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SUSPENDED SOLIDS
AND
DEEP WELL INJECTION SYSTEMS

BY

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B.S.E., Florida Technological University, 1971

THESIS

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ABSTRACT

A test method and the associated equipment have been developed to investigate the effect of suspended solids on the flow of fluid into a deep injection well system. Preliminary testing indicates that the equipment and test method can be used to determine the permeability of rock samples with a high degree of accuracy. Additionally this equipment can be used in a testing program which will eventually lead to the development of guidelines for the degree of pre-injection treatment required for suspended solids so that the operational life of the well is not impaired.

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CHAPTER I

INTRODUCTION

For many years the use of deep well injection systems* was limited to the return of saline water produced during oil production to permeable subsurface strata. Within the past ten years, however, there has been a large increase in the rate of construction and use of deep well injection systems for the disposal of industrial wastes and treated domestic sewage effluent. In addition, the use of injection wells for the subsurface storage of relatively clean water is currently receiving much attention and study.

Several sources of relatively clean water are available. Among these are tertiary treated domestic sewage effluent and stormwater runoff. It is obvious that a tertiary treated effluent would be an excellent source of relatively clean water. Stormwater runoff, on the other hand, possesses several inherent design problems chief among them the intermittency and variability of the flow and the physicochemical and biological characteristics of the fluid. In designing a deep well injection system for

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*A deep well injection system is defined as a well used to introduce a fluid, either under gravity or pressure flow, into a subsurface stratum whose natural formation fluids are saline.

the subsurface storage of stormwater, the engineer is faced with the problem of providing treatment systems whose effluent will not damage the operational life of the injection well.

Experience has shown that the injection fluid should be: 1) chemically non-reactive when in contact with the disposal formation liquids or rock; 2) chemically non-reactive under the disposal formation pressures and temperatures; and 3) free of suspended solids to protect the operational life of the injection well. The chemical aspects of these three items have been studied to some degree and various methods are available which can be used to assess their applicability to a particular situation. There are no methods presently available, however, which can be used to determine the consequences of suspended solids on a particular injection system.

It is obvious that suspended solids in the injection fluid could plug the disposal stratum; but, there are several* industrial installations with injection fluids containing suspended solids with no apparent damage to the storage capacity, injection rate or well pressures. It is reasonable to assume, therefore, that a certain amount of suspended solids can be accommodated by injec-

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*A survey of industrial wells whose injection fluids contain suspended solids is presented in Appendix 1.

tion strata without damage to the operational life of the well. When the engineer begins a design of an injection well pre-injection treatment system, there are no guidelines to aid him in determining the percentage of suspended solids which need to be removed. Therefore, the only proper alternative available is to provide the highest possible suspended solids removal efficiency.

If the nature of the injection stratum is such that it would have accepted the fluid in its natural state, or, after a much lower degree of suspended solids removal, then the cost incurred in the design, construction and operation of the pre-injection treatment systems could be reduced.

Thesis Objectives

It is the intent of this work to develop an experimental method which would aid in the formulation of empirical relationships for the determination of an allowable suspended solids concentration for an injection system fluid. These relationships are to be based on various injection strata, well design, and operational characteristics. In addition, a survey of the history of injection well systems; general design principles and practices; and a brief overview of the requirements imposed by various agencies of the State of Florida will be presented.

CHAPTER II

HISTORY AND PROBLEMS OF DEEP WELL INJECTION SYSTEMS

Since the early 1960's, there has been an increased awareness in the problems associated with the disposal of wastewaters, whether treated or untreated domestic sewage, industrial waste or stormwater runoff, into surface waters. This awareness was brought about, for the most part, by federal and state regulations which imposed controls on the pollution of surface waters. In seeking alternative methods of disposal many industrial firms have utilized deep well injection, a disposal method which was initially recognized and exploited as early as 1928 [1].

Until approximately 1964, when only 30 deep well injection systems were in operation for the disposal of industrial wastes or treated domestic sewage effluent [1], the use of injection wells was limited to oil companies for the return to subsurface zones of large volumes of saline water produced by the extraction of oil [2]. Since 1964, however, a large number of injection wells have been put into operation by both industrial firms and municipal sewage treatment plants.

The most recent survey of deep well injection systems, conducted by the United States Environmental Protection Agency (EPA) [3], listed 278 waste injection wells which have been constructed and are presently in operation, or, which were in operation in the past. In addition, 44 other wells have been permitted or were seeking permits to be drilled. Approximately 80.6 percent of all injection wells identified by the survey were used by manufacturing firms. Of these wells, 84.2 percent (or 67.9 percent of all surveyed) were used by chemical and allied products and petroleum refinement; 9.3 percent were associated with mining; 8.6 percent with sanitary services and 1.5 percent with other miscellaneous industries.

From the broad base of injection well experience developed by the oil production industry it is known that fluids can be injected into almost any type of rock under certain circumstances. Thompson and Warner [3] substantiate this but have found that the majority of injection wells use the following three major injection strata.

1. Tertiary sands of the Gulf Coastal Plains used in Texas, Louisiana and Alabama.

2. Cambro-Ordovician Arbuckle carbonate groups used in Kansas and Oklahoma.

3. Cambrian Mt. Simon Sandstone used in Illinois, Indiana, Michigan and Ohio.

The distribution of primary injection zones based on the 1974 survey consisted mainly of sand and sandstone (62.1

percent) and carbonates (33.8 percent), while Evaporite, shale, and other zones accounted for the remaining 4.1 percent.

The survey also indicated that 41.6 percent of the wells were completed at depths of less than 3000 ft (915 m), 27.9 percent from depths of 3000 to 5000 ft (915 to 1525 m), and 28.3 percent from 5000 to 8000 ft (1525 to 2440 m).

Of the nine injection wells inventoried in Florida by the EPA survey, five have been drilled and are, or have been, in operation; three have been permitted but not drilled and one has been drilled but never used. The five wells which have been in operation vary in depths from 1650 to 3000 ft (500 to 915 m). The injection zone for these wells is the lower Floridan Aquifer which is a dolomitic limestone stratum of Tertiary age. With one exception all of the nine injection wells were, or are, for the disposal of industrial wastes, mainly chemical by-products.

In a different survey of injection wells in the State of Florida conducted by the Florida Department of Pollution Control in October, 1974 [4], 24 well systems (some systems consisted of more than one well) were identified, six of which were those wells reported by the EPA survey. Of the 24 systems, 14 were being used, under construction, or applying for permits, for the disposal of municipal sewage treatment plant effluents; 2 were being constructed for disposal or storage of stormwater runoff; 4 were in operation disposing of industrial wastes; 2 were being constructed for aquifer recharge (salt water intrusion control) and reclamation of injected fluids experiments; and 2 systems had been abandoned.

Problems Associated with Deep Well Injection Systems

The main concern regarding the use of deep well injection systems is the problem associated with contamination of recoverable resources. As opposed to other disposal methods, contamination from injection wells is difficult, if not impossible to detect and/or rectify [1,5].

Although very few problems have arisen from the use of injection wells, due mainly to the proper design and construction of the wells [1], this waste management technique is fraught with conditions which may seriously damage the environment. Among some of the problems which can occur due to improper injection are:

1. Contamination of fresh water supplies
2. Destruction of mineable mineral resources
3. Stimulation of earthquakes

In addition, Ross [2] lists the reduction of subsurface volume available for storage of waste fluids as a fourth problem of deep well injection.

Contamination of fresh water supplies

The Environmental Protection Agency [1] lists five means by which fresh ground waters could be contaminated by deep well injection systems.

1. Escape of wastes into overlying aquifers through the well bore due to insufficient casing and/or failure of the casing.

2. Seepage of waste through overlying aquicludes around the outside of the well casing

3. Seepage of wastes through aquicludes of inadequate thickness and/or permeability

4. Escape into overlying aquifers through nearby wells that have been improperly constructed, plugged or maintained

5. Movement of fresh-saline water interface by the injected wastes

Several authors, among them Kazman [6], have suggested that another means by which fresh water aquifers can be contaminated is by the escape of wastes through fracture planes created either by natural tectonic stresses or by excessive injection pressures.

Destruction of mineable mineral resources

The processes by which valuable mineral resources can be destroyed, or damaged beyond economic retrieval, are the same as with the contamination of fresh water aquifers. However, damage can be done even though all possible precaution is taken if the resource is located within the injection stratum.

Stimulation of earthquakes

The most carefully studied, and only, case of injection well induced earthquakes has been the Rocky Mountain Arsenal well in Denver, Colorado [7]. This study was able to correlate the frequency of earthquakes to the volume and pressure of the fluid injected by the Arsenal well. Up to the end of 1965 over 710 earthquakes, of varying magnitude, were recorded with the epicenter of the majority falling within a 5 mile (8 km) radius of the injection well.

Although the exact causes are not yet known, the EPA [1] suggests that there are two general requirements for the stimulation of earthquakes by deep well injection. These requirements are the presence of a fault system along which movement can occur, and, that the movement will relieve in-situ tectonic stresses.

Since the Rocky Mountain Arsenal well is situated in a fault zone, Evans [7] suggests that the earthquakes were induced principally by the increase in the injection stratum interstitial fluid pressure. Evans points out that rock masses in fluid resevoirs are supported by the total and neutral pressures. As the neutral pressure approaches the total pressure, the shear stresses required to move the rock mass down gentle slopes approaches zero. Therefore, as the injection pressure increased, the stresses required for movement decreased until movement occured.

CHAPTER III

FUNDAMENTALS OF DEEP WELL INJECTION

In the design of deep well injection systems, many of the engineering decisions and calculations can be based upon the large body of knowledge and experience acquired from the construction of extraction wells. However, since the process in question is inherently different from extraction wells, several additional requirements need to be considered. Vernon and Garcia-Bengochea [8] suggest that a satisfactory system can be achieved if the following four basic requirements are met:

1. Injection stratum which can accept the wastes at the design flows and pressures
2. Disposal will not impair the present or future use of the native formation fluids in the injection stratum
3. Disposal will not impair the present or future use of native formation fluids in adjoining or over-, and/or, under-lying strata
4. Disposal will not significantly change the hydraulic and structural characteristics of the disposal stratum

In general, these additional requirements can be reviewed by considering three major aspects of the injection well:

1. The physical location of the well in respect to subsurface conditions
2. The fluid mechanics of injection wells in respect to the effect upon the subsurface strata
3. The physicochemical reactions between the injected and formation fluids

Physical Considerations

Walker and Steward [5] have defined a suitable injection stratum as any stratum which can accomodate the quantity and quality of the injected waste without contamination to any other natural resource. To satisfy the physical aspects of this definition various properties and conditions of the injection stratum need to be considered.

The quantity, flow rates and maximum pressures at which wastes may be injected into any formation are dependent in part upon the structure and stratigraphy of the disposal formation. Stratigraphically the formation may either be confined or unconfined in the horizontal plane and confined in the vertical plane [5]. In the horizontal plane it is desirable that the formation be unconfined. An unconfined stratum, which in most cases outcrops into a large body of water such as an ocean, provides an almost limitless storage reservoir. A confined stratum, however, is limited in regards to its storage capacity by the compressibility of the formation fluids and/or the pressures at which hydraulic fracturing of the stratum occurs.

In the vertical plane, the opposite case is preferable and for the most part required. To prevent contamination of over, and/or, under-lying mineable resources, i.e. water, oil, coal, etc., it is necessary that suitable confining strata be present. Ross [2] reports that clay, unfractured shale, silt, anhydrate, gypsum, marl and bentonite have been found to be suitable confining aquicludes.

The operation of any well, whether injection or extraction, depends entirely upon the presence of voids in the developed formation. Not only must voids be present but they must also be interconnected. Only then can formation fluids, or injected fluids, flow from or to the well. The engineering soil index property which is used to quantify the pore volume in soils is the porosity [9]. However, this index property only represents the ratio of the bulk void volume to the total bulk volume. It does not in any way describe the interconnectedness of the voids. This is evident from the representative porosity values presented by Walton [10] which assigns porosities of 45 to 55 percent to clay, a generally highly impermeable soil, and porosities of 1 to 10 percent to limestone, a generally permeable rock which is extensively used as a source of fresh water and for waste disposal. The effective porosity, on the other hand, directly describes the percentage of the volume which is occupied by interconnected voids [5] and which can be used as an indication of the acceptability of a stratum for injection wells. The lower the effective porosity the lower the amount of fluid which can be stored by the stratum. Warner [11] indicates that sandstones, limestones, and dolomites are the types of rock stratum which are suitable for injection wells. In addition, Warner lists naturally fractured shales and other similar rock strata as possible injection strata. It should be noted that those rock types identified by Warner as the most suitable for injection wells generally exhibit high effective porosity values.

The salinity of the fluids native to the injection formation under consideration is also an important factor in the selection of a suitable stratum. The EPA [1] recommends that minimum salinity concentrations be set, if not already regulated, at at least 1000 mg/l for most areas and as high as 30,000 mg/l in arid regions where desalinization could provide potable water.

Investigations should also be carried out into the structural integrity of the disposal formation. Talbot [12] lists faults, wells (whether abandoned or in operation), springs and other structural phenomena as problems which can seriously affect the suitability of a formation for injection techniques. Each of these items can cause hydrologic short circuits in the formation allowing vertical migration of the wastes to occur.

In general there are three basic types of geologic faults: 1) normal; 2) thrust; and 3) strike-slip faults. Each of these faults involve slippage of subsurface units.

Normal and thrust faults are caused when subsurface units slip along a plane which is vertical or, more commonly, at some angle from the vertical, while strike-slip faults occur from slippage along the horizontal plane. Therefore, normal and thrust fault movement is composed of both vertical and horizontal vectors while strike-slip fault movement only involves a horizontal vector.

The vertical displacement of normal and thrust faulting is what is of importance to injection well disposal stratum selection. If the vertical displacement of a fault system present in the proposed disposal stratum is greater than the thickness of the stratum's confining aquiclude, then it is possible that a hydrologic short circuit is present which would allow fluid movement between the proposed disposal stratum and over-, and/or, under-lying strata.

Wells cause hydrologic short circuits when the formation fluid pressure, which is being increased by the injection of additional fluid, cannot be resisted by weak components in the well structure. Corroded casings and headers, time weakened parts, and inadequately grouted or plugged wells are a few of the weaknesses which can fail causing a hydrologic short circuit.

Because these items can endanger surrounding strata it is important that their presence be investigated. McLean

[13] suggests that various pump tests developed by ground water hydrologists can be used to determine where faults are present. Well permitting agencies can supply information as to the location and status of wells in the area which should then be inspected with regard to their integrity and condition. U. S. Geological Survey topographic maps, areal surveys, state geologic sections and various other local information centers are other sources of data which can give indications of the presence of conditions which are favorable to hydrologic short circuits.

Fluid Mechanics of Injection Wells

Once the disposal stratum is selected based on structural and stratigraphic considerations it is necessary to consider the hydrology of the injection process. Investigations into the storage volume available, hydraulic fracturing pressures and the flow of fluids into the well and disposal formation should be performed.

Fluid storage

Ross [2] suggests that the storage volume of a stratum can be estimated by:

$$V = 23.5(r_V^2)(h)(\phi) \qquad (1)$$

where:

V = storage volume, gals.

r_V = radius of available storage space, ft.

h = thickness of stratum, ft.

ϕ = porosity of stratum, fraction

while Ferris [14] states that any fluid injected into a stratum must be compensated for by the discharge of an equivalent volume of residential fluid elsewhere in the aquifer system. These two definitions of storage volume illustrate two of the three methods which are thought to apply in the storage of fluids in subsurface strata. Several authors, among them Walker and Steward [5] discuss these three methods.

The first, commonly called the U-Tube theory, postulates that horizontally unconfined strata act as u-tubes. As fluid is introduced at the higher elevation orifice, an equal amount of fluid is discharged at the lower elevation orifice. This seems to be especially true for unconfined strata which outcrop in the ocean. Dean [15] documents the history of an injection well whose injection stratum, the lower Floridan Aquifer, is an example of a U-Tube theory formation.

The second and third methods apply principally to horizontally confined strata. Although water is generally assumed to be imcompressible for normal engineering applications, it is known that it is slightly compressible. Since most disposal strata are extensive with respect to their volume, even the slight compressibility of the resident fluid can create large storage volumes.

The third method postulates that the hydraulic loading caused by the increased stratum fluid pressure flexes or lifts the earth's crust. Again, the storage capacity is greatly increased even though the rise is immeasureable because of the generally extensive areas involved.

Although no mention is made in the literature cited, it is the opinion of the writer that the third method of fluid displacement is the least probable of all three and that if such flexure of the crust does occur, then the safety of the injection well would be compromised. As discussed below the third method could be considered to be a form of hydraulic fracturing which if precipitated could cause additional fracturing of the formation and confining aquicludes permitting vertical migration of the injection fluid.

Hydraulic fracturing

Hydraulic fracturing has been used extensively in oil extraction operations since approximately 1949. This technique of oil field development uses hydraulic pressures to crack and fracture oil bearing formations to facilitate the removal of the resource. In addition to pressure, propping agents--usually round silica sand--are introduced into the pressurizing fluid to maintain and propagate the fracture.

Hubbert and Willis [16] discuss the mechanics of hydraulic fracturing on the basis of subsurface stress conditions. Generally, the subsurface stress condition is one in which the three mutually perpendicular principal stresses are unequal in magnitude. It is evident that if the stresses are to be overcome to cause parting of the rock, the pressure required will be proportional to the least principal stress.

In regions where normal faulting has occured the greatest stress is approximately vertical and equal to the effective overburden pressure. The least stress should then be horizontal and equal to between one half and one third of the effective overburden pressure.

Conversely, in regions which are being shortened either by folding or thrust faulting the least principal stress should be vertical and equal to the effective overburden pressure while the greatest stress is horizontal and equal to between two and three times the effective overburden pressure.

Thus, in normal geologic regions hydraulic fracturing will cause vertical cracks when the pressure exceeds between one half and one third of the effective overburden pressure. In regions of active tectonic stresses hydraulic fracturing will cause horizontal cracks when the pressure in the formation exceeds the effective overburden pressure.

Based on these principles, Hubbert and Willis [16] mathematically predicted the pressure required to open and extend a fracture. In normal geologic areas the additional fluid pressure required to open a fracture must equal one half to one third of the effective overburden pressure.

Conservatively then:

$$\Delta p = \frac{\sigma_z}{3} \tag{2}$$

where:

Δp = additional pressure required for fracturing, psi

σ_z = effective overburden pressure, psi

and:

$$\sigma_z = P_{ob} - u \tag{3}$$

where:

P_{ob} = total overburden pressure, psi

u = interstitial pore fluid pressure, psi (neutral stress)

However, the fracture pressure is that required above the native pore fluid pressure. Therefore, the bottom of well injection pressure, P_f, for fracturing is:

$$P_f = \Delta p + u \tag{4}$$

so:

$$P_f = \frac{P_{ob} + 2u}{3} \tag{5}$$

which on a unit depth basis converts to:

$$P_f = \frac{\frac{P_{ob}}{z} + \frac{2u}{z}}{3} \tag{6}$$

where:

z = depth of well, ft.

For normal sedimentary rocks, Hubbert and Willis report a P_{ob}/z of 1.0 psi/ft (22.6 $kN/m^2/m$) and a u/z of 0.46

psi/ft (10.4 $kN/m^2/m$) thereby setting the bottom of well pressure required for fracturing in normal geologic areas, P_t, at approximately 0.64 psi/ft (14.5 $kN/m^2/m$).

Crittendon [17] presents an equation for the bottom of well fracturing pressure:

$$P_f = \frac{P_{ob}}{2}\left[[1 + \frac{(2)(\nu)}{1+\nu}] + [1 - \frac{(2)(\nu)}{1-\nu}]\cos(2\alpha)\right] \qquad (7)$$

where:

ν = Poisson's ratio

α = angle of fracture from horizontal

For the case of vertical fractures, the above relationship simplifies to:

$$P_f = P_{ob}\left[\frac{(2)(\nu)}{1-\nu}\right] \qquad (8)$$

Using an average Poisson ratio reported by Smith [18] for rocks of 0.25 (varies from 0.05 to 0.45 being inversely proportional to the rock hardness), Crittendon's simplified equation yields a bottom of well fracturing pressure of 0.67 psi/ft which closely agrees with Hubbert and Willis' approximated value of 0.64 psi/ft for normal regions.

Flow of fluids into wells and disposal strata

The previous discussion on storage capacity pointed out that the quantity of fluid which a stratum can accommodate is a function of the porosity and thickness of the stratum. The dynamic movement of the fluid from the well and in the stratum, however, is a more complex system to mathematically describe and predict. Several tools--based on extraction well principles--are, nevertheless, available which can be applied in the analysis of injection well flows.

The analysis of the well flow region should generally be performed in three distinct phases. First, the feasibility of the well, using the proposed disposal stratum, should be checked by using ideal conditions (i.e. radial flow, confined isotropic stratum, etc.). This allows the engineer to use simple non-equilibrium equations such as the Theis-Lubin Equation. Second, during the design phase, a more rigorous approach to the flow system should be used to predict the pressure behavior based on the design flows. Third, again during the design phase, the movement of the injected fluid in the disposal stratum should be predicted.

Feasibility analysis. Talbot [12] suggests that the Dupuit-Theim Equation for steady state, fully penetrating well, confined isotropic stratum, and radial flow expressed by:

$$P_w - P_e = \frac{(q)(\mu)(\log(R/r_w))}{(8.95)(10^{-2})(k)(h)} \qquad (9)$$

where:

P_w = pressure at well, psi

P_e = pressure at distance R from well, psi

q = flow rate, gpm

μ = viscosity, centipoise

R = radius of influence, ft.

r_w = radius of well bore, ft.

k = permeability of stratum, darcies

can be used if the piezometric surface is assumed to be inverted as shown in Figure III-1.

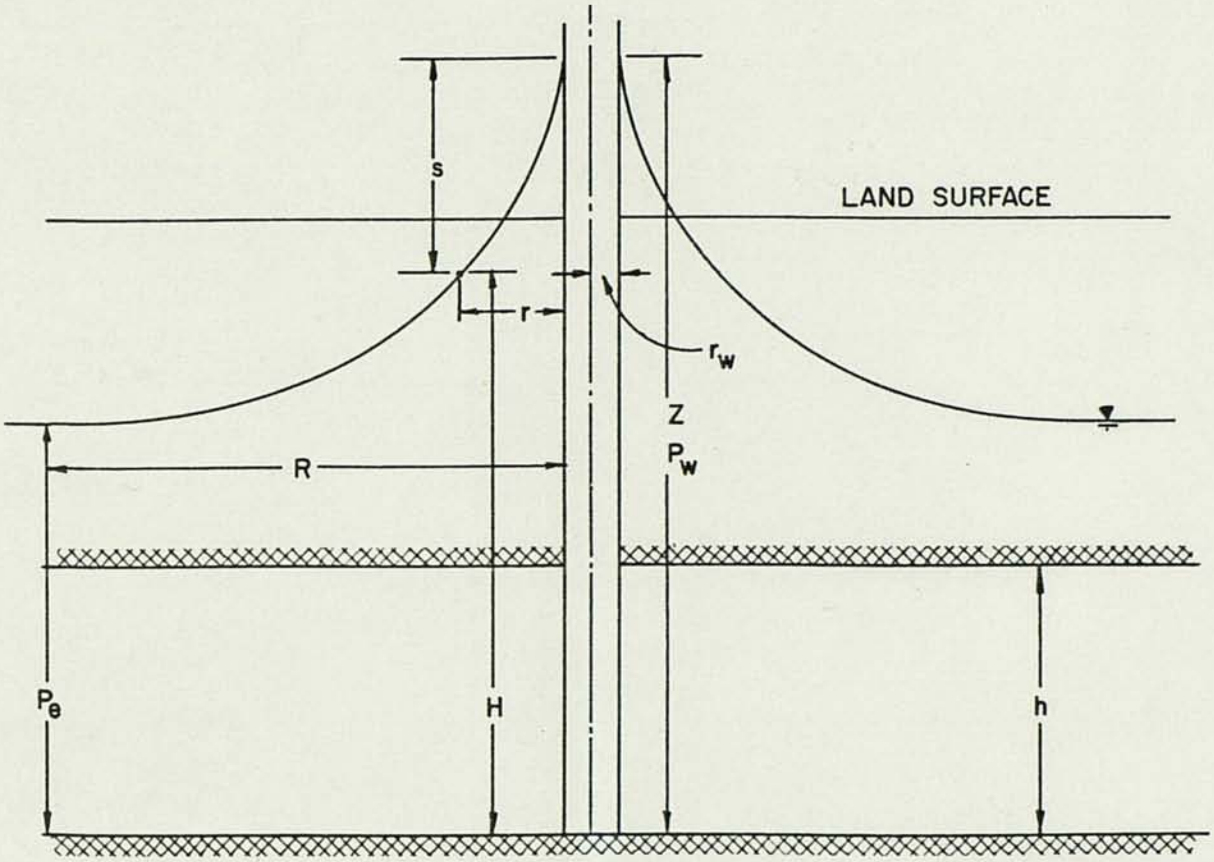

Figure III-1 - Confined, fully penetrating well

McLean [13], and Donaldson, Thomas and Johnston [19], on the other hand, suggest that the Theis-Lubin Equation expressed by:

$$s = \frac{(114.6)(q)(W(U))}{T} \qquad (10)$$

where:

s = drawdown (Z-H), ft.

T = transmissibility, gpd/ft

W(U) = well function

where:

$$U = \frac{(1.87)(r^2)(S)}{(T)(t)} \tag{11}$$

and:

S = coefficient of storage, dim.

r = radial distance, ft.

t = time after pumping, days

is better able to initially predict the pressure changes since the function is based on unsteady radial flow.

Design analysis of flow from well. Various factors affect the pressure-time relationship of flow from the injection well. Those identified by Van Everdingen [20] include permeability, thickness of stratum, viscosity of the fluids, size of the reservoir, radius of the well bore, and the compressibility of the injection and native formation fluids. In his discussion of deep well fluid mechanics, Van Everdingen presents three unit functions which give quantitative information on the pressure change due to a unit rate of injection; the amount of fluid which can be disposed per unit pressure increase; and the effect of an enlarged well bore hole on the injection pressure.

The unit functions presented are based on the same type of differential equations that describe the conduction of heat. Simply put, the equation states that the "difference in volumes flowing in and out of an annulus between two hypothetical concentric rings around a well bore is equal to the expansion of fluids in the annulus" [19]. The functions and the tables and figures relating to the functions, and their application, are discussed in an abstract of Van Everdingen's article presented in Appendix 2.

Analysis of flow in disposal stratum. This aspect of the investigation of the injection well flow regime is very complex. No definitive study has been issued which presents the design engineer with a mathematical means of analysis. However, an attempt should be made to estimate the extent and direction of the waste movement [1].

In the two previous analyses two basic assumptions allow the use of the simplified functions. These two assumptions are:

1. Radial flow
2. Isotropic formation

Neither of these assumptions is valid for the actual case.

The cylindrical flow case imposed by the first assumption is modified in the actual system by natural stratum flow patterns caused by differential pressure gradients within the stratum [1]. The irregularities in the stratum upper and lower boundaries will also modify the assumed behavior. To account for these modifications to the theoretical behavior, the design engineer will discover that piezometric surface and stratigraphic maps of the disposal stratum can be of invaluable aid in estimating the actual behavior of the injected fluid.

The isotropic stratum assumption is probably the easiest assumption to refute since a disposal stratum does not usually have the same properties throughout its extent. As easy as it is to refute, it is the hardest to account for in estimating the effect of nonhomogeneity upon the movement of the injection fluid.

Unless preliminary studies of the disposal stratum have uncovered some non-uniformity in the stratum's porosity, permeability, or other factors which would affect the fluid movement, the acceptance of the assumption as valid should not cause any significant error. The Engineer should, however, make a concerted effort to rule out the presence of non-uniformities within the radius of the predicted fluid movement. In some cases, non-uniformities could be uncovered through an extensive subsurface investigation program; or, by an unexplainable significant diffence between the well pump tests performed on the injection well and previous pump tests performed on other wells penetrating the same stratum; or, by state geologic survey reports and other locally available information.

In addition to using engineering logic and estimates in the determination of the impact of these complex variables on the extent and direction of the waste movement, the design engineer should be aware of, and investigate the applicability of various modeling techniques which have been proposed. Kuo [21] presents such a model for the prediction and simulation of the transportation behavior during injection of fluids into porous media. This model essentially relies upon the same basic assumptions mentioned previously with modifications to account for some of the inconsistencies of these assumptions.

Physicochemical Aspects of Injection Wells

The chemical impact of injected fluids on the disposal stratum and formation fluids is a major consideration in the analysis and design of a deep well injection system. Dean [15] has reported what can happen when the chemical aspects of this disposal method are disregarded:

> "...in one instance of citrus wastes injection into a relatively shallow well, a nearby householder had discovered that his private well was delivering natural gas, produced by the decomposition of the fruit juices. It is reported that he is still heating and cooking with free gas to this day [1965]. He is presumably not drinking water."

As mentioned in Chapter I, experience has shown that if the injected fluid is: 1) chemically non-reactive when in contact with the native formation fluids or rock; 2) chemically non-reactive under disposal stratum temperatures and pressures and; 3) free of suspended solids, then there should be no problem in disposing of the fluid. These items are of concern since if the injected fluid is chemically reactive or contains suspended solids, then the voids in the disposal stratum could become filled with precipitates or suspended solids thereby reducing the effective porosity of the stratum and eventually shutting down the well [5].

Selm and Hulse [22] indicate that plugging precipitates can be caused by the precipitation of the alkaline earth metals as insoluble carbonates, sulfates, orthophosphates and hydroxides; or, by the precipitation of the heavy metals such as iron, aluminum, cadmium, zinc, manganese and chromium as insoluble carbonates, bicarbonates, hydroxides, orthophosphates and sulfides; or, by the precipitation of oxidation-reduction products of reaction. In addition, they suggest that the pressures and temperatures encountered in the disposal stratum could cause the injected fluid to react with itself, leading to the polymerization of resin-like materials to solid precipitates.

Ross [2] points out that the solubility of gases decreases at higher temperatures which could cause the precipitation of calcium carbonates in a calcium containing stratum. The injection of highly acidic or basic fluids can also create problems, especially if acidic fluids are injected into carbonate formations.

Warner [23] has shown that certain chemical reaction precipitates can drastically affect the permeability of unconsolidated sands; the results of which can also be applied to any permeable formation. In his work, Warner found that of three types of precipitates tested--two of crystalline and one of gelatinous nature--the gelatinous precipitate, ferric hydroxide, caused a significant loss in the permeability of the sand (close to 30 percent), while the crystalline precipitates, barium chloride and calcium sulfate, did not affect the permeability.

In this same study, Warner [23] concluded that the mixing of the injected and interstitial fluids was due to hydrodynamic dispersion which could be controlled through the creation of a buffer zone. The buffer zone consists of a zone of non-reactive fluid which is injected prior to the injection of the reactive fluid.

Walker and Steward [5] suggest that a chemical analysis of the injection and interstitial fluids will help in the determination of chemical compatibility. They also report that the DuPont Company in Victoria, Texas, performs two tests to check chemical compatibilities. The first consists of mixing injection and interstitial fluids for eight hours at the formation temperatures. If no precipitates are formed then the fluids are said to be compatible. The second test checks the compatibility of the injection fluid with the disposal stratum by determining the permeability of a core sample of the stratum with the proposed injection fluid.

Li [24] reports on a test in the Romashkina Oil Field, U.S.S.R., performed to check the validity of specified limits to the concentration of iron, suspended solids and petroleum which could be contained by a fluid being injected in an oil producing stratum. The limits for these substances were: 1) Iron - 0.3 mg/l; 2) Suspended solids - 2.0 mg/l; and 3) Petroleum - trace. In this test 4.28 MG (16200 cu. m.) of purified water containing 2 mg/l of Fe^{++}, 16 mg/l of suspended solids consisting of particles not greater than 10 microns, and 20 mg/l of petroleum was injected at a rate of 120 gpm (655 cu.m./day). Output of the well was not affected. Li recommended that the limits for these items be based on the individual geologic aspects of the stratum and methods being used.

In the field of deep well injection used for industrial waste disposal in the United States there are no limits set for allowable suspended solids concentrations in the injected fluid. The most conclusive statement regarding suspended solids found in the literature was by Walker and Steward [5]:

> "The amount of suspended materials should be limited so that clogging of the pores does not occur."

which in effect is the same as Li's recommendation that the limit be based on the geology of each individual well. However, there is presently no known method for determining what amount of suspended solids the injection stratum can accept without clogging of the pores.

CHAPTER IV

DESIGN GUIDELINES FOR DEEP WELL INJECTION SYSTEMS

The intent of this chapter is to briefly describe major design aspects of deep well injection systems. It is not meant to be a comprehensive design guide. Only those aspects which the literature indicates are of importance to a properly designed system will be discussed. References such as Huisman's Groundwater Recovery [25] are excellent sources for more detail discussions on the finer points of well design and construction.

In the design of a deep well injection system the primary consideration of the design engineer should be the protection of subsurface strata, other than the disposal stratum, from contamination [5]. This can be accomplished if the location, size, surface systems, well configuration, construction and operation methods are selected based on sound engineering principles.

Location

The site for an injection well will be determined by the availability of a suitable injection stratum. Basically, the injection stratum should be located vertically below any fresh water horizon; confined by over-, and, under-lying aquicludes; and, of sufficient porosity, permeability and areal extent to store the required volume at safe injection pressures. In addition, abandoned or unplugged wells, faults, and other hydrologic short circuits should not be present [2]. Thick sequences--about 1000 ft. (305 m) or more--of sedimentary rocks, especially those deposited under a marine environment are most likely to contain strata which are suitable for injection wells [1,11].

Size

The size of the system is, of course, determined by the injection flow rate and pressure requirements. In general, the flow rates for most industrial applications vary from 10 to 2000 gpm (0.038 to 7.57 cu.m./min) but fall mainly within a range of 100 to 300 gpm (0.38 to 1.14 cu.m./min). The corresponding pressures showed no average value ranging from gravity flow to 3500 psi (24, 150 kN/m^2) [26].

The maximum allowable bottom of well pressure is commonly specified by regulatory agencies. In general these allowable pressures range from 0.46 to 0.99 psi/ft of depth (10.4 to 22.4 $kN/m^2/m$), but are seldom greater than 0.78 psi/ft (17.7 $kN/m^2/m$) [1].

Surface Systems

This topic covers a broad range of equipment from the pumps to pre-injection treatment systems.

Mechanical systems

The selection of mechanical components of an injection well is based on the rates and pressures required, or, which will be accepted by the injection stratum. Consideration should be given to the nature of the injection fluid in respect to its compatibility with the material through which it is being processed when selecting the equipment, i.e. special coatings are required for corrosive fluids. A general listing of equipment needs would include pumps, monitoring devices, flow lines, holding tanks and stand-by facilities. Stand-by facilities usually consist of holding tanks or secondary wells which can be used in case of breakdown in the primary system [1].

Pre-injection treatment systems

Prior to the injection of the fluid some form of treatment may need to be provided. These treatment systems could vary from simple physical treatment to extensive chemical and/or biological treatment facilities. The decision as to whether treatment is needed, and the degree of treatment, will--in most cases--be regulated by state agencies. The analysis and design of whatever treatment system is to be provided should be based on established waste treatment theory and practice and is not part of this discussion.

Regardless of the source of fluid, the treatment system should produce a fluid which will not be detrimental to the operation of the well. This includes particle sizes, temperature, viscosity, chemical reactivity and biological activity [5].

Well Configuration

Figure IV-1 presents a generalized cross section of a typical deep well injection system well. The well consists of an outer casing running from the surface to at least below the deepest fresh water horizon; an inner casing which runs from the surface to the top of the injection stratum, or further depending upon the completion technique used; and an injection string through which the injection fluid is pumped. The annular space between the well bore hole and the outer casing, and between the outer casing and the inner casing should be grouted [2].

The injection string should be protected from possible corrosion, regardless of the fluid being injected. This can be accomplished by protective inner coatings such as asphalt or plastic. Fiberglass and plastic injection strings have also been used successfully [3].

Fluid, normally treated with a corrosion inhibiting compound, should be circulated through the annular space between the inner casing and the injection string [3,5,15]. This serves a dual purpose as corrosion protection of the inner casing and, as discussed later, as a means of monitoring the integrity of the well [5,15].

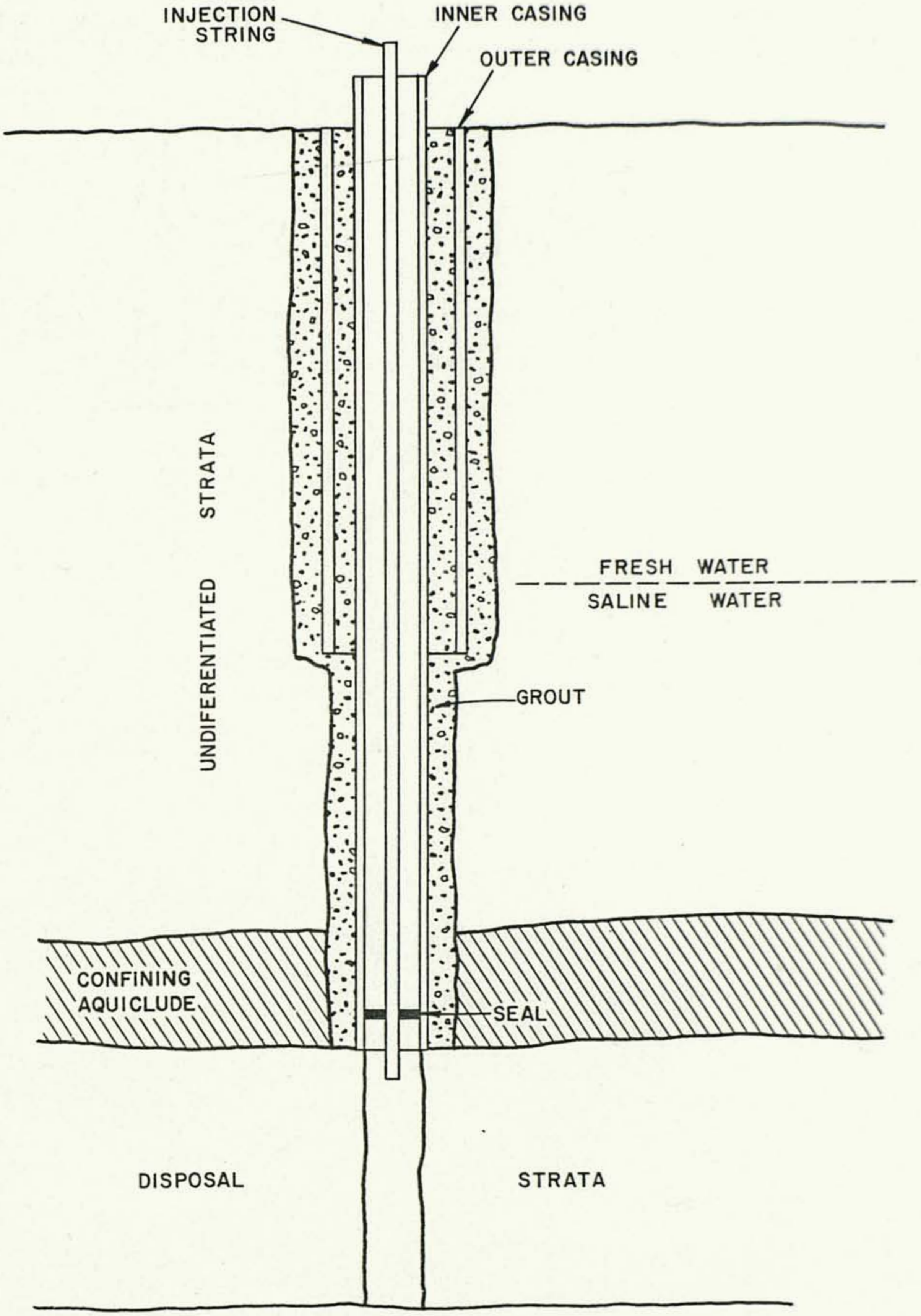

Figure IV-1 - Generalized well cross section

To separate the annular fluid from the injection stratum, either mechanical or fluid seals are used [5]. The DuPont Company in Victoria, Texas, chose to use a fluid seal because of its inherent simplicity and versatility. The seal is formed by using diesel oil as the annular fluid. Oil, being lighter in density than the formation fluids, floats on the fluid. A positive pressure is maintained either by the natural stratum pressure or by the pressure created by the injection [5].

Construction

Generally, the construction of the well follows established extraction well methods. Either rotary or cable-tool drilling is acceptable; however, cable-tool is considered to be preferable, at least in the disposal stratum, since there is less chance of the stratum being plugged by the drilling mud and lost circulation material [2].

Drilling muds with automatic viscosity reversion properties have been found beneficial for the reduction of plugging in sand strata [27].

The completion of the well involves testing of the casing, grouting and injection stratum stimulation [5]. The casings should be tested to ascertain that they do not leak and can sustain design pressures. Grouting provides support for the casing, prevents contamination of over-lying strata and provides electrolytic corrosion protection [5].

From the standpoint of efficiency, injection capacity, operating and maintenance costs and well life, water well completion techniques are superior to oil well completion techniques for injection wells [27].

Stimulation, or well development, is used to increase the fluid acceptance rate. Stimulation can be either chemical or mechanical. Chemical stimulation uses acids, commonly a 15 percent solution of hydrochloric acid, to leech solution channels into the injection stratum, thereby increasing the surface area of the well bore. Mechanical stimulation involves the use of physical means to increase the surface area of the well bore. This includes such techniques as scratching, swabbing, underreaming and hydraulic fracturing (see Chapter II for discussion on hydraulic fracturing) [2].

Operation

Any injection well should be operated in a method which will protect the injection stratum from plugging up, thereby reducing the efficiency and life of the well, and which will prevent contamination of surface or subsurface fresh waters.

Plugging

Plugging at or near the well bore can be caused by bacteria, algae, mold or suspended solids [11]. The biological causes can be controlled by bactericides but care must be taken since some bactericides can react with the formation or injection fluids creating insoluble precipitates [11]. Suspended solids can be controlled through proper pre-injection treatment systems.

Plugging can also be caused by air entrained in the fluid. The entrained air, once in the disposal stratum, can either react with the formation fluids producing plugging precipitates, or plug the stratum simply by filling voids [5].

If the well should become plugged various methods, such as backwashing and flushing or re-stimulation, can be used to revitalize the injection stratum [11,27].

Prevention of contamination

This item, as discussed throughout this thesis, is the primary concern to both the designer and the operator. Once in operation several aspects of the well can be monitored which aid in the prevention of accidental contamination of surface or subsurface fresh waters. The following characteristics of the well operation should be monitored as a minimum [1,2,15]:

1. Pressures and quantities of fluid injected
2. Composition and pressure of annulus fluid
3. Retention of injected fluid in the injection stratum

The recording of wellhead pressures, preferably on continuous recording devices, can provide useful information on the efficiency and safety of the well. Normally the pressure will rise initially after the start-up of the well, and then will stabilize for a given rate of injection. A gradual, but larger than normal, pressure rise during steady operation can indicate formation clogging [3].

A sudden increase in the flow rate at the beginning of operations can indicate hydraulic fracturing. Otherwise, this sudden rate increase is indicative of failure of the casing, grout or seal [2].

A change in the annulus fluid composition or pressure can indicate a malfunction in the injection string or the failure of the seal [5].

To monitor the retention of the injected fluid in the injection stratum, monitor wells need to be provided at various distances and depths from the injection well. These wells substantially increase the total project cost and are considered of limited value due to the difficulties in predicting the movement of the waste in the injection stratum so that the wells can be placed to intercept the waste front [1]. It is more feasible to monitor the over-lying strata and injection stratum pressures and fluid composition by the use of existing extraction wells. However, regulatory agencies may specify the need of monitor wells. An excellent method of providing at least one monitor well, as well as stand-by equipment, is to construct two injection wells. One would serve as the primary injection well while the other provides a monitoring capability and serves as the back-up well in case of malfunctions in the primary.

General operational considerations

Experience has shown that rapid or extreme variations in the rates, pressures or quality of the injection fluid can damage the facilities [1]. Provisions should be made for shutting down the system in the event of these extreme variations.

CHAPTER V

LEGAL CONSIDERATIONS

As with any other engineering project, the design engineer and system operator should be aware of the legal ramifications of the project. In general, these consist of legal and regulatory pressures whose main concerns are the prevention of, and relief from, pollution of the subsurface and surface [5].

Legal Action

Most of the legal principles and precedents involved in deep well injection systems have been carried over from the experiences of the gas and oil industry [5]. The most important principle developed by these industries is the rule of capture which, loosely defined, states that a well operator can extract from the ground whatever he can capture with his well, no matter whether the substance was initially within his boundaries. For deep well injection this rule is reversed by saying that whatever is injected does not necessarily need to remain within the confines of the well operators property. This in effect allows the operator to trespass upon his neighbors subsurface property rights; however, it does not allow the operator to damage the trespassed property [5].

Briefly, the adjudication of claims of subsurface groundwater pollution and destruction of, or interference with mineable mineral deposits have embraced the doctrines of trespass, negligence, nuisance and strict liability [28].

Trespass

Cases of relief being received through the doctrine of trespass are rare; but, if the proper circumstances are present the operator can be held liable. Most modern decisions regarding trespass have allowed recovery of damages only if the plaintiff is able to prove that actual damages occured, how it occured and the identity of the offending party or parties [26].

An example of the use of the doctrine of trespass is Delhi-Taylor vs. A. W. Gregg and Christian R. Holmes, et. al. [29] which ruled that the law of trespass can be used to prevent fracturing of a stratum when the fractures would cross lease lines. In its decision the Texas Supreme Court declared that the "invasion alleged is direct and the action taken is intentional. Gregg's well would be, for practical purposes, extending to and partially completed into Delhi-Taylor leasehold." [29].

Nuisance

Many courts have reasoned that the owner of land is entitled to the use of underground water, or other valuable resource, in its natural state and that other land owners have no right to limit this use. In general this limits any conduct that interferes with the enjoyment and possession of land to an unreasonable and substantial degree [28].

Negligence

Failure to exercise reasonable care constitutes the tort of negligence. In most cases, the burden of proof rests with the plaintiff; however, when the defendant has complete control of the cause of the claim, then the principle of res ipsa loquitor (the thing speaks for itself) applies. This principle shifts the burden of proof to the defendant. Since the operator of a deep well injection system has complete and absolute control of the process he is usually required to prove his innocence when faced with a charge of negligence [28].

Strict liability

Strict liability does not require that fault be a prerequisite for liability. It is usually applicable in instances where inherent hazards are associated with the enterprise although all possible precautions are taken. Whether the deep well injection system operator will face such action depends entirely upon a judicial determination that the operation is inherently hazardous [28]. There has been an increased tendency in the courts, however, to accept the doctrine of strict liability in cases concerning deep well injection [5].

Regulatory Agencies

All injection wells in the United States fall within the regulatory jurisdiction of the U. S. Environmental Protection Agency. In addition, each well is subject to state and possibly regional regulation. Only the policies and requirements of the EPA will be discussed in this section since they apply to all wells and since, in all probability, the state regulations parallel these.

Basically, the EPA's goal in regards to the subsurface emplacement of fluids is to protect the subsurface from pollution [30]. The policies for achieving this goal are designed to:

1. Prevent improper injection or ill-sited injection wells

2. Ensure that adequate engineering and geological safeguards are incorporated into all phases of the project life

3. Encourage the development and use of safer disposal techniques other than subsurface emplacement

To satisfy these policies, all proposals for subsurface emplacement of fluids will be reviewed to determine that [30]:

1. The subsurface injection alternative is the most satisfactory alternative in terms of environmental protection

2. Technical evidence indicates that the present or potential use of the subsurface resources will not be

impaired

3. The fate of the injected fluid has been determined as best as possible

4. The design of the injection well meets current state of the art technology and provides maximum environmental protection

5. An adequate monitoring program has been designed into the system

6. Contingency plans have been prepared, and the necessary means to carry them out have been provided, in order to cope with any system failure

7. Provision has been made for plugging of the well and for the monitoring of the plug when the well has been abandoned

A list of items which the EPA requires as a minimum for review of an injection well proposal is presented in Appendix 3.

No matter how outstanding the facility may be, the EPA requires that subsurface emplacement of fluids be recognized as a temporary solution. If wastes are being disposed, the injection is temporary until new technology is available which provides a more assured environmental protection. If fluids are being stored or recycled by injection, then the system will be discontinued or modified when it becomes a hazard to the environment or natural resources [30].

CHAPTER VI

DEEP WELL INJECTION IN THE STATE OF FLORIDA AND STORMWATER AS A SOURCE OF INJECTION FLUID

Deep Well Injection in Florida

The hydrogeology of the state of Florida is dominated by a highly porous subsurface unit from which the majority of the water used for public, industrial and private use is produced. This unit, commonly called the Floridan Aquifer, underlies all of Florida and parts of Alabama, Georgia and South Carolina and consists of nearly 2000 feet (610 m) of porous limestone [31].

This aquifer is horizontally unconfined in that its shoulders are exposed at the Atlantic and Gulf of Mexico shelves of the state of Florida [32]. Vertical confinement is provided by a layer of variable clastic sediments ranging from shell marls, sands, gravels, clays and limestones of low permeability. In general, the aquiclude is present in all portions of Florida with the exception of the northeast panhandle and along the western side of the peninsula. The thickness of the aquiclude varies from a few feet to over 1000 feet (305 m) except where it is absent [32].

Although thought of as a single unit, the Floridan Aquifer actually consists of several strata of varying permeability with thin to thick sequences of dense, impermeable strata. For general use though, the unit can be considered to consist of an upper and lower aquifer with impermeable strata separating them. The upper aquifer usually contains high quality fresh water while the lower contains brackish water.

Stratigraphic boring logs of many deep wells drilled for gas or oil production/exploration have indicated that the lower portion of the Floridan Aquifer, called the Boulder Zone by some authors, is highly permeable containing large cavernous sections [32].

Because of the high permeability, solution channels, salinity and presence of confining aquicludes the hydrogeology of large areas of Florida are highly favorable for discharge, or storage, of large volumes of fluids [33].

Florida regulations

The Department of Environmental Regulation (DER) has regulatory and permitting powers for the construction and use of deep well injection systems. The policies of the DER are based upon the needs of the state and the policies of the EPA which were discussed previously. To provide a uniform interpretation of some of the generalized guidelines of the EPA, the DER has amplified upon the need and degree of pre-injection treatment systems and various other aspects of the design.

For those fluids which can be described as industrial, municipal or domestic wastes, the guidelines require that industrial wastes be treated by the latest modern techniques available as approved by the department while a 90 percent treatment, or better, must be provided for municipal and domestic wastes. If nutrient removal or other advanced wastewater treatment methods are not provided, in addition to a 90 percent reduction in BOD_5 and suspended solids, then the guidelines for industrial wastes would apply to municipal or domestic wastes [34].

The use of surface or flood waters for storage in confined saline aquifers for future use, or for salt water intrusion prevention and control is encouraged by the DER provided that the best practicable measures for pre-injection treatment of the fluids have been applied [34]. Exactly what type and degree of treatment this specifies is not defined but indicates that the treatment system is to be determined on a case by case basis.

Additional requirements include:

1. As a minimum, the operation of the system must be under the control and supervision of a full time certified operator and graduate engineer [33]

2. In most cases three wells will be required; one injection, one standby injection and one permanent monitoring well [34]

3. The well, where feasible, will be located seaward of the 1000 ppm isochlor line [34]

In addition to the emphasis on pre-injection treatment and the protection of the environment, the DER regulations require that the injection well be properly engineered, constructed and tested. The normal construction sequence imposed by these regulations consists of [35]:

1. Submittal of application for construction of test well
2. Construction of test well and testing of fluid properties and characteristics of the various aquifers penetrated by the well to determine suitability of site for injection and to select injection stratum
3. Submittal of application for construction of injection well including results of testing program
4. Construction of injection system

Usually, the test well can be constructed in such a manner that the test well can be converted to the injection, standby or monitor well with little additional cost.

To receive approval from the DER for the installation of a deep well injection system various reports and data must be submitted. This information is the same as that required by the EPA presented in Appendix 3.

Use of Stormwater Runoff as a Source of Injection Fluid

One of the more recent developments in the use of deep well injection systems has been the consideration of storing relatively clean water in subsurface strata for future use.

This is of special interest in areas with evaporation rates which would significantly reduce the stored volume of surface reservoirs.

The source of water which is most often considered as a source of injection fluid for subsurface storage is surface stormwater runoff and excess flood waters. However, a problem associated with their use as an injection fluid is the variability of their physicochemical and biological characteristics and the intermittency of the flow.

Characteristics of stormwater runoff

Various studies have investigated the physicochemical and biological characteristics of stormwater runoff. Results from several of these studies, which are of importance to the design engineer of a stormwater runoff injection well, are presented in Table VI-1.

These results indicate that no average values can be assigned to the various characteristics of stormwater runoff for all runoff basins in the United States. Instead, they strongly point out that the characteristics must be determined for each basin. Although no average values can be assigned, these results can indicate to the engineer the magnitude of the pollutant loads which could be present in stormwater runoff.

To put the pollutant loads imposed on surface waters by storm water runoff in perspective, Colston [38] compared

TABLE VI-1

SELECTED CHARACTERISTICS OF STORMWATER RUNOFF

Constituent	*Results of Studies						
	36**	37	38	39	40	41	42
Total Suspended Solids (mg/l)	2 11300	99	1223	87	227	84	280
BOD_5 (mg/l)	1 >700	7.2	-	-	-	-	-
COD (mg/l)	5 3100	-	170	-	-	-	-
Total P (mg/l)	0.1 125	0.26	0.82	-	-	-	-
Total N (mg/l)	0.2 18.5	2.32	0.96	-	-	-	-
Total Coliforms (#/100 ml)	200 $146x10^6$	-	2300	-	-	-	-

* Number refers to reference number
**Values given indicate average ranges

the characteristics of runoff water with those of treated municipal waste effluents which were discharged into the same stream. This comparison indicated that of the total Chemical Oxygen Demand (COD), ultimate Biological Oxygen Demand (BOD) and suspended solids load on the stream under study, 82, 77 and 99 percent of the loads, respectively, were contributed by stormwater runoff. These loads are representative for those times of urban runoff, which for Colston's study occured 19 percent of the time. Obviously then, for approximately 20 percent of the time, the quality of the stream was not controlled by treated effluent point sources but by stormwater runoff.

Pre-injection treatment of stormwater runoff

Treatability of stormwater runoff. In general there are three basic types of treatment methods: 1) physical; 2) chemical; and 3) biological. With respect to the pre-injection treatment of stormwater runoff the intermittency of the flow, in regards to both the volume and time, will have the greatest influence on the selection of the treatment method.

Stormwater runoff, which is typified by large flows at intermittent periods, is generally not conducive to effective biological treatment methods due to the continuous food requirements and low resistance to shock loadings of the microorganisms [38]. Physicochemical treatment processes, including sedimentation, dissolved air flotation, micro and fine mesh screening, filtration and special swirl and helical separation, appear then to be appropriate for the pre-injection treatment of stormwater runoff [43].

Colston [38] evaluated the efficiency of sedimentation either plain or with coagulants, as a method for treatment of urban stormwater runoff through a laboratory pilot plant study. This investigation indicated that plain sedimentation for 15 minutes under ideal quiescent conditions resulted in a 60, 77 and 53 percent reduction in COD, suspended solids and turbidity respectively. Sedimentation after the addition of alum, with or without coagulant aids, resulted in an

84, 97 and 94 percent reduction in COD, suspended solids and turbidity respectively.

Rebhun and Hauser [44] investigated the use of cationic and anionic polyelectrolytes for the removal of suspended solids from surface runoff or flood waters. Their results indicated that cationic polymers, in conjunction with small doses of alum, were effective in the removal of suspended solids. In addition, a field installation was constructed to determine the feasibility of using polyelectrolytes for the pre-injection treatment of surface runoff or flood waters. Figure VI-1 presents a schematic diagram of the field installation. This pilot plant was able to effectively handle flow rates ranging from 0.716 to 1.44 MGD (113 to 227 m^3/hr) reducing the suspended solids concentrations from between 120 and 250 mg/l, to between 9 and 30 mg/l, with most of the effluent having less than 20 mg/l of suspended solids prior to injection into recharge wells.

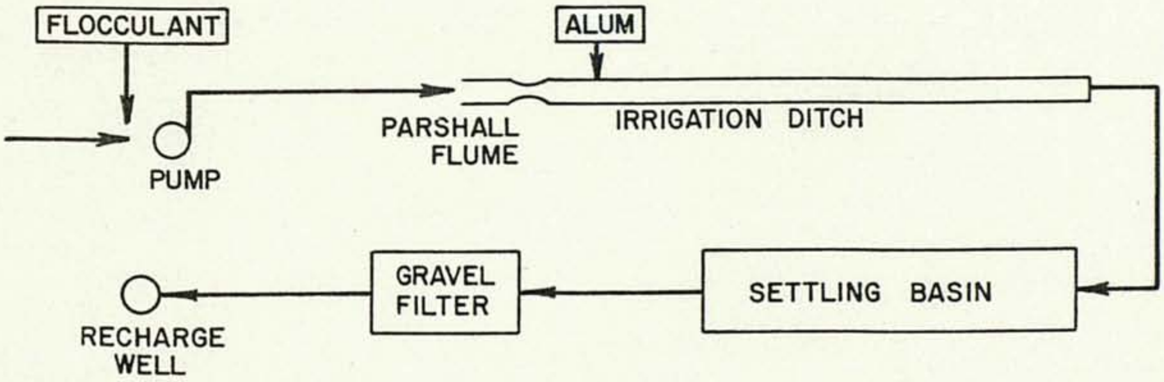

Figure VI-1 - Schematic diagram of Rebhun and Hauser's field installations

One of the problems faced by Rebhun and Hauser during the field experimentation was that the recharge wells, which were completed into an unconfined, fine sand aquifer, were gradually plugged up by the suspended solids remaining in the treated water. The wells were easily redeveloped by bailing. Examination of the bailed water indicated that the clogging was mainly due to micro-floc which did not penetrate very far into the formation.

Rebhun and Hauser concluded that the use of polyelectrolytes is preferable to conventional flocculants (iron and aluminum sulfates) due to lower dosage rates; heavier and larger floc particles; and little pH change.

Is treatment required? Previous mention was made of the characteristics of stormwater runoff. Other than suspended solids the main characteristics of runoff, with regard to its suitability for injection into subsurface formations, are its oxygen demand--or degradeable organics--and fecal coliforms. A substantial amount of research has been performed on the removal of degradeable organics and fecal coliforms through land spreading on permeable sands; however, to the writer's knowledge, no actual research has been conducted on this same topic with respect to subsurface disposal. Goolsby [45] reported that the injection of various organic acids, amines, alcohols, ketones and inorganic salts resulted in decomposition of organic compounds and nitrate reduction with the production of a gas (54 percent methane, 14 percent nitrogen, and 20 percent carbon dioxide).

Subsequent changes in the pre-injection treatment process decreased the pH of the wastes from 5.2 to 3.3. This reduction in pH terminated the production of the gas and nitrate reduction. Although the initial pH (5.2) was not within the optimum pH range for anaerobic digestion of organics (6.6 to 7.6 [46]) it is possible that the methane gas was produced anaerobically. Regardless of the process involved, problems could have occured by the production of a gas through plugging of the disposal stratum by the gas.

The treated surface flood waters injected by Rebhun and Hauser [44] contained over 550 coliform organisms per 100 ml of water. Water pumped from an irrigation well, completed into the same formation as the injection wells and 66 feet (20 m) away from the injection well, contained no coliform organisms for several days after injection and in no instance contained over 2.2 organisms per 100 ml.

Viruses can also be an important consideration in the design of any type of disposal system. However, so little is known about the methods by which they can be collected, isolated and identified that any significant conclusions are not possible.

From these examples it is the writer's opinion that prior to the injection of stormwater runoff, two characteristics of the fluid need to be modified: 1) suspended solids; and 2) oxygen demand. The degree of treatment will, of course, depend on the characteristics of the influent and on the requirements of the well system. In instances where the oxygen demand of the influent is low, then no reduction would be necessary. The treatment provided should reduce the oxygen demand rate to a level which will not cause serious plugging of the disposal stratum from the production of gas by anaerobic digestion of the wastes. It is the intent of this work to initiate research into the degree of suspended solids reduction required prior to injection.

Treatment systems, such as used by Rebhun and Hauser [44], consisting of simple flocculation, sedimentation and filtration, are suitable for the pre-injection treatment of runoff water. This reliable treatment process should produce an effluent which will not damage or impair the proper operation of an injection well.

CHAPTER VII

RESEARCH

As mentioned in previous chapters there is very little data available on suspended solids and ineffective injection well operations. The purpose of this work was to develop a test method by which guidelines could be developed to indicate the level of suspended solids removal efficiency required for the succesful operation of deep well injection systems.

Test Rationale and Set-Up

Since whatever guidelines which may be developed with this test method will be entirely dependent upon empirical knowledge, the test equipment and methods should simulate injection systems disposing of a fluid containing suspended solids.

The basic features which the equipment should provide are:

1. A test chamber to hold samples of varying lengths
2. Pumping capability at varying pressures
3. Mixing and feed apparatus for fluids and solids
4. Ability to perform permeability tests

Figure VII-1 presents a schematic representation of the test equipment which simulates the pumping of a fluid through a differential volume of rock from the wall of an injection well. The two feed barrels (A) are set up to reduce the possibility of entraining air in the fluid and to supply the pressure pump (B). In addition they serve as the constant head source for the permeability tests.

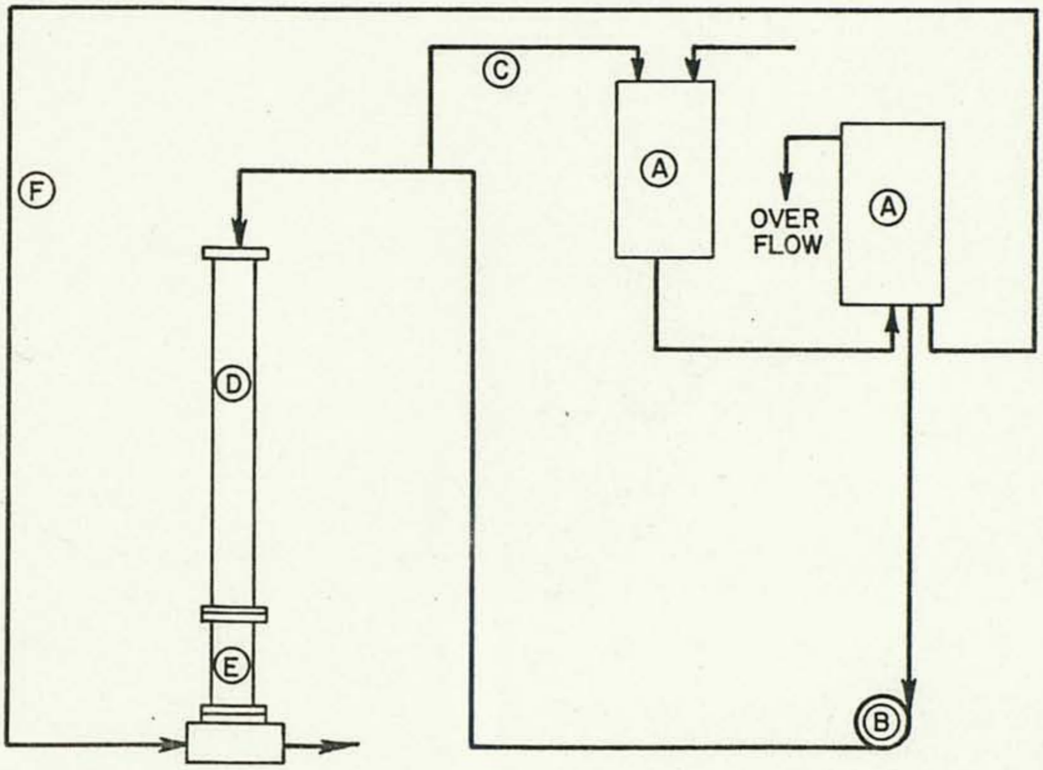

Figure VII-1. Schematic diagram of test equipment set-up showing: (A) feed barrels; (B) pressure pump; (C) pressure control return line; (D) test chamber; (E) test section; (F) permeability test supply line.

Pressure pump (B), a 2.1 gpm (0.46 cu.m./hr) at 200 psi (1380 kN/m^2) displacement pump, is used to pump the fluid through the test sample. Return line (C) is provided to control the test pressures from 0 to 170 psi (0 to 1173 kN/m^2). The upper limit is set by the popping pressure of a relief valve incorporated into the test chamber piping.

The test chamber (D), a flanged 6 inch I.D. (15 cm) galvanized pipe, provides various test control and measuring devices and is connected to the test section (E) which houses the test sample. The test section is also constructed from flanged 6 inch I.D. (15 cm) galvanized pipe. Flow around the sides of the sample is restricted by, and sample containment is provided by, epoxying the sample in place.

Plastic tubing is provided in the permeability test supply line (F) which allows both constant and falling head permeability tests to be performed. All other piping is galvanized.

Samples are taken from boulders of varying size, sampled from rock quaries, by coring with a 6 inch O.D. (15 cm) diamond bit coring barrel.

It should be noted that an earlier design of the test chamber (D and E) using plexiglass failed to maintain the required pressures.

Method of Test

Three types of operations are performed for each testing cycle. The initial test determines the permeability of the sample, using either constant or falling head test methods. Second, the pressure test, or simulation of injection, is performed and finally the sample is backflushed in preparation for the next testing cycle.

Permeability tests

The equipment is designed so that an upward flow permeability test may be performed under either of the two head conditions. The test procedure follows standard established procedures for soils such as found in ASTM D-2434 [47] or Soil Testing for Engineers [48].

Pressure tests

These tests are performed at constant pressures and suspended solids concentrations. For each suspended solid concentration, a series of tests are performed at different pressures which are maintained constant.

Although actual injection wells operate on a constant flow, rather than a constant pressure basis, this test was developed for constant pressure since time requirements necessitated the use of whatever pump was readily available. Using a constant suspended solids concentration does, on the other hand, model an actual injection system. Prior to injection most systems will provide either treatment or some sort of flow equalization, or both. In either case the pre-injection processing of the fluid will tend to equalize the suspended solids concentration, thereby maintaining it at a constant concentration.

The test consists of determining the flow out of the sample by measuring the time required for the discharge of a known volume at various times while maintaining a constant pressure above the sample and a constant suspended solids concentration in the feed barrels. Sample of the discharge are also taken for determination of the discharge suspended solids concentration.

Backflushing

This operation is performed immediately after each pressure test to dislodge as many of the solid particles, which were trapped within the sample, as possible. This is simply a reverse flow under pressure. At the same time, the upper surface of the sample is pneumatically cleaned of any caked sediment.

Miscellaneous tests

After the sample is taken, a portion of the discarded material is used to determine the physical properties of the test sample. These properties are:

1. Dry unit weight
2. Specific gravity
3. Absorption
4. Porosity
5. Void ratio

Test Results

To determine the validity of this test method, and to correct whatever problems existed with the design of the equipment and test methods, several pressure tests were to be performed on at least two different samples. The failure of the initial plexiglass design, however, limited the amount of testing which could be completed within the time frame imposed on this work. Instead, 12 pressure tests, three different suspended solids concentrations at four different pressures, were accomplished on one sample.

Properties of test sample

The sample used in this testing was cored from a boulder of limerock obtained from the Center Hill Quarry of the Shands and Baker Division of Florida Rock Industries. The limerock was a slightly friable sample of the Tertiary Crystal River Group of the Ocala Formation which was found at an approximate elevation of 100 feet (30 m) MSL.

A representative portion of the boulder was used for laboratory tests to determine various properties of the test sample. The results of these tests are:

1.	Dry unit weight	103	lb/ft^3
2.	Apparent specific gravity	2.3	
3.	Bulk specific gravity	1.7	
4.	Porosity (based on apparent specific gravity)	.28	
5.	Void ratio (based on apparent specific gravity)	.38	
6.	Absorption	.15	
7.	Size of test sample		
	a) diameter	5.76	inches

b) length 4.00 inches

It should be noted that the limerock sample was not homogeneous and that these results may not apply throughout the boulder's cross-section; however, for the purposes of this research the assumption that they do represent the sample can be made.

General test set-up

One of the most difficult aspects of preparing the test sample was sealing the sides of the core and providing positive seating for the core in the test section. Various alternatives were considered including O rings and support chairs, but epoxying was finally selected as the easiest method. Still, problems occured when in epoxying the sample in place an excess of epoxy was used which coated the upper surface of the core. The problem was overcome by grinding the layer of epoxy from the core's surface which did not change any of the samples's characteristics.

Commercially available driller's mud (bentonite) was used as the source of suspended solids. Bentonite was selected since its small particles should approximate the size of the particles which stormwater runoff would contain after settling out of the larger sand grains. It is felt that no problem would be caused by the swelling tendencies of bentonite since the length of time which the particles remain in suspension would allow for the particles to swell prior to introduction into the test chamber.

Permeability tests

A problem encountered in the first permeability test was that the equipment did not provide a means for releasing the trapped air beneath the core. This was solved by pressurizing the container below the test section to approximately 40 psi (276 kN/m^2) for 5 to 10 minutes. This forced the air through the core with no appreciable effects on the accuracy of the tests. In subsequent tests, the permeability test was performed immediately after backflushing of the sample. The backflushing operation essentially accomplished the removal of the air through the same means.

Fourteen permeability tests were performed on the sample consisting of 64 individual flow/time readings.

The results of these tests indicate that the test sample has an average permeability of 6 x 10^{-4} ft/min (3 x 10^{-4} cm/sec). In addition, there is a 99 percent confidence (based on a student-t distribution) that this value does not vary by more than 8 x 10^{-5} ft/min (4 x 10^{-5} cm/sec). Since these tests were performed both before and after each backflushing operation, the high degree of confidence in the permeability results indicates that the backflushing was successful in restoring the sample to approximately the same initial state.

Pressure tests

Two basic problems were encountered during the pressure tests, the second of which will be discussed later. The first consisted of difficulties in controlling the test pressure. It is felt that this was due to slug flow caused by the displacement pump. At best the test pressures reported herein are a general average. In actuality the test pressure most often instantaneously varied from the average by as much as ±10 psi (69 kN/m^2).

As previously mentioned, 12 pressure tests were performed on one test sample. Three suspended solids concentrations were used--100,350 and 600 mg/l--at four different pressures, 10, 25, 40 and 60 psi (69, 172.5, 276 and 414 kN/m^2) figures VII-2 through VII-5 graphically present the results of a test series (a series is defined as four tests at different pressures for one suspended solids concentration) for the 600 mg/l concentration. These four tests typify all three series.

Some of the typical aspects of these tests are:

1. A period in which the flow establishes and stabilizes. This period was usually considered to be 15 minutes in length

2. The test sample acted as a filter. Analysis of the fluid which passed through the sample indicated that its suspended solids concentration was less than 1 mg/l at all times for each test pressure

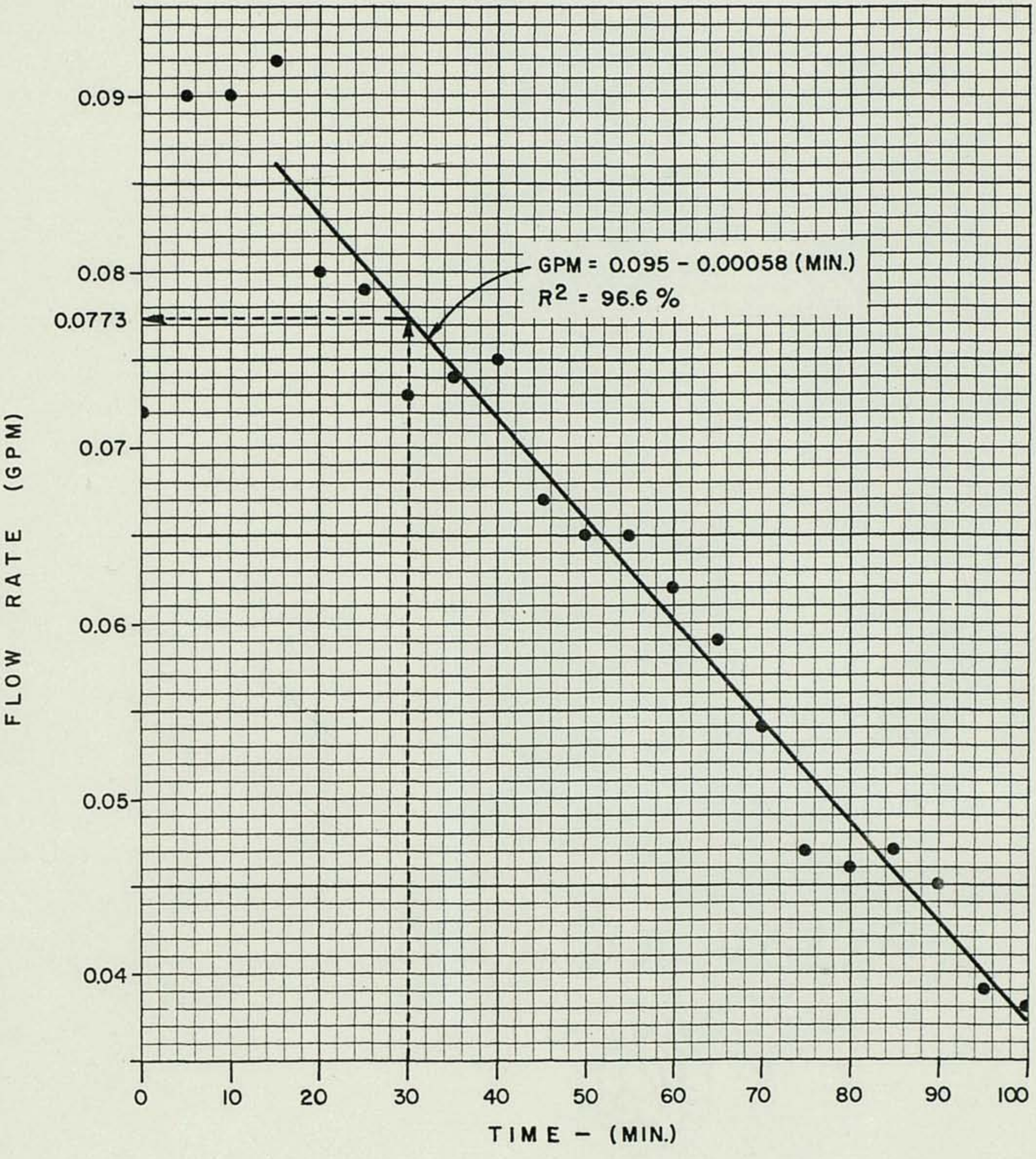

Figure VII-2 - Flow vs. time for a pressure test at 10 psi using a 600 mg/l bentonite suspension

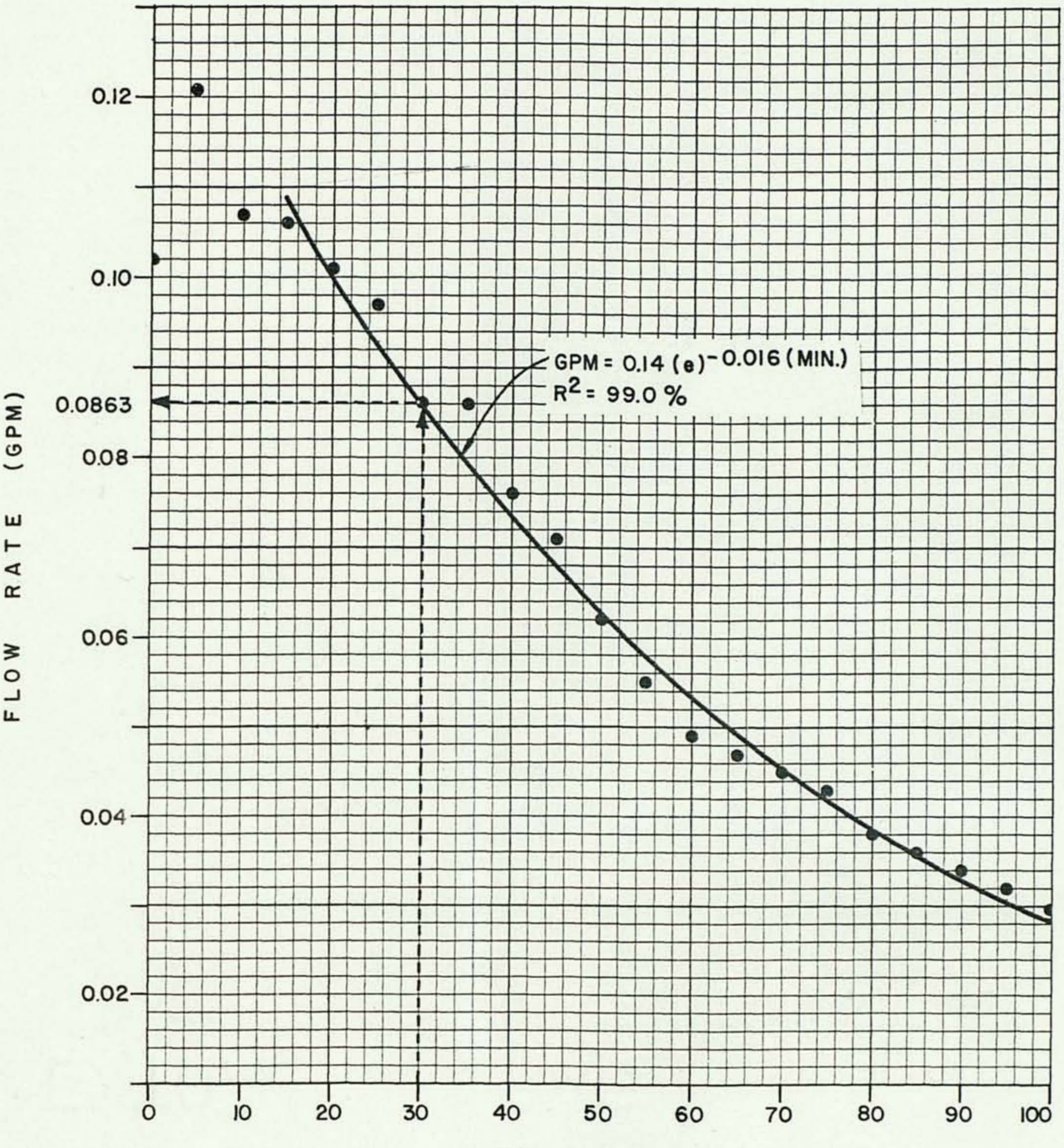

Figure VII-3 - Flow vs. time for a pressure test at 25 psi using a 600 mg/l bentonite suspension

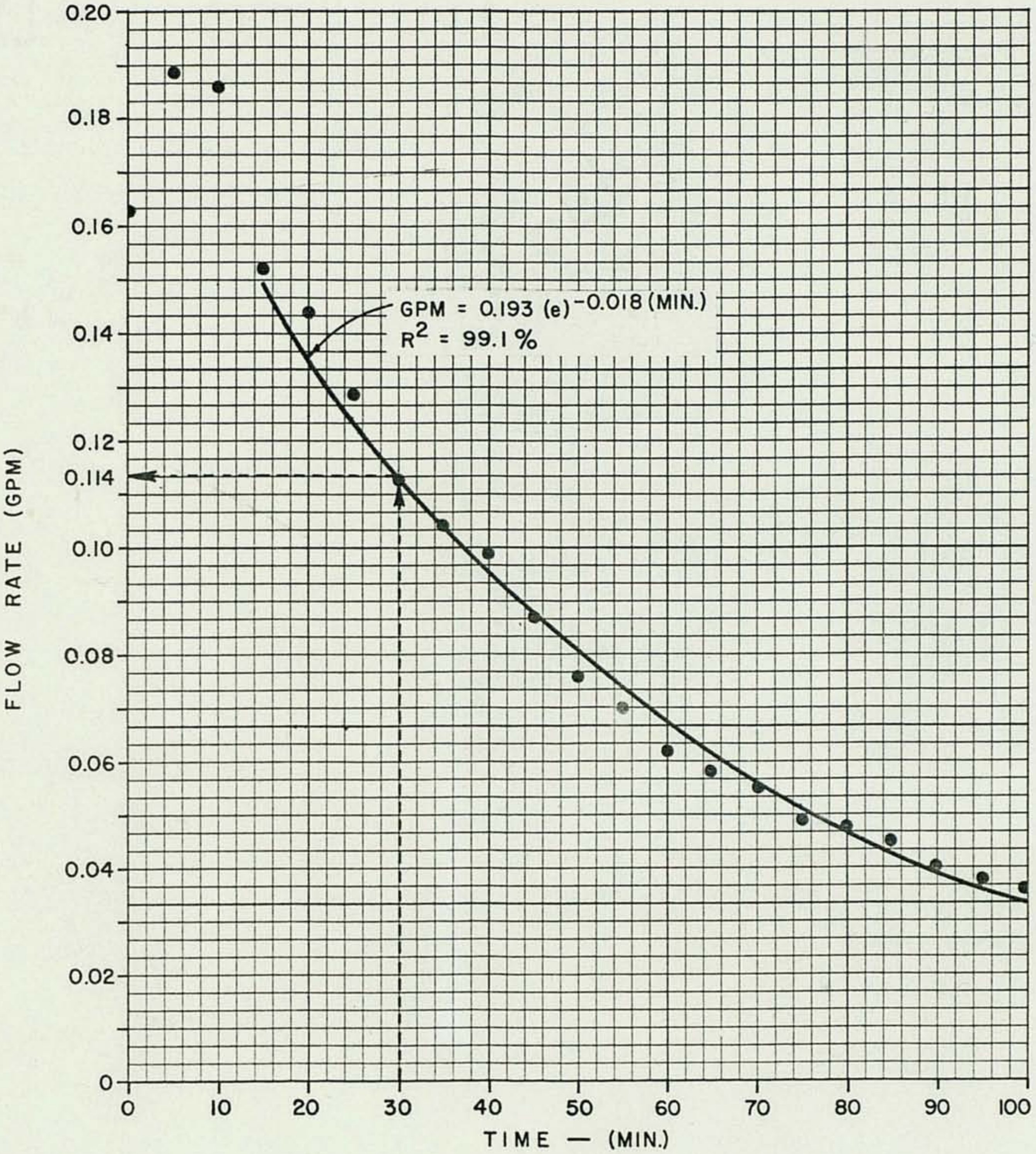

Figure VII-4 - Flow vs. time for a pressure test at 40 psi using a 600 mg/l bentonite suspension

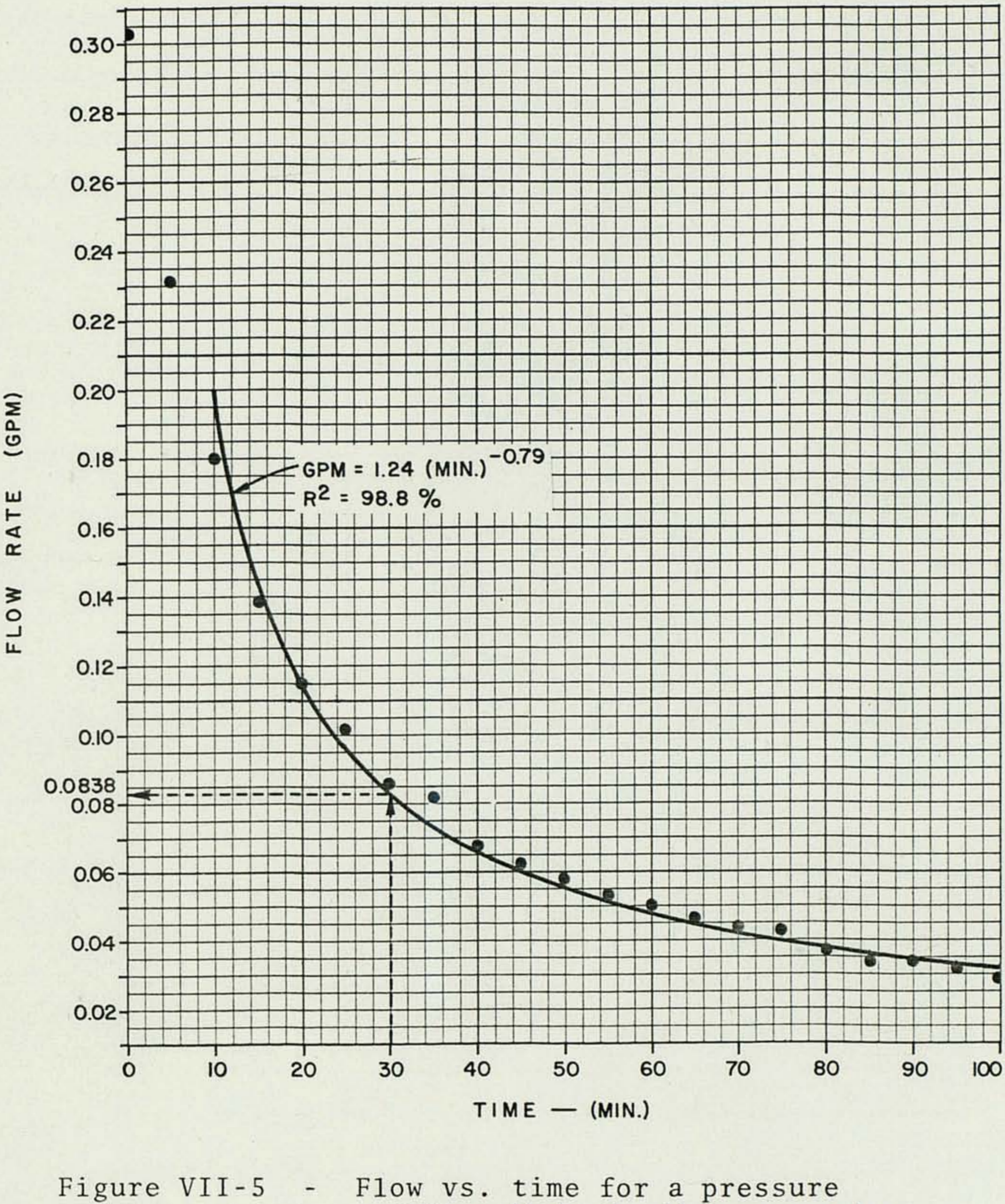

Figure VII-5 - Flow vs. time for a pressure test at 60 psi using a 600 mg/l bentonite suspension

3. The form of the equation which best fits the data (based on the regression coefficient R^2), and the coefficients of these equations, for each pressure, are consistent for all tests. This pattern is evident in Table VII-1 which presents the best fit equations for all pressure tests.

TABLE VII-1

BEST FIT EQUATIONS FOR ALL PRESSURE TESTS

Pressure (psi)	Bentonite Suspension Concentration (mg/1)	Equation of best fit	Regression Coefficient R^2 (%)
10	100	$GPM=0.06-0.000097(MIN)$	79.9
	350	$GPM=0.14-0.00018(MIN)$	86.1
	600	$GPM=0.09-0.00058(MIN)$	96.9
25	100	$GPM=0.127(e)^{-0.0056(MIN)}$	98.4
	350	$GPM=0.137(e)^{-0.01(MIN)}$	98.6
	600	$GPM=0.139(e)^{-0.016(MIN)}$	99.0
40	100	$GPM=0.18(e)^{-0.0099(MIN)}$	97.7
	350	$GPM=0.15(e)^{-0.014(MIN)}$	97.5
	600	$GPM=0.14(e)^{-0.016(MIN)}$	99.1
60	100	$GPM=0.91(MIN)^{-0.55}$	98.0
	350	$GPM=1.14(MIN)^{-0.73}$	97.5
	600	$GPM=1.24(MIN)^{-0.79}$	98.8

To summarize the data from the pressure tests, the flow rate at arbitrarily selected times (30, 60 and 90 minutes) was plotted versus the test pressure. Figure VII-6 presents the results of this summarization for a bentonite suspension of 600 mg/1. The shape and trends of these curves are the

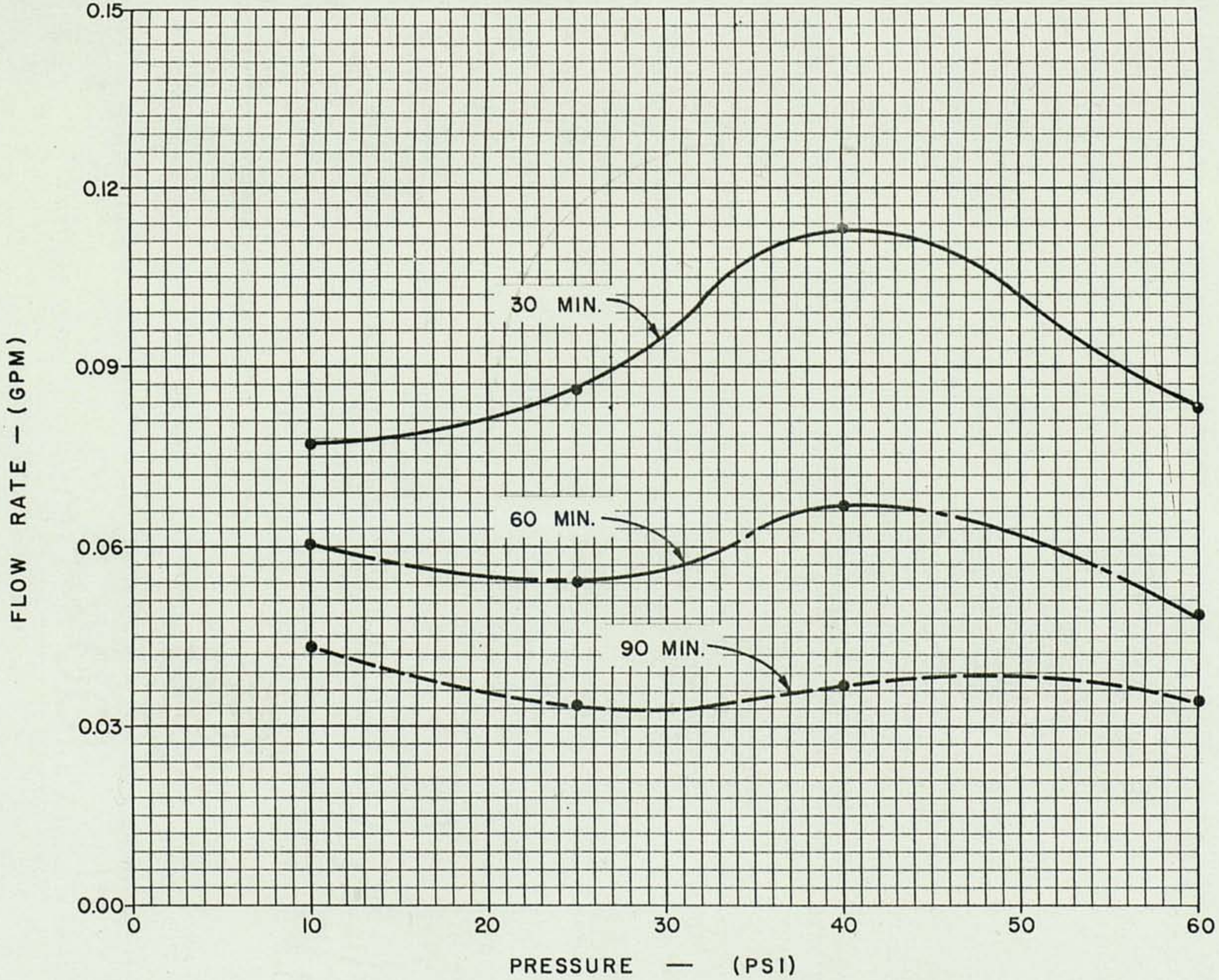

Figure VII-6 - Flow vs. pressure for a 600 mg/l bentonite suspension same for the other two bentonite suspension concentrations.

A linear regression analysis of the data shown in Figure VII-6, and the other data not presented for 350 and 100 mg/l bentonite suspensions, indicated that an equation of the form

$$Y = \frac{X}{A + BX} \tag{12}$$

whose linear transformation is

$$\frac{X}{Y} = A + BX \tag{13}$$

best fits the data. The data was then plotted in the linear transformation form (i.e. ordinate is X/Y) and is presented in Figures VII-7 through VII-9. It should be noted that these figures were constructed using only four points and although the regression coefficient (R^2) for these equations is included, it is not necessarily significant for these data.

It is interesting to note that the units of the ordinate, of Figures VII-7 through VII-9, after the proper conversions is min/ft^2 which correspond to the units of the inverse of transmissibility.

Using this approach, Figures VII-7 through VII-9 would then indicate that the transmissibility of the test sample is decreased as the pressure and suspended solids concentrations increase. Although it is not immediately apparent, this can also be seen in Figure VII-6. The problem with this presentation (Figure VII-6) is that it indicates

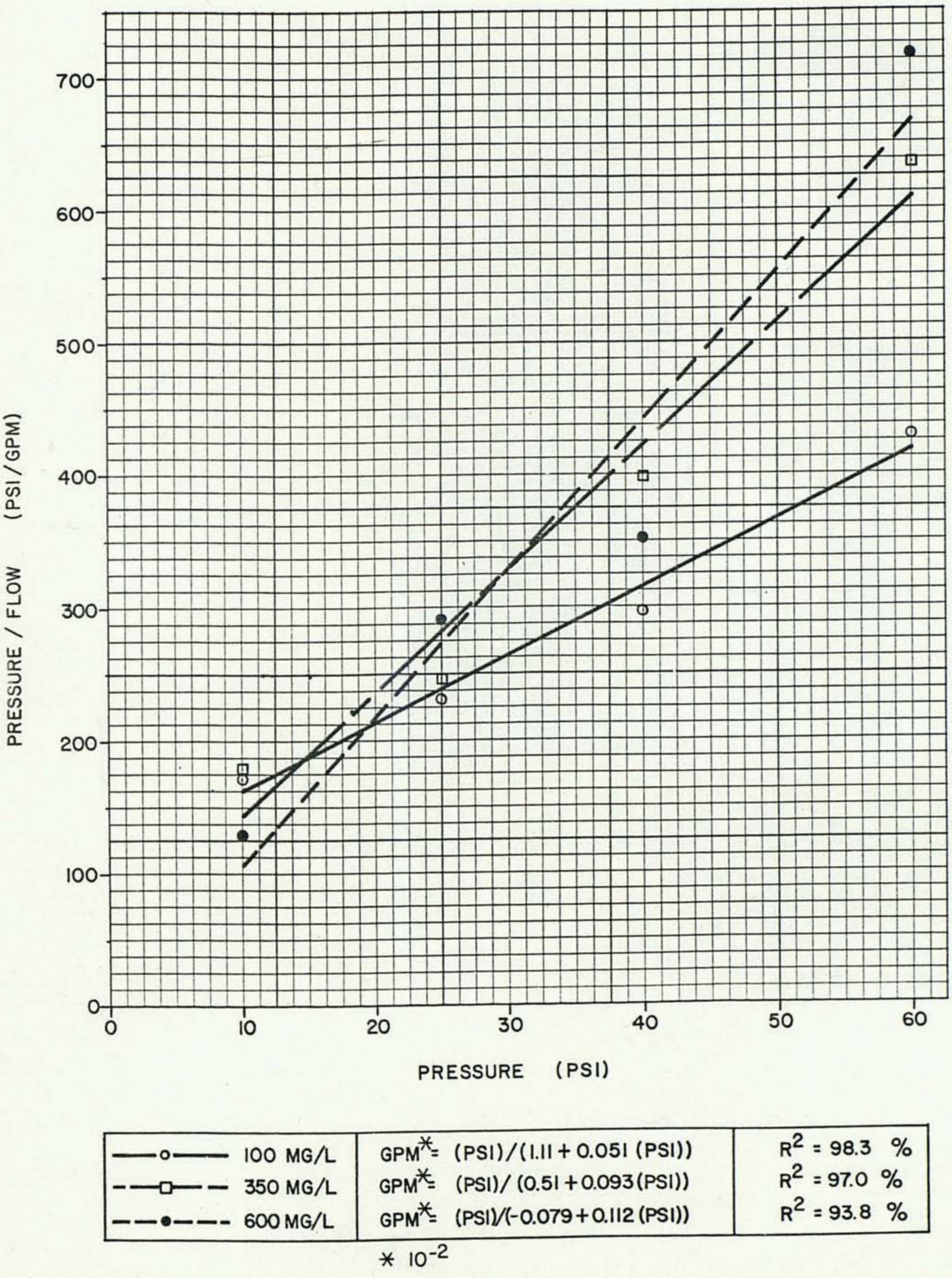

Figure VII-7 - Pressure/flow rate vs. pressure after 30 minutes of flow for various bentonite concentrations

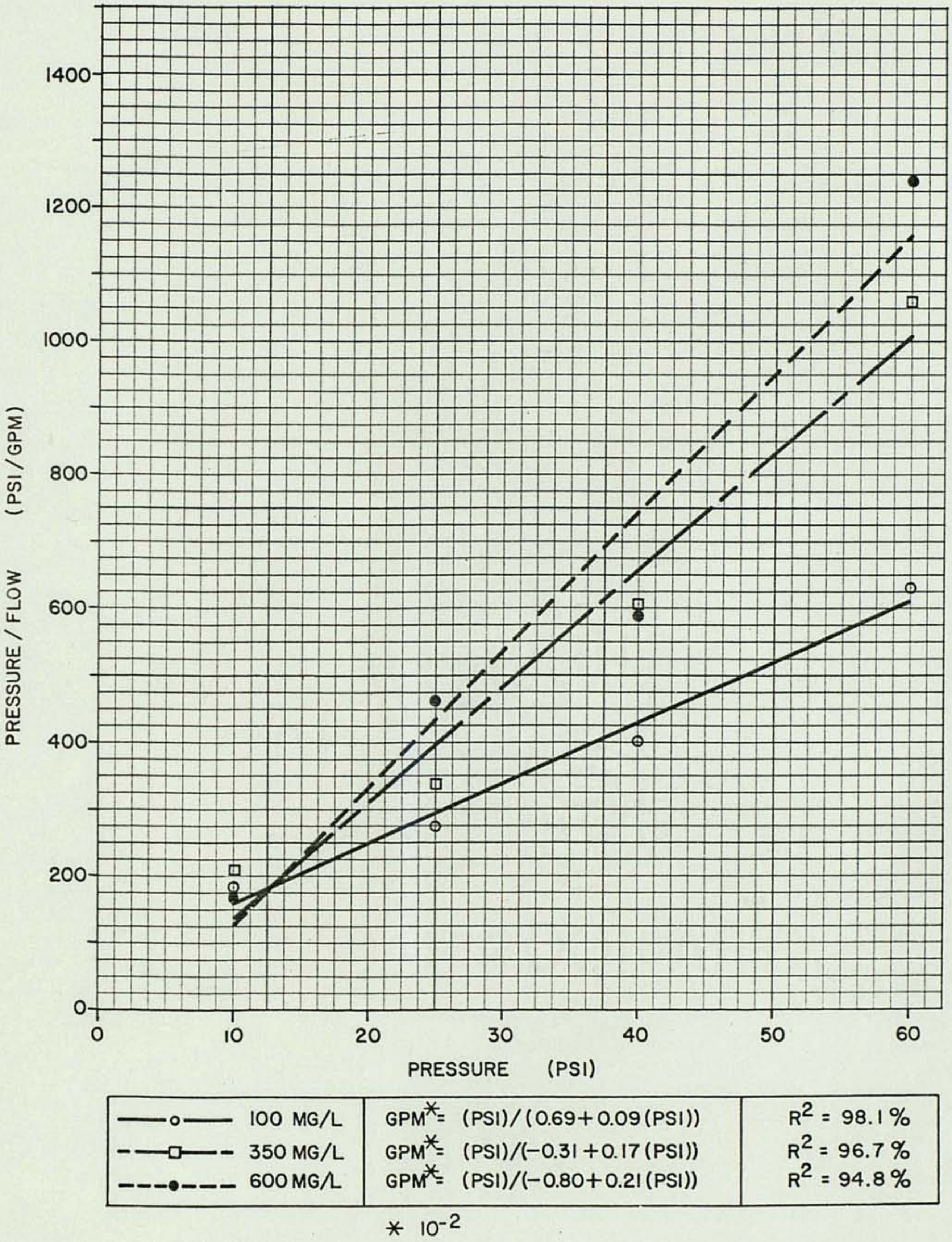

Figure VII-8 - Pressure/flow rate vs. pressure after 60 minutes of flow for various bentonite concentrations

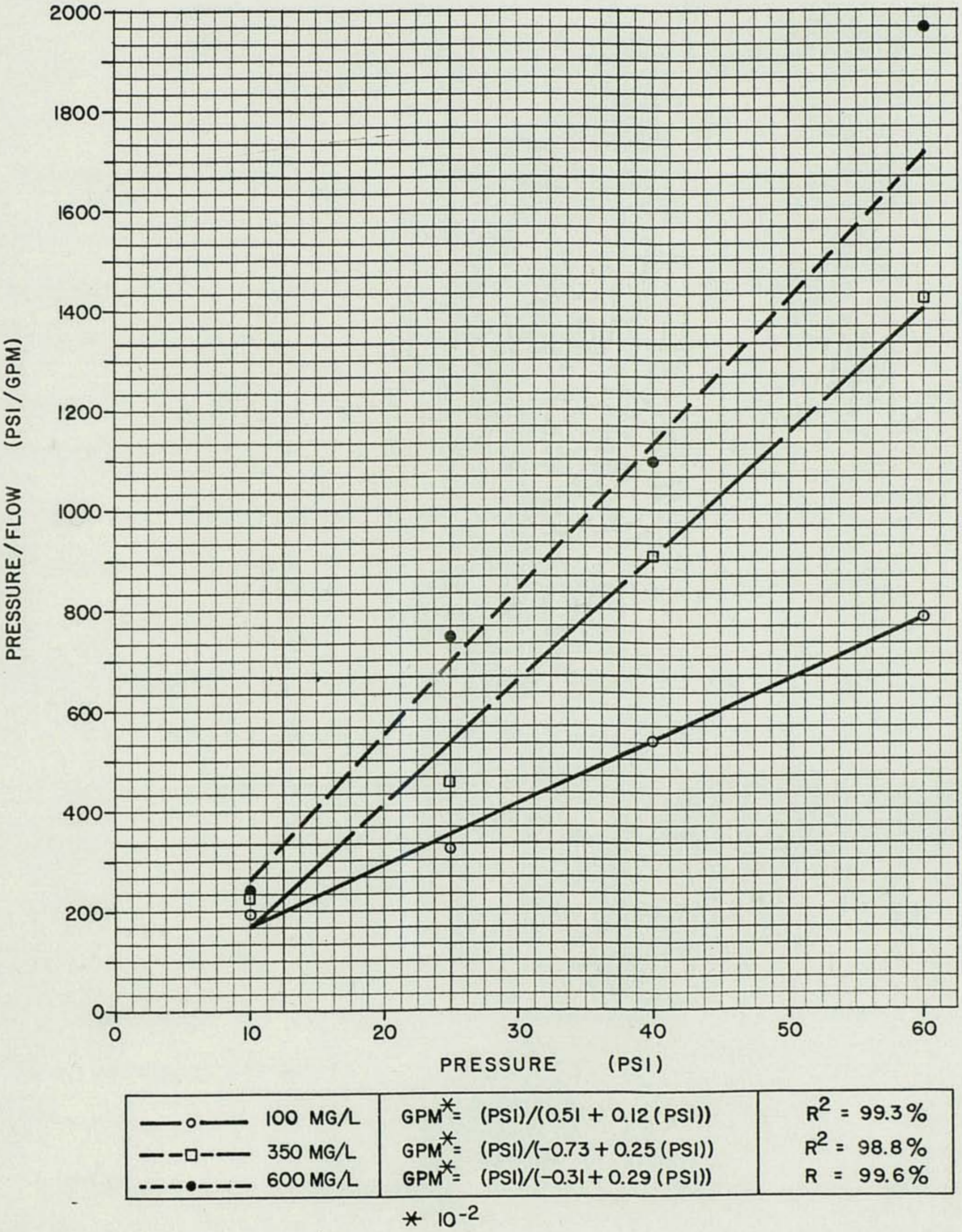

Figure VII-9 - Pressure/flow rate vs. pressure after 90 minutes of flow for various bentonite concentrations

that the flow tends to increase up to about 40 psi (276 kN/m^2) and then decreases. On first glance this would indicate an increase in the transmissibility up to 40 psi and then a decrease. However, the pressure has to be considered as well as the flow rate. Since the flow rate, based on Darcy's Law, is directly proportional to the product of transmissibility and applied head, then it can be seen that the flow may increase when the transmissibility is decreased if the applied head is increased. This is the case in Figure VII-6.

Visual examination of the interior of the test sample after removal from the test section revealed pockets of trapped bentonite. These pockets and other evidence indicated that bentonite was carried for a distance of approximately two thirds to three fourths of the sample's length into the core principally through interstitial channels.

The second problem alluded to at the beginning of this discussion was that a thin layer of bentonite was observed to have been formed on the test sample's upper surface. Whether this layer formed by settling of the bentonite during the test--the test flow rates impose very small velocities in the test chamber--or after the pressure test could not be determined. Therefore, it cannot be definitively concluded that the decrease in the sample's transmissibility is due entirely to plugging of interstitial pores in these tests.

Summary and Conclusions

Deep well injection systems have been in use for over 50 years principally by the oil production industry. Within the past 10 years, however, there has been a significant increase in their use as a means of disposing of industrial liquid wastes, treated domestic sewage and for the storage of relatively clean water for future use and for salt-water intrusion control.

Although there have been few major problems caused by injection wells, their nature is such that massive damage may be caused to the environment. Generally the problems which may be caused by injection wells are:

1. Contamination of subsurface fresh water supplies
2. Destruction of mineable subsurface mineral resources
3. Stimulation of earthquakes

Since the design of an injection well is based on the experience of extraction well design, construction and use, there is a large amount of knowledge which substantially defines the configuration of an injection well. However, since the injection well process is diametrically opposed to the extraction well process our knowledge of the kinetics of the system is limited.

A survey of the literature on this subject revealed that there was little, if any, data concerning the effect which suspended solids, when present in the injection fluid has on the operational life of the well.

The purpose of this work was to design and test a method of experimentation which could provide useful data concerning suspended solids injected into a porous stratum. The method selected consists of simulating the injection well process by forcing water containing a bentonite suspension through a six inch diameter test sample. The sample is encased in a test section which allows the test to be performed at various pressures up to a maximum of 170 psi (1173 kN/m^2). Various test parameters can be recorded, specifically flow rate, time, pressure, and suspended solids concentrations in and out of the test section, which can then be used to describe the process.

Conclusions

The following conclusions can be made based on the discussions presented in this thesis.

1. There are many areas in the State of Florida, especially where a cavernous limerock zone known as the Boulder Zone exists, which are suitable for deep well injection systems

2. Stormwater runoff can be a source of injection fluid for possible future use or salt-water intrusion control

3. A brief view of the characteristics of untreated stormwater runoff indicates that the Biological Oxygen De-

mand and suspended solids concentration levels of the fluid may need to be reduced through treatment prior to injection. The degree of treatment to these two characteristics cannot be established based on available data and could vary from system to system

4. In areas where deep well injection system techniques are being considered for the disposal of stormwater runoff the major factor in the economics of the system will be flow equalization basins (storage facilities). This would be especially critical in highly developed urban areas

5. The permeameter aspects of the test equipment produces highly reproducible results which can describe the permeability of test samples

6. The results of the pressure tests indicate that some form of clogging is taking place. Whether the clogging is due to interstitial pore clogging or to the formation of a thin impermeable layer of settled bentonite is not known. It is most probably a combination of both

7. The process related to deep well injection systems may be simulated by pilot studies in the laboratory. These laboratory studies should provide useful information on design criteria, especially with regards to the effect of suspended solids when present in the injection fluid

Recommendations

1. Modifications in the experimental apparatus are recommended as follows:

   a. the displacement pump should be replaced with a centrifugal type pump

   b. a mixer should be installed inside of the test chamber to prevent the settling of the solids during pressure tests

   c. an air relief valve should be installed in the test section immediately below the test sample

2. Testing should be initiated on a great number of samples at various pressures and suspended solids concentrations and for different types of solids. This testing program should have as its goal the development of guidelines which could aid the design engineer of an injection well system in determining the degree of suspended solids removal efficiency required for the successful long term operation of the well. Specifically:

   a. pressures up to the maximum allowable pressure should be used in the pressure tests

   b. the suspended solids concentrations should be varied to a greater degree, with emphasis on lower concentrations consistent with the levels which would be experienced in an actual system

APPENDIX 1

SURVEY OF INJECTION WELLS INJECTING FLUIDS CONTAINING SUSPENDED SOLIDS

The following Tables A1-1 through A1-3 were compiled from Thompson and Warner's [3] survey of industrial injection wells in the United States. Of the 333 injection wells listed in their audit, 33 inject fluids containing some concentration of suspended solids. These 33 wells, located in 13 states, are summarized in these tables.

LEGEND TO ABBREVIATIONS USED IN TABLES

Well No.

Identification number as assigned by Thompson and Warner.

Operational Status

PDR - Permitted, drilled
PDP - Permitted, drilled, plugged
PND - permitted, not drilled
O - Operating
NOP - Not operating, plugged
NOUP - Not operating, unplugged

Formations Used

dLS - Dolomitic limestone
DT - Dolomite
LS - Limestone
S - Sand
ST - Sandstone

TABLE A1-1

SURVEY OF INJECTION WELLS DISPOSING OF WASTES CONTAINING SUSPENDED SOLIDS*

WELL NO	OPERATIONAL STATUS	DESCRIPTION OF WASTE	SUSP. SOLIDS CONC (mg/1)	FORMATION POROSITY	FORMATION PERMEA-BILITY (mdarcy)	FORMATION USED
FL- 3	PDR-O	Stripping column effluent - dilute acetic acid and insoluble fibers	500-2800	very	very	Lower Floridan (limerock)
FL- 5	PND-PND**	Inorganic nondegradeable chemicals	9000	26.5	-	Lawson (DT)
IL- 1	PDR-NOUP	Spent hypochlorite process liquor	59-417	-	-	Salem (dLS)
IL- 7	PDR-O	Spent hypochlorite process liquor	50-580	-	-	limestone
IN- 1	PDR-O	Floor and filter washing waste	118	-	-	limestone
IN- 2	PDR-O	Floor and filter washing waste	118	-	-	limestone
IN- 4	PDR-NOUP	Miscellaneous chemical wastes	10	6	6 - 8	Mt. Simon (ST)
KS- 6	PDR-O	Hydraulic salt mining wastes	10	-	-	Arbuckle (dLS)
KY- 2	PDR-O	Aqueous hydrochloric acid solution	1	-	-	Knox (DT)
KY- 3	PDR-O	Aqueous hydrochloric acid solution	1	-	-	Knox (DT)
LA-11	PDR-O	Blowdown water	50	25	-	Nacatosh (S)
LA-29	PDR-O	Inorganic and organic salts	20***	30	5000	Sand
MI-15	PDR-NOUP	Chemical process water and solid residues	13500-15500	cavity	-	Salina (evaporites)

* See introductory remarks for legend to abbreviations.

** The Florida Department of Pollution Control lists this system as operational as of October, 1974.

*** Pre-injection treatment system consists of sand filters which limit the suspended solid particle size to less than 10 microns.

TABLE A1-2

SURVEY OF INJECTION WELLS DISPOSING OF WASTES CONTAINING SUSPENDED SOLIDS*

WELL NO	OPERATIONAL STATUS	DESCRIPTION OF WASTE	SUSP. SOLIDS CONC (mg/1)	FORMATION POROSITY	FORMATION PERMEA-BILITY (mdarcy)	FORMATION USED
MI-19	PDR-O	Effluent from the manufacture of metallurgical coke and by-product chemicals	3450	-	-	Mt. Simon (ST)
NV-1	PDR-O	Ferrous sulfate solution from mining of copper	1	20	-	Valmy (quartzite)
OH-1	PDP-NOP	Spent pickling liquors from steel processing	4705	10.4	9	Mt. Simon (ST)
OH-2	PDR-O	Hydrochloric acid pickle liquor and pickle rinse	9-15**	7-14	66-524	Mt. Simon (ST)
OH-3	PDR-O	Hydrochloric acid pickle liquor and pickle rinse	9-15**	7-14	66-524	Mt. Simon (ST)
OH-4	PDR-O	Acrylonitrile and methacrylonitrile production wastes	66	14.4	-	Mt. Simon (ST)
OH-6	PDR-O	Acrylonitrile and methacrylonitrile production wastes	66	14	-	Mt. Simon (ST)
OK-10	PDR-O	Fresh water and cement slurries from well services plant	1.28×10^{6}	low	low	Red Beds (shales)
PA-4	PDP-NOP	Drilling mud (bentonite) with quartz and sand grains	300	-	-	Bellefonte (DT)

* See introductory remarks for legend to abbreviations.

** Pre-injection treatment system consists of leaf type pressure filter which limit the suspended solid particle size to less than 2 microns.

TABLE A1-3

SURVEY OF INJECTION WELLS DISPOSING OF WASTES CONTAINING SUSPENDED SOLIDS*

WELL NO	OPERATIONAL STATUS	DESCRIPTION OF WASTE	SUSP. SOLIDS CONC (mg/1)	FORMATION POROSITY	FORMATION PERMEABILITY (mdarcy)	FORMATION USED
TX-1	PDR-O	Chemical wastes from the manufacturing of cumene phenol	49	30	15-2400	Oakville (S)
TX-7	PDR-O	Cooling tower and boiler blowdown water	1440	10-30	300	Santa Rosa (ST)
TX-8	PDR-O	Cooling tower and boiler blowdown water	50	27.2-35.7	193-1389	Sand
TX-9	PDP-NOP	Hydrochloric acid from gas production	16	-	-	Sand
TX-14	PDR-O	Waste from petroleum chemical production; acetaldehyde, adipic acid butanol and others	50	27.2-35.7	193-1389	Sand
TX-16	PDR-O	Nylon production wastes	16-95	12	7	San Andres (LS)
TX-33	PDR-O	Chemical plant wastes	50	31.3	333	Sand
TX-41	PDP-NOP	Water softening waste slurries	32900	-	-	Castile (LS)
TX-69	PDR-O	Aldehydes and glycols	20-150	31.1	333	Sand
TX-72	PDR-O	Domestic sewage treatment effluent	20	-	-	Shallow Sands
WY-1	PDR-O	Chemical plant wastes	50	5-25	475	Hygiene (ST)

* See introductory remarks for legend to abbreviations.

APPENDIX 2

FLUID MECHANICS OF FLOW FROM WELL

The method of analysis presented herein has been abstracted from reference 19, "Fluid Mechanics of Deep Well Disposals" by A. F. VanEverdingen.

Unit functions

Using three conversion formula to define time, rate and volume parameters, the three unit functions (P_t, Q_t and $\overline{P}_t$) can give quantitative data on pressure and volume changes.

The P_t function gives the cumulative pressure change at the well's radius for a unit rate of production or flow from time zero onward. The values of P_t are listed in Table A2-1 and shown graphically in Figure A2-1.

The Q_t function gives the cumulative volume of fluid processed from time zero onward for a unit pressure change. The values for Q_t are listed in Table A2-2.

The $\overline{P}_t$ function gives the pressure change for a unit rate of production or flow after the well bore has been increased. The values for $\overline{P}_t$ are listed in Table A2-8 and shown graphically in Figure A2-1.

The values of each of these unit functions are determined by entering into the tables with a conversion formula data point. The conversion formulas are:

1. Time conversion:

$$\tau = \frac{0.155(k)(T)}{(144)(\mu)(\phi)(c)(r_w^2)}$$

2. Rate conversion:

$$q_t = \frac{2.07(q)(\mu)}{(2\pi)(k)(h)}$$

3. Volume conversion:

$$Q_t = \frac{(.134)(Q)}{(2\pi)(\phi)(c)(h)(r_w^2)}$$

where:

T = time, secs

q = injection rate, gpm

Q = volume of fluid injected, gals

k = permeability, darcies

μ = viscosity, centipoise

ϕ = porosity, fraction

c = compressibility, vol/vol/atm

r_w = well radius, ft

h = formation thickness, ft

When used with the proper dimensions given above, the conversion formulas give dimensionless values.

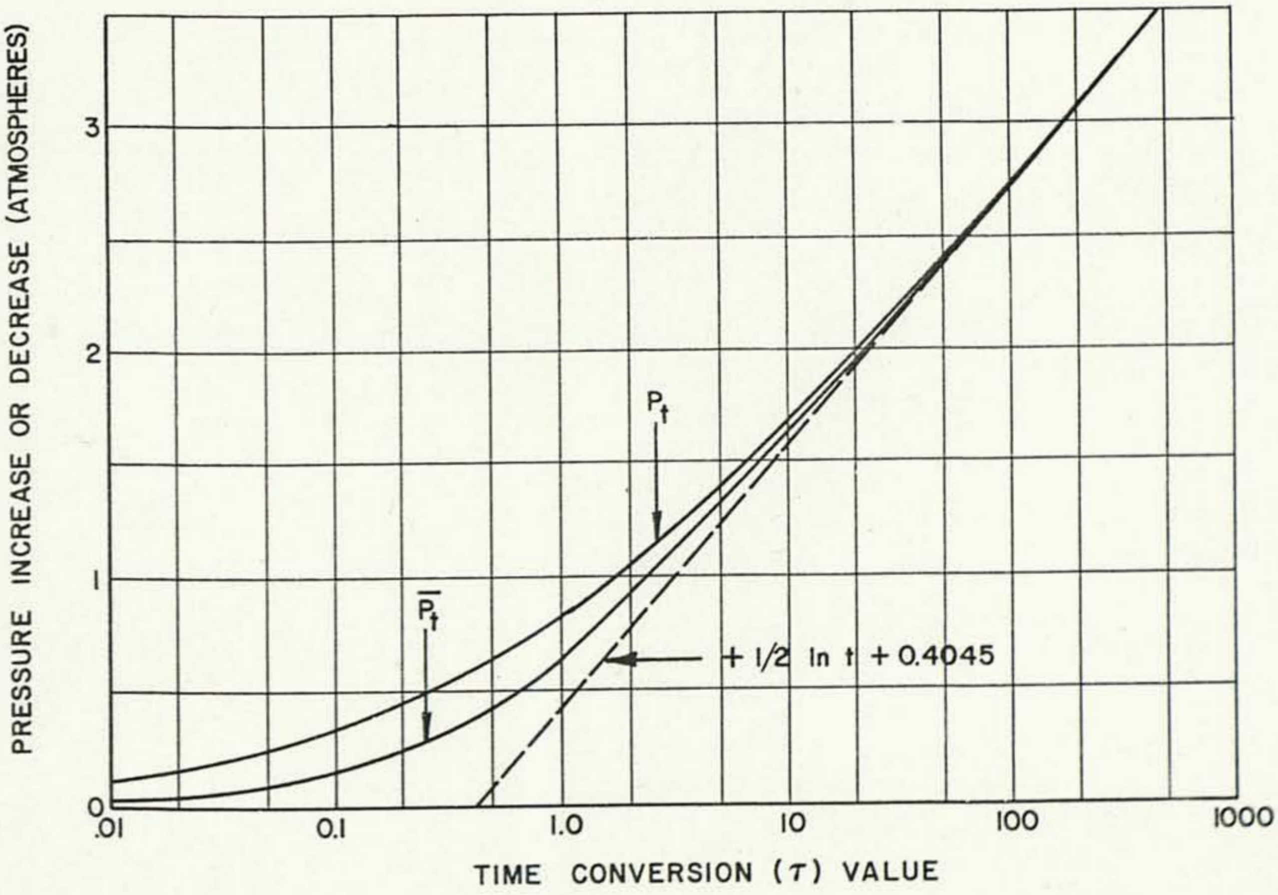

Figure A2-1 - P_t and $\overline{P}_t$ functions per unit time. Note convergence with (½ln τ + 0.4045) curve.

TABLE A2-1

VALUES FOR THE CUMULATIVE PRESSURE CHANGE FOR A UNIT TIME (P_t)

Time, τ	P_t	Time, τ	P_t
0.010	0.1081	4.00	1.2765
0.015	0.1312	6.00	1.4377
0.020	0.1503	8.00	1.5573
0.030	0.1818	10.00	1.6554
0.040	0.2077	15.00	1.8323
0.060	0.2499	20.00	1.9615
0.080	0.2846	30.00	2.1481
0.100	0.3144	40.00	2.2831
0.150	0.3753	60.00	2.4762
0.200	0.4245	80.00	2.6148
0.300	0.5028	100.00	2.7231
0.400	0.5650	150.00	2.9204
0.600	0.6628	200.00	3.0626
0.800	0.7394	300.00	3.2627
1.000	0.8030	400.00	3.4051
1.500	0.9278	600.00	3.6064
2.000	1.0235	800.00	3.7495
3.000	1.1678	1,000.00	3.8606

TABLE A2-2

VALUES FOR THE CUMULATIVE VOLUME FOR A UNIT PRESSURE CHANGE (Q_t)

τ	Q_t	τ	Q_t	τ	Q_t
0.010	0.117	1.0×10^{3}	2.9262×10^{2}	1.0×10^{8}	1.1021×10^{7}
0.015	0.146	1.5×10^{3}	4.1489×10^{2}	1.5×10^{8}	1.6180×10^{7}
0.020	0.169	2.0×10^{3}	5.3245×10^{2}	2.0×10^{8}	2.1245×10^{7}
0.030	0.210	3.0×10^{3}	7.5848×10^{2}	3.0×10^{8}	3.1199×10^{7}
0.040	0.245	4.0×10^{3}	9.7640×10^{2}	4.0×10^{8}	4.0989×10^{7}
0.060	0.305	6.0×10^{3}	13.9659×10^{2}	6.0×10^{8}	6.0267×10^{7}
0.080	0.357	8.0×10^{3}	18.0267×10^{2}	8.0×10^{8}	7.9220×10^{7}
0.100	0.404	1.0×10^{4}	2.1989×10^{3}	1.0×10^{9}	0.9797×10^{8}
0.150	0.508	1.5×10^{4}	3.1594×10^{3}	1.5×10^{9}	1.4411×10^{8}
0.200	0.598	2.0×10^{4}	4.0904×10^{3}	2.0×10^{9}	1.8963×10^{8}
0.300	0.756	3.0×10^{4}	5.8944×10^{3}	3.0×10^{9}	2.7910×10^{8}
0.400	0.896	4.0×10^{4}	7.6460×10^{3}	4.0×10^{9}	3.6742×10^{8}
0.600	1.144	6.0×10^{4}	11.0466×10^{3}	6.0×10^{9}	5.4109×10^{8}
0.800	1.365	8.0×10^{4}	14.3536×10^{3}	8.0×10^{9}	7.1228×10^{8}
1.000	1.568	1.0×10^{5}	1.7594×10^{4}	1.0×10^{10}	0.8798×10^{9}
1.500	2.029	1.5×10^{5}	2.5494×10^{4}	1.5×10^{10}	1.3239×10^{9}
2.000	2.445	2.0×10^{5}	3.3191×10^{4}	2.0×10^{10}	1.7124×10^{9}
3.000	3.200	3.0×10^{5}	4.8186×10^{4}	3.0×10^{10}	2.5249×10^{9}
4.000	3.888	4.0×10^{5}	6.2817×10^{4}	4.0×10^{10}	3.3265×10^{9}
6.000	5.148	6.0×10^{5}	9.1351×10^{4}	6.0×10^{10}	4.9093×10^{9}
8.000	6.148	8.0×10^{5}	11.9223×10^{4}	8.0×10^{10}	6.4675×10^{9}
10.000	7.402	1.0×10^{6}	1.4662×10^{5}	1.0×10^{11}	0.8014×10^{10}
15.000	9.949	1.5×10^{6}	2.1366×10^{5}	1.5×10^{11}	1.2996×10^{10}
20.000	12.316	2.0×10^{6}	2.7923×10^{5}	2.0×10^{11}	1.7391×10^{10}
30.000	16.741	3.0×10^{6}	4.0746×10^{5}	3.0×10^{11}	2.5000×10^{10}
40.000	20.884	4.0×10^{6}	5.3301×10^{5}	4.0×10^{11}	3.3333×10^{10}
60.000	28.658	6.0×10^{6}	7.7874×10^{5}	6.0×10^{11}	4.8000×10^{10}
80.000	35.991	8.0×10^{6}	10.1315×10^{5}	8.0×10^{11}	6.4000×10^{10}
100.00	43.025	1.0×10^{7}	1.2568×10^{6}	1.0×10^{12}	0.7407×10^{11}
150.00	59.744	1.5×10^{7}	1.8389×10^{6}		
200.00	75.653	2.0×10^{7}	2.4099×10^{6}		
300.00	105.789	3.0×10^{7}	3.5297×10^{6}		
400.00	134.519	4.0×10^{7}	4.6289×10^{6}		
600.00	189.325	6.0×10^{7}	6.8045×10^{6}		
800.00	241.784	8.0×10^{7}	8.9280×10^{6}		

TABLE A2-3

VALUES OF EXPONENTIAL FUNCTION FOR VALUES OF $(R^2/4T)$ BETWEEN 1×10^{-10} and 1×10^{-4}

```
*************************************************************************************
*       *          *          *          *          *          *          *          *
*   X   *   E-04   *   E-05   *   E-06   *   E-07   *   E-08   *   E-09   *   E-10   *
*       *          *          *          *          *          *          *          *
*************************************************************************************
*       *          *          *          *          *          *          *          *
*  1.0  *0.4317E 01*0.5468E 01*0.6619E 01*0.7770E 01*0.8922E 01*0.1007E 02*0.1122E 02*
*       *          *          *          *          *          *          *          *
*  2.0  *0.3970E 01*0.5121E 01*0.6273E 01*0.7424E 01*0.8575E 01*0.9726E 01*0.1088E 02*
*       *          *          *          *          *          *          *          *
*  3.0  *0.3767E 01*0.4919E 01*0.6070E 01*0.7221E 01*0.8372E 01*0.9524E 01*0.1068E 02*
*       *          *          *          *          *          *          *          *
*  4.0  *0.3624E 01*0.4775E 01*0.5926E 01*0.7077E 01*0.8229E 01*0.9380E 01*0.1053E 02*
*       *          *          *          *          *          *          *          *
*  5.0  *0.3512E 01*0.4663E 01*0.5814E 01*0.6966E 01*0.8117E 01*0.9268E 01*0.1042E 02*
*       *          *          *          *          *          *          *          *
*  6.0  *0.3421E 01*0.4572E 01*0.5723E 01*0.6875E 01*0.8026E 01*0.9177E 01*0.1033E 02*
*       *          *          *          *          *          *          *          *
*  7.0  *0.3344E 01*0.4495E 01*0.5646E 01*0.6797E 01*0.7949E 01*0.9100E 01*0.1025E 02*
*       *          *          *          *          *          *          *          *
*  8.0  *0.3277E 01*0.4428E 01*0.5579E 01*0.6731E 01*0.7882E 01*0.9033E 01*0.1018E 02*
*       *          *          *          *          *          *          *          *
*  9.0  *0.3218E 01*0.4369E 01*0.5521E 01*0.6672E 01*0.7823E 01*0.8974E 01*0.1013E 02*
*       *          *          *          *          *          *          *          *
*************************************************************************************
```

TABLE A2-4

VALUES OF EXPONENTIAL FUNCTION FOR VALUES OF $(R^2/4T)$ BETWEEN 0.0005 AND 0.0585

X	-1/2EI(-X)	X	-1/2EI(-X)	X	-1/2EI(-X)
0.0005	0.3512E 01	0.0200	0.1677E 01	0.0395	0.1347E 01
0.0010	0.3166E 01	0.0205	0.1665E 01	0.0400	0.1341E 01
0.0015	0.2963E 01	0.0210	0.1653E 01	0.0405	0.1335E 01
0.0020	0.2820E 01	0.0215	0.1642E 01	0.0410	0.1329E 01
0.0025	0.2708E 01	0.0220	0.1631E 01	0.0415	0.1323E 01
0.0030	0.2617E 01	0.0225	0.1620E 01	0.0420	0.1317E 01
0.0035	0.2541E 01	0.0230	0.1609E 01	0.0425	0.1312E 01
0.0040	0.2474E 01	0.0235	0.1598E 01	0.0430	0.1306E 01
0.0045	0.2415E 01	0.0240	0.1588E 01	0.0435	0.1300E 01
0.0050	0.2363E 01	0.0245	0.1578E 01	0.0440	0.1295E 01
0.0055	0.2316E 01	0.0250	0.1568E 01	0.0445	0.1290E 01
0.0060	0.2272E 01	0.0255	0.1559E 01	0.0450	0.1284E 01
0.0065	0.2233E 01	0.0260	0.1549E 01	0.0455	0.1279E 01
0.0070	0.2196E 01	0.0265	0.1540E 01	0.0460	0.1274E 01
0.0075	0.2162E 01	0.0270	0.1531E 01	0.0465	0.1269E 01
0.0080	0.2130E 01	0.0275	0.1522E 01	0.0470	0.1263E 01
0.0085	0.2099E 01	0.0280	0.1513E 01	0.0475	0.1258E 01
0.0090	0.2071E 01	0.0285	0.1504E 01	0.0480	0.1253E 01
0.0095	0.2044E 01	0.0290	0.1496E 01	0.0485	0.1248E 01
0.0100	0.2019E 01	0.0295	0.1488E 01	0.0490	0.1244E 01
0.0105	0.1995E 01	0.0300	0.1480E 01	0.0495	0.1239E 01
0.0110	0.1972E 01	0.0305	0.1472E 01	0.0500	0.1234E 01
0.0115	0.1950E 01	0.0310	0.1464E 01	0.0505	0.1229E 01
0.0120	0.1929E 01	0.0315	0.1456E 01	0.0510	0.1225E 01
0.0125	0.1909E 01	0.0320	0.1448E 01	0.0515	0.1220E 01
0.0130	0.1889E 01	0.0325	0.1441E 01	0.0520	0.1215E 01
0.0135	0.1871E 01	0.0330	0.1433E 01	0.0525	0.1211E 01
0.0140	0.1853E 01	0.0335	0.1426E 01	0.0530	0.1206E 01
0.0145	0.1835E 01	0.0340	0.1419E 01	0.0535	0.1202E 01
0.0150	0.1819E 01	0.0345	0.1412E 01	0.0540	0.1197E 01
0.0155	0.1803E 01	0.0350	0.1405E 01	0.0545	0.1193E 01
0.0160	0.1787E 01	0.0355	0.1398E 01	0.0550	0.1189E 01
0.0165	0.1772E 01	0.0360	0.1391E 01	0.0555	0.1184E 01
0.0170	0.1757E 01	0.0365	0.1385E 01	0.0560	0.1180E 01
0.0175	0.1743E 01	0.0370	0.1378E 01	0.0565	0.1176E 01
0.0180	0.1729E 01	0.0375	0.1372E 01	0.0570	0.1172E 01
0.0185	0.1716E 01	0.0380	0.1365E 01	0.0575	0.1168E 01
0.0190	0.1703E 01	0.0385	0.1359E 01	0.0580	0.1164E 01
0.0195	0.1690E 01	0.0390	0.1353E 01	0.0585	0.1160E 01

TABLE A2-5

VALUES OF EXPONENTIAL FUNCTION FOR VALUES OF $(R^2/4T)$ BETWEEN 0.059 AND 0.780

X	-1/2EI(-X)	X	-1/2EI(-X)	X	-1/2EI(-X)
0.0590	0.1156E 01	0.0785	0.1022E 01	0.0980	0.9206E 00
0.0595	0.1152E 01	0.0790	0.1019E 01	0.0985	0.9183E 00
0.0600	0.1148E 01	0.0795	0.1016E 01	0.0990	0.9160E 00
0.0605	0.1144E 01	0.0800	0.1013E 01	0.0995	0.9137E 00
0.0610	0.1140E 01	0.0805	0.1011E 01	0.1000	0.9115E 00
0.0615	0.1136E 01	0.0810	0.1008E 01	0.1200	0.8298E 00
0.0620	0.1132E 01	0.0815	0.1005E 01	0.1400	0.7621E 00
0.0625	0.1128E 01	0.0820	0.1002E 01	0.1600	0.7046E 00
0.0630	0.1125E 01	0.0825	0.9993E 00	0.1800	0.6549E 00
0.0635	0.1121E 01	0.0830	0.9965E 00	0.2000	0.6113E 00
0.0640	0.1117E 01	0.0835	0.9938E 00	0.2200	0.5727E 00
0.0645	0.1114E 01	0.0840	0.9910E 00	0.2400	0.5381E 00
0.0650	0.1110E 01	0.0845	0.9883E 00	0.2600	0.5069E 00
0.0655	0.1106E 01	0.0850	0.9856E 00	0.2800	0.4787E 00
0.0660	0.1103E 01	0.0855	0.9829E 00	0.3000	0.4528E 00
0.0665	0.1099E 01	0.0860	0.9802E 00	0.3200	0.4292E 00
0.0670	0.1096E 01	0.0865	0.9775E 00	0.3400	0.4074E 00
0.0675	0.1092E 01	0.0870	0.9749E 00	0.3600	0.3872E 00
0.0680	0.1089E 01	0.0875	0.9723E 00	0.3800	0.3686E 00
0.0685	0.1086E 01	0.0880	0.9697E 00	0.4000	0.3512E 00
0.0690	0.1082E 01	0.0885	0.9671E 00	0.4200	0.3350E 00
0.0695	0.1079E 01	0.0890	0.9645E 00	0.4400	0.3199E 00
0.0700	0.1075E 01	0.0895	0.9619E 00	0.4600	0.3057E 00
0.0705	0.1072E 01	0.0900	0.9594E 00	0.4800	0.2924E 00
0.0710	0.1069E 01	0.0905	0.9569E 00	0.5000	0.2799E 00
0.0715	0.1066E 01	0.0910	0.9543E 00	0.5200	0.2681E 00
0.0720	0.1062E 01	0.0915	0.9518E 00	0.5400	0.2570E 00
0.0725	0.1059E 01	0.0920	0.9494E 00	0.5600	0.2465E 00
0.0730	0.1056E 01	0.0925	0.9469E 00	0.5800	0.2366E 00
0.0735	0.1053E 01	0.0930	0.9444E 00	0.6000	0.2272E 00
0.0740	0.1050E 01	0.0935	0.9420E 00	0.6200	0.2183E 00
0.0745	0.1046E 01	0.0940	0.9396E 00	0.6400	0.2098E 00
0.0750	0.1043E 01	0.0945	0.9371E 00	0.6600	0.2018E 00
0.0755	0.1040E 01	0.0950	0.9347E 00	0.6800	0.1942E 00
0.0760	0.1037E 01	0.0955	0.9324E 00	0.7000	0.1869E 00
0.0765	0.1034E 01	0.0960	0.9300E 00	0.7200	0.1800E 00
0.0770	0.1031E 01	0.0965	0.9276E 00	0.7400	0.1734E 00
0.0775	0.1028E 01	0.0970	0.9253E 00	0.7600	0.1671E 00
0.0780	0.1025E 01	0.0975	0.9229E 00	0.7800	0.1610E 00

TABLE A2-6

VALUES OF EXPONENTIAL FUNCTION FOR VALUES OF $(R^2/4T)$ BETWEEN 0.8 AND 9.6

X	-1/2EI(-X)	X	-1/2EI(-X)	X	-1/2EI(-X)
0.8000	0.1553E 00	2.4500	0.1331E-01	5.8000	0.2266E-03
0.8200	0.1498E 00	2.5000	0.1246E-01	5.9000	0.2020E-03
0.8400	0.1446E 00	2.5500	0.1166E-01	6.0000	0.1800E-03
0.8600	0.1395E 00	2.6000	0.1093E-01	6.1000	0.1605E-03
0.8800	0.1347E 00	2.6500	0.1024E-01	6.2000	0.1432E-03
0.9000	0.1301E 00	2.7000	0.9591E-02	6.3000	0.1277E-03
0.9200	0.1257E 00	2.7500	0.8990E-02	6.4000	0.1140E-03
0.9400	0.1214E 00	2.8000	0.8428E-02	6.5000	0.1017E-03
0.9600	0.1174E 00	2.8500	0.7903E-02	6.6000	0.9079E-04
0.9800	0.1134E 00	2.9000	0.7412E-02	6.7000	0.8106E-04
1.0000	0.1097E 00	2.9500	0.6954E-02	6.8000	0.7238E-04
1.0500	0.1009E 00	3.0000	0.6524E-02	6.9000	0.6464E-04
1.1000	0.9300E-01	3.1000	0.5747E-02	7.0000	0.5774E-04
1.1500	0.8578E-01	3.2000	0.5067E-02	7.1000	0.5159E-04
1.2000	0.7920E-01	3.3000	0.4470E-02	7.2000	0.4610E-04
1.2500	0.7321E-01	3.4000	0.3945E-02	7.3000	0.4119E-04
1.3000	0.6773E-01	3.5000	0.3485E-02	7.4000	0.3682E-04
1.3500	0.6271E-01	3.6000	0.3080E-02	7.5000	0.3292E-04
1.4000	0.5811E-01	3.7000	0.2724E-02	7.6000	0.2943E-04
1.4500	0.5389E-01	3.8000	0.2410E-02	7.7000	0.2632E-04
1.5000	0.5001E-01	3.9000	0.2134E-02	7.8000	0.2354E-04
1.5500	0.4644E-01	4.0000	0.1890E-02	7.9000	0.2105E-04
1.6000	0.4315E-01	4.1000	0.1674E-02	8.0000	0.1883E-04
1.6500	0.4012E-01	4.2000	0.1484E-02	8.1000	0.1685E-04
1.7000	0.3733E-01	4.3000	0.1316E-02	8.2000	0.1508E-04
1.7500	0.3474E-01	4.4000	0.1168E-02	8.3000	0.1349E-04
1.8000	0.3236E-01	4.5000	0.1037E-02	8.4000	0.1208E-04
1.8500	0.3015E-01	4.6000	0.9205E-03	8.5000	0.1081E-04
1.9000	0.2810E-01	4.7000	0.8176E-03	8.6000	0.9678E-05
1.9500	0.2621E-01	4.8000	0.7265E-03	8.7000	0.8666E-05
2.0000	0.2445E-01	4.9000	0.6457E-03	8.8000	0.7760E-05
2.0500	0.2282E-01	5.0000	0.5742E-03	8.9000	0.6949E-05
2.1000	0.2131E-01	5.1000	0.5107E-03	9.0000	0.6224E-05
2.1500	0.1990E-01	5.2000	0.4543E-03	9.1000	0.5575E-05
2.2000	0.1860E-01	5.3000	0.4043E-03	9.2000	0.4994E-05
2.2500	0.1738E-01	5.4000	0.3599E-03	9.3000	0.4474E-05
2.3000	0.1625E-01	5.5000	0.3205E-03	9.4000	0.4009E-05
2.3500	0.1520E-01	5.6000	0.2854E-03	9.5000	0.3593E-05
2.4000	0.1422E-01	5.7000	0.2543E-03	9.6000	0.3220E-05

TABLE A2-7

VALUES OF EXPONENTIAL FUNCTION FOR VALUES OF $(R^2/4T)$ BETWEEN 9.7 AND 10.0

```
*************************************
       X                -1/2EI(-X)
*************************************

     9.7000             0.2886E-05
     9.8000             0.2586E-05
     9.9000             0.2319E-05
    10.0000             0.2079E-05

*************************************
```

TABLE A2-8

VALUES FOR THE PRESSURE CHANGE FOR A UNIT RATE OF PRODUCTION ($\overline{P}_t$)

τ	$\overline{P}_t$
0.010	0.01727
0.015	0.02509
0.020	0.03257
0.030	0.04675
0.040	0.06009
0.060	0.08486
0.080	0.10770
0.100	0.12920
0.150	0.17730
0.200	0.21980
0.300	0.29320
0.400	0.35560
0.500	0.41030
0.600	0.45910
0.700	0.50320
0.800	0.54350
0.900	0.58070
1.000	0.61520
1.500	0.75830
2.000	0.86890
2.500	0.95930
3.000	1.03600
4.000	1.16100
6.000	1.34400
8.000	1.47700
10.000	1.58200
15.000	1.77700
20.000	1.91600
30.000	2.11400
40.000	2.25500
60.000	2.45600
80.000	2.60000
100.000	2.71700

Application

In order to illustrate the use of these unit functions the following example is presented:

An injection strata has the following characteristics:

1) thickness - 100 feet
2) permeability - 6.37×10^{-4} ft/min = 335 millidarcies
3) transmissibility - 690 gpd/ft
4) coefficient of storage - 0.018
5) porosity - 20%
6) fluid compressibility - 3.3×10^{-6} /psi
7) fluid viscosity - 1 centipoise
8) fluid pressure - 720 psi
9) maximum allowable fluid pressure - 1040 psi (based on 0.65 psi/ft)
10) depth to bottom of strata - 1700 feet

The injection well uses an open hole, 12 inches in diameter to inject a fluid whose viscosity in 1 centipoise and a compressibility of 3.3×10^{-6} /psi.

Determine:

1. Disregarding the maximum pressure allowable, what is the pressure change due to the injection of 4200 gpm after one second and one day.

2. The well is to be designed for a 10 year life of continuous operation. It will be injecting the effluent of a tertiary treatment plant of 275,000 gpd capacity (assume an evenly distributed flow for the entire life of the well).

Design the well providing a factor of safety of 1.5 in the maximum allowable formation pressure. If more than one well is required, the factor of safety may be reduced to 1.25.

3. What well diameter is required to inject the total amount through one well.

Problem 1

Rate conversion: $q_t = \frac{2.07\ q\mu}{2\pi\ kh}$

$$q_t = \frac{(2.07)(4200)(1)}{(2)(\pi)(.335)(100)} = 41.3$$

Time conversion: $\tau = \frac{.155\ kT}{\mu\phi c r_w^2 (144)}$

$$\tau = \frac{(.155)(.335)\ T}{(144)(1)(.2)[(3.3 \times 10^{-6} + 3.3 \times 10^{-6})(14.7)](0.5)^2}$$

$$\tau = 74.35T$$

for one second, $T = 1, \rightarrow \tau = 74.35$

from Table A2-1, $P_t = 2.5756$

then, $P = P_t(q_t) = (2.5756)(41.3) = 106.37$ atm. = 1564 psi

for one day, $T = (1)(24)(60)(60) = 86{,}400$ seconds

$$\tau = 6.424 \times 10^6$$

Since from $t = 1000$, the P_t function approaches a simple logarithmic form, P_t is calculated by:

$$P_t = \tfrac{1}{2} \ln \tau + .4045$$

$$P_t = 8.24 \rightarrow \Delta P = 8.24(41.3)(14.7) = 5004 \text{ psi}$$

Problem 2

maximum pressure change for one well $= \dfrac{1040 - 720}{1.5} = 213$ psi

pressure adjustment $= \dfrac{14.7}{213} = .069$

volume conversion: $Q_t = \dfrac{Q}{2\pi\phi chr_w{}^2}$

$$Q = \frac{Q_t(2)(\pi)(\phi)(c)(h)(r_w{}^2)}{(\text{pressure adjustment})(.134)}$$

$$Q = \frac{Q_t(2)(\pi)(.2)(.97 \times 10^{-4})(100)(.5)^2}{.069\ (.134)} = .32\ Q_t$$

for design life, T = 10 years = (10)(365)(24)(60)(60) = 3.1536×10^8 seconds. Since the time conversion has no units of flow it is applicable for all flow rates; therefore, the time conversion calculated in Problem 1 is used here: $\tau = 74.35\ T \quad \rightarrow \quad \tau = 2.345 \times 10^{10}$

from Table A2-3, $Q_t = 1.993 \times 10^9$

$$Q = (.32)(Q_t) = (.32)(1.993 \times 10^9)$$

$$Q = 6.38 \times 10^8 \text{ gals/10 yrs}$$

Q = 121 gpm; call 125 gpm = 180,000 gpd

does not allow for full disposal--requires additional well. There are several ways to approach this problem. The two most evident are:

A - two wells with injection of 137,500 gpd each

B - one well, 180,000 gpd and one well 95,000 gpd

Approach A

Pressure - time relationship -- 1 well at 137,500 gpd

Rate conversion: $q_t = \frac{(2.07)(137500)}{(24)(60)(2\ )(.335)(100)} = .939$

time conversion still remains $\tau = 74.35T$

Time	τ	P_t	ΔP
1 yr	2.35×10^9	11.19	154.5 psi
2 yr	4.69×10^9	11.54	159.3 psi
3 yr	7.03×10^9	11.74	162.0 psi
4 yr	9.34×10^9	11.88	164.0 psi
5 yr	1.17×10^{10}	11.99	165.6 psi
10 yr	2.35×10^{10}	12.34	170.4 psi

after injection of 137,500 gpd for 10 years, $\Delta P = 170.4$ psi

maximum P allowable $= \frac{1040 - 720}{1.25} = 256$ psi

$$\Delta P \text{ left} = 256 - 170 = 86 \text{ psi}$$

Next, we need to determine the distance between the wells which will cause a pressure interference, ΔP_{int}, of not more than 86 psi

$$\Delta P_{int} = q_t\ (14.7)n - \tfrac{1}{2}Ei\ (-r^2/4\tau)$$

where:

r = distance between wells expressed in multiples of the well radii

τ = time conversion factor

n = number of additional wells

q_t = rate conversion factor

Therefore:

$$-\tfrac{1}{2}Ei\ (-r^2/4\tau) = \frac{\Delta P_{int}}{q_t(14.7)(n)}$$

$$= \frac{86}{.939(14.7)(1)}$$

$$-\tfrac{1}{2}Ei\ (-r^2/4\tau) = 6.23$$

From Table A2-3,

$$\text{for:}\quad -\tfrac{1}{2}Ei(-X) = 6.23$$

$$X = 2 \times 10^{-6}$$

$$\text{or:}\quad \frac{r^2}{4\tau} = 2 \times 10^{-6}$$

$$r^2 = (2 \times 10^{-6})(4)(2.35 \times 10^{10})$$

$$r^2 = 1.88 \times 10^5$$

$$r = 433.6$$

for a 6 inch radius well bore:

$$r = 433.6(.5) = 217 \text{ feet}$$

Approach B

Pressure - time relationship for 180,000 gpd well:

$$q_t = \frac{2.07\ (180{,}000)(1)}{(24)(60)(2\pi)(.335)(100)} = 1.23$$

$$\tau = 74.35T$$

Time	τ	P_t	ΔP
1 yr	2.35×10^9	11.19	202.3 psi
2 yr	4.69×10^9	11.54	208.6 psi
3 yr	7.03×10^9	11.74	212.3 psi
4 yr	9.34×10^9	11.88	214.8 psi
5 yr	1.17×10^{10}	11.99	216.8 psi
10 yr	2.35×10^{10}	12.34	223.1 psi

maximum ΔP allowable = 256 psi

$$\Delta P_{int} = 256 - 223 = 33 \text{ psi}$$

for well with Q = 95,000 gpd

$$q_t = \frac{2.07\ (95{,}000)(1)}{(24)(60)(2\pi)(.335)(100)} = .649$$

$$-\tfrac{1}{2}Ei(-X) = \frac{\Delta P_{int}}{q_t(14.7)(n)}$$

$$-\tfrac{1}{2}Ei(-X) = \frac{33}{(.649)(14.7)(1)}$$

$$-\tfrac{1}{2}Ei(-X) = 3.46$$

From Table A2-3

for: $-\tfrac{1}{2}Ei(-X) = 3.46$

$$X = 6 \times 10^{-4}$$

$$\frac{r^2}{4\tau} = 6 \times 10^{-4}$$

$$r^2 = (6 \times 10^{-4})(4)(2.35 \times 10^{10})$$

$$r^2 = 5.64 \times 10^7$$

$$r = 7{,}510$$

for a 6 inch radius well bore:

$$r = (7{,}510)(.5) = 3{,}755 \text{ feet}$$

The results of these two approaches are:

A -- 2 wells - 137,500 gpd each

217 feet between wells

B -- 2 wells - 1 @ 180,000 gpd
1 @ 95,000 gpd

3,755 feet between wells

A decision can now be made based on the land availability and economics.

Problem 3

Rate conversion - $q_t = \frac{(2.07)(190.97)(1)}{(2)(\pi)(.335)(100)} = 1.88$

Since one well is to be used, ΔP maximum is 213 psi

$$\Delta P = \overline{P}_t q_t (14.7)$$

$$\overline{P}_t = \frac{\Delta P}{q_t(14.7)} = \frac{213}{(1.88)(14.7)} = 7.71$$

Since this value of $\overline{P}_t$ if off the scale on Table A2-8 we can use the logarithmic approximation:

$$\overline{P}_t = \tfrac{1}{2}\ln \tau + .4045$$

$$\tau = e^{(\overline{P}_t - .4045)(2)}$$

$$\tau = e^{(7.71 - .4045)(2)}$$

$$\tau = 2.216 \times 10^6$$

$$\tau = \frac{.155kT}{(144)\,\mu\phi\, c r_w^{\,2}} \qquad T = 10 \text{ yrs} = 3.1536 \times 10^8 \text{ secs.}$$

or

$$r_w^{\,2} = \frac{.155kT}{(144)\,\mu\phi\, c} = \frac{.155(.335)(3.1536 \times 10^8)}{(144)(1)(.2)(.97 \times 10^{-4})(2.216 \times 10^6)}$$

$$r_w^{\,2} = 2645.14$$

$$r_w = 51.4 \text{ feet}$$

$$D = 103 \text{ feet}$$

APPENDIX 3

RECOMMENDED DATA FOR DEEP WELL INJECTION SYSTEM PERMIT APPLICATIONS

The following list of data concerning a proposed injection project which should be submitted with the permit application is taken from the EPA's Administrator's Decision Statement No. 5 [30].

1. Plat of well location including surface elevations, features, boundaries and ownership of both surface and mineral rights

2. Map indicating location of all artificial penetrations of the subsurface within twice the radius of influence of the proposed well. In addition, the depths, elevations, and the deepest formation penetrated; and plugging and abandonment records of all wells should be noted

3. Maps indicating vertical and lateral limits of potable water supplies including short term and long term variations in surface water supplies and subsurface aquifers containing water with less than 10,000 mg/l total dissolved solids. Consideration should be given to available amounts, present and potential use of these waters as well as projected public water supply requirements

4. Description of mineral resources present or be-

lieved to be present in the areas of the project and the effect of the project on these resources

5. Detailed geologic structure and stratigraphic section maps for the local area. Generalized regional geologic maps should also be supplied

6. Description of physical, chemical and biological properties of the fluid to be injected

7. Potentiometric maps of the proposed disposal stratum and of the aquifers immediately above and below the injection horizon. Copies of drill-stem test charts, extrapolations and data used in the compilations of such maps should be attached

8. Description of the location and nature of present or potentially useable minerals from the zones of influence

9. Volume, rate and injection pressure of fluid

10. The following geologic and physical characteristics of the injection and overlying and underlying aquiclude strata:

a) thickness
b) areal extent
c) lithology
d) grain mineralogy
e) type and mineralogy of matrix
f) clay content
g) clay mineralogy
h) effective porosity including explanation

of how determined

i) permeability including explanation of how determined

j) coefficient of aquifer storage

k) amount and extent of natural fracturing

l) location, extent and effects of known or suspected faulting indicating whether faults are sealed, or fractured avenues for fluid movement

m) extent and effects of natural solution channels

n) degree of fluid saturation

o) formation fluid chemistry including local and regional variations

p) temperature of formation including explanation of how determined

q) formation and fluid pressure including original and modifications resulting from fluid withdrawl or injection

r) fracturing gradients

s) diffusion and dispersion characteristics of the waste and the formation fluids including effects of gravity segregation

t) compatibility of injected wastes with the physical, chemical, and biological characteristics of the reservoir

u) injectivity profiles

11. The following engineering data:

a) diameter of hole and total depth of well

b) type, size, weight and strength of all surface intermediate and injection casing strings

c) specifications and proposed installation of tubing and packers

d) proposed cementing procedures and type of cement

e) proposed coring program

f) proposed formation testing program

g) proposed logging program

h) proposed artificial fracturing or stimulation program

i) proposed injection procedure

j) plans of surface and subsurface construction details of the system including engineering drawings and specifications of the system

k) plans for monitoring including multipoint fluid pressure monitoring system constructed to monitor pressure above as well as within the injection zones and description of annular fluid

l) expected changes in pressure, rate of native fluid displacement by injected fluid, directions of dispersion and zone affected by the project

m) contingency plans to cope with all shut-ins or well failures in a manner that will obviate any environmental degradation

12. The report transmitting the above data should also assess:

a) the alternative disposal schemes in terms of maximum environmental protection

b) the pressure - time relationship for both the injection and overlying strata with particular attention to fresh water aquifers

c) the problems associated with possible chemical interactions between injected wastes, formation fluids and mineralogical constituents

GLOSSARY OF SYMBOLS

c - compressibility, vol/vol/atm

h - thickness of disposal stratum, ft

k - permeability, darcies

1 darcy = 1.902×10^{-3} ft/min for water @ $20^{\circ}C$

n - number of additional wells

ΔP - additional pressure required for fracturing, psi
- change in pressure

P_{int} - pressure of interference, psi

P_e - pressure at distance R from well, psi

P_{ob} - total overburden pressure, psi

P_f - bottom of well injection pressure required for fracturing, psi

P_t - cumulative pressure change function

$\overline{P}_t$ - pressure change function

P_w - pressure at well, psi

q - flow rate of injection, gpm

q_t - rate conversion, dimensionless

Q - total volume of fluid injected, gals

Q_t - volume conversion, dimensionless
- cumulative volume function

r - radial distance from well, ft
- distance between wells, multiples of well radii

r_v - radius of available storage space, ft

r_w - radius of well, ft

R - radius of influence, ft

R^2 - linear regression analysis coefficient of fit

s - well "drawdown", ft

S - coefficient of storage, dimensionless

t - time, days

T - transmissibility, gpd/ft
- time, seconds

u - neutral stress, psi

U - well function parameter

V - storage volume, gals

$W(u)$ - well function (exponential intergral)

z - depth of well, ft

Z - well pressure, ft

α - angle of fracture from horizontal, degrees

μ - viscosity, centipoise

ν - Poisson's Ratio

σ_z - effective overburden pressure, psi

τ - time conversion, dimensionless

ϕ - porosity, dimensionless

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