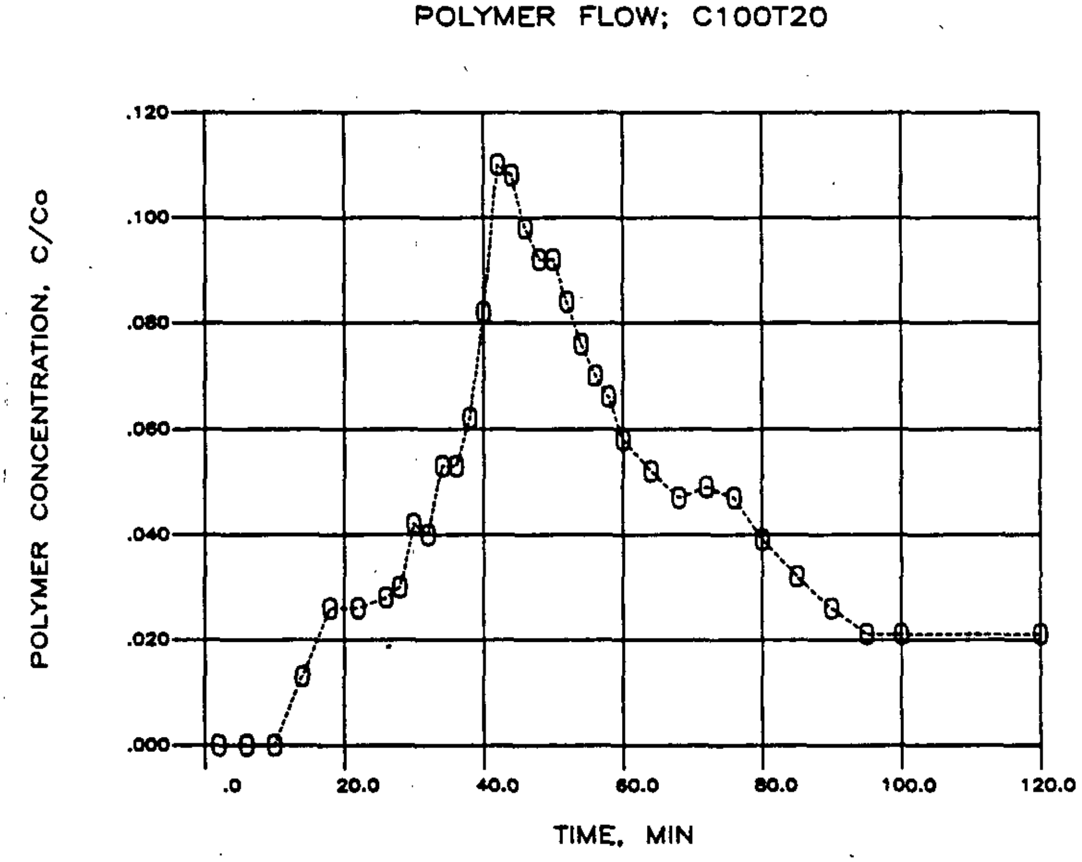


Figure 25. Polymer Concentration Profile at the Outlet End of Sand Column (C = 100 ppm, Slug Size = 20 cm)

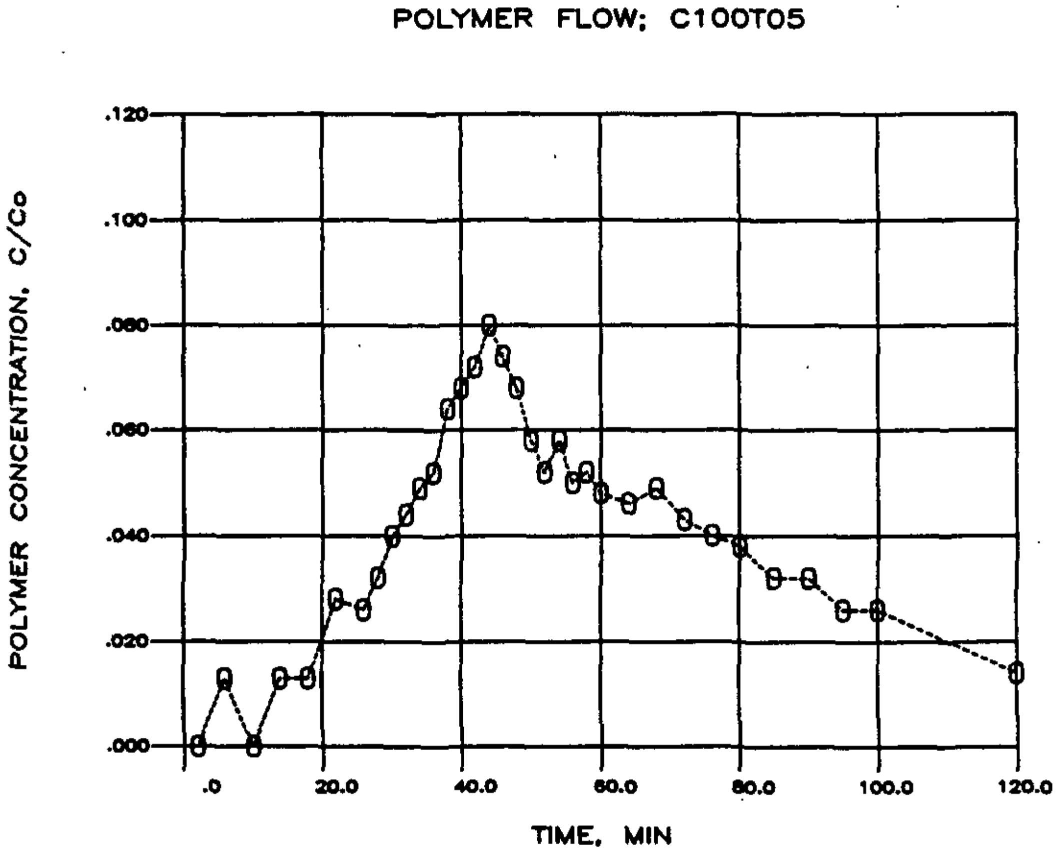


Figure 23. Polymer Concentration Profile at the Outlet End of Sand Column (C = 100 ppm, Slug Size = 5 cm)

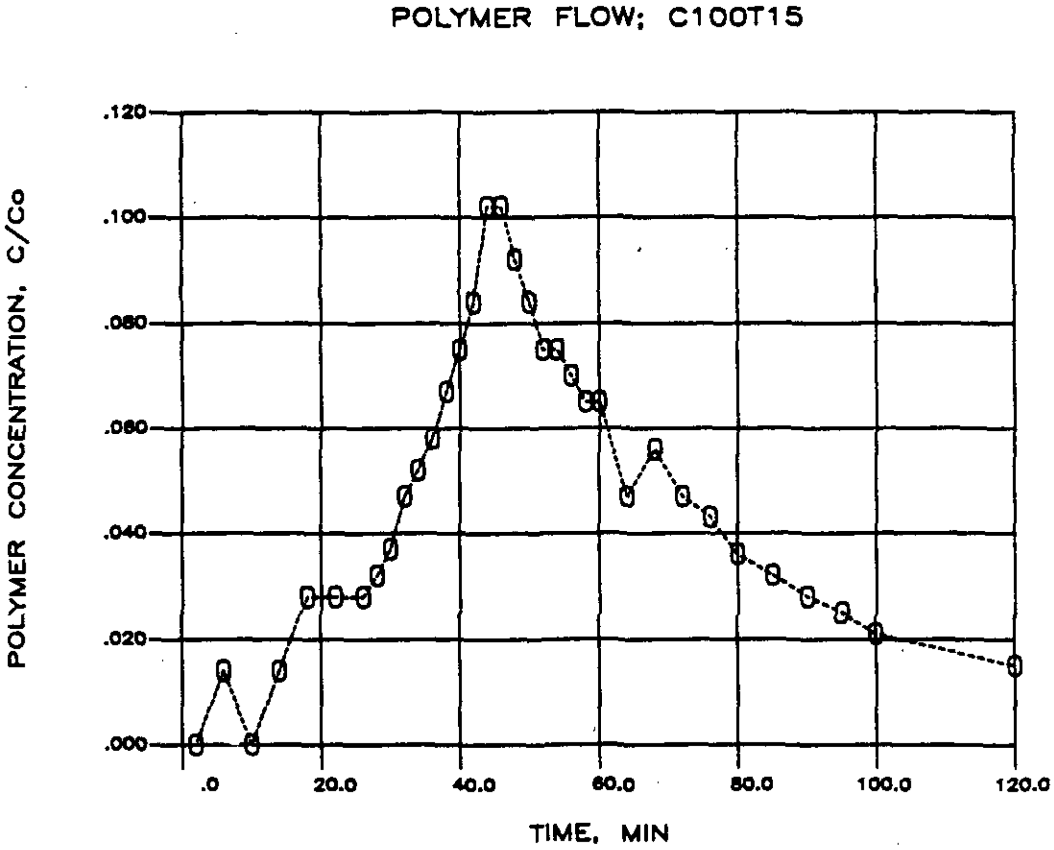


Figure 24. Polymer Concentration Profile at the Outlet End of Sand Column (C = 100 ppm, Slug Size = 15 cm)

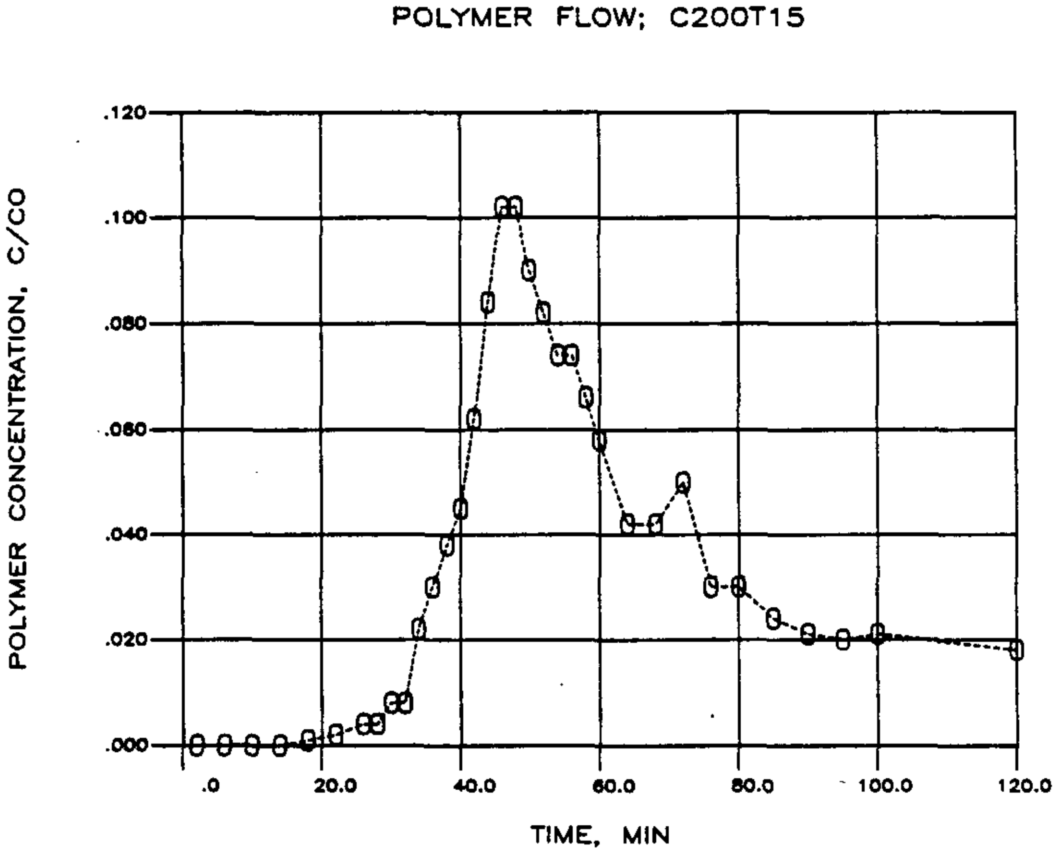


Figure 26. Polymer Concentration Profile at the Outlet End of Sand Column (C = 200 ppm, Slug Size = 15 cm)

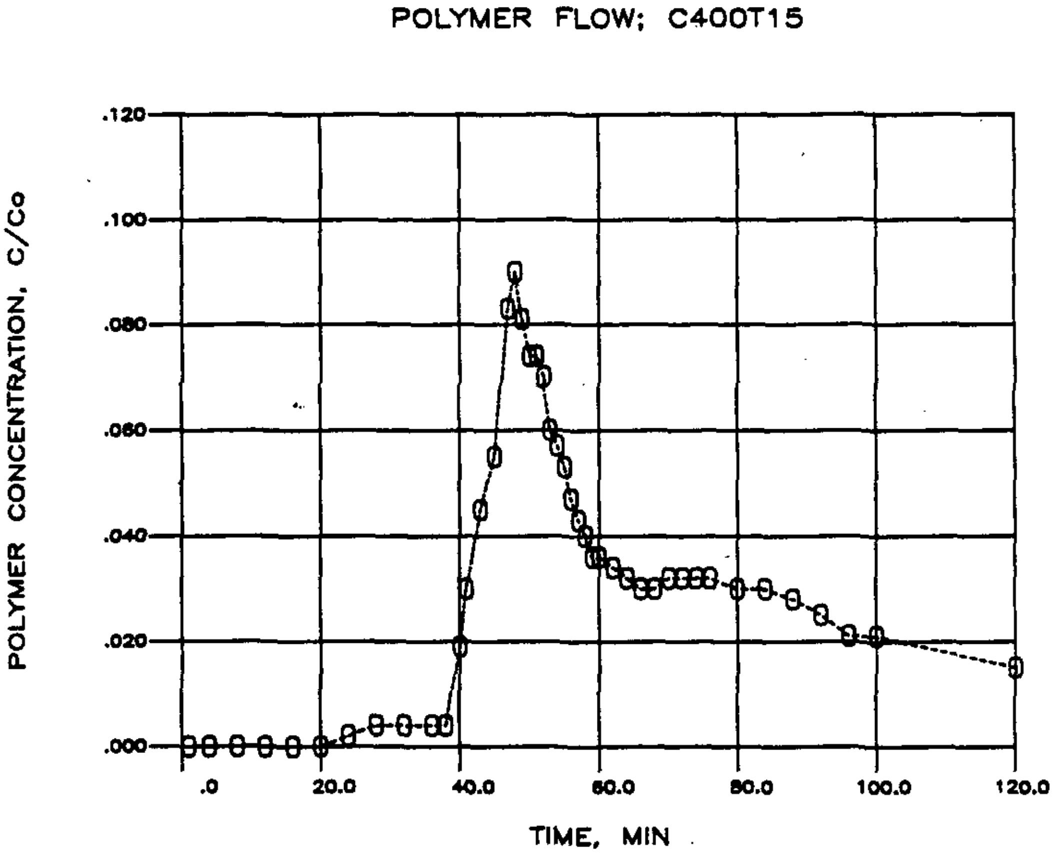


Figure 27. Polymer Concentration Profile at the Outlet End of Sand Column (C = 400 ppm, Slug Size = 15 cm)

In the case of 400 ppm experiment, the viscosity was about 140 cp. Because of this large viscosity contrast between water and polymer, it appears that the polymer slug was not able to maintain its effectiveness, thus leading to some "fingering effect." Alternatively, significant portions of the polymer mass did not exit the column within the two-hour (3 pore volume) time of the experimental duration. This particular experiment required more pore volumes of water injection to return the hydraulics of the system to its original level, and this could be attributed to the instability of the polymer slug at such high polymer concentrations.

Relevance to Groundwater Applications

From the results obtained in this experimental study, it can be reported that the polymer slug was relatively more stable at lower concentrations than at higher concentrations. Because of the instability of the polymer slug that is associated with high polymer concentrations, it is very unlikely that such high concentrations of polymer solutions will be used for groundwater applications. The use of high polymer concentrations may prove beneficial when the existing fluid (or contaminant in the groundwater) is more viscous.

Polymer Transport Model Prediction

The analytical model developed for the polymer transport included basically the convective transport, the dispersive transport, and a "pseudo-adsorptive" retardation factor. While the dispersivity term, α_1 (shown as DL in the figures) takes into consideration the spread of the concentration curve, the peak of the concentration curve as well as a time-shift of the curve are appropriately considered by the retardation factor, R_d.

The initial analysis of the data took into consideration only the advective transport and the dispersive transport. As stated in the earlier sections of this chapter, since it is not a "true dispersion" phenomenon, the polymer concentration values predicted by the advective, dispersive model did not agree well with the experimental data. Therefore, the retardation factor, R_d, was included in the polymer transport model.

The dispersivity parameter, α_1, and the retardation factor, R_d, were evaluated by using the "Least Squares Method." In this method, the sum of squared differences between the experimental data and the theoretically predicted values is minimized to find the optimum dispersivity, α_1, and retardation factor, R_d. Computer program was written to predict the theoretical polymer concentration values using Equation 6.20.

The polymer concentration experimental data as well as the model predictions for 100 ppm polymer solution of 5cm thick slug and 15 cm thick slug are shown in Figure 28 and Figure 29 respectively. The data for 400 ppm and 15 cm thick slug is presented in Figure 30. The dispersivity, retardation factor, and the dispersion coefficient values evaluated using the model are summarized in Table 18.

As can be seen from Figure 28 and Figure 29, the polymer transport model predicted the concentration for 5 cm and 15 cm thick slugs of 100 ppm polymer solution, that agreed well with the experimental data. This is especially significant, considering the fact that this is not a "true dispersion" phenomenon. In the case of 400 ppm polymer solution of 15 cm thick slug, the model predictions did not agree well with the experimental data; especially, the concentration peak predicted by the model was about half (0.050) of the experimental value (0.090).

An analysis of the dispersion and retardation parameters presented in Table 18 clearly reveals that the longitudinal dispersivity, α_1, as well as the retardation factor, R_d, increased both with the increase in polymer slug thickness as well as polymer concentration. This suggests that as the polymer concentration or polymer slug size increases, the polymer flow in the porous media deviates from the ideally-dispersive flow.

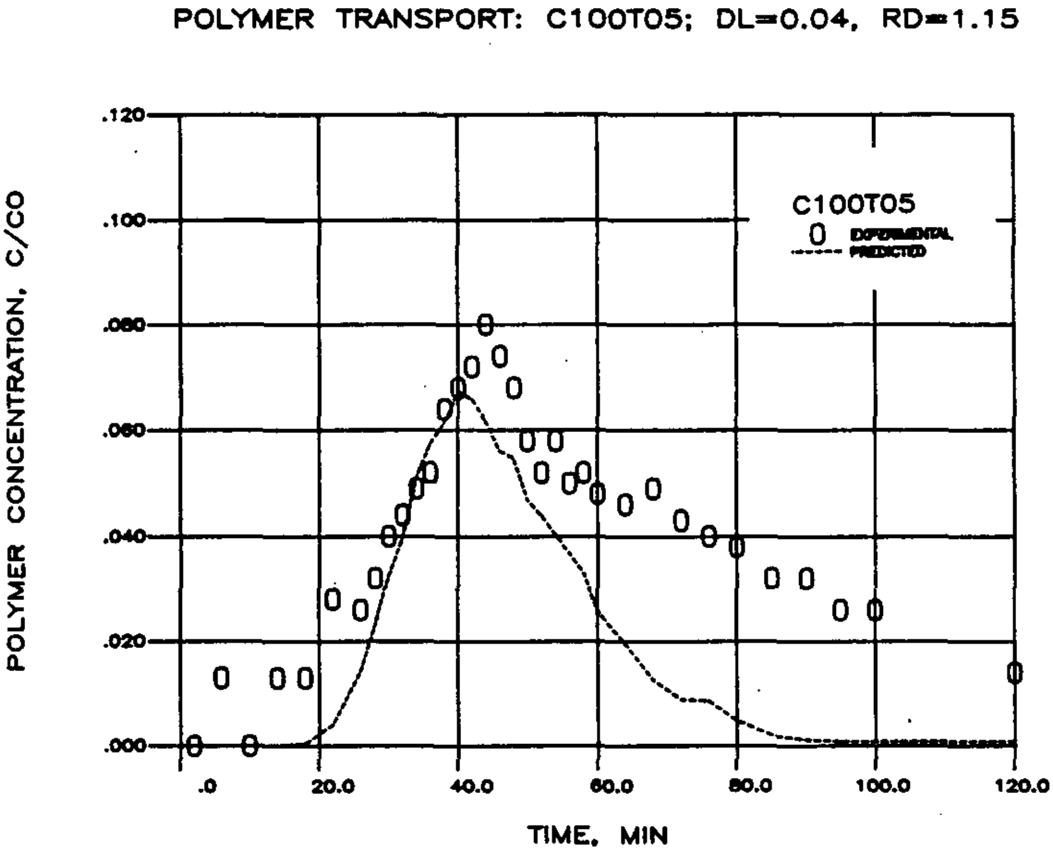


Figure 28. Polymer Concentration Profile and Polymer Transport Model Prediction (C = 100 ppm, Slug Size = 5 cm)

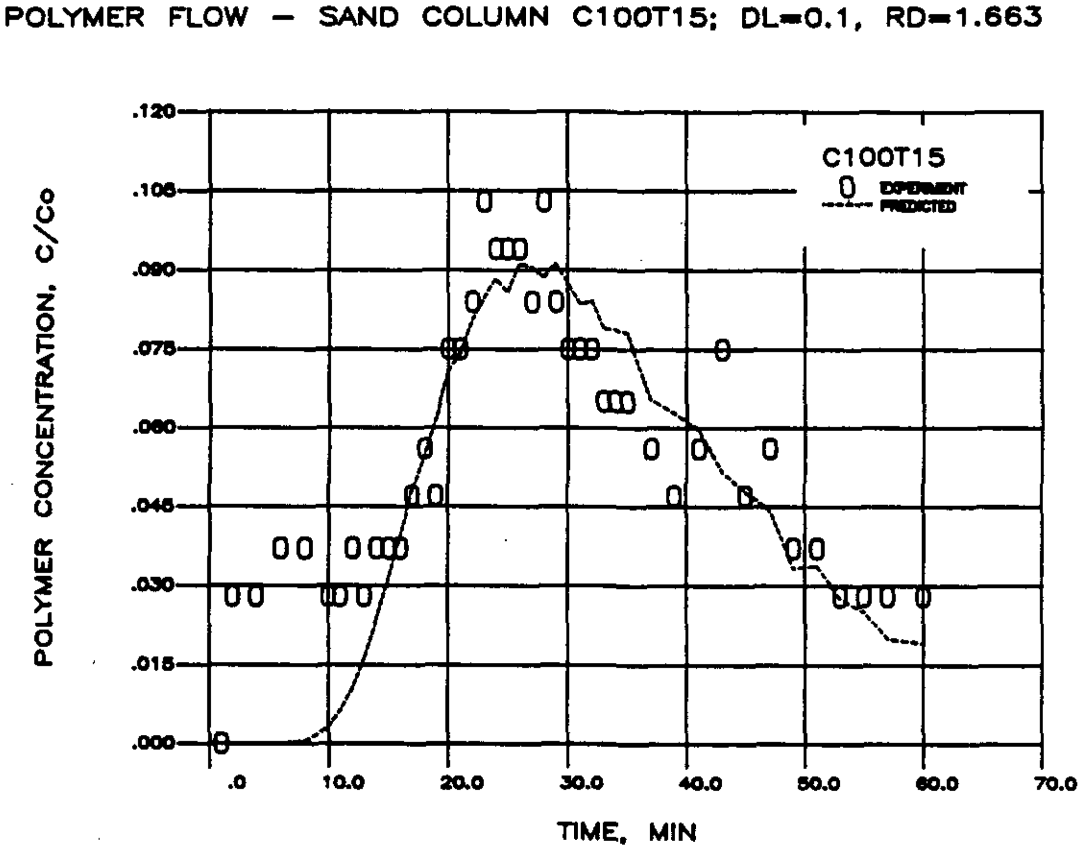


Figure 29 Polymer Concentration Profile and Polymer Transport Model Prediction (C = 100 ppm, Slug Size = 15 cm)

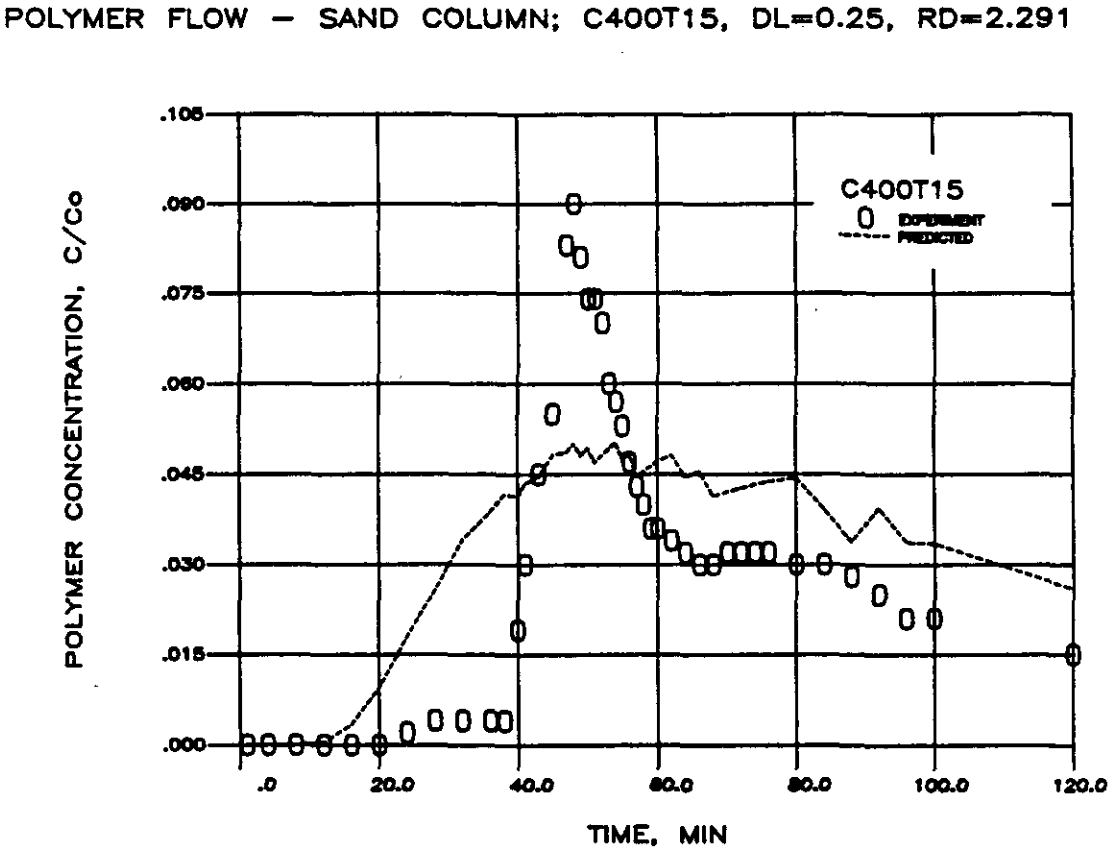


Figure 30. Polymer Concentration Profile and Polymer Transport Model Prediction (C = 400 ppm, Slug Size = 15 cm).

Table 18. Dispersion Parameters and Retardation Factor Values Evaluated Using the Polymer Transport Model.

ID/Parameter	Dispersivity α_l, m	Retardation R_d	Dispersion Coeff., m^2/s
C100T05	0.04	1.250	6.12×10^{-6}
C100T15Q20	0.10	1.663	3.07×10^{-5}
C400T15	0.25	2.291	3.83×10^{-5}

Hydraulic Model Results

The hydraulic model described in the earlier sections was developed for the purpose of analyzing the pressure/hydraulic head in the system. The final equation (Eq. 6.16) was derived for the total pressure/hydraulic head in the system ($P_i - P_e$), which includes the pressure contribution due to both water as well as polymer portions. The computer program was written to compute total pressure ($P_i - P_e$), as well as the individual pressure contributions due to water portion (Eq. 6.8) and (Eq. 6.12), and polymer portion (Eq. 6.10). The pressure equations thus developed did not include the effects of dispersion.

The experimental pressure data and the model predicted pressure values for 100 ppm and 15 cm polymer slug (with a volumetric flow rate of 20.0 ml/min) are shown in Figure 31. It is quite clear from these graphs that the model results did not match well with the experimental pressure data. This is because of the fact that the viscosity measured by using the Brookfield viscometer (in centipoise) is not a true representative viscosity as far as flow through porous media is concerned. The resistance to viscous fluid flow in porous media is quite different from the resistance that is observed on the spindle of the Brookfield viscometer. Therefore, the viscosity values were adjusted, and alternatively, another parameter called "mobility" ($\lambda = k/\eta$) was evaluated using the experimental data and the equations developed in the hydraulic model.

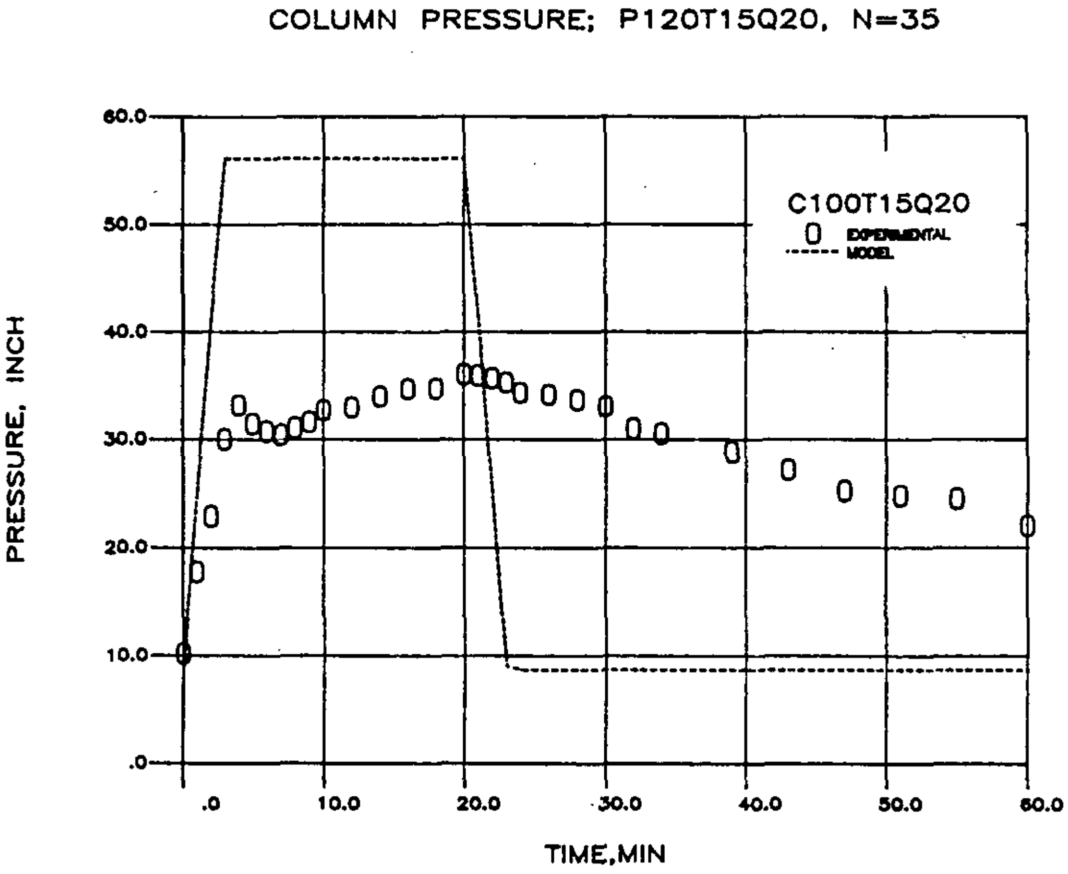


Figure 31. Pressure in the Sand Column Apparatus (C = 100 ppm, Slug Size = 15 cm, Q = 20 ml/min, η = 35 cp). λ = 1.094 X 10^{-11} m^2/cp

The pressure data and model results for 5 cm and 15 cm slugs of 100 ppm polymer concentration are presented in Figure 32 and Figure 33 respectively. The model results in these two cases were obtained after adjusting the mobility, λ, to match the initial portion of the experimental data. The adjusted viscosity values were 20 cp for 5 cm slug and 19 cp for 15 cm slug sizes, and their respective mobility parameters were found to be 1.915×10^{-11} m^2/cp and 2.016×10^{-11} m^2/cp.

The experimental data and the model curves have three regions. The first part is the increasing pressure due to the entry of viscous polymer into the sand column. During the time the polymer is entering into the sand column, a steady increase in pressure was observed in the experimental system, but the increase in the experimental data was not as sharp as the model predicted.

The second part of the graph has a steady flat region during the time when the polymer slug remains in the sand column. The third part of the curve is a steady decline in the pressure during the time the polymer slug is exiting the column. The model predicted a steady flat region and a sudden decline in the pressure while the experimental data showed a slow decrease of pressure. This discrepancy in the pressure data is because of the dispersion that is caused due to the "fingering effect". Due to this effect, it is apparent that the polymer slug was not moving through the column as a "plug". This is

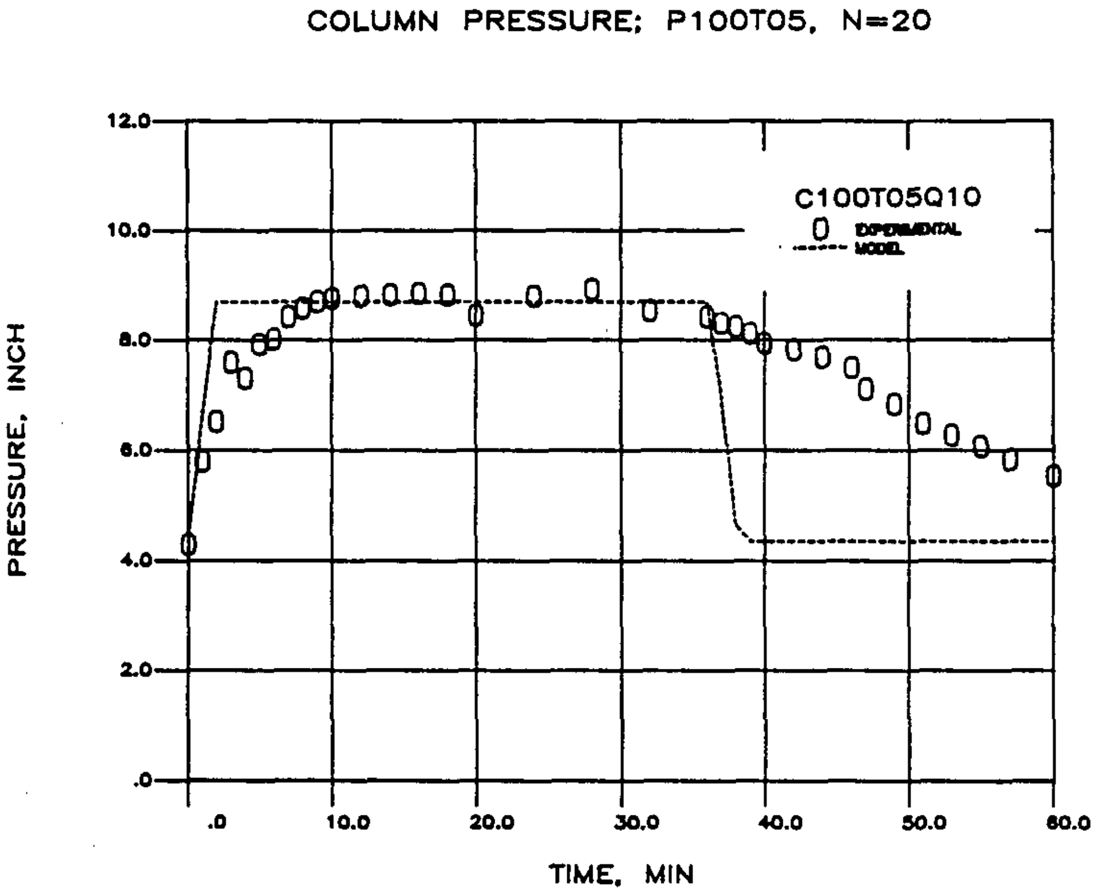


Figure 32. Pressure in the Sand Column Apparatus (C = 100 ppm, Slug Size = 5 cm, Q = 10 ml/min, η = 20 cp). $\lambda = 1.915 \times 10^{-11} m^2/cp$

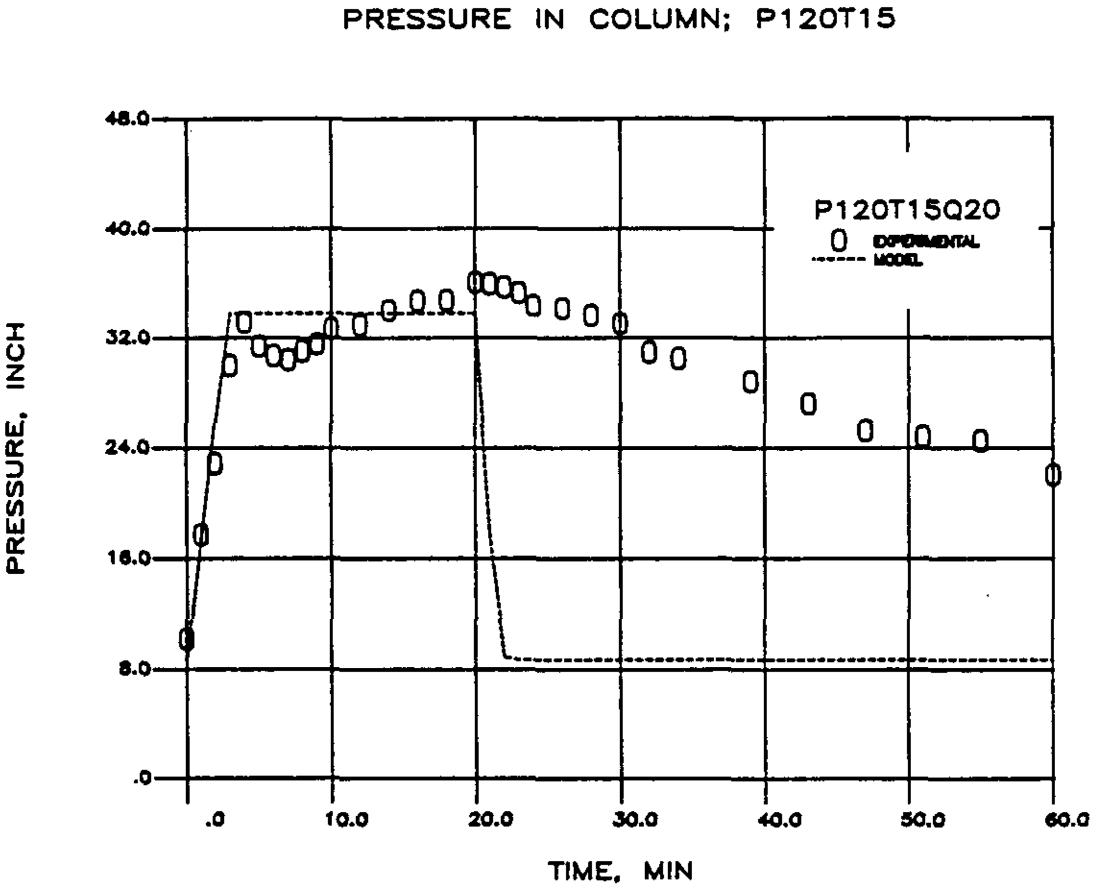


Figure 33. Pressure in the Sand Column Apparatus (C = 100 ppm, Slug Size = 15 cm, Q = 20 ml/min, η = 19 cp). $\lambda = 2.016 \times 10^{-11} m^2/cp$

also substantiated by the long trail of polymer concentration data obtained in the experiments. The pressure data obtained in these experiments more or less followed the trend of the polymer concentration data, i.e. a slow decrease of the pressure in the column with time.

An analysis of the pressure data suggests that, as the slug size or polymer concentration decreased the model predictions agreed better with the experimental data. Once adjusted for the mobility parameter, the model was able to give a better representation of the immediate pressure changes in the system due to the entry of polymer solution into the sand column. However, the model did not give good predictions for the trailing edge of the polymer front.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary

The purpose of this research study was to develop an understanding of the flow of polyacrylamide polymer solutions in the porous media, and to evaluate the suitability of using such polymers in the management of groundwater contamination incidents. Presented below is a summary of the overall findings of this research study.

Based on the results of this study, it can be reported that the polymers can be selectively used for certain groundwater cleanup applications. It should however be noted that high concentrations of polymer solutions tend to be less mobile than the water that flows behind the polymer slug. This results in the "fingering effect," thereby reducing the integrity of the polymer slug. Therefore, the use of polymer solutions of high concentrations may not be applicable to most groundwater applications.

In certain situations, the contaminated groundwater may be several times more viscous than that of water (e.g. sanitary landfill leachate is more viscous than that of water). The use of polymer solutions of high concentrations may provide better sweep efficiency in such cases, thereby providing better cleanup of groundwater contamination.

The polyacrylamide polymer by itself may not be toxic; however, the acrylamide monomer is considered to be toxic. Because of the increasing toxicity concerns associated with such chemicals, the regulatory agencies may not approve the use of polymers in the groundwater cleanup applications. In addition, because of the increasing post-cleanup liability on the groundwater cleanup industry, the real world application of this technology seems to be too far from becoming reality.

Conclusions

Based on the experimental data and the results obtained in this research study, the following conclusions can be made:

1. The viscosity data was consistent and yielded an excellent polymer concentration-viscosity relationship. The polymer solution viscosity was found to vary linearly with concentration, within the range of 0 ppm to 500 ppm concentrations investigated. The viscosity relationship was able to predict the viscosity values that were in close agreement with the experimental data. It should however be

noted that the viscosities of different batches of polymer solutions varied slightly.

2. The adsorption of polymer on Ottawa sand was negligible. In terms of groundwater applications, this translates into the complete removal of polymer solutions from the porous media after the intended purpose has been served.

3. The viscosity of polymer solutions decreased with increasing shear rate. The decrease in viscosity was greater at higher concentrations and, relatively smaller at lower concentrations. It can also be concluded that the viscosity decreased much more rapidly at lower shear rates than at higher shear rates. In terms of groundwater applications, the decrease in viscosity with increasing shear rate corresponds to lower viscosities at higher volumetric polymer injection rates.

4. The effect of polymer slug size (thickness of polymer slug) was not quite apparent. It appears that as the polymer slug size was increased from 5 cm to 20 cm, the leading edge of the polymer front was relatively sharp, but, contrary to the expected behavior, the polymer slug did not maintain its integrity at larger slug sizes.

5. The effect of polymer concentration, and therefore the effect of viscosity was more obvious than the effect of slug size. The polymer slug was relatively more stable at 100 ppm concentration than at 400 ppm concentration. The mass balance of polymer at the lower concentrations matched well with the experimental values than at the higher concentrations. It can also be said that at 400 ppm concentration the polymer slug was unstable due to the fingering effect.

6. The advective, dispersive, "pseudo-adsorptive" retardation mathematical model predicted the polymer concentration profiles well at the 100 ppm polymer concentrations for both 5 cm (2 inch) slug and 15 cm (6 inch) slug. However, the model did not give good prediction values for 400 ppm concentration experiment. An analysis of the dispersivity parameters and the retardation parameters clearly indicates that the dispersion and the retardation increased with increasing either the slug size or the polymer concentration.

NOMENCLATURE

		Eq. #
A	cross sectional area of flow, L^2	3.5
Ab	absorbance at a given wave length	7.1
C	concentration of a constituent, M/L^3	6.18
C_e	equilibrium liquid phase concentration of polymer, M/L^3	4.1
C_o	initial polymer concentration in solution, M/L^3	4.1
C_o	influent polymer concentration, M/L^3	6.19
e	void ratio (volume of voids/volume of solid particles)	3.1
erfc	complementary error function	6.20
e_t	analog output from pressure transducer, volt	5.1
G_s	specific gravity of solids	3.2
g	gravitational acceleration, 9.81 m/s^2, L/T^2	3.6
h	free water surface elevation, L	5.1
ΔH	differential head, L	3.5
K	hydraulic conductivity, $K=k\rho g/\eta$, L/T	3.5
k	permeability of porous media, L^2	3.6
l	distance in the direction of flow, L	6.3
l_e	linear distance upto the last pressure tap, L	6.11
l_i	linear distance upto first pressure tap, L	6.7
l_1	linear distance upto the interface separating the inner portion and polymer, L	6.7

l_2	linear distance up to the interface separating the polymer and outer portion, L	6.9
M	mass of polymer injected, M	
n	porosity of the porous media, fraction	3.3
p	pressure ($p = \rho gh$), M/LT^2	6.4
P_e	pressure at length l_e, M/LT^2	6.11
P_i	pressure at length l_i, M/LT^2	6.7
P_1	pressure at length l_1, M/LT^2	6.7
P_2	pressure at length l_2, M/LT^2	6.9
Q	volumetric flow rate, L^3/T	3.5
R_d	retardation factor	6.18
t	time, T	
t_p	time of polymer injection, T	6.20
U_c	uniformity coefficient,	7.2
V	Darcy velocity (seepage velocity), Q/A, L/T	6.1
V_s	volume of solids, L^3	3.1
V_t	total volume of the wet specimen (sand+water), L^3	3.1
W	mass of sand in polymer solution, M/L^3	4.1
W_s	weight of dry soil, M	3.2
x	distance in the X-direction, L	6.18
ΔX	length of the sand sample, L	3.5
X_e	equilibrium solid phase loading of polymer per unit mass of sand (mass of polymer/ mass of sand), M/M	4.1

Greek Letters

α_l	longitudinal dispersitivity (α_l = D/V), L	6.18
ρ	density of fluid, M/L^3	3.6
η	dynamic viscosity, M/LT	3.6
η_p	dynamic viscosity of polymer, M/LT	6.9
η_w	dynamic viscosity of water, M/LT	6.7
η	viscosity using Brookfield viscometer, centipoise	7.3
λ	mobility ($\lambda = k/\eta$), L^3T/M	
ν	kinematic viscosity ($\nu = \eta/\rho$), L^2/T	6.3

APPENDICES

A. EXPERIMENTAL DATA

B. FIGURES AND TABLES

C. GLOSSARY OF TERMS

D. POLYMER SOLUTION PREPARATION

E. COMPUTER PROGRAM LISTINGS

APPENDIX - A

EXPERIMENTAL DATA

Table A1. Absorbance and Viscosity Data for Standard Curve (Batch 1).

Polymer Concentration, ppm	Absorbance[1]	Viscosity, cp
0	0.01	1.0
0	0.01	1.0
100	0.095	35.0
100	0.10	33.0
200	0.24	65.0
200	0.26	63.0
300	0.332	91.0
300	0.35	94.0
400	0.48	125.0
400	0.50	127.0
500	0.62	160.0
500	0.61	158.0

[1] Absorbance at 470 nm (Foshee et al., 1976)

Table A2. Absorbance and Viscosity Data for Standard Curve (Batch 3).

Polymer Concentration[1] ppm	Absorbance[2]	Viscosity[3] cp
0	0	1.0
100	0.112	40.0
200	0.24	71.0
300	0.39	103.0
400	0.511	140.0
500	0.64	180.0

[1] Polymer solutions prepared in deionized distilled water.

[2] Absorbance measured at 470 nm with Bausch & Lomb Spectronic 20.

[3] Viscosity measurements by Brookfield Synchro-Lectric Viscometer, at 6 rpm and 21° C. (Room Temperature).

VISCOSITY TEST REPORT

BY: PBR

TEST INFORMATION:

Viscosity of Polymer Solutions (Batch 1).

pH=7.0, Temperature=19 degrees C.

SAMPLE	MODEL	SPINDLE	R.P.M.	DIAL READING	FACTOR	VISCOSITY CPS.
100 ppm	LVT	1	6	3.5	10	35.0
100 ppm		1	6	3.3	10	33.0
200 ppm		1	6	6.5	10	65.0
200 ppm		1	6	6.3	10	63.0
300 ppm		1	6	9.1	10	91.0
300 ppm		1	6	9.4	10	94.0
400 ppm		1	6	12.5	10	125.0
400 ppm		1	6	12.7	10	127.0
500 ppm		1	6	16.0	10	160.0
500 ppm		1	6	15.8	10	158.0

CONCLUSIONS:

VISCOSITY TEST REPORT

BY: PBR

TEST INFORMATION:

Viscosity of Polymer Solutions (Batch 2)

pH=6.9, Temperature=18.5 degrees C.

SAMPLE	MODEL	SPINDLE	R.P.M.	DIAL READING	FACTOR	VISCOSITY CPS.
100 ppm	LVT	1	6	4.1	10	41.0
100 ppm		1	6	4.0	10	40.0
200 ppm		1	6	7.0	10	70.0
200 ppm		1	6	7.2	10	72.0
300 ppm		1	6	10.4	10	104.0
300 ppm		1	6	10.4	10	104.0
400 ppm		1	6	14.1	10	141.0
400 ppm		1	6	14.0	10	140.0
500 ppm		1	6	17.9	10	179.0
500 ppm		1	6	18.1	10	181.0

CONCLUSIONS:

VISCOSITY TEST REPORT

BY: PBR

TEST INFORMATION:

Viscosity of Polymer Solutions (Batch 3)

pH=7.0, Temperature=21 degrees C.

SAMPLE	MODEL	SPINDLE	R.P.M.	DIAL READING	FACTOR	VISCOSITY CPS.
100 ppm	LVT	1	6	4.0	10	40.0
			12	5.5	5	27.5
			30	8.5	2	17.0
			60	12.0	1	12.0
200 ppm		1	6	7.1	10	71.0
			12	9.8	5	49.0
			30	14.4	2	28.8
			60	19.5	1	19.5
300 ppm		1	6	10.3	10	103.0
			12	13.9	5	69.5
			30	20.3	2	40.6
			60	27.5	1	27.5
400 ppm		1	6	14.0	10	140.0
			12	18.9	5	94.5
			30	25.0	2	50.0
			60	37.0	1	37.0
500 ppm		1	6	18.0	10	180.0
			12	23.0	5	115.0
			30	32.5	2	65.0
			60	42.5	1	42.5

CONCLUSIONS:

VISCOSITY TEST REPORT

BY: PBR

TEST INFORMATION:

Viscosity of Polymer Solutions (Batch 4)

pH=7.0, Temperature=20 degrees C.

SAMPLE	MODEL	SPINDLE	R.P.M.	DIAL READING	FACTOR	VISCOSITY CPS.
100 ppm	LVT	1	6	4.5	10	45.0
			12	5.6	5	28.0
			30	8.7	2	17.4
			60	12.2	1	12.2
200 ppm		1	6	7.5	10	75.0
			12	9.8	5	49.0
			30	14.5	2	29.0
			60	20.0	1	20.0
300 ppm		1	6	10.5	10	105.0
			12	14.2	5	71.0
			30	20.3	2	40.6
			60	27.5	1	27.5
400 ppm		1	6	14.3	10	143.0
			12	19.1	5	95.5
			30	25.7	2	51.4
			60	37.0	1	37.0
500 ppm		1	6	18.0	10	180.0
			12	23.0	5	115.0
			30	31.1	2	62.2
			60	46.2	1	46.2

CONCLUSIONS:

VISCOSITY TEST REPORT

BY: PBR

TEST INFORMATION:

Viscosity of Polymer Solutions (Batch 5)

pH=7.0, Temperature=20 degrees C.

SAMPLE	MODEL	SPINDLE	R.P.M.	DIAL READING	FACTOR	VISCOSITY CPS.
100 ppm	LVT	1	6	4.3	10	43.0
			12	5.6	5	28.0
			30	8.3	2	16.6
			60	12.0	1	12.0
200 ppm		1	6	7.4	10	74.0
			12	9.8	5	49.0
			30	14.2	2	28.4
			60	19.8	1	19.8
300 ppm		1	6	10.5	10	105.0
			12	14.0	5	70.0
			30	20.1	2	40.2
			60	27.5	1	27.5
400 ppm		1	6	14.1	10	141.0
			12	18.5	5	92.5
			30	25.2	2	50.4
			60	36.5	1	36.5
500 ppm		1	6	17.8	10	178.0
			12	22.9	5	114.5
			30	30.7	2	61.4
			60	46.0	1	46.0

CONCLUSIONS:

Table A8. Experimental Data of Polymer Concentration and Viscosity (Batch 5).

Polymer Concentration ppm	Viscosity[1] cp
0.0	1.0
0.0	1.0
100.0	43.0
100.0	42.0
200.0	74.0
200.0	74.0
300.0	105.0
300.0	104.0
400.0	141.0
400.0	140.0
500.0	178.0
500.0	178.0

[1] Brookfield Viscometer at 6 rpm and 20° C.

Table A9. Diameter of Sand Column - Volumetric Experiment.

The diameter measurements taken at both the ends of the sand column (without ports) were different by about 1.5 mm. Therefore to get a more representative diameter of the sand column, the column was filled with water, and the volume of water was measured. The average diameter of the sand column was then computed as follows:

Volume, $V = \pi r^2 h = \frac{\pi D^2 h}{4} = 982$ ml.

Length of the column = 90.2 cm.

Therefore, $D^2 = \frac{4V}{\pi h}$ or, $D = (4V/\pi h)^{1/2} = 3.723$

The diameter of the column = 3.723 cm.

= 1.4658 in.

Use this diameter in all calculations.

Inside radius = 1.86 cm.
= 0.73 in.

Use this radius in all calculations.

Table A10. Porosity Determination - Experimental Data.

Weight of empty sand column = 1134.7 g.

Weight of sand column with dry sand = 2763.8 g.

Weight of sand column with water = 3085.4 g.

Volume of water pumped into column = 327 ml.

(Experimentally measured)

Weight of empty pan (used for sand drying) = 1068.0 g.

Weight of pan with dried sand (110 ± 5°C, 4 hrs) = 2714.0 g

Specific gravity of sand (H_2O = 1.0) = 2.65.

Length of sand column (excluding portion with the rubber stoppers)
= 87.4 cm (34.4 in).

Inside diameter of column (based on volumetric measurements of water)
= 3.72 cm (1.47 in).

(Note: Use this diameter in all calculations. The diameter varied; so a representative diameter was obtained based on the volume of water.)

Inside radius = 1.86 cm.
= 0.73 in.

Volume of wet specimen (column) = 950.0 cm^3

Table A11. Ottawa Sand Porosity Computations.

Volume of wet specimen, $V_t = 949.92\ cm^3 \approx 950\ cm^3$

Weight of dry soil, $W_s = 1646.0\ g$

Specific gravity of solids, G_s ($H_2O = 1.0$) = 2.65*

Volume of solids, $V_s = 621.13\ cm^3 = 621.0\ cm^3$

Void ratio, e = 0.5298 = 0.53

Porosity, n = 0.3462 = 0.35

Based on the porosity of 0.35, the volume of water occupying the pore space would be (0.35)(950)=332.5 ml. Experimental measurements yielded 327 ml, which is in close agreement with the calculations.

---

* Specific gravity from the Ottawa Silica product data brochure supplied by the Ottawa Industrial Sand Co., a subsidiary of Ottawa Silica Company, Ottawa, Illinois.

Table A12. Polymer Adsorption Equilibrium Experimental Data (Dowell J333).

Flask ID	Mass of Sand, g	C_o mg/l	Absorbance[1]	C_e mg/l	W, g/l	X_e mg/g	X_e mg/kg
110	10	100	0.106	86.5	200	0.0675	67.5
120	20	100	0.105	85.7	400	0.0358	35.8
130	30	100	0.1	81.6	600	0.0307	30.7
140	40	100	0.093	75.9	800	0.0301	30.1
210	10	200	0.241	196.7	200	0.0165	16.5
220	20	200	0.24	195.9	400	0.0103	10.3
230	30	200	0.24	195.9	600	0.0068	6.8
240	40	200	0.23	187.8	800	0.0153	15.3
310	10	300	0.36	293.9	200	0.0305	30.5
320	20	300	0.365	298.0	400	0.0050	5.0
330	30	300	0.36	293.9	600	0.0102	10.2
340	40	300	0.351	286.5	800	0.0169	16.9
410	10	400	0.485	395.9	200	0.0205	20.5
420	20	400	0.487	397.5	400	0.0063	6.3
430	30	400	0.486	396.7	600	0.0041	4.1
440	40	400	0.483	394.3	800	0.0071	7.1

Notes continued on next page.

Table A12. Polymer Adsorption Equilibrium Experimental Data (Continued).

pH of the polymer solution = 7.0

C_o= initial liquid phase concentration, mg/l.

C_e= equilibrium liqiud phase concentration, mg/l.

From standard curve C_e = 816.3 X Absorbance.

W = mass of sand in the solution, g/l.

[1] Absorbance at 470 nm, Bausch & Lomb Spectronic 20, (Foshee et al., 1976)

APPENDIX - B

FIGURES AND TABLES

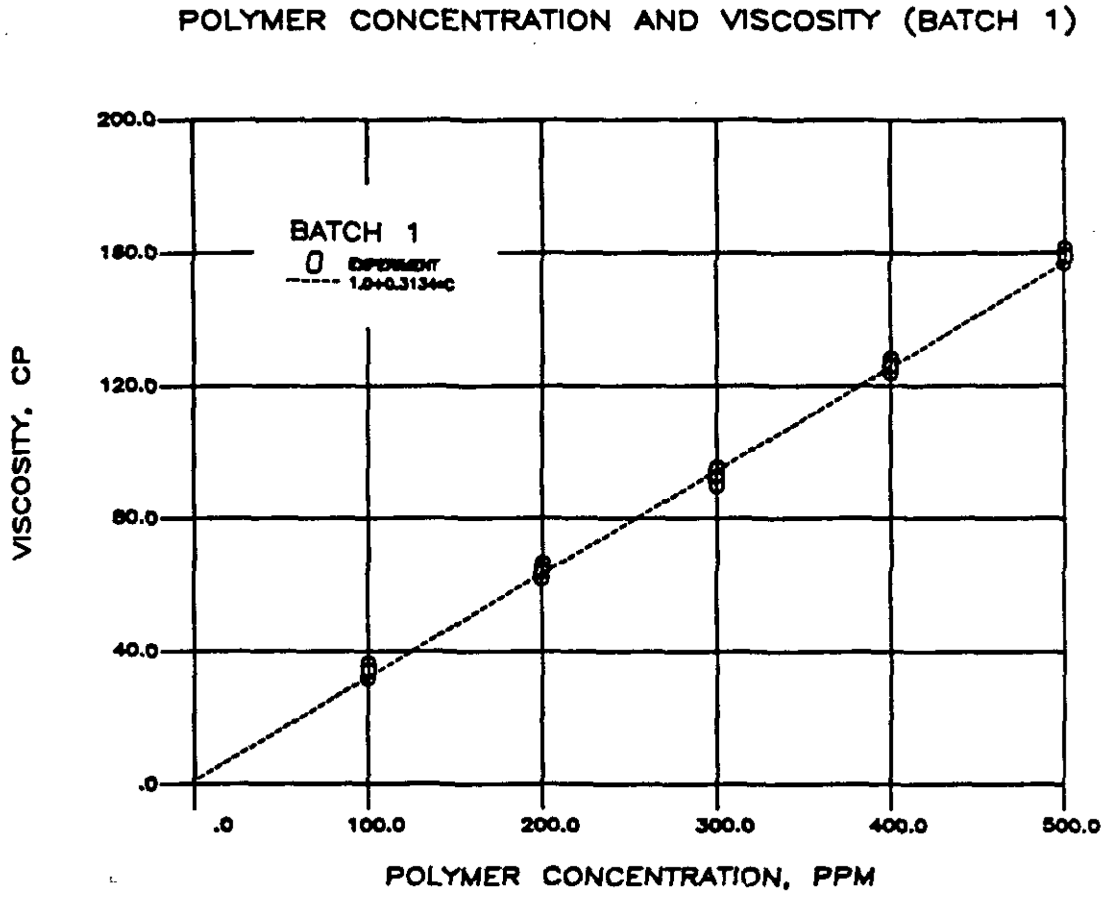


Figure B1. Polymer Concentration and Viscosity Relationship (Batch 1); η (cp) = 1.0 + (0.3134) (C).

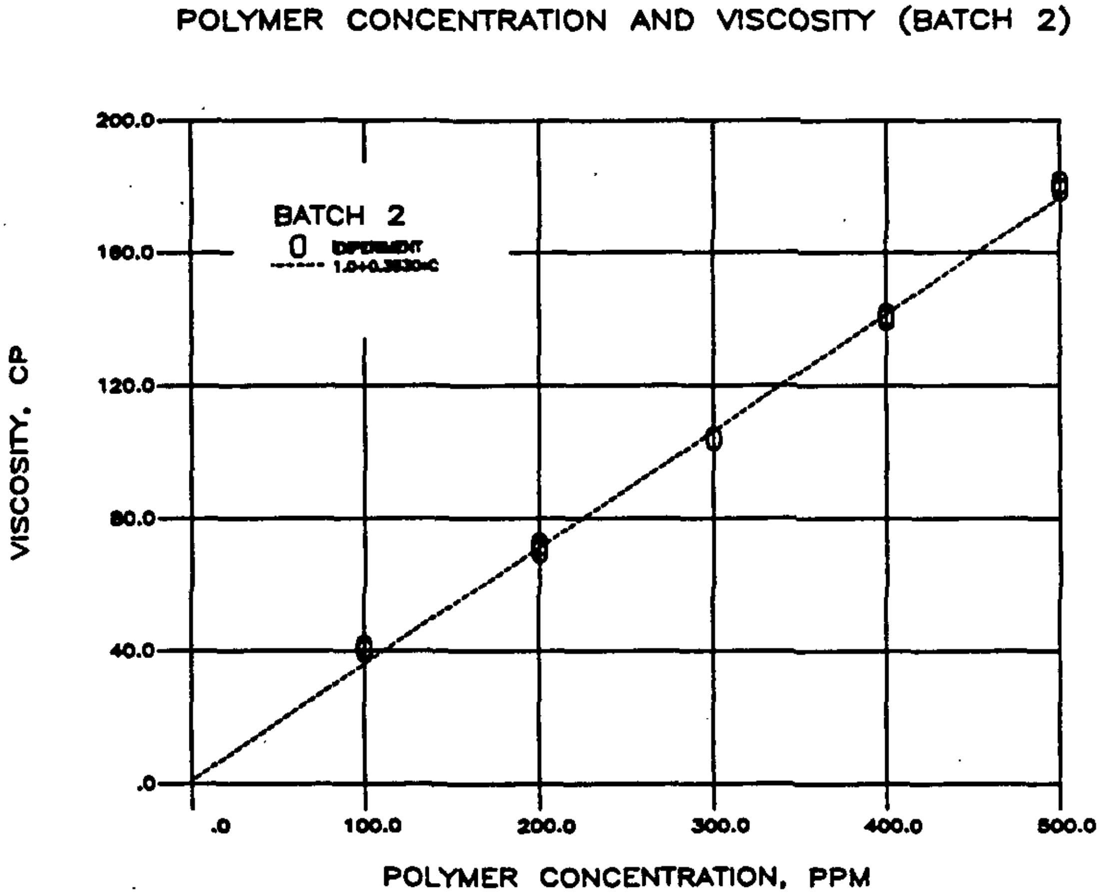


Figure B2. Polymer Concentration and Viscosity Relationship (Batch 2); η (cp) = 1.0 + (0.3530) (C).

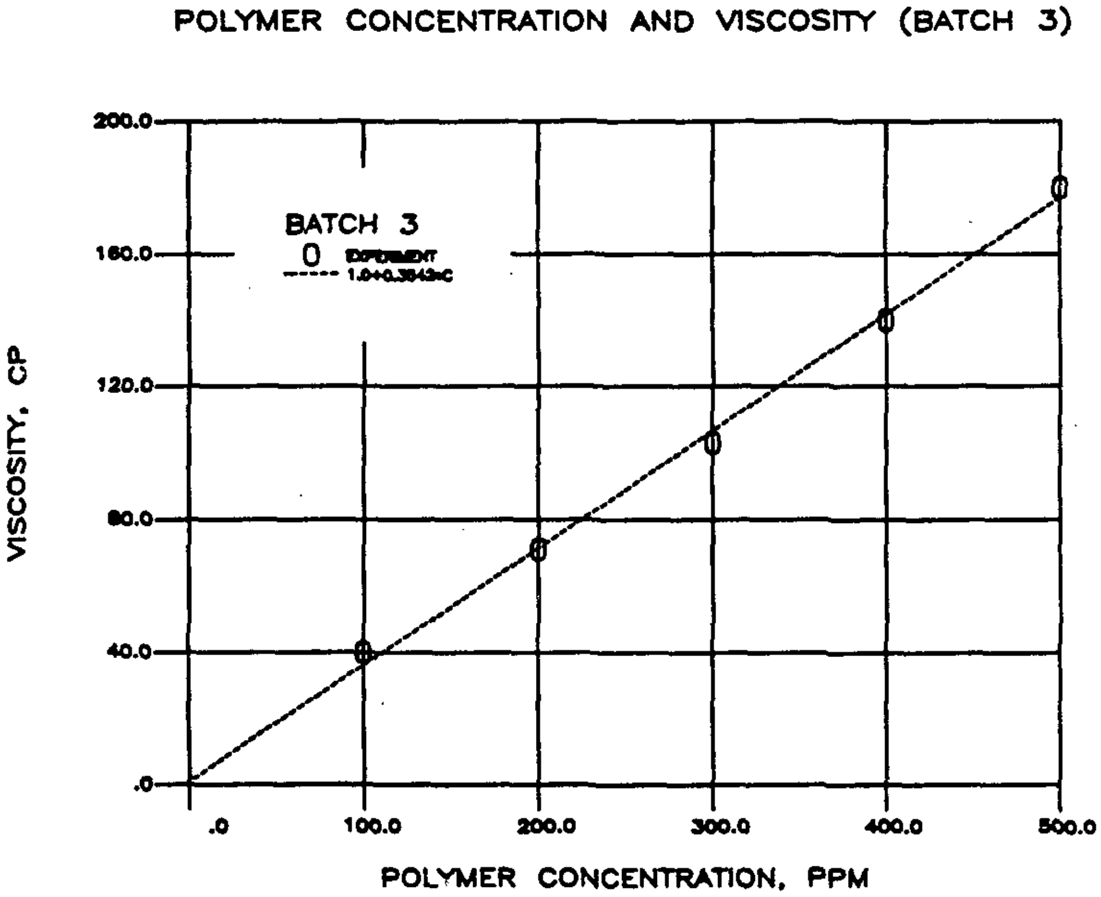


Figure B3. Polymer Concentration and Viscosity Relationship (Batch 3); η (cp) = 1.0 + (0.3542) (C).

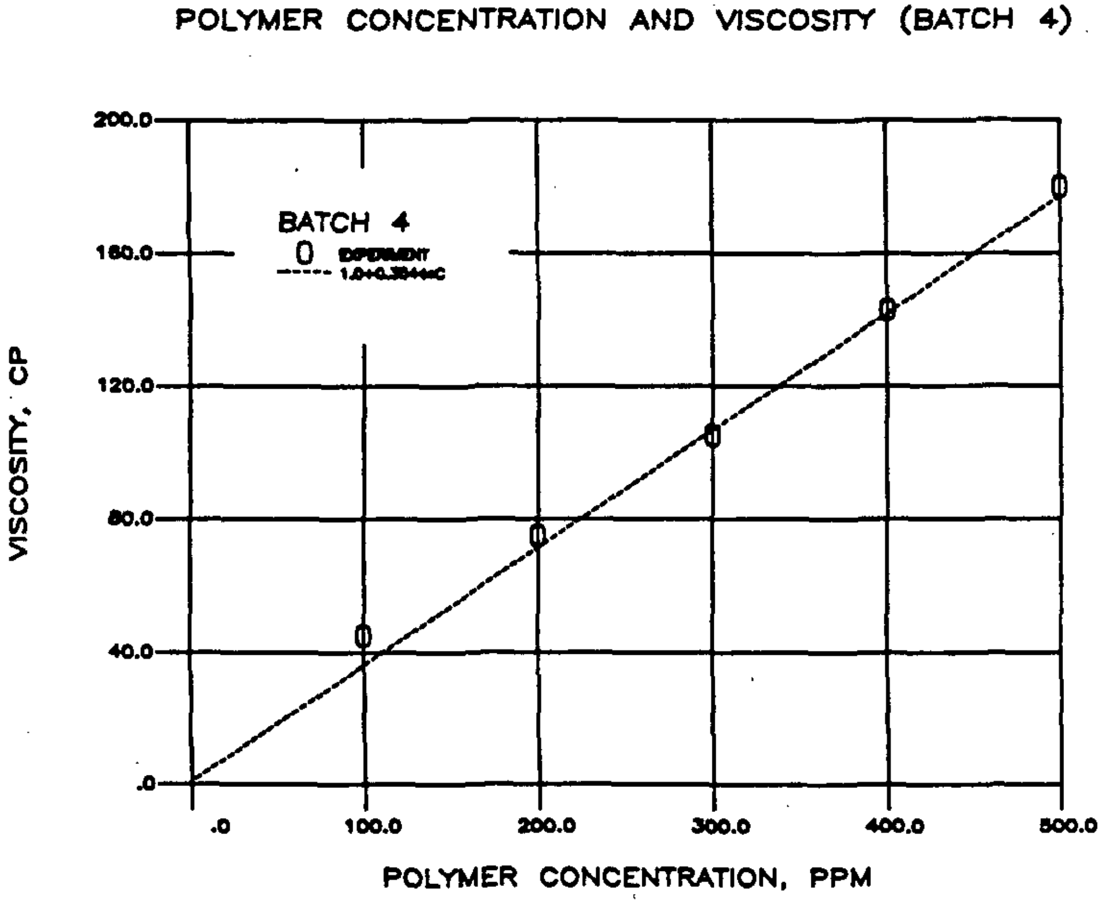


Figure B4. Polymer Concentration and Viscosity Relationship (Batch 4); η (cp) = 1.0 + (0.3544) (C).

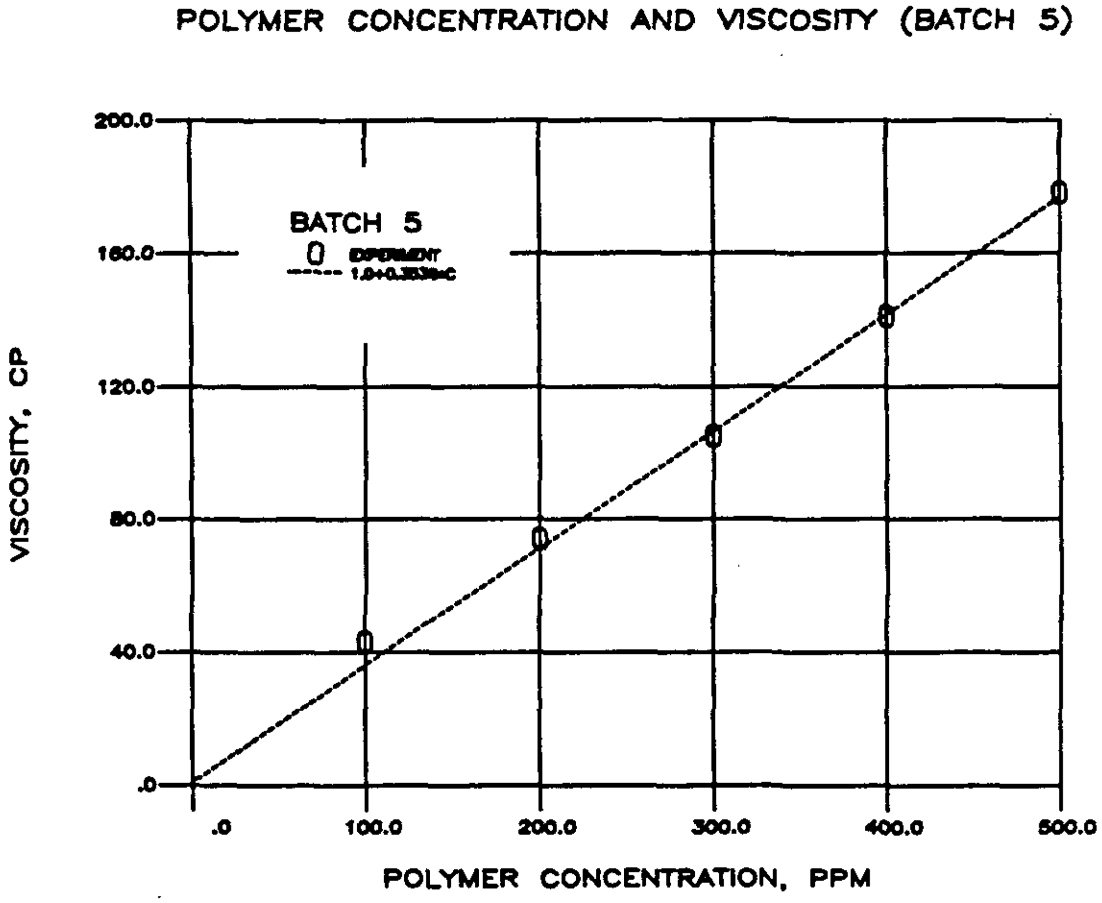


Figure B5. Polymer Concentration and Viscosity Relationship (Batch 5); η (cp) = 1.0 + (0.3536) (C).

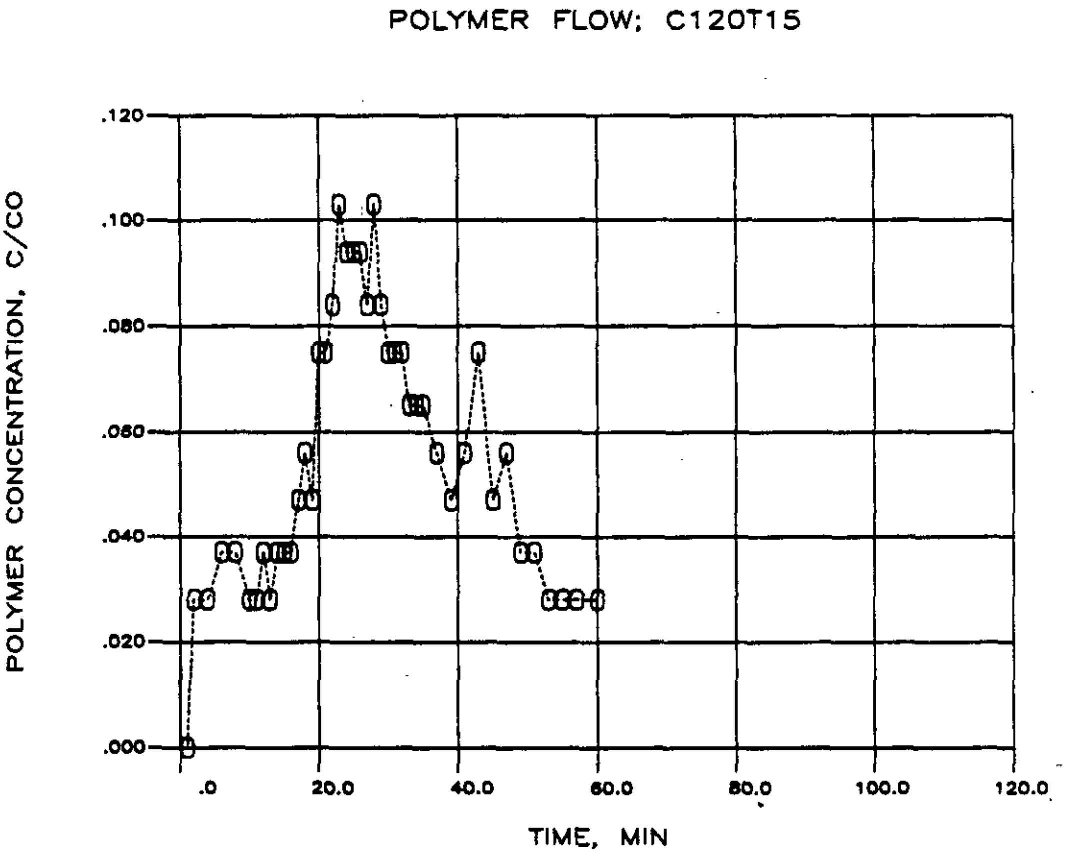


Figure B 6. Polymer Concentration Profile at the Outlet End of the Sand Column (C = 100 ppm, Slug Size = 15 cm, Q = 20 ml/min).

APPENDIX - C

GLOSSARY OF TERMS

GLOSSARY OF TERMS

Acute Toxicity:	Health effects that manifest after a single or short exposure to a compound. These effects are usually of rapid onset, and are of short duration.
Centipoise (cp):	A unit of viscosity equal to 0.01 poise. A poise equals 1.0 dyne-second/cm^2. Viscosity of water at 20°C is 1.0 cp.
Effective Size:	The 90 percent retained size of sand as determined from grain-size analysis; therefore 10 percent of the sand is finer and 90 percent is coarser.
Enhanced Oil Recovery (EOR) Process:	A technique for recovering additional oil from petroleum reservoir beyond that economically recoverable by conventional primary and secondary recovery.
LD_{50}:	Lethal Dose for 50 percent kill, is the single dose that when administered to test animals results in the death of 50 percent of the population. The LD_{50} is expressed in milligrams of compound per kilogram of body weight, mg/kg.
Mobility (λ):	A measure of the ease with which a fuid moves through the porous media, expressed as the ratio of media permeability to fluid viscosity, $\lambda = k/\eta$.

Polyacrylamide:	Chemical formula $-(CH_2CH-CONH_2)_{\overline{n}}$
Polymer:	A type of organic compound characterized by a long chain molecule formed by thousands of repeating units called monomers; it is added to water in polymer flooding.
Systemic Toxicity:	Health effects that manifest in the body after a substance has been absorbed into the blood stream. Absorption may take place through the skin, gastro-intestinal tract or lungs.
Uniformity Coefficient:	A numerical expression of the variety in particle sizes, defined as the ratio of the sieve on which 40 percent (by weight) of the material is retained, to the sievesize on which 90 percent of the material is retained.

APPENDIX - D

POLYMER SOLUTION PREPARATION

POLYMER SOLUTION PREPARATION

Laboratory Technique for Making Solutions of Dowell Mobility Control Polymers (J332, J333, J334).

Solutions of Dowell polymers usually are prepared as a concentrate (approximately 0.5 percent) and diluted to test concentrations as required. Filtration of the polymer solution is recommended as a routine laboratory procedure.

Vigorous agitation is necessary for initial dispersion of the dry polymer. A magnetic stirrer should be adjusted so the bottom of the water vortex is 30 to 50 percent of the diameter of the beaker. To prevent the formation of "slubs" or "fish eyes", drop the polymer just below the upper curve or shoulder of the vortex, as shown in Figure D1. The addition rate should be adjusted so that it is dispersed over a period of 50 to 60 seconds. As soon as all of the polymer has been added, adjust the stirrer to a low speed that just keeps the solid particles from settling to the bottom. The lowest possible speed should be used.

Stir the solution gently for approximately 3 hours. If the solution contains calcium or magnesium adjust the pH to approximately 7.0 using acetic acid and stir for an additional 20 minutes. Solutions are then ready for dilution and filtration as needed. Concentrated solutions of Dowell polymer may be stored at laboratory temperature in brown bottles for two to three weeks without loss of effectiveness.

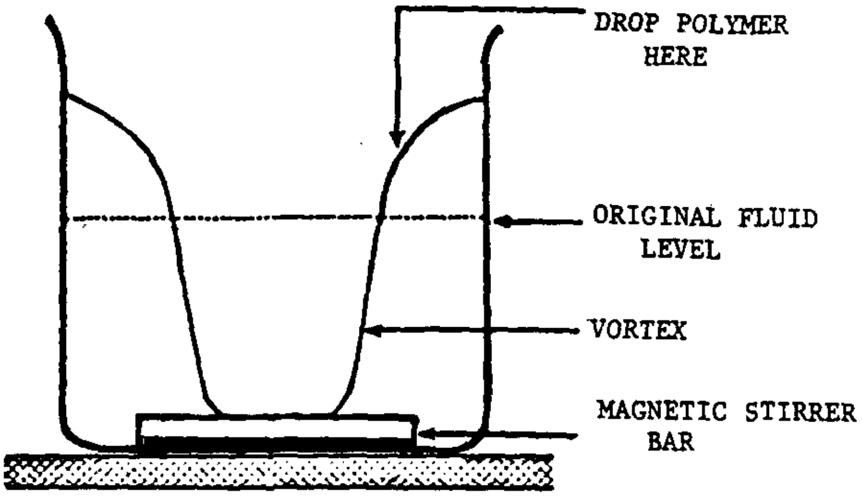


Figure D1. Mixing Apparatus for Polyacrylamide Polymer Solutions.

APPENDIX - E

COMPUTER PROGRAM LISTINGS

```
100 ''       LDT2801.BAS
110 ''       VERSION 4.5
120 ''   REVISION DATE OCTOBER 18, 1985
130    DEFINT C
135 OPTION BASE 1
140 BA  = &H20 'BASE ADDRESS
150 CR  = BA+1 'COMMAND REGISTER
160 SR  = BA+1 'STATUS REGISTER
170 DR  = BA   'DATA REGISTER
180 CW  = &H4  'COMAND WAIT
190 WW  = &H2  'WRITE WAIT
200 RW  = &H5  'READ WAIT
210 CRESET    =  &H0
220 CCLEAR    =  &H1
230 CERROR    =  &H2
240 CCLOCK    =  &H3
250 CDAOUT    =  &H8
260 CSDA      =  &H9
270 CWDA      =  &HA
280 CTEST     =  &HB
290 CADIN     =  &HC
300 CSAD      =  &HD
310 CRAD      =  &HE
320 CSTOP     =  &HF
330 CCONT     =  &H20
340 FS(1,1) = 0     :  FS(1,2) = 10!
350 FS(2,1) = 0     :  FS(2,2) = 5!
360 FS(3,1) = 0     :  FS(3,2) = 2.5
370 FS(4,1) = 0     :  FS(4,2) = 1.25
390 FACTOR# = 4096 :  RANGE = 20  : OFFSET = 10
410 DIM MENU$(4,5)
420 DIM GAIN(4)
440 ''==================SCREEN CONTROL==============================
450 A$= CHR$(27)+"["
460 PS$= A$ + "0J"
470 P$ = A$+"2J"+A$+"H"
480 PR$ = A$+"7m"
490 PA$ = A$+"0m"
500 PIN$ = A$+"1m
510 PE$ = A$+"0K"
520 DEF FNAT$(X,Y)= CHR$(27)+"["+MID$(STR$(X),2)+";"+MID$(STR$(Y),2)+"f"
530 DEF FNSC$(X,Y) = CHR$(27)+"["+MID$(STR$(X),2)+";"+MID$(STR$(Y),2)+"r"
540 ''================= HI AND LOW BYTE ==========================
550 DEF FNHBYTE(X) = INT(X/256)
560 DEF FNLBYTE(X,Y) = INT(X-(256*Y))
570 ''================= MAIN MENU ======================
580 MENU.CONT=1     :  MENU.ITEM=4
590 PROG.CONT=0
600 HEADER$="                     MAIN MENU                  "
610 MENU$(1,1)="TEST"
620 MENU$(1,2)="RESET"
630 MENU$(1,3)="ANALOG TO DIGITAL CONVERSION"
640 MENU$(1,4)="PRINT DATA FILE"
650 IF X=0 THEN GOTO 900  ' INITIAL RESET
660 X=1: GOSUB 770  '' GET USER CHOICE
670 ON PROG.CONT GOTO 1020,900,680,3330
680 ''================= A/D MENU ======================
```

```
690 MENU.CONT=2     : MENU.ITEM=3
700 PROG.CONT=0
710 HEADER$="           ANALOG TO DIGITAL CONVERSION          "
720 MENU$(2,1)="SINGLE CONVERSION        "
730 MENU$(2,2)="MULTIPLE  CONVERSION  "
740 MENU$(2,3)="CALIBRATION CONVERSION"
750 GOSUB 770  '' GET USERS CHIOCE
760 ON PROG.CONT GOTO 1440,1720,2210
770 ''==================== PRINT MENU & GET CHOICE ============
780 PRINT PS
790 PRINT FNATS(3,16);PRS;PIN$;HEADER$;PAS:PRINT
800 FOR L = 1 TO MENU.ITEM
810 PRINT TAB(20);
820 PRINT USING "##";L;
830 PRINT" --  "MENU$(MENU.CONT,L)
840 NEXT L
850 PRINT FNATS(14,27);"ENTER NUMBER OF SELECTION";PE$;:INPUT PROG.CONT
860 IF(PROG.CONT>=1 AND PROG.CONT <= MENU.ITEM) THEN RETURN
870 PRINT FNATS(18,30);PINS;"ILLEGAL SELECTION";PA$
880 PRINT TAB(27);"LEGAL VALUES ARE 1 TO";MENU.ITEM
890 GOTO 850
900 ''====================== RESET========================
910 GOSUB 930
920 GOTO 660
930 STAT= INP(SR)
940 IF NOT ((STAT AND &H70)=0) THEN 4360
950 OUT CR,CSTOP
960 TEMP=INP(DR)
970 WAIT SR,  CW
980 OUT  CR, CRESET
990 WAIT SR, RW
1000 TEMP=INP(DR)
1010 RETURN
1020  ''=================== TEST DT2801 ====================
1030 GOSUB 3780  ' CHECK FOR LEGAL STATUS REGISTER & STOP DT 2801
1040 ER.CNT       = 0
1050 WAIT SR,  CW
1060 OUT  CR, CTEST
1070 '' Read the first 256 test bytes from the Data Out Register.
1080 '' Check each test byte to see if it has the expected value.
1090 PRINT PS;FNATS(11,32);"PERFORMING TEST"
1100 FOR L = 1 TO 255
1110 WAIT SR,  RW
1120 DATA.VAL = INP(DR)
1130 STAT = INP(SR)
1140 IF (STAT AND &H80) THEN GOTO 4360
1150 IF NOT (DATA.VAL = L) THEN GOSUB 1380
1160 NEXT L
1170 L = 0
1180 WAIT SR,  RW
1190 DATA.VAL = INP(DR)
1200 STAT = INP(SR)
1210 IF STAT AND &H80 THEN GOTO 4360
1220 IF NOT (DATA.VAL = L) THEN GOSUB 1380
1230 '' Check for Command Overwrite Error.
1240   GS=1 : GOSUB 4360 : GS=0 :STAT = INP(SR)
1250 IF (STAT AND &H80) = 0 THEN GOTO 1330
1260 IF NOT (ER1 = 2) THEN GOTO 1330
1270 IF NOT (ER2 = 0) THEN GOTO 1330
1280 IF NOT (ER.CNT = 0) THEN GOTO 1300
1290 GOTO 660
1300 PRINT : PRINT "TEST Operation Completed with ";ER.CNT;
1310 PRINT " Data Errors" : PRINT
1320 PRINT CHR$(7) : PRINT CHR$(7) : GOTO 3580
1330 PRINT : PRINT "Error, incorrect board state after stop."
1340 PRINT "Status Register. bit 7 should be set.";
```

```
1350 PRINT "Error Register, Byte 1 should equal 2 hexidecimal."
1360 PRINT "Error Register, Byte 2 should equal 0 hexidecimal."
1370 GOTO 4360
1380 '' If wrong test value, print actual value and expected value.
1390 '' Increment the error count by one for each bad test value.
1400 ER.CNT = ER.CNT + 1
1410 PRINT ER.CNT:"  ERRORS, VALUE READ IS ";HEX$(DATA.VAL);
1420 PRINT " HEXIDECIMAL, SHOULD BE ";HEXS(L)
1430 PRINT CHRS(7) : PRINT CHR$(7) : RETURN
1440  ''================== READ A/D IMMEDIATE ===================
1450 GOSUB 3070
1460 GOSUB 2800 ' Get A/D gain.
1470 GOSUB 2930 ' GET A/D CHANNEL.
1475 DIM ADH(1,1),ADL(1,1)
1480 CYCLES = 1  : NCHAN = 1
1490 '' Write READ A/D IMMEDIATE command.
1500 WAIT SR,  CW
1510 OUT  CR, CADIN
1520 '' Write A/D gain byte.
1530 WAIT SR,  WW, WW
1540 OUT  DR,    GAIN.CODE
1550 '' Write A/D channel byte.
1560 WAIT SR,  WW, WW
1565 GOSUB 2441 ''ANYKEY
1570 OUT  DR,    CHAN(1)
1600 WAIT SR,  RW
1610 ADL(1,1)=INP(DR)
1620 WAIT SR,  RW
1630 ADH(1,1)= INP(DR)
1640 GOSUB 3730  ' '  Wait for READY, Chech for ERROR
1650 GOSUB 2470  ' CALCULATE AND PRINT A/D READING IN VOLTS
1655 ERASE ADH,ADL
1660 PRINT FNATS(19,25);"Do You Want Another Conversion";PES;:INPUT YS
1670 IF YS="Y" OR YS="y" THEN GOTO 1460
1680 IF YS = "N" OR Y$ = "n" THEN GOTO 1700
1690 GOSUB 3870 : GOTO 1660
1700 PRINT FNATS(0,0);PS$;FNATS(5,20);"SINGLE CONVERSION A/D Operation Complete"
1710 GOTO 3580
1720  '' ================READ MULT. A/D ================
1730 GOSUB 3070   ' A/D HEADER
1740 GOSUB 2800 ' GET GAIN
1750 GOSUB 2930  ' Get A/D channel.
1760 GOSUB 3900  ' GET CLOCK RATE
1761 MAX1#=INT(5000/NCHAN)
1762 MAX2#=INT(65535!/(PERIOD#*NCHAN))
1763 IF MAX1#<MAX2# THEN MAX!=MAX1# ELSE MAX!=MAX2#
1770 PRINT PSS;FNAT$(8,29);PSS;PINS;"NUMBER OF CONVERSIONS";PA$
1790 PRINT FNATS(10,15);"Legal values for number of conversion cycles are :"
1800 PRINT FNATS(11,33);"1 through ";:PRINT USING "####";MAX!
1810 PRINT FNATS(13,22);PE$;"Number of conversion cycles value = ";: INPUT CYCLES
1820 IF (CYCLES >= 1 AND CYCLES =<3)  THEN CYCLES=3
1825 IF (CYCLES >= 3 AND CYCLES =<MAX!) THEN GOTO 1845
1830 PRINT FNATS(16,20)"PLEASE USE LEGAL NUMBER OF CONVERSIONS VALUE."
1840 GOTO 1810
1845 DIM ADH(CYCLES,NCHAN)
1846 DIM ADL(CYCLES,NCHAN)
1850 '' Do a SET A/D PARAMETERS command to set up the A/D converter.
1860 '' Write SET A/D PARAMETERS command.
1870 NUM.CONV = CYCLES*NCHAN*IGNORE
1880 WAIT SR,  CW
1890 OUT  CR, CSAD
1900 '' Write A/D gain byte.
1910 WAIT SR,  WW, WW
1920 OUT  DR,    GAIN.CODE
1930 '' Write A/D start channel byte.
1940 WAIT SR.  WW. WW
```

```
1950 OUT  DR,    START.CHAN
1960 '' Write A/D end channel byte.
1970 WAIT SR,  WW, WW
1980 OUT  DR,    END.CHAN
1990 '' Write high and low bytes of NCONVERSIONS#.
2000 NUMBERH = INT(NUM.CONV/256)
2010 NUMBERL = NUM.CONV - NUMBERH * 256
2020 WAIT SR,  WW, WW
2030 OUT  DR,    NUMBERL
2040 WAIT SR,  WW, WW
2050 OUT  DR,    NUMBERH
2060 '' Write READ A/D command.
2061 GOSUB 2441  ' ANY KEY
2070 PRINT FNAT$(6,0);PS$;FNAT$(14,30);"CONVERSION UNDERWAY"
2075 IF TIMEFLAG=1 THEN 2161
2076 IF NCHAN=1 THEN 2151
2080 WAIT SR,  CW
2090 OUT  CR, CRAD
2100 FOR I = 1 TO CYCLES
2110 FOR K = 1 TO IGNORE
2120 FOR J= 1 TO NCHAN
2130 WAIT SR,  RW :  ADL(I,J) = INP(DR)
2140 WAIT SR,  RW :  ADH(I,J) = INP(DR)
2145 NEXT J :NEXT K: NEXT I
2150 GOTO 2176
2151 WAIT SR,  CW
2152 OUT  CR, CRAD
2153 FOR I = 1 TO CYCLES
2154 FOR K = 1 TO IGNORE
2155 WAIT SR,  RW :  ADL(I,1) = INP(DR)
2156 WAIT SR,  RW :  ADH(I,1) = INP(DR)
2157 NEXT K: NEXT I
2160 GOTO 2176
2161 IF NCHAN=1 THEN GOTO 2170
2162 WAIT SR,  CW
2163 OUT  CR, CRAD
2164 FOR I = 1 TO CYCLES
2165 FOR J= 1 TO NCHAN
2166 WAIT SR,  RW :  ADL(I,J) = INP(DR)
2167 WAIT SR,  RW :  ADH(I,J) = INP(DR)
2168 NEXT J: NEXT I
2169 GOTO 2176
2170 WAIT SR,  CW
2171 OUT  CR, CRAD
2172 FOR I = 1 TO CYCLES
2173 WAIT SR,  RW :  ADL(I,1) = INP(DR)
2174 WAIT SR,  RW :  ADH(I,1) = INP(DR)
2175 NEXT I
2176 GOSUB 3730  ' ' Wait for READY,Check for ERROR
2177 GOSUB 2470 ' Calculate and print the A/D readings in volts.
2180 GOSUB 3130 ' SAVE DATA
2181 ERASE ADH,ADL
2182 PRINT FNAT$(6,0);PS$;FNAT$(12,20);"Do You Want Another Conversion Run";
       PE$ ;:INPUT Y$
2183 IF Y$="Y" OR Y$="y" THEN GOTO 1730
2184 IF Y$="N" OR Y$="n" THEN GOTO 2190
2185 GOSUB 3880:GOTO 2182
2190 PRINT FNAT$(0,0);PS$;FNAT$(5,25);"MULTIPLE A/D Operation Complete"
2200 GOTO  3580
2210 ''====================== CALIBRATION A/D ====================
2220 GOSUB 3070
2230 GOSUB 2800
2240 GOSUB 2930
2250 PRINT FNAT$(6,0);PS$;FNAT$(20,25);PIN$;"PRESS ANY KEY TO STOP";PA$
2260 Y$=INKEY$
2270 '' Write READ A/D IMMEDIATE command.
```

```
2280 WAIT SR,  CW
2290 OUT  CR, CADIN
2300 '' Write A/D gain byte.
2310 WAIT SR,  WW, WW
2320 OUT  DR,    GAIN.CODE
2330 '' Write A/D channel byte.
2340 WAIT SR,  WW, WW
2350 OUT  DR,    CHAN(1)
2360 WAIT SR,  RW :  LOW = INP(DR)
2370 WAIT SR,  RW :  HIGH = INP(DR)
2380 VOLTS= HIGH*256+LOW
2390 IF VOLTS > 32767 THEN VOLTS = VOLTS -65536!
2400 VOLTS = VOLTS*((FS(GC,2)-FS(GC,1))/4096)+FS(GC,1)
2410 PRINT FNAT$(13,30);"VOLTS = ";PE$;:PRINT USING "###.######";VOLTS
2420 IF Y$="" THEN GOTO 2260
2421 PRINT FNAT$(6,0);PS$;FNAT$(12,20);"Do You Want To Calibrate Another Channel";
       :INPUT Y$
2422 IF Y$="Y" OR Y$="y" THEN GOTO 2230
2423 IF Y$="N" OR Y$="n" THEN GOTO 2430
2430 PRINT PS;FNAT$(5,20);"CALIBRATION A/D Operation Complete"
2440 GOTO 3580
2441 ''====================== ANY KEY ===============================
2442 PRINT FNAT$(6,0);PS$;FNAT$(12,25);"PRESS ANY KEY TO TAKE READING";
2443 Y$=INKEY$:IF Y$="" THEN 2443
2444 RETURN
2450 ''====================== A/D VOLTAGE OUTPUT=====================
2460 '' Calculate and print the A/D reading in volts.
2470 IF PROG.CONT = 1 THEN GOTO 2520
2480 FOR I = 1 TO NCHAN
2490 CHAN(I) = START.CHAN+I-1
2500 IF CHAN(I) => 16 THEN CHAN(I) = CHAN(I)-16
2510 NEXT I
2515 M=1
2520 FOR J = 1 TO CYCLES
2530 FOR L = 1 TO NCHAN
2540 ADH(J,L)  = ADH(J,L)*256 + ADL(J,L)
2550 IF ADH(J,L) > 32767 THEN ADH(J,L) = ADH(J,L) -65536!
2560 ADH(J,L) = ADH(J,L)*((FS(GC,2)-FS(GC,1))/4096)+FS(GC,1)
2561 ADL(J,L)= M*PERIOD#
2562 M=M+1
2570 NEXT L: NEXT J
2590 IF PROG.CONT = 1 THEN GOTO  2750
2600 PRINT FNAT$(6,0);PS$;"CYCLE";
2610 FOR I = 1 TO NCHAN: COLUMN! = I*20-7: PRINT FNAT$(6,COLUMN!);
       "TIME    CHAN ";: PRINT USING "##";CHAN(I);:NEXT I
2620 ROW = 6 : PRINT FNAT$(7,1);PS$;
2630 FOR J= 1 TO CYCLES
2640 ROW!=ROW!+1
2650 PRINT PS$;: PRINT USING "####";J;:PRINT "   ";
2655 FOR K = 1 TO NCHAN
2660 PRINT USING "####.####";ADL(J,K);
2680 PRINT USING "###.#######";ADH(J,K);: NEXT K
2685 PRINT
2690 IF J= CYCLES THEN ROW!=21
2700 IF ROW!= 21 THEN PRINT FNAT$(23,5);PIN$;
       "PLEASE PRESS ANY KEY TO CONTINUE    E TO EXIT";PA$;
2710 IF ROW!= 21 THEN Y$=INKEY$ : IF Y$ ="" THEN 2710
2715 IF Y$="E" OR Y$="e" THEN 2740
2720 IF ROW!= 21 THEN ROW!=7:PRINT FNAT$(ROW!,1);PS$;
2730 NEXT J
2740 RETURN
2750 PRINT FNAT$(12,15);PS$;"INPUT VALUE ON CHANNEL ";
2751 PRINT USING "###";CHAN(1);
2752 PRINT FNAT$(12,43);"IS";
2760 PRINT USING "###.######";ADH(1,1);
2770 PRINT "   VOLTS" : PRINT
```

```
2780 RETURN
2790 ''====================== GAIN SELECTION ======================
2800 GAIN(1)=1  :  GAIN(2)=2  : GAIN(3)=4  : GAIN(4)=8
2810 CODE(1)=0 :CODE(2)=1:CODE(3)=2:CODE(4)=3
2820 PRINT FNAT$(8,30);PS$;PIN$;"   GAIN SELECTION";PA$;PE$
2830 PRINT FNAT$(10,31);"Legal values are :"
2840 PRINT FNAT$(12,27);"GAIN";FNAT$(12,43);"VOLTAGE RANGE"
2850 PRINT FNAT$(14,26);GAIN(4);FNAT$(14,40);"0 to 1.25 Volts "
2860 PRINT FNAT$(15,26);GAIN(3);FNAT$(15,40);"0 to 2.50 Volts   "
2870 PRINT FNAT$(16,26);GAIN(2);FNAT$(16,40);"0 to 5.00 Volts "
2880 PRINT FNAT$(17,26);GAIN(1);FNAT$(17,40);"0 to 10.0 Volts"
2890 PRINT FNAT$(19,34);"Gain value = ";PE$;: INPUT Y
2900 FOR I = 1 TO 4 : IF GAIN(I) = Y THEN GAIN.CODE=CODE(I) :GC=I: RETURN
2910 NEXT I
2920 PRINT FNAT$(21,26)"PLEASE USE LEGAL GAIN VALUE." : GOTO 2830
2930 ''====================== CHANNEL SELECTION ===================
2940 '' Get A/D channel.
2950 PRINT FNAT$(8,31);PS$;PIN$;"CHANNEL SELECTION";PA$
2960 PRINT FNAT$(10,18);"Legal values for A/D channels are 0 through 15."
2970 IF PROG.CONT = 2 THEN 3020
2980 PRINT FNAT$(12,30);"A/D Channel value = ";PE$;:INPUT CHAN(1)
2990 IF CHAN(1) < 0 OR CHAN(1) > 15 THEN PRINT FNAT$(15,25);
      "PLEASE USE LEGAL CHANNEL VALUE" : GOTO 2980
3000 NCHAN = 1
3010 RETURN
3020 PRINT FNAT$(12,27);"A/D Start Channel value = ";PE$;: INPUT START.CHAN
3030 PRINT FNAT$(13,27);"A/D End   Channel value = ";PE$;: INPUT END.CHAN
3040 IF START.CHAN < 0 OR START.CHAN > 15 OR  END.CHAN < 0 OR END.CHAN > 15
      THEN PRINT FNAT$(15,25);"PLEASE USE LEGAL CHANNEL VALUE" : GOTO 3020
3050 IF ( END.CHAN-START.CHAN+1 )=<0 THEN NCHAN = END.CHAN-START.CHAN+16 ELSE
      NCHAN = END.CHAN - START.CHAN+1
3060 RETURN
3070 ''====================== A/D SCREEN CONTROL ==================
3080 PRINT FNSC$(6,24);PS;PIN$
3090 PRINT PRS;TAB(80)
3100 PRINT TAB(30);MENU$(MENU.CONT,PROG.CONT);"                          "
3110 PRINT TAB(77);PA$
3120 RETURN
3130 ''====================== DATA FILE OUTPUT ======================
3140 PRINT FNAT$(6,0);PS$:PRINT FNAT$(8,15);
      "Do You Wish To Save This Set Of Data (Y Or N)";PE$;:INPUT Y$
3150 IF Y$="Y" OR Y$="y" THEN GOTO 3180
3160 IF Y$="N" OR Y$="n" THEN RETURN
3170 GOSUB 3880 : GOTO 3140
3180 PRINT FNAT$(10,15);"What Is The Name Of The Data File";PE$;:INPUT Y$
3190 IF LEN(Y$)>9 THEN PRINT FNAT$(12,25);"ILLEGAL FILE NAME":GOTO 3180
3200 FOR I= 1 TO LEN(Y$)
3210 T=ASC(MID$(Y$,I,1))
3220 IF (T<65 OR T>90) AND (T<48 OR T>57) THEN PRINT FNAT$(12,25);
      "ILLEGAL FILE NAME: MUST BE CAPITALS OR NUMBERS":GOTO 3180
3230 NEXT I
3240 Y$=Y$+".DAT"
3250 OPEN "O",#1,Y$
3260 WRITE #1,NCHAN,CYCLES,PERIOD#,GAIN(GC)
3270 FOR I=1 TO NCHAN :WRITE #1,CHAN(I):NEXT I
3280 FOR J=1 TO CYCLES: FOR K=1 TO NCHAN: WRITE #1,ADL(J,K)
3290 WRITE #1,ADH(J,K)
3300  NEXT K:NEXT J
3310 CLOSE #1
3320 RETURN
3330 ''======================== READ A FILE AND PRINT IT ===================
3340 PRINT PS;FNAT$(8,12);"What Is The Name Of The File To Be Printed";
3350 INPUT Y$
3360 IF LEN(Y$)>9 THEN PRINT FNAT$(10,20);"Please Use Legal File Name" : GOTO 3340
3370 Y$=Y$+".DAT"
3380 OPEN "I",#1,Y$
```

```
3390 INPUT #1,NCHAN,CYCLES,PER,RISE
3392 NUM.CONV=CYCLES*NCHAN
3395 DIM ADH(CYCLES,NCHAN),ADL(CYCLES,NCHAN)
3400 FOR I=1 TO NCHAN :INPUT #1,CHAN(I) :NEXT I
3410 FOR J=1 TO CYCLES :FOR K=1 TO NCHAN
3415 INPUT #1,ADL(J,K)
3420 INPUT #1,ADH(J,K)
3430 NEXT K : NEXT J
3440 CLOSE #1
3442 OPEN "O",#1,Y$
3445 WRITE #1, "NAME OF FILE = ";Y$
3450 WRITE #1, "NUMBER OF CHANNELS = ";NCHAN
3460 WRITE #1, "NUMBER OF CYCLES   = ";CYCLES
3470 WRITE #1, "PERIOD = ";PER,"   FREQUENCY = ";1/PER
3480 WRITE #1, "GAIN = ";RISE
3490 ''WRITE #1, :WRITE #1, "CYCLE       ";
3500 ''FOR I= 1 TO NCHAN :WRITE #1, " TIME       CHAN ";I;:NEXT I
3510 ''WRITE #1, " "
3511 ''WRITE #1, "           ";
3512 ''FOR L=1 TO NCHAN : WRITE #1, " SECONDS    VOLTS  ";:NEXT L:WRITE #1
3520 FOR J= 1 TO CYCLES:WRITE #1, USING "####";J;:WRITE #1, "    ";
3530 FOR K=1 TO NCHAN
3535 WRITE #1, USING "####.####";ADL(J,K);
3540 WRITE #1, USING "###.######";ADH(J,K);:NEXT K
3550 WRITE #1: NEXT J
3555 ERASE ADL,ADH
3557 CLOSE #1
3560 PRINT PS;FNAT$(6,20);"File Printing Complete"
3570 GOTO 3580
3580 ''=============== RUN PROGRAM AGAIN ==========================
3590 PRINT FNSC$(0,0)
3600 PRINT FNAT$(8,25);PR$;PIN$;"          OPERATION MENU        ";PA$
3610 PRINT FNAT$(11,28);"1.   RUN PROGRAM AGIAN"
3620   PRINT FNAT$(12,28);"2.   RETURN TO SUB-MENU"
3630   PRINT FNAT$(13,28);"3.   RETURN TO MAIN MENU"
3640   PRINT FNAT$(14,28);"4.   END
3650   PRINT FNAT$(17,24);"ENTER THE NUMBER OF YOUR SELECTION";PE$;:INPUT SEL
3660   IF SEL < 1 OR SEL >4 THEN PRINT FNAT$(20,24);
         "PLEASE USE VALUE BETWEEN 1 AND 4" ELSE GOTO 3680
3670   GOTO 3650
3680   ON SEL GOTO 3690,3720,580,4710
3690   ON MENU.CONT GOTO 3700,3710
3700   ON PROG.CONT GOTO 1020,900
3710   ON PROG.CONT GOTO 1440,1720,2210
3720   ON MENU.CONT GOTO 580,680
3730 ''========  Wait for READY, Check for ERROR==================
3740  WAIT SR, CW
3750  STAT=INP(SR)
3760  IF (STAT AND &H80) THEN GOTO 4360
3770  RETURN
3780 ''============= CHECK FOR LEGAL STATUS REGISTER ===============
3790 STAT=INP(SR)
3800 IF NOT ((STAT AND &H70)=0)  THEN GOTO 4360
3810 ''============== STOP THE DT2801 ==============================
3820 OUT CR, CSTOP
3830 TEMP=INP(DR)
3840 WAIT SR, CW
3850 OUT CR, CCLEAR
3860 RETURN
3870 ''==================== YES OR NO ============================
3880   PRINT : PRINT "          Please respond with Y or N.":RETURN
3890 ''===================== CLOCK SUB-ROUTINE ===================
3900 PRINT FNAT$(8,32);PS$;PIN$;"CLOCK SELECTION";PA$
3910 PRINT FNAT$(10,31);"Legal Values Are :"
3920 PRINT FNAT$(11,26);"Frequency --  Less Than 100 Hz "
3930 PRINT FNAT$(12,21);"Period    --  Greater Than .01 seconds"
```

```
3940 PRINT FNAT$(14,17);"Do you wish to set pacer clock frequency (F) Or"
3950 PRINT FNAT$(15,29);"pacer clock period (P)";PE$;:INPUT Y$
3960 IF Y$ = "F" OR Y$ = "f" THEN GOTO 4010
3970 IF Y$ = "P" OR Y$ = "p" THEN GOTO 4060
3980 PRINT FNAT$(17,27);"Please respond with F Or P"
3990 GOTO 3950
4000 '' Get input in Hertz.
4010 PRINT FNAT$(17,21);"Desired pacer clock frequency in Hertz";PE$;: INPUT FREQ#
4020 IF FREQ# > 100 THEN GOSUB 4090: GOTO 4010
4030 PERIOD#= 1/FREQ#
4040 GOTO 4100
4050 '' Get input in seconds.
4060 PRINT FNAT$(17,21);"Desired pacer clock period in seconds";PE$;: INPUT PERIOD
4070 IF  PERIOD# < .01 THEN GOSUB 4090: GOTO 4060
4080 GOTO 4100
4090 PRINT FNAT$(19,29);"PLEASE USE LEGAL VALUE": RETURN
4100 FREQ#=1/PERIOD#
4110 PRINT FNAT$(19,25);"Frequency =  ";
4120 PRINT USING "###.######";FREQ#;
4130 PRINT "  Hertz"
4140 PRINT FNAT$(20,25);"Period    =  ";
4150 PRINT USING "####.####";PERIOD#;
4160 PRINT "  Seconds"
4170 PRINT FNAT$(22,25);"Are these values correct (Y/N)";:INPUT Y$
4180 IF Y$ = "Y" OR Y$ = "y" THEN GOTO 4201
4190 IF Y$ = "N" OR Y$ = "n" THEN GOTO 3900
4200 GOSUB 3740  : GOTO 4170
4201 TIMEFLAG=0
4205 IF PERIOD#<.1638 THEN TICKS#=PERIOD# : TIMEFLAG = 1 :IGNORE = 1: GOTO 4240
4210 IGNORE = INT(PERIOD#/.1)
4220 TICKS# = PERIOD#/IGNORE
4230 IF TICKS# > .163875  THEN IGNORE = IGNORE+1:GOTO 4220
4240 TICKS# = TICKS#/.0000025
4250 '' Wrtie SET CLOCK RATE command.
4260 WAIT SR,  CW
4270 OUT  CR, CCLOCK
4280 HIGH = INT( FNHBYTE(TICKS#))
4290 LOW  = INT(FNLBYTE(TICKS#,HIGH))
4300 WAIT SR, WW, WW
4310 OUT  DR,   LOW
4320 WAIT SR, WW, WW
4330 OUT  DR,   HIGH
4340 GOSUB 3730   ' ' Wait for READY, Check for ERROR
4350 RETURN
4360 ''=============== ERROR HANDLING ====================
4370 '' Read the Error Register.
4380 OUT. CR, CSTOP : TEMP = INP(DR)
4390 WAIT SR, CW
4400 OUT CR, CERROR
4410 WAIT SR, RW
4420 ER1 = INP(DR)
4430 WAIT SR, RW
4440 ER2=INP(DR)
4450 IF (GS=1) THEN RETURN
4470 PRINT P$;FNAT$(3,25);"Status Register Error bit set"
4480 PRINT
4490 '' Print names of any set error bits.
4500 ERS$ = "                    ERROR "
4510 IF ER1 AND 1   THEN PRINT ERS$;"0, Reserved"
4520 IF ER1 AND 2   THEN PRINT ERS$;"1, Command Overwrite Error"
4530 IF ER1 AND 4   THEN PRINT ERS$;"2, Clock Set Error"
4540 IF ER1 AND 8   THEN PRINT ERS$;"3, Digital Port Select Error"
4550 IF ER1 AND 16  THEN PRINT ERS$;"4, Digital Port Set Error"
4560 IF ER1 AND 32  THEN PRINT ERS$;"5, DAC Select Error"
4570 IF ER1 AND 64  THEN PRINT ERS$;"6, DAC Clock Error"
4580 IF ER1 AND 128 THEN PRINT ERS$;"7, DAC #Conversions Error"
```

```
4590 IF ER2 AND 1   THEN PRINT ERS$;"8, A/D Channel Error"
4600 IF ER2 AND 2   THEN PRINT ERS$;"9, A/D Gain Error"
4610 IF ER2 AND 4   THEN PRINT ERS$;"10, A/D Clock Error"
4620 IF ER2 AND 8   THEN PRINT ERS$;"11, A/D Multiplexer Error"
4630 IF ER2 AND 16  THEN PRINT ERS$;"12, A/D #Conversions Error"
4640 IF ER2 AND 32  THEN PRINT ERS$;"13, Data where Command";
4650 IF ER2 AND 32  THEN PRINT " Expected Error"
4660 IF ER2 AND 64  THEN PRINT ERS$;"14, Reserved"
4670 IF ER2 AND 128 THEN PRINT ERS$;"15, Reserved"
4680 GOSUB 930
4681 PRINT FNAT$(20,27);"PRESS ANY KEY TO CONTINUE"
4682 Y$=INKEY$:IF Y$="" THEN 4682
4683 ERASE ADH,ADL
4690 PRINT P$;FNAT$(5,20);"READ ERROR REGISTER Operation Complete"
4700 GOTO 3580
4710 END
```

Note: Any line in this program without a line number is a continuation line of the previous line. It is printed on two lines just for printing purposes only.

```
0100 ''          THIS PROGRAM READS THE DATA FROM DIFFERENT FILES AND
0110 ''          WRITES ALL THE DATA TO ONE FILE. IT ALSO COMPUTES THE
0120 ''          PRESSURE IN INCHES OF WATER AND PRINTS IT ON PRINTER.
0130 ''                           FILENAME: DATADD.BAS
0135 '' -----------------------------------------------------------------
0140 DIM ADL(160,10), ADH(160,10), SLOPE(10), CONST(10)
0150 NDATA = 0
0160 PRINT P$;"What Is The Name Of The File To Be Read"; : INPUT Y$
0170 IF LEN(Y$)>9 THEN PRINT ; "Please Use Legal File Name" : GOTO 0160
0180 Y$ = Y$+".DAT"
0190 NDATA = NDATA + 3
0200 OPEN "I", #1, Y$
0210 INPUT #1, NCHAN, CYCLES, PER, RISE
0220 IF NDATA > 3 THEN GOTO 0270
0230 OPEN "O", #2, "COPY"
0240 PRINT #2, NCHAN, CYCLES, PER, RISE
0250 FOR I=1 TO NCHAN : INPUT #1, CHAN(I) : PRINT #2, CHAN(I) : NEXT I
0260 GOTO 0280
0270 FOR I = 1 TO NCHAN : INPUT #1, CHAN(I) : NEXT I
0280 FOR J=1 TO CYCLES : FOR K=1 TO NCHAN
0290 INPUT #1, ADL (J,K) : INPUT #1, ADH (J,K)
0300 PRINT #2, ADL (J,K) : PRINT #2, ADH (J,K)
0310 NEXT K : NEXT J
0320 CLOSE #1
0330 PRINT P$; "Do You Want To Read Another File (Y/N)"; : INPUT Y$
0340 IF Y$="Y" OR Y$="y" THEN GOTO 0160
0350 PRINT #2, NDATA
0360 CLOSE #2
0370 PRINT P$; "Do You Want To Save This Data (Y/N)"; : INPUT Y$
0380 IF Y$="N" OR Y$="n" THEN GOTO 0900
0390 PRINT P$; "What Is The Name Of The File"; : INPUT YF$
0400 IF LEN(YF$)>9 THEN PRINT ; "Please Use Legal File Name" : GOTO 0390
0410 YF$ = YF$+".DAT"
0420 NAME "COPY" AS YF$
0430 PRINT P$; "Do You Want To Print This File (Y/N)"; : INPUT Y$
0440 IF Y$="N" OR Y$="n" THEN GOTO 0900
0450 PRINT P$; "What Is The Name Of The File With Slope And Intercept Data";
0460 INPUT YY$
0470 IF LEN(YY$) > 9 THEN PRINT; "Please Use Legal File Name" : GOTO 0450
0480 YY$ = YY$ + ".DAT"
0490 OPEN "I", #3, YY$
0500 FOR I = 1 TO NCHAN : INPUT #3, SLOPE(I), CONST(I) : NEXT I
0510 CLOSE #3
0520 OPEN "I", #1, YF$
0530 INPUT #1, NCHAN, CYCLES, PER, RISE
0540 FOR I = 1 TO NCHAN : INPUT #1, CHAN(I) : NEXT I
0550 FOR J = 1 TO NDATA : FOR K = 1 TO NCHAN
0560 INPUT #1, ADL(J,K) : INPUT #1, ADH(J,K)
0570 NEXT K : NEXT J
0580 INPUT #1, NDATA
0590 CLOSE #1
0600 PRINT P$; "Date of Experiment"; : INPUT Y1$
0610 PRINT P$; "Any Special Remarks About This Experiment"; : INPUT Y2$
0620 LPRINT : LPRINT : LPRINT
0630 LPRINT "             NAME OF FILE = "; YF$
0640 LPRINT "             DATE OF EXPERIMENT = "; Y1$
0650 LPRINT "             REMARKS = "; Y2$
```

```
0660 LPRINT "              NUMBER OF CHANNELS = "; NCHAN
0670 LPRINT "              NUMBER OF CYCLES = "; NDATA/3
0680 LPRINT "              PERIOD = "; PER, "    FREQUENCY = "; 1/PER
0690 LPRINT "              GAIN = "; RISE
0700 LPRINT : LPRINT "               CYCLE  ";
0710 FOR I = 1 TO NCHAN : LPRINT "   CHAN"; I; : NEXT I
0720 LPRINT
0730 LPRINT "                         ";
0740 FOR L = 1 TO NCHAN : LPRINT "  INCH    "; : NEXT L
0750 LPRINT : LPRINT
0760 FOR J=3 TO NDATA STEP 3:LPRINT USING "          ####";J/3;:LPRINT "    ";
0770 FOR K = 1 TO NCHAN
0780 ADH(J,K) = ADH(J,K) * SLOPE(K) + CONST(K)
0790 LPRINT USING "####.#####"; ADH(J,K); : NEXT K
0800 LPRINT : NEXT J
0810 ERASE ADL, ADH
0820 PRINT "File Printing Complete"
0900 END
```

```
100 ''        THIS PROGRAM READS THE TRANSDUCER OUTPUT DATA IN VOLTS
110 ''        (FROM THE DATA FILE SAVED USING "DATADD.BAS" PROGRAM),
120 ''          COMPUTES THE HEAD IN INCHES OF WATER AND PRINTS IT.
130 ''                       FILENAME: DATPRINT.BAS
135 '' ------------------------------------------------------------------
140 DIM ADL(60,10), ADH(60,10), SLOPE(10), CONST(10)
150 PRINT P$;"What Is The Name Of The File To Be Printed"; : INPUT Y$
160 IF LEN(Y$)>9 THEN PRINT ; "Please Use Legal File Name" : GOTO 150
170 Y$ = Y$+".DAT"
180 PRINT P$; "Number Of Data Readings Per Channel"; : INPUT NDATA
190 OPEN "I", #1, Y$
200 INPUT #1, NCHAN, NCYCLES, PER, RISE
210 FOR I = 1 TO NCHAN : INPUT #1, CHAN(I) : NEXT I
220 FOR J = 1 TO NDATA : FOR K = 1 TO NCHAN
230 INPUT #1, ADL(J,K) : INPUT #1, ADH(J,K)
240 NEXT K : NEXT J
250 INPUT #1, NDATA
260 ''FOR I = 1 TO NCHAN : INPUT #1, SLOPE(I), CONST(I) : NEXT I
270 CLOSE #1
280 PRINT P$; "What Is The Name Of The File With Slope And Intercept Data";
290 INPUT YY$
300 IF LEN(YY$) > 9 THEN PRINT; "Please Use Legal File Name" : GOTO 280
310 YY$ = YY$ + ".DAT"
320 OPEN "I", #1, YY$
330 FOR I = 1 TO NCHAN : INPUT #1, SLOPE(I), CONST(I) : NEXT I
340 CLOSE #1
350 PRINT P$; "Date of Experiment"; : INPUT Y1$
360 PRINT P$; "Any Special Remarks About This Experiment"; : INPUT Y2$
370 LPRINT : LPRINT : LPRINT
380 LPRINT "          NAME OF FILE = "; Y$
390 LPRINT "          DATE OF EXPERIMENT = "; Y1$
400 LPRINT "          REMARKS = "; Y2$
410 LPRINT "          NUMBER OF CHANNELS = "; NCHAN
420 LPRINT "          NUMBER OF CYCLES = "; NDATA/3
430 LPRINT "          PERIOD = "; PER, "    FREQUENCY = "; 1/PER
440 LPRINT "          GAIN = "; RISE
450 LPRINT : LPRINT "          CYCLE  ";
460 FOR I = 1 TO NCHAN : LPRINT "   CHAN"; I; : NEXT I
470 LPRINT
480 LPRINT "                    ";
490 FOR L = 1 TO NCHAN : LPRINT "  INCH    "; : NEXT L
500 LPRINT : LPRINT
510 FOR J=3 TO NDATA STEP 3:LPRINT USING "          ####";J/3;:LPRINT "    ";
520 FOR K = 1 TO NCHAN
530 ADH(J,K) = ADH(J,K) * SLOPE(K) + CONST(K)
540 LPRINT USING "####.#####"; ADH(J,K); : NEXT K
550 ''LPRINT ADH(J,K), SLOPE(K), CONST(K) : NEXT K
560 LPRINT : NEXT J
570 ERASE ADL, ADH, SLOPE, CONST
580 PRINT "File Printing Complete"
590 PRINT P$; "Do You Want To Print Another File (Y/N)"; : INPUT Y$
600 IF Y$ = "Y" OR Y$ = "y" THEN GOTO 140
900 END
```

```
0100 ''          THIS PROGRAM READS THE TRANSDUCER OUTPUT DATA IN
0110 ''          VOLTS, FROM THE DATAFILE SAVED USING "DATADD.BAS"
0120 ''          PROGRAM, AND COMPUTES THE LINEAR REGRESSION
0130 ''          COEFFICIENTS. THE COEFFICIENTS ARE ALSO WRITTEN
0140 ''          TO A DATAFILE. PLEASE NOTE THAT HEAD VALUES ARE
0150 ''          ADDED AT THE END OF DATAFILE SAVED IN "DATADD.BAS"
0160 ''                        FILENAME: LINREG.BAS
0170 ''
0200 DIM ADL(60,10), ADH(60,10), HEAD(60), SLOPE(10), CONST(10)
0210 PRINT P$; "Input Number of Data Points"; : INPUT NDATA
0220 OPEN "I", #1, "CALWED1.DAT"
0230 INPUT #1, NCHAN, NCYCLES, PER, RISE
0240 FOR I = 1 TO NCHAN : INPUT #1, CHAN(I) : NEXT I
0250 FOR J = 1 TO NDATA : FOR K = 1 TO NCHAN
0260 INPUT #1, ADL(J,K) : INPUT #1, ADH(J,K)
0270 NEXT K : NEXT J
0280 INPUT #1, NDATA
0290 FOR I = 1 TO NDATA : INPUT #1, HEAD(I) : NEXT I
0300 CLOSE #1
0310 FOR K = 1 TO NCHAN
0320 SUMX = 0.0 : SUMY = 0.0 : SUMXY = 0.0 : SUMX2 = 0.0
0330 FOR J = 1 TO NDATA
0340 SUMX = SUMX + ADH(J,K)
0350 SUMY = SUMY + HEAD(J)
0360 SUMXY = SUMXY + ADH(J,K) * HEAD(J)
0370 SUMX2 = SUMX2 + ADH(J,K) * ADH(J,K)
0380 NEXT J
0390 SLOPE(K) = (NDATA*SUMXY-SUMX*SUMY)/(NDATA*SUMX2-SUMX*SUMX)
0400 CONST(K) = (SUMY*SUMX2-SUMX*SUMXY)/(NDATA*SUMX2-SUMX*SUMX)
0410 PRINT USING "  ####.##### "; SLOPE(K), CONST(K)
0420 NEXT K
0430 OPEN "O", #1, "LINREGW1.DAT"
0440 FOR I = 1 TO 10 : PRINT #1, SLOPE(I), CONST(I) : NEXT I
0450 CLOSE #1
0460 END
```

```
100 ''     PRINTS A TABLE OF VOLT VALUES USING THE BEST FIT EQUATIONS.
110 ''      SLOPE AND INTERCEPT DATA IS SUPPLIED BY THE USER IN DATA
120 ''       STATEMENTS. NUMBER OF ITERATIONS AND INCREMENT OF INCH
130 ''     SHOULD ALSO BE ADJUSTED IN THE PROGRAM AS PER USER'S NEED.
140 ''                       FILENAME: VOLTABL.BAS
145 '' -------------------------------------------------------------------
150 PRINT P$;"What Is The Name Of The Table To Be Printed";
160 INPUT Y$
170 PRINT P$;"Date of Experiment"; : INPUT Y1$
180 ''PRINT P$;"Time of Experiment"; : INPUT Y2$
190 LPRINT : LPRINT : LPRINT
200 LPRINT "          NAME OF TABLE = ";Y$
210 LPRINT "          DATE OF EXPERIMENT = ";Y1$
220 ''LPRINT "          TIME OF EXPERIMENT = ";Y2$
230 LPRINT "          NUMBER OF CHANNELS = 10"
240 LPRINT :LPRINT "           INCH     ";
250 FOR I= 1 TO 10 :LPRINT "   CHAN";I;:NEXT I
260 LPRINT
270 LPRINT "                      ";
280 FOR L=1 TO 10 : LPRINT "  VOLT    ";:NEXT L: LPRINT : LPRINT
285 RESTORE
290 FOR I= 1 TO 10 : READ SLOPE(I), CONST(I) : NEXT I
300 DATA 27.5070,-27.4419,29.3281,-30.8534,27.3731,-27.7965,26.5793,-26.6590
310 DATA 26.7741,-26.8620,28.0226,-28.1700,28.9032,-28.9865,27.4463,-27.9157
320 DATA 27.5951,-27.9037,29.7444,-29.8672
330 HEAD = -.5
340 FOR J= 1 TO 33:HEAD=HEAD+.50:LPRINT USING "          ##.###";HEAD;
345 LPRINT "    ";
350 FOR K=1 TO 10
360 VOLT(K) = (HEAD - CONST(K)) / SLOPE(K)
370 LPRINT USING "####.#####"; VOLT(K);:NEXT K
380 LPRINT : NEXT J
390 LPRINT : LPRINT
400 LPRINT "           CHAN       SLOPE        INTERCEPT " : LPRINT
410 FOR I = 1 TO 10 : LPRINT USING "          ####"; I;
420 LPRINT USING "      ###.#####"; SLOPE(I); CONST(I) : NEXT I
430 PRINT "File Printing Complete"
440 PRINT "Do You Want To Print Another File (Y/N)";:INPUT Y$
450 IF Y$="Y" OR Y$="y" THEN GOTO 150
900 END
```

```
100 ''     PRINTS A TABLE OF HEAD VALUES USING THE BEST FIT EQUATIONS.
110 ''     SLOPE AND INTERCEPT DATA IS SUPPLIED BY THE USER IN DATA
120 ''     STATEMENTS. NUMBER OF ITERATIONS AND INCREMENT OF VOLTS
130 ''     SHOULD ALSO BE ADJUSTED IN THE PROGRAM AS PER USER'S NEED.
140 ''                       FILENAME: INCHTABL.BAS
145 '' ------------------------------------------------------------------
150 PRINT P$;"What Is The Name Of The Table To Be Printed";
160 INPUT Y$
170 PRINT P$;"Date of Experiment"; : INPUT Y1$
180 ''PRINT P$;"Time of Experiment"; : INPUT Y2$
190 LPRINT : LPRINT : LPRINT
200 LPRINT "          NAME OF TABLE = ";Y$
210 LPRINT "          DATE OF EXPERIMENT = ";Y1$
220 ''LPRINT "          TIME OF EXPERIMENT = ";Y2$
230 LPRINT "          NUMBER OF CHANNELS = 10"
240 LPRINT :LPRINT "           VOLTS    ";
250 FOR I= 1 TO 10 :LPRINT "   CHAN";I;:NEXT I
260 LPRINT
270 LPRINT "                      ";
280 FOR L=1 TO 10 : LPRINT "  INCH    ";:NEXT L: LPRINT : LPRINT
285 RESTORE
290 FOR I= 1 TO 10 : READ SLOPE(I), CONST(I) : NEXT I
300 DATA 27.5070,-27.4419,29.3281,-30.8534,27.3731,-27.7965,26.5793,-26.6590
310 DATA 26.7741,-26.8620,28.0226,-28.1700,28.9032,-28.9865,27.4463,-27.9157
320 DATA 27.5951,-27.9037,29.7444,-29.8672
330 VOLT = 1!
340 FOR J= 1 TO 30:VOLT=VOLT+.02:LPRINT USING "         ##.###";VOLT;
345 LPRINT "      ";
350 FOR K=1 TO 10
360 PRESS(K) = VOLT * SLOPE(K) + CONST(K)
370 LPRINT USING "####.#####";PRESS(K);:NEXT K
380 LPRINT : NEXT J
390 LPRINT : LPRINT
400 LPRINT "            CHAN      SLOPE       INTERCEPT " : LPRINT
410 FOR I = 1 TO 10 : LPRINT USING "         ####"; I;
420 LPRINT USING "       ###.#####"; SLOPE(I); CONST(I) : NEXT I
430 PRINT "File Printing Complete"
440 PRINT "Do You Want To Print Another File (Y/N)";:INPUT Y$
450 IF Y$="Y" OR Y$="y" THEN GOTO 150
900 END
```

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