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A STUDY OF WASTE FLUID INJECTION ON THE TEXAS GULF COAST

by

DANAE GEORGES

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

THESIS DIRECTOR'S SIGNATURE:

HOUSTON, TEXAS

JULY, 1977
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# Table of Contents

Purpose and Scope ............................................................... 1
Subsurface Waste Injection: Status in the U. S. ....................... 3
Physical Considerations for Fluid Injection ............................ 12
  Importance of State of Stress ........................................... 12
  Water Storage Capacity of an Aquifer ............................... 13
  Injection Pressure .......................................................... 14
  Formation Pressurization ................................................. 18
Disposal Well Design, Completion, and Monitoring .................... 21
Disposal Wells in Texas: Location, Regulation, and Hazards ....... 27
Aerial Photographic Study of Texas Gulf
  Coast Industrial Waste Injection Wells ............................. 30
  Structural Setting of the Texas Gulf Coast ......................... 30
Aerial Photographs of Texas Gulf Coast
  Injection Well Sites .................................................... 33
  Results and Discussion .................................................. 57
Pressure History of a Two Well Waste Injection
  System on the Texas Gulf Coast ....................................... 67
Geology of Study Area and Disposal Zone Characteristics ............ 67
Waste Characteristics and Injection History .......................... 73
The Theis Equation .......................................................... 75
A Finite Difference Model for Aquifer Pressurization ............... 85
The Computer Program ..................................................... 91
Application of the Model to the Two Well System .................... 93
Results and Discussion .................................................... 102
Table of Contents, continued

Summary and Conclusions .............. 113
References ................................ 115
Appendix .................................. 123
Purpose and Scope

The use of injection wells for fluid waste disposal has increased markedly in the U. S. in the last ten years. A growing need to better evaluate the waste-receiving stratum with respect to both potential hazards that may allow the migration of waste into ground water aquifers and the nature of aquifer pressurization resulting from long-term injection operations has accompanied the increased use of this method for the disposal of toxic wastes. These factors are often neglected in waste injection operations, as most monitoring of waste injection is undertaken at the well proper. However, faults and/or inadequately plugged boreholes may intersect the disposal zone in the vicinity of injection wells, providing conduits for the escape of waste into overlying aquifers. In addition, while fluids are injected with a general knowledge of formation pressure buildup as grossly calculated from formation characteristics and injected volumes, the true nature of the pressure buildup at points away from the injection well is not well elucidated (Mueller and Witherspoon, 1965); this is largely due to the paucity of observation wells associated with fluid injection activities.

This study seeks to demonstrate that a) aerial photographs are valuable tools in the detection of photolineations which may represent the surface traces of faults intersecting disposal zones and b) the pressure response of an aquifer due to waste injection can be modeled accurately by a second-order finite difference solution of the two dimensional flow equation derived from Darcy's law and the continuity
equation. While the present study considers industrial fluid waste injection wells in general and those located on the Texas Gulf Coast in particular, many aspects of this study can be applied to industrial waste injection wells in other parts of the U. S. as well as to radioactive and municipal waste injection systems.

In addition to providing a general background for later sections, the early sections of this work represent a discussion of many topics relevant to waste injection that are extensively treated separately in publications of a wide variety of fields and government agencies. These aspects include the status of waste injection in the nation, the intricate relationships among state of stress, formation characteristics and injection and aquifer pressures, and disposal well design and monitoring.
Subsurface Waste Injection: Status in the U. S.

Subsurface injection is a process of waste disposal by which fluid waste is injected into a permeable formation which is bounded directly above and below by essentially impermeable confining strata. Materials that may be injected include industrial, municipal, and radioactive wastes; fluids which are not toxic may also be stored for later use by injection into confined permeable strata (Kimbler et al., 1975). The salient features of the fluid injection process are the same whether the fluids are injected for purposes of elimination or for those of storage.

The fluid injection process began with the petroleum industry. For the last several decades brines accompanying oil production have been eliminated by reinjection into the subsurface, either in the same oil-producing formation for secondary recovery operations, or into other suitable neighboring formations located above or below the oil bearing stratum. Over 20,000 oil field brine disposal wells are reported to exist in Texas alone, although not all of these are now in operation (Piper, 1969). In contrast, fewer than 25 industrial waste fluid injection wells were in operation prior to 1960; at present, 270 such wells are in operation. An anticipated 30 new wells will be constructed annually (Warner, 1976).

Two factors have led to the accelerated rate of implementation of industrial waste injection wells in the last ten years. First, the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500) call for strict regulation of waste discharge into surface wa-
ters (Hall and Ballentine, 1973). Second, subsurface waste injection is in most cases a far less expensive method of waste disposal than waste discharge into surficial waters (Donaldson, 1972), because treatment of waste for subsurface disposal is less elaborate and therefore less costly than treatment for surface disposal, and the waste usually does not have to be transported very far from the plant site to the disposal well. Despite these attractive aspects, however, federal agencies such as the Environmental Protection Agency (EPA) and the United States Geological Survey (USGS) maintain that the effects of fluid injection on the subsurface and the fate of the injected material once emplaced underground are still not well enough understood to warrant extensive use of the method (Hall and Ballentine, 1973; Sheldrick, 1969). The EPA suggests that subsurface disposal be limited to those wastes that are demonstrated to be not readily treatable in a manner rendering their surficial disposal environmentally safe. In any case, subsurface fluid waste injection is generally considered to be a temporary solution to the waste elimination problem (Piper, 1969; Stallman, 1972).

Because no reports summarizing the status of injection well operations in the U. S. have recently been published, a questionnaire was submitted early this year to appropriate agencies in each state requesting the number and locations of operating, anticipated (by the end of 1977) and shut-down industrial, municipal, and radioactive waste injection wells. Figure 1 illustrates the approximate locations of present industrial waste disposal well systems in the conterminous United States as determined from this survey. Areas that are most
Figure 1 Locations of operating and expected industrial waste injection wells in the United States
favorable for waste injection are the coastal plains, such as the Texas and Louisiana Gulf Coast, and large sedimentary basins (Warner, 1967). As of March, 1977, 270 wells were injecting waste in a total of 22 states. These currently active well sites are represented by dots in Figure 1. Locations of wells expected to begin injecting waste by the end of 1977 are represented by crosses.

The status of industrial waste injection wells by state is summarized in Table 1 according to information obtained from the survey. The last summary of industrial waste injection wells in the U. S. was published in 1973 (Warner, 1973). This report, widely quoted in subsequent literature, stated that 278 industrial waste injection wells were in existence as of mid-1973 and that about two-thirds of these were in operation at the time. Based on the results of the current survey, however, several of the wells reported in existence in 1973 have never actually operated. Indeed, wells may be permitted, drilled and even completed but never ultimately used for injection. Wells in existence include those that inject, those that did inject but have ceased, and drilled wells that will never inject. Existing wells must be distinguished with respect to the above for a study to accurately represent the status of disposal well activities in the nation. In addition, the anticipated number of wells to be added each year should distinguish between those that will be drilled and those that will be actually placed in operation. Based on a comparison of the current number of operating wells and earlier reports (Warner, 1973; Environmental Protection Agency, 1974), the number of operating waste injection wells has increased by roughly 20 each year in the last five
### Table 1

Summary of Industrial Waste Injection Wells in the United States

<table>
<thead>
<tr>
<th>State</th>
<th>In Operation</th>
<th>Expected to Operate by 12/77</th>
<th>Shut-down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alabama</td>
<td>10</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Alaska</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Arizona</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>California</td>
<td>4</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Colorado</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Florida</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Idaho</td>
<td>4</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Illinois</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Indiana</td>
<td>12</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Iowa</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Kansas</td>
<td>43</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Kentucky</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Louisiana</td>
<td>51</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Michigan</td>
<td>21</td>
<td>1</td>
<td>9</td>
</tr>
<tr>
<td>State</td>
<td>In Operation</td>
<td>Expected to Operate by 12/77</td>
<td>Shut-down</td>
</tr>
<tr>
<td>------------------</td>
<td>--------------</td>
<td>------------------------------</td>
<td>-----------</td>
</tr>
<tr>
<td>Mississippi</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Nevada</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>New York</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>North Carolina</td>
<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Ohio</td>
<td>9</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Oklahoma</td>
<td>13</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>2</td>
<td>0</td>
<td>9</td>
</tr>
<tr>
<td>South Dakota</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Tennessee</td>
<td>6</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Texas</td>
<td>72</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Wyoming</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>West Virginia</td>
<td>4</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>270</strong></td>
<td><strong>21</strong></td>
<td><strong>55</strong></td>
</tr>
</tbody>
</table>
years.

Although this study will consider industrial waste injection wells only, radioactive and municipal wastes will be briefly discussed because underground formations are expected to continue to be used as disposal sites for these wastes also (Belter, 1972; Puri et al, 1973). At present, most low-level radioactive solid wastes are disposed of by sanitary landfill (shallow burial in soil) and most low-level liquid wastes are placed in seepage ponds which allow them to eventually percolate into fresh water aquifers (Robertson and Barraclough, 1973). Medium-level radioactive wastes are mixed with cement slurry and injected into deep hydraulically fractured shale formations where the waste-cement mixture eventually hardens in the formation (Tamura, 1972). High-level radioactive wastes are required by law to be delivered in solid form to an interim federal repository within ten years after reprocessing, where they will remain until suitable methods of ultimate disposal are developed (National Academy of Sciences, 1975). Currently, burial in salt bodies appears to be the most promising method of disposal of these high-level wastes (Tamura, 1972). Injection of fluid radioactive wastes from nuclear power plants into permeable formations is not yet practiced on a large scale, but will probably be more widely used in the future, particularly for the disposal of aqueous tritium and noble gas fission products (Belter, 1973). At present only dilute low-level radioactive wastes are injected at selected nuclear power plant sites. Limited quantities of some extremely dilute low-level radioactive wastes from uranium mining activities are also currently injected into deep subsurface res-
ervoirs. The locations of active or completed injection wells for the disposal of low-level radioactive wastes as determined from the results of the current survey are indicated in Figure 2. The dots represent wells in operation and the open circles represent wells that will be injecting within the year.

Figure 2 also shows the approximate locations of shut-down or presently operating municipal waste injection systems. The most extensive use of subsurface injection of municipal wastes in the U. S. has occurred in Oregon, where over 3,000 sewage disposal wells were in operation prior to 1969. These shallow wells injected sewage into the quaternary lavas of central Oregon. Although no instances of contamination of potable ground water were reported, state laws were passed in mid-1969 that required all municipal disposal wells to be shut down by the end of 1974 (Ives and Eddy, 1970), and no disposal wells of any type are in operation in Oregon at present. Disposal wells for treated sewage effluent differ from industrial disposal wells in that injection is into shallow formations, generally less than 1,000 feet deep. In addition, biological activity on sewage effluents proceeds at a more rapid rate than on industrial wastes and this activity renders sewage wastes less toxic in a shorter period of time after injection. Since methane gas is produced during the bio-degradation of sewage, highly regulated injection of municipal wastes into confined aquifers may be of considerable importance in the future.
Figure 2  Locations of radioactive and municipal waste injection wells in the United States; dots represent active radioactive waste injection wells, open circles represent radioactive waste injection wells expected to operate this year, squares represent active municipal injection wells, asterisks represent shut-down municipal wells.
Physical Considerations for Fluid Injection

Importance of State of Stress

To be suitable as an injection zone, a formation must be porous, permeable, of considerable areal extent, and relatively unstressed. The importance of state of stress of the injection area became apparent only in the last few years with the extensive study by the USGS of the "Denver Earthquakes" (Healy et al., 1968). In this case, the U. S. Army operated a disposal well at the Rocky Mountain Arsenal, located 7 1/2 miles northeast of Denver, Colorado, between 1962 and 1966. During this time the well intermittently injected fluid wastes from chemical-manufacturing activities into fractured pre-Cambrian gneiss 12,000 feet below ground level. One month after injection operations began, earthquakes occurred in the area, some registering as high as 5.0 on the Richter scale (Healy et al., 1968). Investigation by the USGS (Healy et al., 1968) revealed that the injection zone gneiss was tectonically stressed to near failure prior to the initiation of injection operation; the increase in fluid pressure due to fluid injection reduced the effective normal stress across faults in the reservoir enough to cause movement along the faults. Subsequently, the USGS investigated earthquakes in the Rangely oil field in Rangely, Colorado, 225 miles west of Denver. The epicenters were found to cluster in two particular areas of the oil field where waterflooding operations had increased pore pressures in the Weber Sandstone formation (6,000 feet below ground level) to values above original fluid pressures (Raleigh et al., 1974). Another documented case of the
prompting of seismic activity by subsurface fluid injection occurred due to secondary recovery operations in the Inglewood oil field west of Los Angeles, California, in the Baldwin Hills. In this instance, fluids injected into the subsiding oil field triggered movement along several pre-existing faults of the Newport-Inglewood fault system. Associated ground rupture caused the failure of the foundation of the Baldwin Hills Reservoir in 1963, resulting in a flood wave (Hamilton and Meehan, 1972). Fortunately, only these three instances of seismic activity due to fluid injection operations in the United States have been reported. Although few in number, these earthquake occurrences have served to emphasize the importance of determining the stress state of the reservoir prior to any fluid injection activity. In addition, the triggering of earthquakes by the increase of fluid pressure has suggested to earth scientists that highly regulated fluid injection may be used as a method for the slow release of stored tectonic stress in earthquake zones, thereby providing a means of earthquake control (Fakiser et al., 1969). In the last few years, the USGS has been conducting experiments to determine the feasibility of this hypothesis (Raleigh et al., 1976).

**Water Storage Capacity of an Aquifer**

As the aquifers into which wastes are injected are usually saturated with connate water, room for the wastes is actually created by dilatation of the rock matrix and dilatation and displacement of pore fluids in response to the emplacement of wastes. An increase in the hydrostatic pressure of the reservoir results. The specific storage
of an aquifer, also referred to as the unit water-storage capacity, is the property which describes the volume of fluid capable of being accepted (or stored) in a unit volume of the reservoir per unit rise of hydraulic head in the stratum (Poland et al., 1972). Thus, the specific storage, denoted $S_s$, is one of the most significant quantities in the evaluation of an aquifer as a potential waste-receiving stratum. It is related to basic aquifer properties as follows:

$$S_s = (w) \cdot (n \cdot c_w + c_r),$$

where $w$ = unit weight of water

$n$ = fractional porosity of the formation

$c_w$ = bulk modulus of compressibility of pore water

$c_r$ = bulk modulus of compressibility of rock matrix.

The volume of a reservoir available to receive wastes is evaluated from knowledge of the subsurface and the total volume of waste that the reservoir can accommodate is determined from the specific storage of the aquifer and the maximum "safe" rise in hydrostatic pressure in the stratum.

**Injection Pressure**

Values of hydrostatic pressures considered "safe" are those less than values known or calculated to activate fault movement or cause hydraulic fracturing in an area. Hydraulic fractures are tension fractures that form perpendicular to the direction of least principal stress in a rock unit (Hubbert, 1957). When the fluid pressure in a formation is increased by an amount equal to or greater than the least principal stress, tension fractures are produced. Thus, the stress
state of the area must be examined and directions and magnitudes of the principal stress axes must be determined prior to the injection of fluids. The well should then inject at pressures below the values that will cause hydraulic fractures.

Kehle (1964) described a method of determining tectonic stresses from formation pumping tests; however, the stress state can generally be inferred from a knowledge of the tectonic history of a region and also from available subsurface data. In tectonically active areas, the maximum principal compressive stress \( s_1 \) is horizontal and the least principal compressive stress \( s_3 \) is vertical and equal to the effective overburden pressure; thus injection pressures that will cause hydraulic fractures can be calculated from the value of the overburden load and the hydrostatic pressure at the depth in question. In tectonically relaxed areas, such as the Gulf Coast and Mid-Continent regions, the situation is reversed; \( s_1 \) is vertical and equal to the effective overburden load, while \( s_3 \) is horizontal and has been generally found to be equal to approximately one third the value of \( s_1 \) (Hubbert, 1957).

The injection pressure, \( P_i \), as measured at the wellhead is governed by the following relationship (Donaldson, 1972):

\[
P_i = P_w - P_h + P_f.
\]

In this equation, \( P_w \) is the bottomhole reservoir pressure, \( P_h \) is the pressure exerted by the fluid filling the length of the injection tubing, and \( P_f \) is the pressure loss due to friction as the fluid travels through the length of the tubing. The latter term may be calculated from the Darcy-Weisbach relation for steady incompressible flow.
in a conduit (Eskinazi, 1965). Injection pressures should be less than the sum of the original formation hydrostatic pressure and $s_3$ as calculated in the preceding paragraph for tectonically active and relaxed areas.

As injection proceeds, the bottomhole pressure, $P_w$, is governed largely by the formation permeability. The permeability quantifies the ability of a porous material to transmit fluid (Lohman et al., 1972); this ability depends on the size, shape, and degree of interconnection of the pore spaces. In formations of lower permeability, greater injection pressures are required and pressure buildup is more rapid. These relationships may be determined quantitatively from formation pumping tests in which the injection pressure is increased incrementally and the corresponding injection rates measured (Donaldson, 1972). A plot of the injection rates vs. injection pressures is a straight line whose slope is the specific injectivity index ($SpI_x$) of the reservoir. Such a plot is shown in Figure 3. The two curves correspond to pumping tests performed one month apart in the same formation; waste injection was continuous in the meantime. The $SpI_x$ is related to the permeability, $k$, as follows (Grandone and Holleyman, 1949):

$$SpI_x = kh/(m \ln R)$$

where $h =$ thickness of formation

$m =$ viscosity of injected fluid

$R =$ ratio of radius of injected volume to radius of wellbore.

The injection pressure is inversely proportional to the permeability. At zero injection rate, the rate vs. pressure line intersects the in-
Figure 3 Injectivity tests for the determination of the specific injectivity index of a formation; after Grandone and Holleyman (1949). Curves obtained from injectivity tests performed exactly one month apart in a 28 ft. thick sand aquifer of the McCune Field, Crawford County, Kansas.
jection pressure axis at the well "shut-in pressure" (Figure 3). This value depends directly on the reservoir pressure and increases as injection proceeds. From the equation of the rate vs. pressure line at zero injection rate, the shut-in pressure, and therefore the reservoir pressure, is seen to vary inversely with the permeability.

Formation Pressurization

The pressure increase that a formation can withstand due to fluid injection is limited by the amount of fluid pressure increase calculated to cause slip along pre-existing faults. Rocks fail by brittle fracture when the shear stress (T) and normal stress (S) across a plane in the rock reach critical values expressed by the equation:

\[ T = \pm (T_0 + S \tan \phi), \]

where \( T_0 \) is the shearing strength and \( \phi \) is the angle of internal friction of the rock (Jaeger, 1969). If a fracture or fault plane is present, the shearing strength across the plane is zero and the criterion for further movement is:

\[ T = S \tan \phi. \]

A plot of T vs. S delimits the Mohr envelope of the material. Figure 4-A shows such a plot for a value of \( \phi \) of 30°, a common value of the coefficient of internal friction for loose sand (Hubbert, 1951). The values of S and T acting on a fault plane that is perpendicular to the plane of \( s_1 \) and \( s_3 \) (the situation depicted in Figure 4-B) may be calculated from the following relationships:

\[ S = \frac{1}{2}(s_1 + s_3) + \frac{1}{2}(s_1 - s_3) \cos 2\alpha, \text{ and} \]
\[ T = \frac{1}{2}(s_1 - s_3) \sin 2\alpha, \]
Figure 4 Mohr representation of stress state; after Hubbert (1951)
where $\alpha$ is the angle between the fault plane and the direction of $s_3$. Given $s_1$ and $s_3$, the Mohr circle for a particular stress state is constructed (Figure 4-C) from which $S$ and $T$ for any orientation of a fault plane perpendicular to the $s_1$ - $s_3$ plane can be determined. As long as $T$ and $S$ fall within the Mohr envelope of the material, no movement occurs along any fault that is present. When the pore pressure is increased, however, the effective principal stresses are decreased, and the Mohr circle is shifted to the left (Hubbert and Rubey, 1959). If the fluid pressures are increased enough to bring the Mohr circle tangent to the Mohr envelope, movement will occur along a fault making an angle of $\alpha'$ with the direction of $s_3$ (Figure 4-D).
Disposal Well Design, Completion, and Monitoring

The construction of each deep disposal well differs with the type and volume of waste injected and with the subsurface geology of the area. However, the main features of most injection wells are very similar. Figure 5 is a schematic representation of the essential features of industrial injection wells. The portion of the deep disposal well that extends from ground level to the injection horizon basically consists of several concentric pipes (Davis and Funk, 1975). The outermost pipe is the conductor pipe, which is the first pipe to be placed during the construction of the disposal well. The conductor pipe is driven into the ground down to about 200 feet below the surface, and the surface hole is then drilled. The purpose of the conductor pipe is the prevention of ground water contamination at shallow depths during the drilling of the surface hole. The surface casing is the next pipe inward from the conductor pipe. It extends from the surface down to about 200 feet below the fresh water zone, and its purpose is the protection of fresh water sands from contamination. After emplacement of the surface casing, cement is filled from the surface casing outward all the way up to the surface of the well site. The protection casing is located next inward from the surface casing. The protection casing extends from ground level to the top of the injection horizon. It is cemented from the injection horizon upward, through the area between the surface casing and protection casing all the way to ground level. The protection casing serves to seal the inner well from all the formations through which the well runs. The in-
Figure 5  Schematic representation of injection well design; from Subsurface Disposal Corporation (undated)
jection tubing is the centermost pipe of the deep well waste disposal. The waste travels through the injection tubing to the injection horizon. The space between the injection tubing and surface casing is the annulus. It is filled with a noncorrosive fluid kept under a pressure that is much higher than the injection pressure; this prevents the possibility of leakage of waste into the annulus. The packer functions to seal the annulus from the injection horizon.

The way that the well is completed depends mainly on the lithology of the disposal zone, but the nature of the waste must also be considered. Figure 6 shows the possible types of disposal zone completions. Open hole completion (Figure 6-A) is possible in strong, cohesive strata such as limestone and some sandstone (Davis and Funk, 1975). The open hole completion is the least expensive completion. It is also desirable because no casing is present in the disposal zone, thus facilitating treatment of the disposal zone if the need arises (Warner, 1967). When the receiving formation is friable, the well bore may eventually cave in, filling the bottom of the hole. In this case, perforated completion is used (Donaldson, 1972). The cement outward from the injection tubing is extended all the way to the bottom of the injection horizon and then perforated (Figure 6-B). Gravel packed sand screen completion is used in disposal zones that are less competent lithologically, such as semi-consolidated sandstones. In such strata, fine particles of sand can infiltrate the well bore and cause eventual plugging of the well. With the gravel packed sand screen completion (Figure 6-C), however, these sand or clay particles are prevented from accumulating at the well bore by
Figure 6  Types of injection well completion; after Donaldson (1972)
both the screens and the gravel packing around the screens (Davis and Funk, 1975). This type of completion is also depicted in the schematic disposal well in Figure 5. As the majority of Texas Gulf Coast disposal wells inject waste into semi-consolidated sand formations, the gravel packed sand screen completion is used widely in the Gulf Coast wells.

Most monitoring of waste injection well systems is undertaken at the well itself (Talbot, 1972). Injection wells can be equipped to continuously record the injection pressure, the pressure of the annulus fluid, and the pressure of the waste-receiving stratum in the vicinity of the well bore. An abrupt increase in either the downhole pressure or the injection pressure may imply plugging of the injection horizon or may indicate the influence of unprecedented geological barriers to fluid flow in the reservoir. As mentioned previously, the annulus of the injection well (Figure 5) contains an inert fluid maintained under high pressure. Changes in the annulus fluid pressure indicate leaks in the injection well tubing; most newer injection wells are equipped with continuous annulus fluid pressure recording units. Some wells also monitor the conductivity of the annulus fluid. Slow leakage of waste into the annulus may not alter the pressure of the fluid significantly, but the resultant change in conductivity of the annulus fluid will be apparent. Some injection wells are perforated in overlying fresh water strata and the quality of the fresh water is monitored through separate tubing at the well site. The final most common monitoring method conducted at the well proper is the continuous measurement of rate of injection of the waste stream. As de-
scribed in the preceding section, injection rate information, particularly when coupled with corresponding injection pressure data, can be a valuable tool in the evaluation of aquifer characteristics and reservoir response.

Monitoring at points away from the well, either in the waste-receiving horizon or in overlying strata, is rare. The primary reason is that the cost of such monitoring is very high, especially if more than one well is needed or if the observation wells are very deep. Also, many believe that the greatest chance of mishap exists at the well site itself and suggest that separate monitor wells only incur additional expense (Warner, 1976). However, a USGS study of a system of 14 observation wells around an injection well site outside Wilmington, North Carolina, revealed leakage of waste constituents into overlying aquifers and provided evidence for considerable reactivity of the injected waste with aquifer constituents (Leenheer et al., 1976). The USGS is currently directing greater attention to the study of long-term effects of waste fluid injection. Some operators of injection wells periodically analyze samples from fresh water wells in the vicinity of the injection site to check for contamination, but no observation systems as extensive as those of the USGS have been installed by any injection well permittees to date.
Disposal Wells in Texas: Location, Regulation, and Hazards

As shown by Table 1, Texas has the greatest number of disposal wells in the nation, followed by Louisiana. Together these states contain one half of the disposal well systems in the U. S. The great number of waste injection wells in Texas and Louisiana is due to both the concentration of much of the petrochemical industry in these states and the favorable subsurface geology. The locations of presently operating industrial waste injection well systems in Texas are shown in Figure 7. The wells are labeled with their Texas Water Quality Board (TWQB) permit numbers. Figure 7 also displays the major tectonic features of Texas. The alternately uplifted and depressed nature of the formations of the high plains, north central and east Texas, and west and southwest Texas provides basins that are suitable for waste disposal. The younger southeasterly dipping coastal sediments, being extremely porous and permeable, are also amenable to subsurface waste disposal and two thirds of the disposal wells in Texas are located on the Gulf Coast.

The TWQB is in charge of issuing permits for industrial, municipal, and radioactive waste injection. Applicants must submit a set of information prescribed by the TWQB (Hill, 1974) regarding the proposed injection well. In addition to a report covering the technical aspects of the proposed injection well, justification for request of subsurface disposal over other waste disposal methods must be provided. A description of the topography and geology local to the injection well site is required as well as the locations of neighboring water
Figure 7 Locations of industrial waste injection wells in Texas; well sites are labelled with their Texas Water Quality Board WDW permit numbers. Base map after Brown et al. (1969); well site locations from Texas Water Quality Board (1962-1976).
wells and locations of documented boreholes within a 2\(\frac{1}{2}\) mile radius of the injection well bore. In most cases a general summary of the surrounding geology, without details of the structural setting of the area, is submitted. Subsurface maps of the injection horizon and overlying aquiclude are not required but are submitted by some applicants.

Two potential mechanisms by which an injected fluid may escape from its aquifer are of primary concern in Gulf Coast waste injection well systems (Ives and Eddy, 1968). Inadequately plugged boreholes that penetrate the disposal zone may provide a conduit for the escape of waste. The TWQF requires that known boreholes in the vicinity of the injection site be examined by the disposal well permittee and re-plugged in the injection zone, if necessary. Many older boreholes remain undocumented, however, and may be inadequately plugged; the escape of waste through such boreholes near an injection well is a potential danger that is difficult to evaluate. Faults in the vicinity of an injection well may also allow the waste to escape into overlying aquifers. Faulting near an injection site may not affect the disposal zone directly but may interfere with the actual disposal well. If a well intersects an active fault the results of movement along the fault may be of concern. If enough subsurface data is available, the nature of nearby faults can be ascertained and potential dangers evaluated. On the other hand, faults near a disposal well site may be undetected, either due to insufficient information or inaccurate interpretation of data.
Aerial Photographic Study of Texas Gulf Coast Industrial Waste Injection Well Sites

Aerial photographs have long been used to investigate structural features in many areas (Pressman, 1968), but only within the last five years have aerial photographs systematically emerged as a means of detecting fault zones on the Texas Gulf Coast. Most studies have concentrated on urban areas that have been visibly disrupted by faulting. In the following paragraphs, a brief summary of the types of faults encountered on the Gulf Coast and previous work dealing with the use of aerial photographs in connection with these faults is presented. Subsequent sections examine aerial photographs encompassing the sites of all currently operating industrial waste injection wells on the Texas Gulf Coast.

Structural Setting of the Texas Gulf Coast

The Texas Gulf Coast is a region in which active faults of extremely low seismicity occur. Three general types of faults can be distinguished in this area. The first class encompasses faults local to areas of salt diapirism. The vertical movement of salt into overlying sediments of higher density causes arching of the sediments and produces graben structures (Currie, 1956). Frequently several normal faults in the overlying strata intersect, producing complex radial patterns about the axis of the salt dome; the degree of faulting is related to the extent of salt diapir development (Spencer, 1969). The second class includes normal "down-to-the-basin" faults and assoc-
iated antithetic "up-to-the-basin" faults (Murray, 1961). Normal faulting has been recurrent, indicating a continuously present stress system characterized by a vertical maximum principal stress \( s_1 \) and a horizontal minimum principal stress \( s_3 \) as described in a previous section. Such a stress system is imposed by the active basinal subsidence of the Gulf Coast geosyncline (Shelton, 1968). The third type of faults occurring on the Texas Gulf Coast are those that are activated due to the withdrawal of fluids such as ground water and oil from the subsurface. As shown in Figure 4-C and 4-D, movement along pre-existing faults occurs when the stress field represented by the Mohr circle becomes tangent to the Mohr envelope. The withdrawal of fluids causes a decrease in the pore pressure of the reservoir which thus increases the magnitude of the effective overburden pressure \( s_1 \) on the Gulf Coast and imposes an additional load to the aquifer skeleton (Gabrysch, 1969). The process results in compaction of the aquifer, thus decreasing the magnitude of \( s_3 \). The overall effect is the enlargement of the Mohr circle, and if enough fluid is withdrawn to bring the circle tangent to the Mohr envelope, movement along faults will accompany subsidence.

Many Gulf Coast fault zones have been recognized because of damage of buildings and pavements due to fault movement. Some examples are the developed area southwest of Clear Lake, the area surrounding the Moccley Fault in northwest Harris County, and the Ellington Air Force Base. In other parts of the Gulf Coast, however, surface faults may be undetected, either because topographic expression of the faults is subtle or because no urban features have been disrupted.
Recently, the use of aerial photographs of the Texas Gulf Coast has been demonstrated to be a useful tool in the detection of lineations that are structurally significant (Clanton and Amsbury, 1975; Kreitler, 1976). Lineations that indicate surface faults are evident because of the difference in moisture content of the upthrown and downthrown sides of the fault; the downthrown side is usually wetter, giving rise to a darker soil color and increased or distinct vegetation (Clanton and Amsbury, 1975).

Kreitler (1976) compared aerial photographs and subsurface maps of nearly 100 oil and gas fields of the Texas Gulf Coast. He found the locations of photolineations to closely parallel or coincide with the locations of extrapolated fault traces in 80% of the fields examined; in the remaining 20% of the fields, photolineations were either not evident or when present their locations did not correlate with those of fault traces. In addition, Kreitler (1976) found some photolineations on the Gulf Coast to be coincident with areas of differential subsidence where no active faulting was occurring. He concluded that lineations can represent portions of active faults, areas of subsidence with or without subsidence-induced faults, or "passive structural features" which may be related to faults. In a 12 square mile area encompassing Ellington Air Force Base in Harris County, Texas, Clanton and Amsbury (1975) plotted over 60 photolineations which they found to be coincident with topographic scarps and damage to man-made structures in the area. Frierson and Amsbury (1974) found several photolineations along the Gulf Coast to be related to abrupt changes in drainage patterns of streams and rivers, some as large as
the Brazos River.

While photolineations are not unequivocally accepted as representa-
tive of the surface traces of faults (Brown, 1961), the above-mentioned studies, as well as earlier studies of the coincidence of photolineations with faults on the Louisiana Gulf Coast (Fisk, 1944; Wermund, 1955) indicate that at least on the Gulf Coast many photolineations are structurally significant. However, more field investi-
gations are needed before the actual degree of reliability of aerial photographs as a means of fault detection can readily be established. This could be accomplished by extensive shallow trenching, coring, and logging in each area in which visible topographic scarps are associated with the locations of photolineations.

Aerial Photographs of Texas Gulf Coast Injection Well Sites

Because the examination of aerial photographs can indicate possible zones on the Gulf Coast where faults have occurred and/or may occur, an aerial photographic study of all presently operating industrial waste fluid injection well systems on the Texas Gulf Coast was undertaken. First, the exact locations of the injection wells were obtained from information in the TWQB Waste Disposal Well (WDW) files (Texas Water Quality Board, 1962-1976). In most of the disposal well files, only industrial plant maps with the wells plotted on them were available; no information regarding latitude and longitude of the well sites was provided. The plant maps were photocopied and appropriate USGS topographic maps were acquired according to the known general location of each plant site. Finally, the exact well site locations
were plotted on the topographic maps after the plant sites were located on the maps by features common to both, such as highways, railroads, and rivers. Using the topographic maps as base maps for the well study sites, 15 aerial photographs encompassing the 48 currently active Gulf Coast wells were then obtained from the NASA Johnson Space Center (G. O. Pilling, pers. comm., 1976). The locations of the aerial photographs and the well sites are shown in Figure 8. A summary of the wells by TWQB WDW permit number, compiled from the TWQB WDW Master Card file (Texas Water Quality Board, 1961-1976), is presented in Table 2. Included in the table are the total depth of the injection well, the depth of the fresh water zone in the vicinity of the well, the formation that receives waste, and the county in which the well is located. The identifying features of each aerial photograph, as numbered in Figure 8, are summarized in Table 3. Except for study site 4, which was black-and-white, all aerial photographs were color-infrared.

Relevant portions of study sites 1 through 15 are presented in Figures 9 through 23 respectively. The figures were traced directly from each aerial photographic frame; photolineations were drawn on transparent overlays superimposing each frame. Photolineations are indicated in the figures by heavier lines, while faults extrapolated from subsurface maps are represented by lighter lines with references adjacent. No subsurface maps were available for site 3 (Figure 11), site 5 (Figure 13), and site 14 (Figure 22), while excessive cloud cover precluded the plotting of lineations over much of site 15 (Figure 23). Faults were extrapolated assuming the dip calculated from
Figure 8  Sites of aerial photographs examined in this study; dots represent one or more active injection well(s). Base map after Texas Water Development Board (1972).
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Figure 12: Aerial photographic site 4
Figure 13. Aerial photographic site 5
Figure 18 Aerial photographic site 10
subsurface maps to be constant throughout overlying strata. However, many Gulf Coast faults actually are curved in cross-section (Cloos, 1968; Bruce, 1973); therefore, the locations of extrapolated fault traces are only approximate.

Results and Discussion

An examination of Figures 9 through 23 indicates that correlation between some photolineations and extrapolated faults exists in study sites with subsurface control. In addition, several photolineations and fault traces in the figures follow or parallel closely changes in drainage patterns of rivers and bayous. Such a relationship is seen in Adams Bayou and Cow Bayou (Figure 9), Millebrandt Bayou (Figure 10), Neches River (Figure 12), San Jacinto River (Figure 13), Buffalo Bayou (Figure 15), Clear Creek (Figure 16), Moses Bayou and Dickinson Bayou (Figure 17), Chocolate Bayou (Figure 18), and Brazos River (Figure 19). Photolineations are found within 11,000 feet of each waste disposal site except WDW 70 (Figure 23).

The impact of faults in the vicinity of a waste injection well has been mentioned in earlier sections. Faults near injection operations may pose three different types of hazards: (1) earthquakes may be induced by the increase of pore pressure along pre-existing faults (Raleigh, 1972), (2) injection casing may break in response to movement along a fault that intersects an injection well, and (3) pollution of ground water may result from the upward movement of waste along a loosely sealed fault (Ives and Eddy, 1968). As discussed previously, movement along existing fault planes will occur if fluid
pressures are increased enough to bring the Mohr Circle representing the stress field tangent to the Mohr envelope of a material (Figure 4). The angle of internal friction, $\phi$, of sedimentary rocks such as those of the Texas Gulf Coast ranges from 40° to 50° (Mandin, 1966; Jaeger, 1969). Assuming a value of 45°, the Mohr envelope representing $T$ vs. $S$, the critical value of shear stress and normal stress, respectively, for slip to occur along normal faults in Gulf Coast Strata is plotted in Figure 24. Mohr Circles representing the state of stress in the injection horizons of three selected Gulf Coast wells prior to the initiation of injection operations are included in the figure. The data used to calculate the stress state were obtained from the TWQBDW Master Card file (Texas Water Quality Board, 1961-1976). The original borehole pressures, depths, and calculated $s_1$ and $s_3$ values for the three example wells are listed in Table 4. In the Gulf Coast, $s_1$ is equal to the effective overburden pressure:

$$s_1 = (Gg) \cdot (h) - (Pp)$$

where $Gg =$ geostatic gradient

$h =$ depth to formation

$Pp =$ pore pressure of the formation,

while $s_3$ is approximately equal to $s_1/3$ (Hubbert and Willis, 1972). For Gulf Coast rocks shallower than 8000 feet, the geostatic gradient is approximately 1.0 psi per foot of depth and the hydrostatic gradient is typically .43 to .47 psi per foot of depth (Hubbert, 1972; Texas Water Development Board, 1972). Thus $s_1$ and $s_3$ can be roughly calculated for other Gulf Coast disposal wells by using Table 2 and the above information. Mohr Circles constructed from $s_1$ and $s_3$ val-
Figure 24  Stress state in the disposal zone of three selected wells prior to injection, as calculated from original borehole pressures and depths (Texas Water Quality Board, 1961-1976)
Table 4

Original Borehole Pressure, Depth, and Calculated Maximum and Minimum Principal Stresses for Three Selected Gulf Coast Industrial Waste Injection Wells: Borehole Pressure and Depth Data from Texas Water Quality Board (1961-1976).

<table>
<thead>
<tr>
<th>WDW</th>
<th>Original Borehole Pressure, psi</th>
<th>Depth, feet</th>
<th>$s_1$, psi</th>
<th>$s_2$, psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>2394</td>
<td>5278</td>
<td>2908</td>
<td>969</td>
</tr>
<tr>
<td>78</td>
<td>2510</td>
<td>5700</td>
<td>3190</td>
<td>1063</td>
</tr>
<tr>
<td>100</td>
<td>2247</td>
<td>4950</td>
<td>2703</td>
<td>901</td>
</tr>
</tbody>
</table>
ues for wells other than the three examples plot in the same vicinity as those depicted in Figure 24, or are smaller and plot to the left of the examples. As is evident from Figure 24, pore pressures would have to be increased by about 500 psi to bring the Mohr Circles tangent to the envelope. This value is very much greater than calculated values of pressure rise at any point in a reservoir due to fluid injection during the usual lifetime (5 to 50 years) of injection wells. Thus even if each photolineation evident near the injection well sites did represent a fault intersecting the injection formation, the inducement of slip along the faults due to fluid injection would be highly unlikely. Despite the unlikelihood of fault activation due to fluid injection in tectonically relaxed regions such as the study area, Raleigh (1972) has suggested that even in these areas, seismic monitoring near the injection wells be undertaken.

In the case of the intersection of the industrial waste injection well by an active fault, rupture of well casing due to fault movement is also unlikely. Nearly all Texas Gulf Coast industrial waste injection wells have stainless steel casings (Texas Water Quality Board, 1961-1976) whose shear strengths range from 40,000 psi to 50,000 psi (American Petroleum Institute, 1976). Only one industrial well has fiberglass casing with a shear strength of approximately 17,000 psi (L. R. Barnhart, pers. comm., 1977). Movement along Gulf Coast faults due to basin-related tectonics occurs by an episodic decrease in the magnitude of the minimum principal stress, $s_3$ (Hubbert and Willis, 1972). The Mohr circle representing the stress state is thus enlarged and movement occurs when it becomes tangent to the envelope.
representing the slip criterion. In Figure 24, if \( s_3 \) were decreased enough to bring the example Mohr circles tangent to the envelope, the shear stress, \( T \), at the time of fault slip would be less than 2500 psi, a value that is only a fraction of the shear strength of the injection casing materials. Shallow concrete sewage pipes at the Ellington Air Force Base have ruptured due to active faulting in the area, however (Clanton and Amsbury, 1975). Sewage waste injection wells on the Gulf Coast were not considered in this study, but six of the nine currently in operation have concrete casings (Texas Water Quality Board, 1961-1976).

Faults extrapolated from photolineations in the vicinity of injection wells in Figures 9 through 22 are found to intersect the waste-receiving formation, in many cases within 5000 feet from the well bore. If a photolineation does represent a fault, then the question of whether waste fluid can migrate up the fault and contaminate overlying aquifers is of importance. This problem is more difficult to treat quantitatively than other potential hazards associated with faults near injection wells discussed above, because insufficient information is available regarding the degree of sealing of faults on the Gulf Coast. Local ground water contamination by brackish water occurs from time to time in areas of oil field brine injection in Texas; in some cases no leaks are found in the injection casing when investigated, and contamination is assumed to occur by migration of brines via unplugged boreholes or faults (C. J. Stump, pers. comm., 1977). No instance of ground water contamination has been reported due to industrial waste injection on the Texas Gulf Coast; however,
all but three Gulf Coast industrial waste injection wells began injection only within the last ten years (Texas Water Quality Board, 1977), while brine disposal wells have been operating much longer and are far more numerous.

Because the fluid pressure in a formation will continuously be increasing in response to active fluid injection, movement of waste along faults is more likely to occur as injection proceeds. The study of the nature of faults along the Gulf Coast is therefore of immediate concern to industrial waste injection activities. Some disposal well permittees do periodically analyze fresh water from wells on the plant site for possible contamination (R. T. Kent, pers. comm., 1975), but areas of contamination may be more than a mile away if the mechanism for waste migration is movement along a fault. Furthermore, such analyses would recognize the problem only after it had occurred; ability to predict areas that may not be safe for long-range fluid injection operations appears more logical.

Two industrial injection systems on the Gulf Coast are of particular interest because more subsurface information is available concerning the actual disposal site than most other Gulf Coast systems. These are WDW 92 at study site 6 (Figure 14) and the system of six injection wells, WDW's 4, 28, 29, 30, 105, and 106, at site 13 (Figure 21). Cross sections across the disposal sites are shown in Figure 25; Figure 25-A illustrates schematically cross-section A-A' of Figure 14, and section B-B' of Figure 21 is shown in Figure 25-B. WDW 92 is located on the northwest margin of the Barber's Hill oil field; the center of Barber's Hill salt dome is less than 1000 feet deep, as
Figure 25-A  Schematic cross section A-A' of Figure 14, after Houston Geological Society (1941). WDW 92 is located 2500 feet north of arrow labelled WDW 92; structural detail not shown.

Figure 25-B  Cross section B-B' of Figure 21, after Price (1972). Injection zones for the wells in this area are the Oakville (O), Catahoula (C), and Greta (G) Sands.
indicated in Figure 25-A. WDW 92, the shallowest disposal well on
the Gulf Coast, injects into Pleocene sands about 2100 feet deep,
500 to 600 feet below fresh water Pleistocene sands (Texas Water
Quality Board, 1961-1976). In addition, this well is permitted to in-
ject 90,000 gallons per month, a volume much less than other Gulf
Coast injection wells (R. T. Kent, pers. comm., 1976). However, in-
trusion of the Barber's Mill salt dome was accompanied by considerable
faulting of surrounding strata; both radial faults and circumferential
step faults occur in the area (Bevier, 1926). Early studies found
brine and gas seepage at the surface (Bevier, 1926). In Figure 18,
many photolineations are evident in the vicinity of Barber's Mill and
the WDW 92 disposal site.

The six injection wells in study site 13 inject into three dis-
posal zones that have been cut by a set of normal and antithetic
faults; a NW-SE cross-section of the disposal zones is shown in Figure
25-B. This section was reproduced from the TWQB WDW files (Texas
Water Quality Board, 1972-1976). When extrapolated, traces of the two
outermost faults of the cross section, the most northwesterly and the
most southeasterly, parallel closely two lineations evident in Figure
21. Fresh water sands occur about 1500 feet above the Oakville sand
disposal zone at this injection site (Texas Water Quality Board, 1961-
1976).

Although no ground water contamination has yet occurred due to
industrial waste injection on the Gulf Coast, waste migration via un-
plugged boreholes and faults is possible. Little can be done about
the presence of undocumented boreholes on a preventive basis, save
regulation of injection in areas where more boreholes are likely to have been drilled (R. T. Kent, pers. comm., 1976). Faults, however, can be more closely investigated. As shown in this study, aerial photographs are one means of locating the surface traces of some faults that may be of concern in areas of waste injection. Additional investigation can be accomplished by coring and logging across suspected faults, and by hydrologic study of several water wells in an area thought to be faulted. Daily measurement of water levels and dissolved gas content can indicate fluctuations in a well or variations between wells that may be due to the presence of a fault, provided water levels are first corrected for atmospheric pressure, diurnal variation, and fluid withdrawal (Ferris et al., 1962; J. A. S. Adams, pers. comm., 1977).
Pressure History of a Two Well Waste Injection System

on the Gulf Coast

Waste disposal wells 33 and 45 were studied in detail because these wells have associated with them a monitor well which penetrates the injection horizon and continuously records the pore pressure of the formation. As no continuous pressure monitor wells are associated with any of the other injection wells in Texas, this system affords a unique opportunity for the investigation of reservoir response due to fluid injection. Before aquifer response can be evaluated, however, characteristics of the disposal zone and waste effluent must be accurately determined, and the injection history must be described.

Geology of Study Area and Disposal Zone Characteristics

The study area is located in the Bayport Industrial Development, about 5 miles northeast of Clear Lake City. A base map of the study area is shown in Figure 26. Principal fresh water aquifers in the area are the Alta Loma Sand and the underlying Lissie Formation, both of Pleistocene age (White, 1967). The depth of the fresh water zone ranges from 1250 to 1500 feet in the area. Pleistocene and Pliocene alluvium deposits consisting of clay, silt, sand, and gravel extend from the Lissie Formation to the top of the Miocene section (Celanese Chemical Company, 1976). The latter is about 3000 feet thick in the area and consists of an upper sequence of sand and clay that grades into a middle sequence of sand, shale, and lime, a lower marginal marine sequence of interbedded sands and shale, and a basal sequence
Figure 26  Base map of study area, after United States Geological Survey (1967, 1969) and Celanese Chemical Company (1976). M denotes monitor well for WDW 33 and 45.
of sand that is about 220 feet thick (Celanese Chemical Company, 1976). This Basal Miocene sand formation is the injection horizon of the study wells. It is underlain by the Anahuac Shale (Oligocene) which has a local thickness of 600 to 700 feet (Houston Geological Society, 1954).

A structure map of the top of the Basal Miocene Sand is shown in Figure 27; Figure 28 is an isopach map of the injection zone. The Basal Miocene Sand was deposited in a coastal-interdeltic environment (Rainwater, 1964). Following the Late Oligocene Anahuac Transgression, the largest Gulf Coast depocenter was located about 80 miles northeast of the study area (Mardin, 1962), but smaller local rivers had steep gradients, allowing them to transport a significant volume of sand to the coast (Rainwater, 1964). Longshore currents distributed much of the sand to beaches and bars, and this activity during a period of marine regression accounted for the accumulation of a considerably uniform lenticular sand interval trending NE-SW (Rainwater, 1964; Glaze, 1967). The Basal Miocene Sand occupies an area of about 625 square miles (Texas Water Quality Board, undated; Houston Geological Society, 1954); while the unit itself is lenticular in shape, the areal dimensions are much greater than the area surrounding the WDW 33 and WDW 45 system considered in this study. The disposal zone in the study area is therefore assumed to be homogeneous.

The physical properties of the Basal Miocene Sand in the study area are summarized in Table 5; references are included in the table. Values of disposal zone porosity, permeability, thickness, temperature, specific storage and connate water density were obtained from
Figure 27  Depth to the top of the Basal Miocene Sand, feet; after Celanese Chemical Company (1976).
Figure 28 Isopach map of Basal Miocene Sand, feet; after Celanese Chemical Company (1976)
Table 5

Physical Properties of the Basal Miocene Sand in the Vicinity of WDW 33 and WDW 45

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>porosity</td>
<td>30%</td>
<td>Halliburton (1967)</td>
</tr>
<tr>
<td>permeability</td>
<td>389 md</td>
<td>Halliburton (1967)</td>
</tr>
<tr>
<td>thickness</td>
<td>200 - 240 feet</td>
<td>White (1967); Barth (1972)</td>
</tr>
<tr>
<td>temperature</td>
<td>140°F</td>
<td>Corley (1972)</td>
</tr>
<tr>
<td>specific storage</td>
<td>1.47 x 10^-6 psi^-1</td>
<td>Barth (1972)</td>
</tr>
<tr>
<td>dissolved solid content</td>
<td>100,000 - 120,000 ppm</td>
<td>Texas Water Development Board (1972)</td>
</tr>
<tr>
<td>connate water density</td>
<td>1.090 - 1.094 g/cc</td>
<td>Wilson (1967); Corley (1972)</td>
</tr>
<tr>
<td>connate water compressibility</td>
<td>3.3 x 10^-6 psi^-1</td>
<td>Warner (1976)</td>
</tr>
<tr>
<td>connate water viscosity</td>
<td>.55 cp</td>
<td>Pirson (1963)</td>
</tr>
<tr>
<td>rock matrix compressibility</td>
<td>4.19 x 10^-7 psi^-1</td>
<td>calculated from equation for specific storage</td>
</tr>
</tbody>
</table>

well log and core sample data in the TWQG WDW 33 and WDW 45 files (Texas Water Quality Board, 1962-1976). Connate water compressibility and viscosity under aquifer conditions were determined from graphs of water compressibility vs. temperature (Warner, 1976) and water viscosity vs. temperature (Pirson, 1963). The compressibility of the rock matrix was calculated from the equation for the specific storage,

\[ S_s = (w) \cdot (n \cdot c_w + c_r), \]

where \( w \) is the connate water density, \( n \) is the fractional porosity of the formation, and \( c_w \) and \( c_r \) are the compressibility of connate water and rock matrix respectively. The known values of \( w, n, c_w \), and \( S_s \) from Table 5 were used in this equation to solve for \( c_r \), the rock matrix compressibility. Based on the environment of deposition and the areal extent of the formation, the properties summarized in Table 5 are assumed to characterize the disposal zone throughout the study area. The hydrostatic pressure distribution in the center of the injection zone prior to waste emplacement is shown in Figure 29.

**Waste Characteristics and Injection History**

The injected material is an aqueous solution (98% water) of organic wastes from petrochemical manufacturing operations. The density of the solution is 1.005 g/cc (C. R. DeRose, written comm., 1976). Values of viscosity and compressibility of the waste are assumed to be similar to those for the formation connate water under aquifer conditions (Pirson, 1963); Warner, 1976).

Effluent injection began at well 33 on 31 October 1967; well 45 was later constructed and began injection on 1 June 1969. The wells
Figure 29  Hydrostatic pressure in the Basal Miocene Sand prior to injection, psi; after Celanese Chemical Company (1976).
are still active and the projected total time of injection of the two wells is 37 years (Texas Water Quality Board, undated). The average injection rates in stock tank barrels (STB) per day for each month from the initiation of injection to the end of 1976 for wells 33 and 45 are plotted in Figures 30 and 31. A total of 39,921,847 barrels were injected during this period. The fluid pressure of the injection zone measured at the monitor well from October, 1967 through December, 1976 is represented by curve (i) of Figure 32. The borehole pressure at the monitor well prior to injection was 2394 psi (Price, 1967).

The Theis Equation

The Theis equation is widely used to calculate aquifer pressurization due to fluid injection in the Gulf Coast (Mill, 1974; R. Henderson, pers. comm., 1975). It is based on a solution of the diffusivity equation, which arises from the combination of Darcy's law with the continuity equation. The development of the diffusivity equation for fluid flow through porous material is described in the following paragraph.

For the case of a vertically confined aquifer in which the thickness is considerably less than the areal dimensions, fluid flow is essentially two dimensional. Darcy's law relates the velocity of a fluid moving through a porous matrix to the pressure gradient \((\nabla P)\) in the formation. Assuming a Cartesian coordinate system in which the \(z\)-direction is vertical, Darcy's law for a homogeneous and isotropic confined aquifer is

\[
\vec{v} = -\frac{k}{

\mu} \left( \frac{\partial P}{\partial x} + \frac{\partial P}{\partial y} \right)
\]  

(1)
Figure 30  Average monthly injection rates in WDW 33; compiled from Texas Water Quality Board (1962-1976)
Figure 31  Average monthly injection rates in WDW 45; compiled from Texas Water Quality Board (1962-1976)
Figure 32 Observed and predicted pressures in the WDW 33 - WDW 45 monitor well. Curve (i) represents the observed pressures and curves (ii) and (iii) represent pressures calculated with the Theis solution and data in Table 6.
where \( k \) is the permeability of the aquifer and \( \mu \) is the viscosity of the fluid moving with velocity \( \vec{v} \). The continuity equation describes the mass flux of a compressible fluid of density \( \rho \) moving with velocity \( \vec{v} \) through an element of an aquifer having a fractional porosity, \( \phi \), as follows:

\[
\text{div}(\rho \vec{v}) = -\frac{\partial}{\partial t} (\phi \rho) \quad (2).
\]

The density of fluids of small and constant compressibility, \( c \), such as water and connate brines, varies with pressure according to the equation of state (Thomas, 1977),

\[
\rho = \rho_0 \exp \left[ c(P - P_0) \right] \quad (3)
\]

where \( \rho_0 \) is the fluid density at pressure \( P_0 \). Differentiation of the equation of state with respect to time and substitution of this expression of \( \rho \partial P/\partial t \) into the right hand member of (2) yields the continuity equation in terms of mass flux and change in pressure:

\[
\text{div}(\rho \vec{v}) = -\rho \frac{\partial P}{\partial t} \quad (4).
\]

A constant porosity is assumed. When Darcy's law is multiplied by the density and the divergence is taken, \( \text{div}(\rho \vec{v}) \) so obtained may be substituted into equation (4). The pressure gradient squared terms, which are multiplied by the compressibility, are neglected, and the resulting equation is

\[
\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = \phi \frac{\mu c}{k} \frac{\partial P}{\partial t} \quad (5).
\]

This is the diffusivity equation in two dimensions.
Theis (1935) presented a solution of the two dimensional diffusivity equation in cylindrical coordinates by considering a confined recharging or discharging aquifer as analogous to a conducting plane having a point heat source or heat sink. The aquifer is assumed to be homogeneous, isotropic, horizontal, and of uniform thickness and infinite areal extent (Mueller and Witherspoon, 1965). The Theis solution expresses the increase or decrease in hydraulic head at a point located a distance $r$ from a wellbore that is recharging or discharging water at a rate $q$, as follows:

$$s = \left[\frac{q}{4\pi k h}\right] \int_0^r \frac{e^{-u/u}}{u'} du'$$ (6)

where

- $s =$ drawdown or buildup of head
- $k =$ permeability
- $h =$ aquifer thickness
- $u = \frac{r^2 S_s}{4kt}$
- $S_s =$ specific storage
- $t =$ time since start of recharge or discharge.

If more than one recharging or discharging well is present, equation (6) is solved separately for the influence of each well at a given point and the solutions are added (Ferris et al., 1962). Wenzel (1942) tabulated values of the definite integral of the Theis solution for a wide range of values of $u$; Wenzel's tables are included in most ground water textbooks.

Equation (6) was solved for the pressure increase at the monitor well due to injection at wells 33 and 45. The injection rates and times for the two injection wells used in the calculations are sum-
marized in Table 6; cumulative yearly injection rates at each well were averaged from the actual monthly rates depicted in Figures 30 and 31. The value of \( r \) indicated with the injection rate data in Table 6 is the distance between the monitor and each injection well. The monitor is located 6224 feet from WDW 33 and 6752 feet from WDW 45 (Celanese Chemical Company, 1976). Also included in Table 6 are the permeability, \( k \), average thickness, \( h \), and the specific storage, \( S_s \), of the disposal zone. Curve (ii) of Figure 32 represents the fluid pressure at the monitor well from October, 1967 through December, 1976 as calculated from the Theis solution using the data in Table 6. As indicated by curves (i) and (ii) of Figure 32, the Theis solution predicts a greater pressure rise than is observed at the monitor well; the difference between the predicted and observed pressures increases with time prior to 1972, after which the predicted and observed pressure curves appear more or less parallel.

Curve (iii) represents pressures calculated in a manner similar to those represented by curve (ii), but with a value of the specific storage increased to \( 5.42 \times 10^{-6} \) psi\(^{-1}\). Values of injection rates, time, and aquifer characteristics used to generate curve (iii) are also summarized in Table 6. A specific storage of \( 5.42 \times 10^{-6} \) psi\(^{-1}\) corresponds to an order of magnitude increase in the compressibility of the rock matrix. As the compressibility of sandstones of widely varying degrees of consolidation ranges from \( 10^{-8} \) to \( 10^{-5} \) psi\(^{-1}\) (Birch, 1966; Warner, 1976), a rock matrix compressibility of \( 4.19 \times 10^{-6} \) is not unreasonable. As indicated in Figure 32, however, the predicted pressures of curve (iii) are higher than the observed
Table 6

Injection System Data for the Calculation of Pressure Rise at the WDW 33 - WDW 45 Monitor Well Using the Theis Solution; Pressure Histories Generated by the Theis Solution are Indicated by Curves (ii) and (iii) in Figure 33.

\[
k = 389 \text{ md}
\]
\[
h = 220 \text{ ft.}
\]
\[
S_s = 1.47 \times 10^{-6} \text{ psi}^{-1}, \text{ for calculation of curve (ii)}
\]
\[
S_s = 5.42 \times 10^{-6} \text{ psi}^{-1}, \text{ for calculation of curve (iii)}
\]

<table>
<thead>
<tr>
<th>Year</th>
<th>t, days</th>
<th>q, STB/day</th>
<th>Year</th>
<th>t, days</th>
<th>q, STB/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1967</td>
<td>61</td>
<td>4450</td>
<td>1969</td>
<td>214</td>
<td>4144</td>
</tr>
<tr>
<td>1968</td>
<td>427</td>
<td>5105</td>
<td>1970</td>
<td>579</td>
<td>3364</td>
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<td>1969</td>
<td>792</td>
<td>4113</td>
<td>1971</td>
<td>944</td>
<td>2947</td>
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<tr>
<td>1970</td>
<td>1157</td>
<td>5258</td>
<td>1972</td>
<td>1310</td>
<td>3050</td>
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<tr>
<td>1971</td>
<td>1522</td>
<td>5537</td>
<td>1973</td>
<td>1675</td>
<td>4247</td>
</tr>
<tr>
<td>1972</td>
<td>1888</td>
<td>6601</td>
<td>1974</td>
<td>2040</td>
<td>4430</td>
</tr>
<tr>
<td>1973</td>
<td>2253</td>
<td>7301</td>
<td>1975</td>
<td>2405</td>
<td>4908</td>
</tr>
<tr>
<td>1974</td>
<td>2618</td>
<td>7096</td>
<td>1976</td>
<td>2771</td>
<td>5501</td>
</tr>
</tbody>
</table>
Table 6, continued

WDW 33
r = 6224 ft.

<table>
<thead>
<tr>
<th>Year</th>
<th>t, days</th>
<th>g, STB/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975</td>
<td>2988</td>
<td>7182</td>
</tr>
<tr>
<td>1976</td>
<td>3349</td>
<td>7369</td>
</tr>
</tbody>
</table>
except in December, 1976, where the curves are seen to meet.

The shape of both curves (ii) and (iii) in Figure 32 is distinct from that of the observed pressure curve. The markedly greater pressures predicted by the Theis solution at earlier histories may be due in part to errors arising from the analogy of an aquifer with a conducting plane in which instantaneous response between observation point and source is assumed (Theis, 1935). The exponential integral involved in equation (6) describes the effect of an impulse at a point source on any point in an infinite, perfectly conducting medium bounded laterally by totally non-conducting media. Theis (1935) applied the point source solution of the two dimensional heat flow equation to ground water hydraulics by assuming that the specific storage of a formation is analogous to the specific heat and formation permeability is analogous to thermal conductivity. While aspects of Theis' analogies appear qualitatively sound, the extent to which a porous and permeable formation behaves as a perfectly conducting plane is uncertain. The permeability in a sense can be considered as a conductivity property (Lohman, 1972), but flow through porous media is extremely circuitous (Bear, 1972). Thus communication between a recharge well and an observation well may not be properly represented by the conditions treated by Theis (1935). Additional limitations of the Theis solution include its applicability only to strictly homogeneous and isotropic media, and the fact that porosity is assumed constant as fluid is injected. Porosity, which is incorporated in the Theis solution in the specific storage term, actually increases as fluid pressure is increased and the rock matrix is compressed (Thomas, 1977).
A Finite Difference Model for Aquifer Pressurization

To further investigate the aquifer response of the study system, a finite difference solution of the diffusivity equation with pressure dependent coefficients was sought. In a finite difference approach, the reservoir or aquifer is treated as a system of blocks and the pressure at each block in response to an injected volume of fluid is calculated simultaneously at each indicated time. The system of equations obtained from the combination of Darcy's law and the continuity equation for a gridded reservoir subjected to fluid injection is developed in the following paragraphs.

Darcy's law is commonly written in terms of the gradient of a flow potential \( \Phi \) (Bear, 1972) as follows:

\[
\nabla \Phi = -\frac{k}{\mu} \rho \nabla \Psi \tag{7}
\]

where

\[
\Psi = \int_{P_1}^{P} \frac{dP}{\rho(P)} \pm h \tag{8}
\]

\( P_1 \) is the pressure at reference elevation \( h=0 \) and \( P \) is the pressure at elevation \( h \). The gradient of \( \Psi \) is

\[
\nabla \Psi = \frac{1}{\rho} \nabla P - \nabla h \tag{9}
\]

where \( h \) is measured positive downward. Substitution of \( \rho \nabla \Phi \) in terms of the potential into the continuity equation (2) yields

\[
\nabla \left[ \frac{k}{\mu} \rho (\nabla P - \rho \nabla h) \right] = \frac{\partial}{\partial t} (\phi \rho) \tag{10}
\]

In a system of injection of material into a brine saturated porous medium, the flow equation must be written for each fluid phase
and the pressure solved simultaneously from the resulting flow equations (Thomas, 1977). Thus for the brine phase \( w \) the flow equation is

\[
\nabla \left\{ \frac{k}{\mu_w} \rho_w (\nabla P - \rho_w \nabla h) \right\} = \frac{\partial}{\partial t} (\phi \rho_w S_w) \tag{11}
\]

and for the injected waste \( w_w \) the equation is

\[
\nabla \left\{ \frac{k}{\mu_{w_w}} \rho_{w_w} (\nabla P - \rho_{w_w} \nabla h) \right\} + Q = \frac{\partial}{\partial t} (\phi \rho_{w_w} S_{w_w}) \tag{12}
\]

\( S_w \) and \( S_{w_w} \) are the fractional volumes of brine and waste, respectively. At any time in a given element of volume of the reservoir, \( S_w + S_{w_w} = 1 \).

\( Q \) is the source term for the injected phase. Because the two phases are similar, no capillary pressure will result due to injection, thus \( P = P_w = P_{w_w} \).

The porosity and densities vary with pressure, so their equations of state must be substituted into (11) and (12). Equation (3) may be expanded in a Taylor series and the terms involving compressibilities of higher order than 1 neglected. The equation of state of the fluid density may then be rewritten

\[
\rho = \rho_i (1 + cP) \cong \rho_i (1 + c_d P_i) \tag{13}
\]

where \( P = P_i + dP \). \( P_i \) is the initial hydrostatic pressure of the reservoir. Similarly, the porosity varies with pressure as follows (Thomas, 1977):

\[
\phi = \phi_i (1 + c_r P),
\]

where \( c_r \) is the compressibility of the rock matrix. Substitution of each equation by the initial brine and waste densities, respectively,
yields

\[
\nabla \left( \frac{k}{\mu_w} (1 + c_{w_i})(1 + c_{w_d}P) \left[ \nabla P - \rho_{wi}(1 + c_{w_i})(1 + c_{w_d}P) \nabla h \right] \right) = \frac{3}{\Delta t} \left[ \phi_i(1 + c_{rP})(1 + c_{w_P})(1 + c_{w_d}P)S_w \right]
\]

(14)

and

\[
\nabla \left( \frac{k}{\mu_{ww}} (1 + c_{ww_P})(1 + c_{ww_d}P) \left[ \nabla P - \rho_{ww}(1 + c_{ww_P})(1 + c_{ww_d}P) \nabla h \right] \right) + Q = \frac{3}{\Delta t} \left[ \phi_i(1 + c_{rP})(1 + c_{w_P})(1 + c_{w_d}P)S_w \right]
\]

(15).

The fluid shrinkage factors \((1 + c_{w_i})(1 + c_{w_d}P)\) and \((1 + c_{ww_P})(1 + c_{ww_d}P)\) are represented by \(B_w\) and \(B_{ww}\), respectively (Thomas, 1973).

(14) and (15) then are rewritten as

\[
\nabla \left( \frac{k}{\mu_w} B_w (\nabla P - B_w \rho_{wi} \nabla h) \right) = \frac{3}{\Delta t} \phi_i(1 + c_{rP})B_w S_w
\]

(16)

and

\[
\nabla \left( \frac{k}{\mu_{ww}} B_{ww} (\nabla P - B_{ww} \rho_{ww} \nabla h) \right) + Q = \frac{3}{\Delta t} \phi_i(1 + c_{rP})B_{ww} S_{ww}
\]

(17).

Equations (16) and (17) are solved in two dimensions with a second-order finite difference technique. The reservoir is divided into \(N_x\) blocks, with \(N_x\) blocks of varying widths \(\Delta x\) in the \(i\)-direction and \(N_y\) blocks of varying lengths \(\Delta y\) in the \(j\)-direction. The reservoir thickness is \(\Delta z\) and \(N_z\), the number of blocks in the \(z\)-direction, is equal to 1. In difference form, equations (16) and (17) will represent the equation for the pressure of each block at \(i, j\).

In the direction of a spatial coordinate \(a\), \(\partial m/\partial a\) of a variable is approximated at a point \(i+\frac{1}{2}\) by the central difference equation

\[
\left( \frac{\partial m}{\partial a} \right)_{i+\frac{1}{2}} = \frac{m_{i+1} - m_i}{2\left( \frac{\Delta a_{i+\frac{1}{2}}}{2} \right)}
\]

(18)

and at point \(i-\frac{1}{2}\) by
\[
\left( \frac{\partial m}{\partial a} \right)_{i-\frac{1}{2}} = \frac{m_i - m_{i-1}}{2 \left( \frac{\Delta a_i}{\Delta t} + \frac{\Delta a_{i-1}}{\Delta t} \right)}
\]

(19).

\[
\frac{\partial}{\partial a} \left( r_a \frac{\partial m}{\partial a} \right)_{i-\frac{1}{2}} \text{ where } r_i \text{ is another variable may be approximated as}
\]

\[
\frac{\left( r_a \frac{\partial m}{\partial a} \right)_{i+\frac{1}{2}} - r_a \left( \frac{\partial m}{\partial a} \right)_{i-\frac{1}{2}}}{\Delta a_i}
\]

(20).

Expansion of the above equation yields

\[
\frac{r_{a i+\frac{1}{2}} (m_{i+1} - m_i)}{\Delta a_i (\Delta a_{i+1} + \Delta a_i)} - \frac{r_{a i-\frac{1}{2}} (m_i - m_{i-1})}{\Delta a_i (\Delta a_i + \Delta a_{i-1})}
\]

(21).

The differential with respect to time of a variable b is expressed in finite differences as \((b^{n+1} - b^n)/\Delta t\), where \(\Delta t\) is the difference in time between time steps n and n+1.

The differential operators \(\nabla\) of (16) and (17) are thus replaced by appropriate difference operators \(\Delta\). Multiplication of (16) by the volume of block \(i,j\) yields

\[\Delta T_{wi}(\Delta P - B_w \rho_{wi} \Delta h) = \frac{P V}{\Delta t} \Delta t \left( 1 + c_r P \right) B_w S_w\]

(22)

and\[\Delta T_{ww}(\Delta P - B_{ww} \rho_{ww} \Delta h) + Q = \frac{P V}{\Delta t} \Delta t \left( 1 + c_r P \right) B_{ww} S_{ww}\]

(23)

where \(PV = \text{pore volume of the block } i,j = \Delta x \Delta y \Delta z \phi_i\) \hspace{1cm} (23-A)

and \(T = \text{transmissibility term} = \left[ (kB)/\mu \right] \Delta x \Delta y \Delta z\)

(23-B).

For each phase,

\[\Delta T \Delta P = \Delta x T_x \Delta x P + \Delta y T_y \Delta y P\]

\[= T_{x i+\frac{1}{2}, j} (P_{i+1, j} - P_{i, j}) - T_{x i-\frac{1}{2}, j} (P_{i, j} - P_{i-1, j}) + T_{y i, j+1} (P_{i, j+1} - P_{i, j})]

-88-
\[-P_{i,j} - T_{y_{i,j-1}}(P_{i,j} - P_{i,j-1})\]  \hspace{1cm} (24).

Expansion of the right hand side of equations (22) and (23) is accomplished with the identity (Scientific Software Corporation, 1975)

\[\frac{1}{\Delta t} \Delta_t(fg) = r^{n+1} \Delta_t g + e^n \Delta_t f\]  \hspace{1cm} (25).

Thus

\[\Delta_t[(1 + c_r P)BS] = (1 + c_r P^{n+1}) \Delta_t (BS) + (BS)^n \Delta_t c_r \Delta_t P\]  \hspace{1cm} (26)

\[= (1 + c_r P^{n+1})[B^{n+1}\Delta_t S + S^n \Delta_t B] + c_r (BS)^n \Delta_t P.\]

Because B is a function of P, \(\Delta_t B = B^t \Delta_t P;\) expansion of the above equation then yields

\[\Delta_t[(1 + c_r P)BS] = [1 + c_r P^{n+1} B^t S + (BS)^n c_r] \Delta_t P\]

\[+ (1 + c_r P)^{n+1} \Delta_t S\]  \hspace{1cm} (27).

The coefficient of \(\Delta_t P\) is denoted \(U_{10}\) and \(U_{13}\) for the brine and waste, respectively. The coefficient of \(\Delta_t S\) is denoted \(U_{11}\) for the brine and \(U_{12}\) for the waste fluid. Thus the flow equations are written (Thomas, 1973)

\[\Delta T_{\text{w}}(\Delta P - \rho_{\text{w}} B_w \Delta h) = U_{10} \Delta_t P + U_{11} \Delta_t S\]  \hspace{1cm} (28)

\[\Delta T_{\text{ww}}(\Delta P - \rho_{\text{ww}} B_{\text{ww}} \Delta h) + Q^* = U_{13} \Delta_t P + U_{12} \Delta_t S\]  \hspace{1cm} (29).

Multiplication of (28) by constant \(A_1\) and (29) by constant \(A_2\) followed by addition of the two equations results in

\[A_1 \Delta T_{\text{w}}(\Delta P - \rho_{\text{w}} B_w \Delta h) + A_2 \Delta T_{\text{ww}}(\Delta P - \rho_{\text{ww}} B_{\text{ww}} \Delta h) + A_2 Q^*\]
= \left[ (A_1)(U_{10}) + (A_2)(U_{13}) \right] \Delta_t P + (A_1)(U_{11}) \Delta_t S_w + (A_2)(U_{12}) \Delta_t S_{ww} \quad (30).

To solve this equation for \( P^{n+1} \), the last two terms of (30) must vanish. This is accomplished if \((A_1)(U_{11}) = (A_2)(U_{12})\), since \( S_w + S_{ww} = 1 \).

Furthermore, the constants \( A_1 \) and \( A_2 \) are arbitrary, so \( A_1 \) is chosen equal to 1; thus \( A_2 = U_{11}/U_{12} \). Equation (30) is then rewritten as

\[
\Delta(T_w + A_2 T_{ww}) \Delta P^{n+1} = \left[ U_{10} + (A_2)(U_{13}) \right] (P^{n+1} - P^n) 
+ \Delta(T_w \rho_{wi} B_w + A_2 T_{ww} \rho_{wwi} B_{ww}) \Delta h - A_2 Q^* \quad (31).
\]

Equation (31) is solved by an iterative procedure; it is rewritten (Thomas, 1973) as

\[
\Delta(T_w + A_2 T_{ww}) \Delta P^{n+1} - c P^{n+1} = -c P^n + \Delta(T_w \rho_{wi} B_w 
+ A_2 T_{ww} \rho_{wwi} B_{ww}) \Delta h - A_2 Q^* \quad (32)
\]

where \( c \) is \( U_{10} = (A_2)(U_{13}) \). In matrix form,

\[\mathbf{A} P^{n+1} = \mathbf{K}\]

(33).

Equation (33) is solved by first substituting all \( P^{n+1} \) terms by the known \( P^n \)s in the matrix \( \mathbf{K} \) and solving for \( P_1^{n+1} \). Then \( \mathbf{A} P_1^{n+1} \) is used to generate \( \mathbf{K}_1 \), which is then used to solve for a new \( P^{n+1} \). The iteration procedure continues until \( P \) at the \( k+1 \) iterate varies insignificantly from the value at the \( k \) iterate. Then \( P \) at the \( k+1 \) iterate is the pressure at new time \( n+1 \). \( S_{ww}^{n+1} \) is calculated from equation (28) once \( P^{n+1} \) is determined. \( S_{ww}^{n+1} \) is calculated from the relation

\[ S_{ww}^{n+1} = 1 - S_w^{n+1} \].
The Computer Program

The Fortran IV computer program for the calculation of pressures with time due to injection of wastes according to the method developed above is listed in the appendix. It was modified from a program prepared for the Bureau of Mines by Thomas (1973). The program was originally developed for oil field fluid injection; many sections of routines dealing with gas phases and gas mobilities were eliminated for the present study. The program consists of a main routine and eight subroutines. The subroutines are summarized in Table 7. In INPUT1, the constant properties of the reservoir are read. These include block dimensions and depths, initial viscosities, densities, pressure and porosity, and x- and y- direction permeabilities. In INIT, the system is initialized and the hydrostatic pressure of each block prior to initiation of injection is calculated from the initial pressure (PI) of a block at depth (HI) and the difference in depths between blocks. INPUT2 reads the injection well data, such as indices of blocks where wells are located, the rates of injection, the time step size and the total time up to which this injection well data is valid. COEF calculates the transmissibility (T) terms of equation (32) according to known pressures and saturations. PRODN assigns rates of injection to each well. In ITER, the elements of \( \bar{A} \) and \( \bar{R} \) are determined and the criterion for closure is set. ITER calls SOLVE which employs a band algorithm, BANDSOLVE (Scientific Software Corporation, 1975) to calculate \( P_k^{n+1} \) where \( k \) is the iteration number. The solution is tested for convergence in ITER and if closure has not been attained the coefficients of \( \bar{R} \) are updated and SOLVE is again
Table 7
Summary of Subroutines in the Two-dimensional Finite Difference Flow Model

<table>
<thead>
<tr>
<th>Subroutine</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT1</td>
<td>reads constant and initial reservoir properties</td>
</tr>
<tr>
<td>INIT</td>
<td>initializes system; calculates hydrostatic pressure in each block prior to injection</td>
</tr>
<tr>
<td>INPUT2</td>
<td>reads injection data: location of wells in grid, injection rates, target time, and time step size</td>
</tr>
<tr>
<td>COEF</td>
<td>calculates transmissibility of each block</td>
</tr>
<tr>
<td>PRODN</td>
<td>assigns injection rates to wells</td>
</tr>
<tr>
<td>ITER</td>
<td>determines matrix elements and closure criterion; calls SOLVE and checks for convergence</td>
</tr>
<tr>
<td>SOLVE</td>
<td>solves for new pressure, $P_{k+1}^n$ at $k^{th}$ time step using LU decomposition</td>
</tr>
<tr>
<td>OUTPUT</td>
<td>prints pressure distribution</td>
</tr>
</tbody>
</table>
called. Once converged, the solution is used to calculate $S_w$ and $S_{sw}$. The results are printed in OUTPUT.

**Application of the Model to the Two Well System**

To simulate the injection history of the WDW 33 - WDW 45 system using the finite difference model described above, the study area reservoir was gridded into 23 by 23 blocks, as depicted in plan view in Figure 33. The $x$-direction of the grid trends NW-SE and the $y$-direction trends NE-SW; $i$ (x-direction) and $j$ (y-direction) block indices are indicated in Figure 33. WDW 33 is located at block 13,13 and WDW 45 at 11,11. The monitor is at block 12,18. Locations of these wells are shaded in Figure 33.

The model reservoir strikes N45E and dips 2°SE; these values reflect the regional strike and dip of the Basal Miocene Sand (Figure 27). All blocks having the same $i$-index therefore have the same depth and original hydrostatic pressure. In addition, the $x$-direction width of each block was chosen equal to the $y$-direction width of each similarly indexed block. Values of block widths, depths, and original hydrostatic pressure for the model are listed in Table 8. In Table 9, properties of the reservoir, connate water, and waste read in the INPUT1 subroutine are summarized. The values of these properties used in the computations are also listed in this table.

As the actual injection volumes and reservoir area are great, the system was scaled down to render computer treatment economically feasible. This is why the model reservoir is only 20,526 feet by 20,526 feet (Figure 33). The time of injection was likewise reduced,
Figure 33 Plan view of model reservoir grid drawn to scale; shaded areas represent injection well blocks (11,11 and 13,13) and monitor block (12,18).
<table>
<thead>
<tr>
<th>I: i-index</th>
<th>DX(I), feet: width of block of i-index I (equal to width of block of j-index equal to i)</th>
<th>H(I,J), feet: depth to block i,j for i=I and j = 1 through 23</th>
<th>P(I,J), psi: initial hydrostatic pressure of block i,j for i=I and j = 1 through 23</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1500</td>
<td>4946</td>
<td>2236</td>
</tr>
<tr>
<td>2</td>
<td>958</td>
<td>4989</td>
<td>2256</td>
</tr>
<tr>
<td>3</td>
<td>654</td>
<td>5017</td>
<td>2270</td>
</tr>
<tr>
<td>4</td>
<td>300</td>
<td>5034</td>
<td>2278</td>
</tr>
<tr>
<td>5</td>
<td>654</td>
<td>5050</td>
<td>2286</td>
</tr>
<tr>
<td>6</td>
<td>958</td>
<td>5078</td>
<td>2299</td>
</tr>
<tr>
<td>7</td>
<td>1500</td>
<td>5121</td>
<td>2319</td>
</tr>
<tr>
<td>8</td>
<td>1500</td>
<td>5174</td>
<td>2344</td>
</tr>
<tr>
<td>9</td>
<td>958</td>
<td>5217</td>
<td>2365</td>
</tr>
<tr>
<td>10</td>
<td>654</td>
<td>5244</td>
<td>2378</td>
</tr>
<tr>
<td>11</td>
<td>300</td>
<td>5262</td>
<td>2386</td>
</tr>
<tr>
<td>12</td>
<td>654</td>
<td>5278</td>
<td>2394</td>
</tr>
<tr>
<td>L(J)(I)</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>300 feet</td>
<td>654</td>
<td>958</td>
<td>5340</td>
</tr>
<tr>
<td>2402 feet</td>
<td>2412</td>
<td>2423</td>
<td>2444</td>
</tr>
</tbody>
</table>

Table 8, continued
Table 9

Properties of Reservoir, Connate Water, and Waste Read in INPUT1 for the Computations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Property</th>
<th>Value Read in Computations</th>
</tr>
</thead>
<tbody>
<tr>
<td>NX</td>
<td>number of blocks in x-direction</td>
<td>23</td>
</tr>
<tr>
<td>NY</td>
<td>number of blocks in y-direction</td>
<td>23</td>
</tr>
<tr>
<td>NZ</td>
<td>number of blocks in z-direction</td>
<td>1</td>
</tr>
<tr>
<td>HI</td>
<td>depth to reference block</td>
<td>5278 feet</td>
</tr>
<tr>
<td>PI</td>
<td>pressure of reference block</td>
<td>2394 psi</td>
</tr>
<tr>
<td>DWS</td>
<td>density of connate water</td>
<td>68.30 lb/cu ft.</td>
</tr>
<tr>
<td>DGS</td>
<td>density of waste water</td>
<td>68.05 lb/cu ft.</td>
</tr>
<tr>
<td>VW</td>
<td>viscosity of connate water</td>
<td>.55 cp</td>
</tr>
<tr>
<td>VWW</td>
<td>viscosity of waste water</td>
<td>.55 cp</td>
</tr>
<tr>
<td>CR</td>
<td>compressibility of rock matrix</td>
<td>$4.19 \times 10^{-7}$ psi$^{-1}$</td>
</tr>
<tr>
<td>CW</td>
<td>compressibility of connate water</td>
<td>$3.30 \times 10^{-6}$ psi$^{-1}$</td>
</tr>
<tr>
<td>CWW</td>
<td>compressibility of waste water</td>
<td>$3.30 \times 10^{-6}$ psi$^{-1}$</td>
</tr>
<tr>
<td>DX(I)</td>
<td>x-direction width of block with i-index I</td>
<td>see Table 8</td>
</tr>
<tr>
<td>Symbol</td>
<td>Property</td>
<td>Value Read in Computations</td>
</tr>
<tr>
<td>--------</td>
<td>----------------------------------------------</td>
<td>---------------------------------------------</td>
</tr>
<tr>
<td>DY(J)</td>
<td>y-direction width of block with j-index J</td>
<td>see Table 8</td>
</tr>
<tr>
<td>DZ(K)</td>
<td>z-direction width of block with k-index K</td>
<td>220 feet</td>
</tr>
<tr>
<td>H(L)</td>
<td>depth to block L having indices i,j</td>
<td>see Table 8</td>
</tr>
<tr>
<td>FXX</td>
<td>x-direction permeability</td>
<td>389 md (first execution)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>389 md (second execution)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>420 md (third execution)</td>
</tr>
<tr>
<td>FKY</td>
<td>y-direction permeability</td>
<td>389 md (first execution)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>272.3 md (second execution)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200 md (third execution)</td>
</tr>
<tr>
<td>FKZ</td>
<td>z-direction permeability</td>
<td></td>
</tr>
<tr>
<td>PHI</td>
<td>fractional porosity</td>
<td>1 md</td>
</tr>
<tr>
<td></td>
<td></td>
<td>.30</td>
</tr>
</tbody>
</table>
as was the total injected volume. The latter was estimated from the specific storage and model reservoir volume as the volume necessary to increase the pressure of the system by 60 psi. The injection rates, model times, and time step sizes used in the computations are listed in Table 10. The scale factor for both time and volume is .0275, while scale factors for all other properties in the system are unity. 90 days therefore represent 3270 days (through November, 1976) and well 45 begins injection at 16 model days. In the scale modeling of systems characterized by low Reynolds numbers, i.e., systems such as the one considered in this study in which viscous forces are much greater than inertial forces, scale factors for volume and time are essentially independent (Hubbert, 1937). However, to maintain an injection rate scale factor of unity, volume and time were scaled equally. The rates were partitioned as indicated in Table 10 according to the actual percentages of waste injected at each well, and for well 33 the percentage injected prior to June of 1969.

Three computer runs were made with identical input except that the $x$- and $y$-direction permeabilities ($k_x$ and $k_y$) were changed in each run. In the first run, both $k_x$ and $k_y$ were 389 md. This is the value of the permeability of the Basal Miocene Sand reported from formation tests prior to injection (Halliburton, 1967). To investigate whether asymmetric flow of waste in the formation could account for the lower observed pressures than predicted by the Theis solution (Figure 32), $k_y$ was reduced by 30% in the second run. In the third run, $k_y$ was reduced further to 200 md and $k_y$ was increased to 420 md.
<table>
<thead>
<tr>
<th>Time, days</th>
<th>Time Step Size, days</th>
<th>Injection Rate at 13,13, STB/day</th>
<th>Injection Rate at 11,11, STB/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>4599</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>4599</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>4599</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>4599</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>5</td>
<td>4599</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>24</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>32</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
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<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>48</td>
<td>8</td>
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<td>5792</td>
</tr>
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<td>56</td>
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<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>64</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>72</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>Time, days</td>
<td>Time Step Size, days</td>
<td>Injection Rate at 13.13, STB/day</td>
<td>Injection Rate at 11.11, STB/day</td>
</tr>
<tr>
<td>------------</td>
<td>----------------------</td>
<td>----------------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>80</td>
<td>8</td>
<td>7669</td>
<td>5792</td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>7669</td>
<td>5792</td>
</tr>
</tbody>
</table>
Results and Discussion

Figures 34, 35, and 36 are graphs of the computed pressure increase in psi vs. model time in days at grid blocks 12,18 and 18,12 for the three sets of input described above; blocks 12,18 and 18,12 are equidistant from the center of the reservoir along the grid coordinate axes (Figure 33). The observed pressure rise at the monitor well vs. actual time in years is included in the figures.

As seen in Figure 34, the change in pressure at 12,18 and 18,12 is virtually identical for the first execution in which $k_x=389$ md and $k_y=389$ md. The curve representing the computed pressure at these blocks approximates the observed pressure curve within 4 psi and at times under 48 days particularly closely. In the second execution, $k_x=389$ md and $k_y=272.3$ md. The differences in pressures computed in this execution at 12,18 and 18,12 are not great (Figure 35), but the computed curve for the monitor well better approximates the observed at earlier injection times than does the curve representing the rise at 18,12 or the computed curve of the first execution. The results of the final execution are presented in Figure 36. In this case, $k_x=420$ md and $k_y=200$ md. Again the differences in pressure rise at 12,18 and 18,12 are not great, having a maximum difference of 6 psi. However, the computed pressure rise at the monitor well at very early and late injection histories is similar to the observed, while the computed pressure increase at 18,12 is greater than the observed at all times.

The most striking result of the model executions is the great difference between the computed and observed pressures and those pre-
Figure 34 Pressure increase vs. time as computed at (12,18) and (18,12) when $k_x = 389 \text{md}$ and $k_y = 389 \text{md}$.
Figure 35: Pressure increase vs. time as computed at (12,18) and (18,12) when k_x=399 md and k_y=272.3 md.
Figure 36 Pressure increase vs. time as computed at (12,18) and (18,12) when $k_x = 420 \text{ md}$ and $k_y = 200 \text{ md}$
dicted by the Theis solution (Figure 32). As mentioned previously, the Theis solution assumes instantaneous response throughout the aquifer. Moreover, this solution is a form of the exponential integral which yields the response at an infinitesimal point due to an infinitesimal point source (Theis, 1935); in such a treatment, pressure at the source is infinite, as seen by the fact that equation (6) approaches infinity as \( r \) approaches zero (Abramowitz and Stegun, 1964). The Theis solution will therefore always yield greater pressure responses at monitor points than would be observed.

The computations involving anisotropic permeability were undertaken to investigate the possibility of non-radial flow in the WDW 33 and WDW 45 system, as mentioned previously. The injected waste has a lower density than the connate water, and the regional dip of the Basal Miocene Sand is 2°SE. In addition, a comparison of the contour map (Figure 27) with the hydrostatic pressure distribution (Figure 29) of the formation indicates a slight northwesterly hydraulic gradient. As the monitor well is located practically on strike with the injection wells, a greater fluid flow in the NW-SE direction due to both gravitational force and pre-existing ground water movement could result in lower pressures at the monitor well than expected for the case of perfectly radial flow. Laboratory experiments of the injection of fluids of varied densities into scale model aquifers have demonstrated changes in the configuration of the injected volumes with dip and hydraulic gradient (Painter, 1971; Esmail, 1973). In the WDW 33 - WDW 45 system, the hydraulic gradient, dip, and density differences are slight, but the observed pressure curve is better approximated by
the computed pressure of block 12,18 at early injection times in the computations in which $k_y$ is reduced, as indicated in Figure 35.

Although a permeability reduction of 30% in the direction of the monitor well may account for the nature of the observed pressure rise at the monitor well at early histories, none of the computed curves display the distinct hump of the observed pressure curve which is evident between 1971 and 1975. After 1975 (80 model days) the computed results are not reliable because boundary effects greatly influence computations as the model reservoir is filling up. The rate of observed pressure rise in the WDW 33 - WDW 45 monitor well increases markedly in 1972 and decreases in 1975, as seen in Figure 35. This change in rate of pressure buildup could be due to the presence of a fault near the monitor well, reaction between injected waste and aquifer constituents, inhomogeneities within the formation, or a change in specific storage as injection proceeds. Although faults associated with the deep-seated Clear Lake Salt Dome disrupt the Basal Miocene Sand 1½ miles west of the monitor well, no faults are evident in structure maps of the Basal Miocene in the vicinity of the injection system (Pitt, 1962; Klotzman, 1970; Celanese Chemical Company, 1976). If faults are present, the offset is not considerable. Reactions between waste and aquifer could yield precipitates that clog the formation, causing increased formation pressures. However, laboratory waste-formation compatibility tests under aquifer conditions were undertaken prior to injection in the WDW 33 - WDW 45 system (R. Henderson, pers. comm., 1975). Such compatibility tests are currently performed before most injection wells are constructed (Davis
and Funk, 1975). For reasons already discussed, an abrupt facies change within the Basal Miocene Sand in the study area is unlikely. Early work on the Gulf Coast Miocene (Meyer, 1939; Ellisor, 1944) as well as well log data and knowledge of the depositional environment (Rainwater, 1964; Glaze, 1964; LeBlanc, 1972) evince that in the study area the disposal zone is homogeneous.

The final possible reason for the change in rate of pressure buildup cited above is a change in the specific storage of the formation during fluid injection. The equation for the specific storage incorporates porosity, fluid density, and water and rock matrix compressibility. In the computations in the present study, porosity and fluid density are functions of pressure while the pore water and rock matrix compressibility are constant. The compressibility of water decreases very slightly with increasing pressure; at pressures under 7000 psi and at aquifer temperatures, the decrease of water compressibility is on the order of $10^{-10}$ psi$^{-1}$/psi (Katz and Coats, 1968).

In a porous medium, the bulk rock matrix compressibility, denoted $c_b$, is the sum of two compressibility components (Domenico, 1974),

$$c_b = \phi c_p + c_s$$

(34),

where $\phi$ is porosity, $c_p$ is pore volume compressibility, and $c_s$ is the solid matrix material compressibility. While the latter is essentially constant over a wide range of pressures for sandstone constituents (Birch, 1966; Domenico, 1974), the pore volume compressibility increases with increasing pore pressure (Van der Knapp, 1959). For Gulf Coast Frio Sand (Oligocene) with a 30% porosity, the pore volume compressibility increases by approximately $3 \times 10^{-9}$ psi$^{-1}$/psi over the
range of pore pressures encountered in the present study (Van der Knapp, 1959).

At early injection histories in the study system, the change in the pore volume compressibility would not greatly affect the bulk rock matrix compressibility. As injection proceeds, however, increases in pore pressure, particularly in the vicinity of the injection wells, are great enough to increase this value. At well 33 (block 13,13), the computed rise in fluid pressure was 70 psi at 40 days and nearly 100 psi at 80 days. If a pressure derivative of pore volume compressibility similar to that of the Frio Sand is assumed, these values of pore pressure would result in an increase in the pore volume compressibility of $2.1 \times 10^{-7}$ psi$^{-1}$ at 40 days and $2.9 \times 10^{-7}$ psi$^{-1}$ at 80 days. Recalling that the bulk rock matrix compressibility calculated for the Basal Miocene Sand was $4.19 \times 10^{-7}$ psi$^{-1}$, equation (34) yields values of $c_b$ equal to $4.3 \times 10^{-7}$ psi$^{-1}$ at 40 days and $5.1 \times 10^{-7}$ psi$^{-1}$ at 80 days in the vicinity of the injection wells when the increase in $c_p$ is considered. Thus at later injection histories the bulk rock compressibility increases in response to increased pore pressures. This accounts for the decreased rate of pressure rise observed at the monitor well evident from mid-1974 through 1976.

While the behavior of the observed pressure buildup at later time is justified by a pressure dependent pore volume component of the bulk rock matrix compressibility, the marked increase in rate of pressure rise in mid-1972 remains unresolved. However, this can readily be explained by the fact that a finite amount of compression
of the shale bordering the Basal Miocene Sand will accompany injection; this was not accounted for in the model. Many previous studies have also treated reservoirs as isolated units bounded by totally incompressible and impermeable layers (Van Poojen et al., 1969; Scientific Software Corporation, 1975). While the permeability of shale is extremely low, the compressibility varies from $1.2 \times 10^{-6}$ psi$^{-1}$ to $1.6 \times 10^{-6}$ psi$^{-1}$ for a wide range of shale composition and porosity (Birch, 1966). To accurately reproduce the observed pressure rise (Figure 34), the rock compressibility in the computations would have to include an additional pressure dependent (and weighted) component due to the neighboring shale. Based on a comparison of the nature of the observed pressure rise and that computed at the monitor for the first and second executions (Figures 34 and 35), this component would be constant up to a 20 psi increase in pore pressure. After 20 psi the contribution of the shale compressibility would fall off rapidly, approaching zero at increases in pressure of about 42 psi.

Limited computer funding precluded additional computations with an expression for the bulk rock matrix compressibility involving pressure dependent components due to shale and pore volume compressibility incorporated in the model. In light of the results of the computations and the above discussion, the nature of the pressure buildup observed at the monitor well of the study system is clearly influenced by a slight asymmetry in the flow pattern of the injected waste, the compression of overlying and underlying shale units at early injection times, and an increased compressibility resulting from higher pore
pressures at later times. The greatest shortcoming of the treatment of the study system was the scaling down of the reservoir by economic necessity. The reported specific storage of the Basal Miocene Sand and the model reservoir volume were used to calculate the injection volumes for the computations. If the reported specific storage were erroneous, the error would not be detected in a scaled model. On the other hand, if the physical properties of a system are known with a reasonable degree of certainty, this study demonstrates that the system can feasibly be scaled down at considerably reduced computational cost to investigate reservoir response.

This study also demonstrates that a finite difference solution yields a better approximation to observed pressure rise than the commonly employed Theis solution. In the subdivision of a reservoir into a set of discrete blocks, errors arising from a point source impulse function are eliminated. An additional advantage of approximating a reservoir by a set of finite grid blocks is that an inhomogeneous reservoir can readily be investigated with slight modifications in the computer program. In the present study, the reservoir was homogeneous and no faults of considerable displacement were present. The INFUT1 subroutine (Table 7) reads the physical properties of the reservoir; if inhomogeneities are present, this subroutine can be modified to read the porosity, permeability, thickness, and rock matrix compressibility of each block of the reservoir. Similarly, the presence of a fault can be represented by a row of blocks having a lower permeability or a decreased thickness than the rest of the system. The permeability and thickness are incorporated in the
transmissibility term for each block, as seen in equation (23-B). Therefore a reduction in either k or \( \Delta z \) will reduce the transmissibility if a fault is to be simulated.
Summary and Conclusions

Subsurface injection is not a widespread means of waste disposal, but the number of operating industrial waste injection wells is increasing by about 20 each year in the United States. Currently, 270 industrial waste injection wells are in operation; 55 wells previously injected, but are now shut-down. The greatest volume of data pertaining to industrial waste injection wells in the U. S. concerns the construction and completion of the wells and evaluation of compatibility of waste with the aquifer matrix and connate water. This information is indeed crucial, but based on occurrences of groundwater contamination due to oil field brine injection, disposal zones must be more carefully examined for faults that allow the migration of waste into ground water. This is particularly important in the Gulf Coast, which is an area subject to recurrent normal faulting. One half of the nation's industrial waste injection wells are located on the Gulf Coast.

In this study, the examination of aerial photographic sites encompassing all currently operating Texas Gulf Coast industrial waste injection wells demonstrated that aerial photographs are a means of detecting the surface traces of faults that may intersect the disposal zone. Evidently, not all photolineations represent faults, therefore field studies should supplement aerial photographic examination of well sites. Supplementary studies should include field investigation for topographic scarps, electric logging, shallow trenching, and monitoring of water levels in areas where fault planes extrapolated from
photolineations intersect the waste disposal zone.

The Theis solution, used widely to predict Gulf Coast aquifer response to waste injection, yields pressures that are too high due to the nature of the exponential integral involved. This should be borne in mind when the pressure buildup in monitors is investigated, because lower pressures encountered may be mistakenly interpreted as indicative of either a greater specific storage than originally determined or unprecedented inhomogeneity in the aquifer. Application of a finite difference solution of the flow equation obtained from the combination of Darcy's law and the continuity equation was shown to more accurately represent the pressure buildup at the monitor well associated with a two well industrial waste injection system on the Gulf Coast. The finite difference model can be modified to include pressure dependent components of the aquifer compressibility or inhomogeneities and faults in the reservoir; however, these modifications were not implemented in the present study. The pressure buildup observed at the monitor well is affected by a slight asymmetry in flow of injected waste due to aquifer dip, waste - connate water density difference, and hydraulic gradient. Deviation of the computed pressure buildup from the observed is due to failure of the model to include a pressure dependent rock matrix compressibility. At early injection times, compression of shale immediately overlying and underlying the disposal zone will accompany injection, while at later times the pore volume component of the bulk rock matrix compressibility increases in response to increased pore pressures.
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Appendix
0036  CALL INPUT2
0037     IEND= IEND+1
0038  380  CONTINUE
0039     CALL COEF
0040     CALL PRODN
0041     CALL ITER
0042     CALL OUTPUT
0043     IF(TIME.LT.TTARGET)GO TO 380
0044     GO TO (376.378.3791.IEND
0045  379  CONTINUE
0046  378  CONTINUE
0048     RETURN
0049     END
NR=NX
NR1=NR+1
NST=1
NGWT=10
NB=NX*NY*NZ
NXY=NX*NY
NZP1=NZ+1
NXP1=NX+1
NYP1=NY+1
N1=1
N2=NY
N3=N2
N4=NY+1
N5=NY+2
N6=N5
N7=2*NY+1
GO TO 398
398 CONTINUE
IF(NZ.EQ.1) IVFLO=1
IF(IOPT.EQ.0) GO TO 407
407 CONTINUE
DO 150 K=1,NZ
150 KL(K)=NX*NY*(K-1)
DO 155 J=1,NY
155 JL(J)=NX*(J-1)
READ(5,50) (DX(I),I=1,NX)
READ(5,50) (DY(J),J=1,NY)
READ(5,50) (DZ(K),K=1,NZ)
FORMAT(14F5.0)
50 CONTINUE
521 CONTINUE
READ(5,60) FXX,FKY,FKZ,PHI,SINX,SINY,H111
60 FORMAT(7F10.4)
IY1=1
JM1=1
KM1=1
U3=0.
U1=2.*FXX*0.00633/5.61458
DO 453 K=1,NZ
453 U2=0.
DO 452 J=1,NY
452 JK=JL(J)+KL(K)
U0=0.
DO 451 I=1,NX
451 L=I+JK
SUBROUTINE INIT
COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)
COMMON HI(100),PV(100),TX(100),TY(100),TZ(100),SW(100),PCW(100).
2 DG(100),KRW(100),KRG(100),BW(100),BG(100),P(100),TXW(100),
3 TXG(100),TYG(100),TZW(100),TZG(100),RHW(100),RHG(100),
3 IST(100)
COMMON CXP(100),CXM(100),CYP(100),CYM(100),CZP(100),CZM(100),
2 RI(100),BGP(100),DP(100),C(100),CWP(100),CGP(100),CWSS(100)
COMMON WKRW(10),Q(10),BHP(10),PW(10),CW(10),CGP(10),
2 CGI(10),INDW(10),QW(10),JW(10),KCU(10),KL(10),QW(50),QG(50),
3 QWS(50),QWP(50),CGP(50),WBC(10,5),WM(5),GM(5),TM(5)
COMMON SWT(2,15),KRTW(2,15),KRG(2,15),PCWT(2,15),SWIR(2),SGC(2),
2 PT(25),RGT(25),VGT(25)
COMMON ALPHA(15)
COMMON HGWIPCGIPHI,BWIDWS,VW,DSG,CW,CR,GPI,VIPI,DTTD,TDTIME,
2 SUMW,SUMG,OMEGA,WIP,GIP,DPT
COMMON DPMX,DSMX,DTMX,DPMAX,DSMAX,TTARGT,SRES
COMMON NPT,NGT,NB,NST,L1,J,K,NX,Y,LMAX,NW,NIT,NCYC,ITN,ICYC,ITRN,
2 ISOLVE,N1,N2,N3,N4,N5,N7,NX1,NY1,NZ1,NFP,NLP1,NRP1,IVFLO
COMMON PIN,UBG,UBGP,UGD,UVG,BW,W,CW,W
DIMENSION PCG(1),QON(1)
EQUIVALENCE (PCG(1),PCW(1)),(CGP(1),QON(1))
COMMON IOUT1,IOUT2,IOUT3,IOUT4,IOPS,IOWS,IOEL,IOPS,ITAP,IENT,IMX,JMX,
2 KNX,JS,KS,TIME,ITOPT,ICUTM,IBUG
REAL KRTW,KRTW,KRG
DIMENSION PGH(100),PWH(100),SG(100)
EQUIVALENCE (CXP(1),PGH(1)),(CYP(1),PWH(1)),(CZP(1),SG(1))
SUM=0
ITIME=0
SUMC=0
TIME=0
BW=1+CW*PI
DWS=DWS/144.
DGS=DGS/144.
BW=1+CW*PI
C COMPUTE RELATIVE PERMEABILITY TABLE
NGWT=2
SWT(1,1)=0.
SWT(1,2)=1.
KRG(1,1)=1.
KRG(1,2)=0.
KRW(1,1)=0.
KRW(1,2)=1.
HMX=(-1000000.)
HMN=(-HMX)
DO 10 L=1,NB
   IF(PV(L).LE.0.)GO TO 10
   UH=H(L)
   IF(HMX.LT.UH)HMX=UH
   IF(HMN.GT.UH)HMN=UH
10 CONTINUE
NWDT='GWNT'
PWM(I)=0.*
NDH=51
DH=(HMX-HMN)/(NDH-1.*)
DO 35 K=1.,NDH
   PWM(K+1)=0.*
35 CONTINUE
C INITIALIZE GAS WATER SYSTEM
TOL=0.0001
U1=(H1=HMN)/DH+1.*
I1=U1
FRC=U1*I1
UDH=(FRC)*DH
C WATER ONLY
PIN=P1
PWM(I)=PIN+UDH*DWS*
UDH=(DH)
I1=I+1
IF(I1.EQ.0.)GO TO 42
DO 42 I1=1.,I1
32 PWM(I)=PWM(I+1)+UDH*DWS*(1. +CW*(PWM(I+1)-P1))
42 CONTINUE
I1=I+2
IF(I1.GT.NDH)GO TO 28
DO 33 I1=I1,NDH
33 PWM(I)=PWM(I-1)+DH*DWS*(1. +CW*(PWM(I-1)-P1))
29 CONTINUE
28 CONTINUE
DO 150 L=1,NB
   IF(PV(L).LE.0.)GO TO 110
   M=IST(L)
   UH=H(L)
   U1=(UH=HMN)/DH+1.*
   I1=U1
   FRC=U1*I1
C COMPUTE FLUID PROPERTIES AND INITIAL FLUID IN PLACE

0094  WIPI=0.
0095  GIP1=0.
0096  UVG=VW
0097  DO 170 L=1,NB
0098  IF(PV(L) .LE. 0. )GO TO 170
0100  KRW(L)=KRW(L)/VW
0101  KRG(L)=KRG(L)/UVG
0102  UI=PV(L)*(1.+CR*(P(L)=PI))
0103  BW(L)=BW1*(1.+CW*(P(L)=PI))
0104  WIPI=WIPI+UI*SW(L)*BW(L)
0105  CONTINUE
0106  IF(IDTPT.LT.3)GO TO 450
0108  450 CONTINUE
0109  RETURN
0110  END
SUBROUTINE INPUT2
COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)
COMMON H(100),PV(100),TY(100),TZ(100),SW(100),PCW(100),
DG(100),KRW(100),KRG(100),BLC(100),BG(100),P(100),TW(100),
TXY(100),TYW(100),TYG(100),TZW(100),TZG(100),RHW(100),RHR(100),
IST(100)
COMMON CXH(100),CXM(100),CYP(100),CYM(100),CZP(100),CZM(100),
2 R(100),BGP(100),DP(100),C(100),CW(100),CQW(100),CQG(100),CQS(100),
COMMON WKRW(10),O(10),BHP(10),PWF(10),CWP(10),CI(10),CGP(10),
2 CGI(10),INDW(10),IW(10),IW(10),KCI(10),KCL(10),QW(50),QG(50),
3 QWS(50),QWP(50),QGP(50),WBC(10),S(10),W(5),G(5),GM(5),TM(5),
COMMON SWT(2,15),KRWT(2,15),KRG(2,15),PCWT(2,15),SW(2,15),SGC(2),
2 PT(25),BGT(25),VGT(25)
COMMON ALPHA(15)
COMMON HGW,PCGI,PI,HI,BW,DWS,VW,DGS,CW,CR,GPI,GIPI,WIPI,DTT,DT,TIME,
2 SUMW,NUMG,OMEA,WE,W,GI,GPI,DPT
COMMON DPMX,DSMX,DIMX,PDMAX,DSMAX,TGTARQ,SRES
COMMON NPT,NGWT,NB,NST,L,J,K,NX,Y,LMX,NW,NIT,NCYC,ITN,ICYC,ITRN
2 ISOLVE,N1,N2,N3,N4,N5,N6,N7,NXP1,NYP1,NZP1,NVLO
COMMON PIN,UBG,UBGP,UDG,UGV,BW_BV,CWV,WW
DIMENSION PCG(1),QON(1)
EQUIVALENCE (PCG(1),QCN(1),QCN(1))
COMMON IOUT1,IOUT2,IOUT3,IOUT4,IFO5,IFO6,IFO7,IFAP,IFAP1,IFAP2,IFAP3,
2 KMX,JS,KS,ITIME,IOPTPT,ICTMX,IBUG
REAL KRG,KRWT,KRW,KRG
READ(5,70)IQT,IOTPT,IOPT
70 FORMAT(1I3)
71 IF(IOQ.EQ.0)GO TO 385
READ(5,75)NWCHG,NW
75 FORMAT(2I3)
76 DO 381 I1=1,NWCHG
381 READ(5,80)L,LW,LW,LX,LY,LW,LX,LY,LW,LX,LY,LX,LY,LX,LY,LX,LY,
80 FORMAT(6I3,2F10.2)
394 CONTINUE
385 CONTINUE
386 CONTINUE
90 IF(IOTPT.EQ.0)GO TO 389
91 READ(5,95)IFO5,IFO6,IFO7,IFO8,IFO9,IFO10,IFO11
95 FORMAT(4I3)
96 IOUT=5
97 NIT=1
98 NITN=2
99 IOUT1=0
100 IOUT2=0
101 IOUT3=0
IOUT4=0

CONTINUE

READ(5,90) TTARGT, DT, DTMX, DPMX, DSMX

FORMAT(5F9.2)

IF(DPMX.LE.0.) DPMX=100.

IF(DTMX.LE.0.) DTMX=91.25

IF(DSMX.LE.0.) DSMX=0.025

RETURN

END
SUBROUTINE COEF
COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)
COMMON H(100),PV(100),TX(100),TY(100),TZ(100),SW(100),PCW(100)
COMMON DG(100),KRG(100),KRRG(100),Bw(100),BGW(100),P(100),XW(100)
3 TXG(100),TYG(100),TZG(100),SWH(100),RHW(100),RFG(100)
COMMON CXP(100),CXM(100),CYP(100),CYM(100),CZP(100),CZM(100)
3 R(100),BGU(100),DP(100),C(100),QWP(100),CQWP(100),CQWS(100)
COMMON WKRW(100),Q(100),RHP(100),PWM(100),CWP(100),CWP(10),CQR(100)
3 CG(100),INDW(10),INW(10),JW(10),KCU(10),KCL(10),QW(100),QRG(50)
3 QWS(50),QWP(50),QG(50),BAC(10,5),WM(5),GM(5),TM(5)
COMMON SWT(2,15),KRWT(2,15),KRG(2,15),PCW(2,15),SWH(2,15),SGC(2,15)
3 PT(25),RGT(25),VGT(25)
COMMON ALPHA(15)
COMMON HGWI,PCG1,PI,HI,BWI,DWS,VW,DGS,CW,CR,GIPI,WIP,DTT,DTIME
2 SUMW,SUMG,OMEGA,WIP,GIP,DPT
COMMON DPMX,DSMX,DTMX,DPMAX,DSMAX,TTARGT,SRES
COMMON NPT,NGWT,NT,ST,L,I,J,K,NXY,LMAX,NW,NIT,NCYC,ITN,ICYC,ITRN
3 ISOLVE,N1,N2,N3,N4,N5,N6,N7,NXP1,NXP2,NZP1,IVFLO
COMMON PIN,UBG,UBGU,UGD,UVG,BWVW,CWW,VWW
DIMENSION PCG(1),QON(1)
EQUIVALENCE (PCG(1),PCW(1)),(CQWP(1),QON(1))
COMMON IOUT1,IOUT2,IOUT3,IOUT4,IDS,IODIV,OPS,ITAP,IEND,IMX,JMX,
2 KMX,IS,JX,KS,ITIME,IODPT,ICUTM,IBUG
REAL KRG,WRW,KRG
IF(DT,GT,0.)GO TO 455
DTH=N*.5*(1.+ABS(DT)/DSMAX)*DTT
IF(DT,GT,DTMX)DTT=DTMX
GO TO 456
455 DT=TDT
456 TIME=TIME+DTT
457 IF(ABS(TIME-TTARGT),GE,U1)GO TO 457
458 TIME=TTARGT
IF(TIME=LE,TTARGT)GO TO 458
DTH=DTT*TIME+TTARGT
TIME=TTARGT
CONTINU
458 CONTINUE
459 ITIME=ITIME+1
460 DO 300 L=1,NB
461 RXW(L)=0.
462 RXG(L)=0.
463 TXW(L)=0.
0040  TXG(L)=0.
0041  TYW(L)=0.
0042  TYG(L)=0.
0043  TZW(L)=0.
0044  TZG(L)=0.
0045  CONTINUE
0046  DO 340 K=1,NZ
0047    LK=KL(K)
0048  DO 340 J=1,NY
0049    JK=LJ+JL(J)
0050  DO 340 I=1,NX
0051    L=I+JK
0052    IF(PV(L)*LE.0.)GO TO 340
0053        LM1=L
0054    LM1=L
0055    DH=H(L)*H(LM1)
0056    DELP=P(L)-P(LM1)
0057    U1=KRW(L)*KRM(LM1)
0058    IF(U1*LE.0.)GO TO 311
0059    U4=1.+CW**0.5*(P(L)+P(LM1))
0060    U0=TX(L)*BW1*(U4+CW**PI)
0061  U3=DELP
0062  U3=DELP
0063  U2=DSW*U4*DH
0064  IF(U3*LE.U2)GO TO 305
0065  TXW(L)=U0*KRW(L)
0066  GO TO 310
0067  305 TXW(L)=U0*KRW(LM1)
0068  CONTINUE
0069  310 CONTINUE
0070  311 CONTINUE
0071    U1=KRG(L)*KRG(LM1)
0072    IF(U1*LE.0.)GO TO 340
0073    U0=TX(L)*0.5*(BG(L)+BG(LM1))
0074    U3=DELP
0075  0.5*(BG(L)+BG(LM1))*DH
0076    IF(U3*LE.U2)GO TO 325
0077    TXG(L)=U0*KRG(L)
0078  GO TO 339
0079  325 TXG(L)=U0*KRG(LM1)
0080  CONTINUE
0081  339 CONTINUE
0082  340 CONTINUE
0083    IF(NY*EQ.1.)GO TO 370
0084    DO 365 K=1,NZ
0085      LK=KL(K)
0086  DO 365 J=1,NY
0087      JK=LJ+JL(J)
0088  DO 365 I=1,NX
0089      IL=I+LK
DO 365 J=2, NY
L=JL(J)+IL
IF(PV(L)*LE.0.0*)GO TO 365
JM1=L*NX
DH=H(L)-H(JM1)
UP=P(L)
DELP=P(L)-P(JM1)
U1=KRW(L)+KRW(JM1)
IF(U1*LE.0.*)GO TO 336
U4=1.0*CW*(UP+P(JM1))*0.5
U0=TY(L)*BWI*(U4=CW*PI)
U3=DELP
U2=DWS*U4*DH
IF(U3*LE.U2)GO TO 334
TYW(L)=U0*KRW(L)
GO TO 335

TYW(L)=U0*KRW(JM1)
CONTINUE

U1=KRG(L)+KRG(JM1)
IF(U1*LE.0.*)GO TO 365
U0=TY(L)*0.5*(BG(L)+BG(JM1))
U3=DELP
U2=0.5*DH*(DG(L)+DG(JM1))
IF(U3*LE.U2)GO TO 395
TYG(L)=U0*KRG(L)
GO TO 364

TYG(L)=U0*KRG(JM1)
CONTINUE

RIGHT HAND SIDE
LP1=1
KM1=1
DO 414 K=1,NZ
JM1=1
DO 412 J=1,NY
LM1=1
DO 410 I=1,NX
L=LP1
LP1=L+1
IF(I*EQ.NX)LP1=1
JP1=L+NX
0139       IF(J.EQ.NY)JP1=1
0141       IF(J.GT.1)JM1=L-NX
0143       IF(K.GT.1)KM1=L-NXY
0145       KP1=L+NX
0146       IF(K.EQ.NZ)KP1=1
0147       U1=(P(LP1)-P(L))
0149       U2=P(L)-P(LM1)
0150       U3=H(LP1)-H(L)
0151       U4=H(L)-H(LM1)
0152       U5=1.*CW0.5*(P(LP1)+P(L))*DWS
0153       U6=1.*CW0.5*(P(L)+P(LM1))*DWS
0154       RHW(L)=TXW(LP1)*(U1-U3+U5)=TXW(L)*(U2=U4+U6)
0155       U5=0.5*(DG(LP1)+DG(L))
0156       U6=0.5*(DG(L)+DG(LM1))
0157       RHG(L)=TXG(LP1)*(U1-U3+U5)=TXG(L)*(U2=U4+U6)
0158       U1=P(JP1)-P(L)
0159       U2=P(L)-P(JM1)
0160       U3=H(JP1)-H(L)
0161       U4=H(L)-H(JM1)
0162       U5=1.*CW0.5*(P(JP1)+P(L))*DWS
0163       U6=1.*CW0.5*(P(JM1)+P(L))*DWS
0164       RHW(L)=RHW(L)+TYW(JP1)*(U1-U3+U5)=TYW(L)*(U2=U4+U6)
0165       U5=0.5*(DG(JP1)+DG(L))
0166       U6=0.5*(DG(L)+DG(JM1))
0167       RHG(L)=RHG(L)+TYG(JP1)*(U1-U3+U5)=TYG(L)*(U2=U4+U6)
0168       U1=P(KP1)-P(L)
0169       U2=P(L)-P(KM1)
0170       U3=H(KP1)-H(L)
0171       U4=H(L)-H(KM1)
0172       U5=1.*CW0.5*(P(KP1)+P(L))*DWS
0173       U6=1.*CW0.5*(P(L)+P(KM1))*DWS
0174       RHW(L)=RHW(L)+TZW(KP1)*(U1-U3+U5)=TZW(L)*(U2=U4+U6)
0175       U5=0.5*(DG(KP1)+DG(L))
0176       U6=0.5*(DG(KM1)+DG(L))
0177       RHG(L)=RHG(L)+TZG(KP1)*(U1-U3+U5)=TZG(L)*(U2=U4+U6)
0178       IF(I.EQ.NX)LP1=L+1
0180       410 LMI=L
0181       412 CONTINUE
0182       414 CONTINUE
0183       IF(IBUG.EQ.0)GO TO 406
0185       406 CONTINUE
0186       RETURN
0187       END
SUBROUTINE PRODN
COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)
COMMON H(100),PV(100),TX(100),TY(100),TZ(100),SW(100),PCW(100).
2 DG(100),KRW(100),KRG(100),BW(100),BG(100),P(100),TXW(100).
3 TXG(100),TYG(100),TZG(100),RTW(100),RHW(100),RHWG(100).
COMMON CXP(100),CXM(100),CYP(100),CYM(100),CZP(100),CZM(100).
2 R(100),BG(100),DP(100),C(100),QWP(100),CGP(100),CQWS(100).
COMMON WKR(10),Q1(10),BHP(10),PWF(10),CW(10),CGP(10).
2 CG(10),INDW(10),JW(10),KCU(10),KCL(10),QW(50),QG(50).
3 QWS(50),QWP(50),QGP(50),WBC(10),WM(5),GM(5),TM(5).
COMMON SWT(2,15),KRW(2,15),KRG(2,15),PCW(2,15),SWIR(2,15),SGC(2).
2 PT(25),BGT(25),VGT(25).
COMMON ALPHA(15).
COMMON HGW,PPI,PIS,HI,BWI,DWS,VW,DGS,CW,CR,GIP,WIP,DIT,DT,TIME.
COMMON DPMX,DSMX,DTMX,DPMAX,DSMAX,TTARGS,SRES
COMMON NPT,NWT,NB,NDT,US,J,K,NXY,LMAX,NW,NIT,NIC,XC,YC,YRN.
2 ISOLVE,N1,N2,N3,N4,N5,N6,N7,NXP1,NXP2,NXP3,NVLO.
COMMON PIN,UBG,UBGP,UIDG,UGW,BWI,CW,WVW,VW
DIMENSION PCG(1),QON(1)
EQUVALENCE (PCG(1)=PCW(1)),(QGP(1)=QON(1))
COMMON IOUT1,IOUT2,IOUT3,IOUT4,IOS,IXW,IXS,ITAP,IXN,IXM,IXJ,
2 KMX,IS,JS,ITIME,ITPT,ICUTMx,IBUG
REAL KRG, KRW, KRG
DO 500 M=1,NW
I=IW(M)
J=JW(M)
I=I+JL(J)
K1=KCU(M)
K2=KCL(M)
K11=K1
L2=LMAX+1
L1=IJ+KL(K1)
DO 510 K=I1,LMAX
LL=L2+K
QW(LL)=0
QG(LL)=0
QWP(LL)=0
QWS(LL)=0
510 CONTINUE
DO 310 M=1,NW
INT=INDW(M)
RATE=Q(M)
IF (RATE .EQ. 0.) GO TO 500
PW = 0.
UW = 0.
UG = 0.
ML1 = H(L1)

MOBILITIES
SUM1 = 0.
SUM2 = 0.
SUM3 = 0.
DO 520 K = K1, K2
LR = K * K1
L = I + KL(K)
IF (PV(L) .LE. 0.) GO TO 520
LP1 = L + 1
IF (I .EQ. NX) LP1 = 1
U2 = TX(L) + TX(LP1)
WM(LR) = U2 * KRW(L) * BW(L)
GM(LR) = U2 * KRG(L) * BG(L)
TM(LR) = WM(LR) + GM(LR)
SUM1 = SUM1 + WM(LR)
SUM3 = SUM3 + GM(LR)
CONTINUE
520
SUMT = SUM1 + SUM3
GO TO (540, 560), IW
540
CONTINUE
560
IF (RATE .LT. 0.) GO TO 585
U1 = RATE / SUMT
DO 571 K = K1, K2
LR = K * K1
L = I + KL(K)
LL = L + LR
GG(LL) = TM(LR) * U1
CONTINUE
571
GO TO 500
585
CONTINUE
500
PW(M) = PW
END
SUBROUTINE ITER

COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)
COMMON H(100),PV(100),TX(100),TY(100),TZ(100),SW(100),PCW(100),
   2 DG(100),KRW(100),KRG(100),BW(100),BG(100),PL(100),WX(100),
   3 TG(100),TYG(100),TZG(100),RHW(100),RHG(100),
   3 IST(100)
COMMON CXP(100),CXM(100),CYP(100),CYM(100),CZP(100),CZM(100),
   2 R(100),BG(100),DP(100),C(100),CW(100),CGP(100),CQWS(100),
COMMON WKW(10),Q(10),BHP(10),PWF(10),CWP(10),CGI(10),
   2 CGI(10),INDW(10),W(10),JW(10),KCU(10),KCL(10),QW(50),QM(50),
   3 QWS(50),QWP(50),QGP(50),BC(10),WM(5),GM(5),TM(5)
COMMON SWT(2,15),KRT(2,15),KRTG(2,15),PCW(2,15),SWIR(2),SGC(2),
   2 PT(25),BGT(25),VGT(25)
COMMON ALPHA(15)
COMMON HGWI,PCGI,PI,HI,AWI,DWS,VW,DGS,CW,CR,GIPI,WIPI,DTT,DT,TIME,
   2 SUMW,SUMG,OMEGA,WP,GP,DPT
COMMON DPMX,DSMX,DTMX,DPMAX,DSMAX,TTARGT,SRES
COMMON NPT,NGWT,NB,NST,L,J,K,NXY,LMAX,NW,NYT,NCYC,ITN,ICYC,ITRN,
   2 ISOLVE,N1,N2,N3,N4,N5,N6,N7,NXP1,NYP1,NZP1,IVFLO
COMMON PIN,UGB,UBGP,UDG,UGV,BWI,CWV,WW
COMMON PCG(1),QON(1)
COMMON IOUTL,IOUT3,IOUT4,IOFS,IOEL,IOPS,ITAP,IEND,IMX,JMX,
COMMON KMX,IS,KS,TIME,ITPT,ICUTMX,IBUG
REAL KRGT,KRW,KG
SUMQ=0.
NWQT=NGWT
ITRNX=NIT*NCYC
RWP=BWI*CW
ICUT=0
DO 600 L1=1,NB
IF(PV(LL),LE,0.)GO TO 600
BGP(L)=0.
DO 26 L=0.
R(L)=0.
IF(SW(L),GE,1.)GO TO 600
P(L)=0.
CALL PVU
BGP(L)=UBGP
CONTINUE
DO 626 L1=1,NB
CQWP(L)=0.
CQGP(L)=0.
CQWS(L)=0.
0038  626 CONTINUE
0039  6637 IF(IBUG*EQ.0) GO TO 6637
0040  CONTINUE
0041  DO 605 LL=1, NW
0042      IF(Q(LLL)*EQ.0.) GO TO 605
0043      I=IWL(LLL)
0044      J=JWL(LLL)
0045      IJ=I+JL(J)
0046      K1=KCU(LLL)
0047      K2=KCL(LLL)
0048      KK=MAX*(LL-1)+1-K1
0049      DO 615 K=K1,K2
0050         L=IJ+KL(K)
0051         M=K+KK
0052      IF(PV(L).LE.0.) GO TO 615
0053      CQWS(L)=CQWS(L)+QWS(M)
0054      RHG(L)=RHG(L)+QG(M)
0055      RHW(L)=RHW(L)+QW(M)
0056      CQP(L)=CQP(L)+QPM(M)
0057      CQGP(L)=CQGP(L)+QGM(M)
0058      SUMQ=SUMQ+ABS(QW(M))+ABS(QG(M))
0059  615 CONTINUE
0060  605 CONTINUE
0061  606 CONTINUE
0062      DPMAX=0.
0063      DSMAX=0.
0064      ITRN=0
0065      ICYC=1
0066      IRSID=1
0067  595 CONTINUE
0068      SRES=0.
0069      LKM=0
0070      LJM=0
0071      LJP=0
0072      LJM=0
0073      DO 702 K=1,NZ
0074         LK=KL(K)
0075         LKP=LK+NX
0076      IF(K*EQ.NZ)LKP=0
0077      IF(J*EQ.NY)LJP=0
0078      DO 701 J=1,NY
0079         LJ=JL(J)
0080         LJP=LJ+NX
0081      IF(J*EQ.NY)LJP=0
0082      LMI=1
0083      IJ=I+LJ
0084      JMK=LJM+LK
2U4+TZG(L)*U6
0132  IF(IRESID.EQ.0) GO TO 650
0134 625 CONTINUE
0135  USG=1.*USW
0136  IF(USG.LT.0.) USG=0.
0138  U13=USG*(UPVDT*UBGP+U0CR*UBG)-CQGP(L)
0139  A1=U11/U12
0140  C(L)=A1*U13+U10
0141  RESID=A1*RDG+RDW+C(L)*UDP
0142  CXP(L)=A1*TXG(LP1)+TXW(LP1)
0143  CXM(L)=A1*TXG(L)+TXW(L)
0144  CYP(L)=A1*TYG(JP1)+TYW(JP1)
0145  CYM(L)=A1*TYG(L)+TYW(L)
0146  CZP(L)=A1*TZG(KP1)+TZW(KP1)
0147  CZM(L)=A1*TZG(L)+TZW(L)
0148  C(L)=CXP(L)+CXM(L)+CYP(L)+CYM(L)+CZP(L)+CZM(L)+C(L)
0149  P(L)=A1*RHG(L)+RHW(L)
0150 640 SRES=SRES+ABS(RESID)
0151  GO TO 700
0152 650 CONTINUE

C CONVERGENCE TO SOLUTION
0153  USWK=USW*(RDW-U10*UDP)/U11
0154  IF(USWK.LT.0.) USWK=0.
0155  IF(USWK.GT.1.) USWK=1.
0156 705 CONTINUE

C COMPUTATION OF DP MAX AND DSMAX
0157  CXM(L)=USWK*USW
0158  CZM(L)=UBGK

0161  ADS=ABS(DSMAX)
0162  IF(ABS(CXM(L)).LT.ADS) GO TO 728
0164  IS=I
0165  JS=J
0166  KS=K
0167  DSMAX=CXM(L)
0168  ADS=ABS(DSMAX)
0169 728 CONTINUE

0170  ADP=ABS(DP MAX)
0171  IF(ABS(DP(L)).LT.AD P) GO TO 700
0173  DPMAX=DP(L)
0174  IMX=I
0175  JMX=J
0176  KMX=K
0177 700 LMI=L
0178 701 LJM=LJ
702  LKM=LK
  C  RESET ITERATION AND CHECK FOR CONVERGENCE
  0180  IF( IRESID.EQ.0 ) GO TO 720
  0182  IF( SUMQ.GT.0.01 ) SRES=SRES/SUMQ
  0184  IF( (ITRN.GE.ITRMX).OR.(SRES.LT.0.02) ) IRESID=0
  0186  IF( IRESID.EQ.0 ) GO TO 595
  0188  ITRN=ITRN+1
  0189  CALL SOLVE
  0190  GO TO 595
  0191  720  CONTINUE
  0192  DO 741  L=1,NY
  0193  IF( PV(L).LE.0.0 ) GO TO 741
  0195  BG(L)=CZM(L)
  0196  SW(L)=SW(L)+CXM(L)
  0197  PL(I)=PL(I)+DP(L)
  0198  741  CONTINUE
  C  COMPUTATION OF FLUID PROPERTIES
  0199  DO 730  L=1,NB
  0200  IF( PV(L).LE.0.0 ) GO TO 730
  0202  PIN=PL(I)
  0203  CALL PVT
  0204  DLL(L)=UDG
  0205  UVG=UVG
  0206  BW(L)=BW(L)*(1.0+CW*(PL(I)-PI))
  C  RECOMPUTATION OF RELATIVE PERMEABILITY
  0207  USW=SW(L)
  0208  CON=1.0-USW
  0209  CADS=S(CON)
  0210  USW=USW/(1.0+CADS)
  0211  KR(L)=USW/VW
  0212  KRG(L)=(1.0-USW)/UVG
  0213  730  CONTINUE
  0214  735  CONTINUE
  0215  RETURN
  0216  END
SUBROUTINE SOLVE
COMMON NX, NY, NZ, IPRT, IFMT, KL(25), JL(25)
COMMON H(100), PV(100), TX(100), TY(100), TZ(100), SW(100), PCW(100),
2 DG(100), KRW(100), KRG(100), BW(100), BG(100), P(100), TXW(100),
3 TXG(100), TYW(100), TYG(100), TZW(100), RH(100), RW(100), RHG(100),
3 IST(100)
COMMON CXP(100), CXY(100), CYM(100), CZP(100), CZM(100),
2 R(100), BGP(100), DP(100), C(100), CQWP(100), CQG(100), CQWS(100),
COMMON WKRW(10), Q(10), AWP(10), PWF(10), CW(10), CGP(10),
2 CGI(10), INDW(10), JW(10), LW(10), KCU(10), KCL(10), QW(50), QQ(50),
3 QWS(50), QWP(50), UHP(50), WBC(10, 5), WM(5), GM(5), TM(5),
COMMON SWT(2, 15), KRWT(2, 15), KRG(2, 15), PCWT(2, 15), SWIR(2), SGC(2),
2 PT(25), BGT(25), VGT(25)
COMMON ALPHA(15)
COMMON HWI, PCG, PI, HI, BWI, DWS, VW, DGS, CW, CR, GIPI, WIPI, DTT, DT, TIME,
2 SUMW, SUMG, OMEGA, WIP, GIP, DPT
COMMON DPMX, DSMX, DTMX, DPMAX, DSMAX, TTARGT, SRES
COMMON NPT, NGW, NB, NST, L(1), J, K, NXY, LMAX, NW, NIT, NCY, ITN, CYC, IRCN,
2 ISOLVE(1), N2, N3, N4, N5, N6, N7, NWP, NYP, NWP1, NYP1, NP, NFLO
COMMON PIN, UIC, UBGP, UDG, UVG, BW, CW, VW, WW
DIMENSION PCG(1), QON(1)
EQUIVALENCE (PCG(1), PCW(1)), (CQWP(1), QON(1))
COMMON IOUT1, IOUT2, IOUT3, IOUT4, IOUT5, IOW, IOWEL, IOPS, ITP, IEND, IMX, JMAX,
2 KMX, IS, JS, ITIME, ISTOP, ILOAD, ICUTMX, IBUG
REAL KRG, KRWT, KRW, KRG
CONTINUE
C SETTING OF COEFFICIENTS
DO 1 L=1, N
DO 1 J=1, N
A(L, J)=0.
1 N0=N3+N2
DO 2 K=1, N2
L=KL(K)
1 K1=K-N0
DO 2 J=1, N1
LJ=JL(J)
2 JK=JL+L
1 JK1=K1+J*NZ
DO 3 I=1, N1
L=JK1+I*NZ
2 L=L+1
1 A(L, N3)=CZH(L1)
A(L+N2) = CYM(L1)
A(L+N1) = CXM(L1)
A(L+N5) = CZP(L1)
A(L+N6) = CYP(L1)
A(L+N7) = CXP(L1)
IF(C(L1).EQ.0.)C(L1) = 0.01
A(L+N4) = C(L1)
DP(L) = R(L1)
CONTINUE
NB1 = NB + 1
LR = (N7+1)/2
LRI = LR = 1
DO 10 K = 1, LR1
LRR = LR = K
DO 20 I = 1, LRR
DO 30 J = 2, N7
30 A(K, J) = A(K, J)
NR1 = NB1 = K
MI1 = N7 + 1
A(NR1, MI1) = 0.
20 A(K, N7) = 0
CONTINUE
NBM = NB - 1
DO 40 I = 1, NBM
U2 = 1./A(I, 1)
DP(I) = DP(I) * U2
DO 80 J = 2, N7
80 A(I, J) = A(I, J) * U2
I1 = I + 1
DO 190 K = I1, LR
U1 = A(K, 1)
DP(K) = DP(K) * U1 * DP(I)
DO 100 J = 2, N7
100 A(K, J) = A(K, J) * U1 * A(I, J)
190 A(K, N7) = 0.
IF(LR * NB + NB) LR = LR + 1
CONTINUE
C BACK SUBSTITUTION
DP(NB) = DP(NB) / A(NB, 1)
JM = 2
NBM = NB + 1
DO 130 K = 1, NBM
KK = NB - K
DO 12 J=2*JM
JRR1=KK=1+J
12 DP(KK)=DP(KK)=A(KK,J)*DP(JRR1)
IF(JM.NE.N7)JM=JM+1
CONTINUE
DO 134 K=1+NZ
LK=KL(K)
K1=K=N0
DO 134 J=1,NY
JK=LK+JL(J)
JK1=K1+J*NZ
DO 134 I=1,NX
L=I+JK
L1=N3*I+JK1
R(L)=DP(L1)
CONTINUE
DO 136 L=1,NB
DP(L)=R(L)
RETURN
END
SUBROUTINE OUTPUT

COMMON NX,NY,NZ,IPRT,IFMT,KL(25),JL(25)

COMMON H(100),PV(100),TX(100),TY(100),TZ(100),SW(100),PCW(100),
2 DG(100),KR(100),KRG(100),BW(100),BG(100),PI(100),TXW(100),
3 TX(100),TYW(100),TYP(100),TZW(100),ZG(100),RHW(100),RHG(100),
3 IST(100)

COMMON CXM(100),CXP(100),CYM(100),CYP(100),CZM(100),CZP(100),
2 R(100),BGP(100),DP(100),C(100),CQW(100),CQGP(100),CQWS(100)

COMMON WKR(10),Q(10),BHP(10),PWF(10),CWP(10),CW(10),CGP(10),
2 CG(10),INDW(10),IW(10),JW(10),KCU(10),KCL(10),QW(50),QG(50),
3 QWS(50),QWP(50),QGP(50),WBC(10),WM(5),GM(5),TM(5)

COMMON SWT(2,15),KRWT(2,15),KRG(2,15),PCWT(2,15),SWIR(2),SGC(2),
2 PT(25),BT(25),VTG(25)

COMMON ALPHA(15),
2 COMMON HGI,PCGI,PI,HI,BWI,DWS,DSG,CW,CR,GIPI,WIPW,DTT,DTTIME,
2 SUMW,SUMG,OMEGA,WP,G,WDT

COMMON DPMX,DSMX,DTMX,DPMAX,DSMAX,TARGET,RES

COMMON NPT,NGWT,NB,NST,L,I,J,K,NXY,LMAX,NW,NIT,NCYC,ITN,ICYC,ITRN,
2 ISOLVE,N1,N2,N3,N4,N5,N6,N7,N8,JX1,JY1,JZ1,JX2,JY2,JZ2,JX3,JY3,
2 NXP1,NYP1,NZP1,IVFLO

COMMON PIN,UBG,UBGP,UDG,UVG,BWIW,CWW,VWW

DIMENSION PCG(1),QON(1)

EQUIVALENCE (PCG(1),PCW(1)),(CQW(1),QON(1))

COMMON IOUT1,IOUT2,IOUT3,IOUT4,IOUT5,IOWE1,IOPS,ITAP,IEND,IMX,IMX
2 KMX,IS,JS,KS,ITIME,ITOPT,ICUTMX,IBUG

REAL KRG,KRWT,KG,KG

DIMENSION SGL(100)

DIMENSION ARRAY(1),KLM(20)

U00=0.

DO 732 LL=1,NW
UW=0.
UG=0.
IF(Q(L),EQ.0.)GO TO 732

I=IW(LL)
J=JW(LL)
IJ=I+J

K1=KCU(LL)
K2=KCL(LL)
KK=LMAX*(LL-1)+1=K1

DO 734 K=K1,K2
L=IJ+K(K)
M=K+KK

QW=M=QW(M)+QWP(M)*UDP+QWS(M)*CXM(L)

QG(M)=QG(M)+QGP(M)*UDP

732 CONTINUE
0037    UW=UW+QW(M)
0038    UG=UG+QG(M)
0039    SUMW=SUMW+QW(M)*DTT
0040    SUMG=SUMG+QG(M)*DTT
0041    734 CONTINUE
0042    RHW(LL)=UW
0043    RHG(LL)=UG
0044    U00=U00-UG
0045    IF(UW.GT.0.) GO TO 733
0046    CPI(LL)=CPI(LL)+UW*DTT
0047    GO TO 735
0049    733 CPI(LL)=CPI(LL)+UW*DTT
0050    735 CONTINUE
0051    IF(UG.GT.0.) GO TO 737
0053    CGP(LL)=CGP(LL)+UG*DTT
0054    GO TO 732
0055    737 CGP(LL)=CGP(LL)+UG*DTT
0056    732 CONTINUE
0057    WB=1.*
0058    GO=1.*
0059    GBI=1.*
0060    WIP=0.*
0061    GIP=0.*
0062    DO 900 L=1,NB
0063    IF(PV(L).LE.0.) GO TO 900
0065    UI=PV(L)*(1.+CR*(P(L)-PI))
0066    IF(SW(L).LT.0.) SW(L)=0.*
0068    IF(SW(L).GT.1.) SW(L)=1.*
0070    WIP=WIP+U1*BW(L)*SW(L)
0071    USG=1.*SW(L)
0072    GIP=GIP+U1*BG(L)*USG
0073    900 CONTINUE
0074    900 CONTINUE
0075    ERR=0.*00*01
0077    IF(ABS(SUMW).GT.ERR*WPI)WB=(WPI=WB)/SUMW
0077    IF(ABS(SUMG).GT.ERR*GPI)GB=(GPI=GPI)/SUMG
0079    IF(ITIME.EQ.1.)GIP=GIP
0081    IF(U00.NE.0.) GBI=(GIP=GIP)/(U00*DTT)
0083    GIPO=GIP
0084    I=1MX
0085    J=1MX
0086    K=1MX
0087    WRITE(6,736)TIME,WB,I,J,K,DPMAX,GB,IS,JS,KS,DSMAX,GBI,BRES,ITRA
0088    736 FORMAT(///50X,6HTIME = .F10.2*2X,4HDAYS///35X,9HWAT BAL = .F10.4*5X,26HDPMAX(,3(12,1H),,4H) = .F10.2*2X,3HPSI//35X,9HST BAL = .F10.4*)
C COMPUTATION OF FIELD SUMMARY

0101 IOUT1 = 0
0102 UWI = 0.
0103 UWP = 0.
0104 UGP = 0.
0105 UGI = 0.
0106 S2 = 0.
0107 S3 = 0.
0108 S4 = 0.
0109 S5 = 0.
0110 DO 758 LL = 1, NW
0111 S2 = S2 + CWP(LL)
0112 S3 = S3 + CGP(LL)
0113 S4 = S4 + CWI(LL)
0114 S5 = S5 + CGI(LL)
0115 IF (RHW(LL) GT 0.) GO TO 761
0117 UWP = UWP + RHW(LL)
0118 GO TO 762
0119 761 UWI = UWI + RHW(LL)
0120 IF (RHG(LL) GT 0.) GO TO 763
0122 UGP = UGP + RHG(LL)
0123 GO TO 758
0124 763 UGI = UGI + RHG(LL)
0125 758 CONTINUE
0126 U1 = UGP + UWP
0127 IF (U1 NE 0.) FWF = UWP / U1
0129 SUM1 = 0.
0130 SUM2 = 0.
0131 DO 765 L = 1, NB
0132 IF (PV(L) LE 0.) GO TO 765
0134 U1 = PV(L) * (1 + CR*(PL**PI))
0135 SUM1 = SUM1 + U1
0136 SUM2 = SUM2 + U1 * PL
C COMPUTATION OF WELL SUMMARY
DO 771 LL=1,NW
I=IW(LL)
J=JW(LL)
FW=0.
U1=RHGL(LL)+RHW(LL).
IF(U1.LT.0.)FW=RHW(LL)/U1
771 CONTINUE

C PRINT PRESSURE AND SATURATION ARRAYS

757 CONTINUE:
II=IPRT
I8=1
IF(NX.LT.I8)I8=NX
K=N7
U1=NX
U1=U1/I8
I3=U1
I2=I3
I2=I2+1
IF(U1.GT.U2)I2=I2+1
IF(I1.EQ.2)GO TO 40
DO 40 I3=1,I2
I5=(I3=1)*I8+1
I6=I3*I8
IF(NX.LT.I6)I6=NX
DO 20 I4=1,I8
KLM(I4)=I4+(I3=1)*I8
0190      WRITE(6,21) (KLM(I),I=1,I8)
0191     21 FORMAT(2H J,2H I,11(6X,2H ,I3))
0192     LL=IS+KL(K)
0193     200 CONTINUE
0194     DO 22 J=1,NY
0195     L1=LL+JL(J)
0196     L2=L1+I6=I5
0197     22 WRITE(6,33)J,(P(I),I=L1,L2)
0198     33 FORMAT(1H ,12,2X,11F11.1)
0199     GO TO 24
0200    24 CONTINUE
0201  I1=IPRT
0202     I8=11
0203     IF(NX.LT.I8)I8=NX,
0204         K=NZ
0205     U1=NX
0206     U1=U1/I8
0207     U2=I3
0208     U2=I3
0209     IF(U1.GT.U2)I2=I2+1
0210     IF(I1.EQ.2)GO TO 50
0211    50 DO 64 I3=I1,I2
0212     S=(I3=1)*I8+1
0213     I6=I3*I8
0214     IF(NX.LT.I6)I6=NX
0215     DO 69 I4=1,I6
0216    60 KLM(I4)=I4+(I3=1)*I8
0217    61 FORMAT(//2H J,2H I,11(6X,2H ,I3))
0218    LL=IS+KL(K)
0219    105 DO 122 J=1,NY
0220     L1=LL+JL(J)
0221     L2=L1+I6=I5
0222     WRITE(6,63)J,(SG(I),I=L1,L2)
0223    63 FORMAT(1H ,12,2X,11F11.4)
0224    122 CONTINUE
0225    64 CONTINUE
0226    752 CONTINUE
0227    IF(IOUT4.NE.ITAP)GO TO 756
0228    756 CONTINUE
0229    RETURN
0230