A Literature Overview of Methods to Evaluate and Monitor Class I Underground Injection Sites in Mississippi

By Richard A. Rebich

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CONVERSION FACTORS AND ABBREVIATED UNITS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.01894	meter per kilometer
square feet (ft^2)	0.0929	square meter
mile (mi)	1.609	kilometer
milligram per liter (mg/L)	8.345	pound per million gallons
foot per day (ft/d)	0.3048	meter per day
millidarcy (permeability) (md)	1.06×10^{-14}	feet squared

Temperatures may be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) with the following formulas:

$$°C = (°F - 32) / 1.8$$

$$°F = 1.8 (°C) + 32$$

A LITERATURE OVERVIEW OF METHODS TO EVALUATE AND MONITOR CLASS I UNDERGROUND INJECTION SITES IN MISSISSIPPI

by Richard A. Rebich

ABSTRACT

This report is a literature overview of methods used to evaluate and monitor Class I underground injection sites. The information from this report will be useful to local regulatory agencies in making decisions concerning Class I injection sites in Mississippi. Mississippi has six Class I wells: hazardous waste is injected into two wells in Jackson County and three wells in Harrison County; and non-hazardous waste is injected into one well in Hinds County.

Methods used to evaluate the area of review of a potential Class I injection site can be divided into three common steps: collection of comprehensive site data, identification of potential hydrogeologic problems, and injection simulation using mathematical models. Data-collection techniques include geophysical logging and core testing. Information from the data is used to identify potential hydrogeologic problems within the area of review. Four common problems associated with Class I wells include chemical compatibility between the injected waste and the injection zone materials, abandoned wells, seismic activity, and subsurface migration of the injected waste out of the injection zone. Mathematical models may be used in the evaluation of a potential Class I site by simulating injection over time. Four models summarized in this report include the Basic Plume Method, the Intercomp model, the Heat and Solute Transport model, and the Saturated-Unsaturated Transport model. The application of a specific model depends on the amount of detail necessary to accurately simulate a particular injection operation. More case studies are available in which the Intercomp model has been used to simulate the fate and transport of injected waste than the other three models, probably because the Intercomp model has been available approximately 10 years longer than the others.

In addition to a comprehensive site evaluation, a monitoring program is required to prevent or detect contamination problems within the area of review for Class I injection sites. A monitoring program includes minimum requirements common to all Class I operations and may include additional monitoring based on site-specific evaluations. Minimum requirements for the monitoring program primarily address the injection well operation only. Requirements include monitoring the nature of the injected fluid, the injection pressure, the flow rate, and the annulus pressure. Additional monitoring may be required if potential contaminant movement is suspected or if contamination is considered a significant threat to potable drinking water supplies.

INTRODUCTION

Underground injection of industrial waste is a disposal process in which liquid waste is injected and stored beneath the surface of the earth. Underground injection was developed by the petroleum industry around the 1930's for disposal of liquid wastes such as brines from oil and gas production. Since then, other industries have used underground injection to dispose of wastewater that is impractical to treat for surface-water discharge. Advantages of underground injection include eliminating a wastewater to be discharged into surface waters; eliminating the need for land-consuming treatment facilities; and decreasing energy consumption by eliminating treatment facilities.

Underground injection requires a location where the geology provides an acceptable injection (receiving) zone and adequate confinement for the wastewater. Generally, the evaluation of the geology of an injection zone at a potential underground injection site addresses both physical and chemical characteristics. Required physical characteristics of the injection zone include a functional amount of void space as well as the ability to transmit fluid. Chemical compatibility in the injection zone between the waste, formation fluid, and formation material is required to ensure environmental protection. Chemical compatibility eliminates problems such as hazardous chemical reactions, as well as the ensuing physical responses associated with those chemical reactions. Evaluation of the geology of a potential underground injection site also addresses the need for confinement for the wastewater. A confining unit is defined as virtually impermeable material adjacent to one or more aquifers. For the purposes of underground injection, a confining unit prohibits waste stored in the injection zone from moving into and contaminating other ground-water resources, typically any overlying freshwater aquifers. These confining units need to be laterally extensive to completely contain the waste both locally and regionally.

This report is an overview of available literature on methods used to evaluate and monitor Class I underground injection sites, which are defined currently (1993) as sites that contain wells used to inject hazardous or non-hazardous liquid waste below a formation containing the lowermost underground source of drinking water [U.S. Environmental Protection Agency (EPA), 1990, p. 683]. This report was prepared by the U.S. Geological Survey (USGS) in cooperation with the Office of Pollution Control (OPC) of the Mississippi Department of Environmental Quality, which regulates and issues permits for underground injection operations in Mississippi. Information from this report will be useful to the OPC in making sound decisions concerning Class I injection sites in Mississippi.

History of Underground Injection Regulations

The regulation of underground injection started with oil-field brine wells. However, as injection practices expanded to include the injection of more hazardous materials, federal regulation also expanded. The first regulatory policy statements concerning injection were adopted in 1970 by the Federal Water Quality Administration (FWQA) (Walker and Cox, 1976). These statements were later revised in 1973 by the Environmental Protection Agency (EPA), which succeeded the FWQA. The Federal Water Pollution Control Act (FWPCA), passed in 1972, contained the most direct reference to injection at that time and established a waste discharge permit program, the National Pollutant Discharge Elimination System (NPDES). However, other details of the FWPCA, such as the NPDES permit process concerning injection and EPA's authority under the FWPCA regulating injection, were vague and many lawsuits resulted. For example, the U. S. District Court for the Southern District of Texas overruled EPA's authority to use the FWPCA to prohibit use of an injection well by a particular industry in 1975 (Walker and Cox, 1976). However, the Safe Drinking Water Act (SDWA) was passed a few months earlier in 1974 granting jurisdiction of injection to EPA; therefore, that particular lawsuit had no lasting effects.

The SDWA provides EPA the authority to develop regulations for forming State injection control programs. Each State is required to adhere to EPA regulations not only to adopt and implement their own program but also to properly enforce that program. Under the SDWA, EPA opposes any injection practice unless strict controls are applied (Walker and Cox, 1976). EPA's policy is characterized by the following seven general criteria, which provide federal control but also gives States the flexibility to adopt more specific criteria to meet local hydrogeologic needs (Hernandez, 1977):

- Other disposal alternatives are evaluated and determined to be less environmentally safe.
- Adequate and accurate testing is conducted to predict waste movement once injected.
- Conclusive evidence indicates that current and potential drinking-water sources are protected from the injected waste.
- Construction of the injection system is designed to provide maximum environmental protection.
- A monitoring system is provided.

- Contingency plans are provided for well shut-ins (operations cease) or well-failures.

- Provisions are made for well plugging and future monitoring of waste movement.

EPA's general Underground Injection Control (UIC) regulations, established by the SDWA in 1974, satisfy these injection policy criteria to evaluate injection control programs for each State. The principal provisions of the UIC regulations include types of waste injections controlled, permitting of existing wells, permitting of new wells, and general requirements for all wells (Hernandez, 1977). Wells constructed prior to the establishment of UIC regulations were allowed to continue operation without permit for a period of 5 years. After this period, the operator was to apply for a permit to continue operation or was to cease operation. All new wells were permitted or ceased operation, and all permitted wells met minimum requirements specified by the UIC regulations. Many articles have been written concerning adoption of UIC programs for specific States. An article by Visocky and others (1986) outlines UIC regulations in Illinois. The article covers topics of strengthening regulatory practices, well design requirements, waste character analysis, geologic requirements, and injection alternatives. Similar articles have been written with parts dedicated to regulatory practices for New Mexico (Wilson and Holland, 1984), Florida (Meyer, 1989), and Mississippi (State of Mississippi, 1989).

Well Classification

The UIC regulations classify all injection wells into five basic categories or classes with both general and specific requirements for each class well. A brief description of each class is provided as specified in the "Code of Federal Regulations" (U.S. Environmental Protection Agency, 1990, p. 683-684):

(A) Class I - (1) Wells used to dispose of waste classified as hazardous, below the lowermost formation containing an underground source of drinking water located within one-quarter mile of the well bore.

- (2) Wells used to dispose of other industrial waste not necessarily classified as hazardous, below the lowermost formation containing an underground source of drinking water located within one quarter-mile of the well bore.

(B) Class II - (1) Wells used to dispose of fluids brought to the surface during normal natural gas storage and natural gas and oil production.

- (2) Wells used to inject fluids for the enhanced recovery of oil or natural gas.

- (3) Wells used to store liquid hydrocarbons.

(C) Class III - (1) Wells used to inject fluids for mining of sulfur.

- (2) Wells used to inject fluids for the in situ production of uranium or other metals.

- (3) Wells used for solution mining of salts or potash.

(D) Class IV - Wells used for disposal of hazardous or radioactive wastes into or above an underground source of drinking water or any other aquifer located within one-quarter mile of the well bore.

(E) Class V - Wells not included in Classes I, II, III, and IV.

Mississippi currently (1992) has three Class I injection sites containing a total of six wells. Hazardous waste is injected into two wells located in Jackson County and three wells in Harrison County; both counties are located in southeastern Mississippi (fig. 1) bordering the Gulf of Mexico. Non-hazardous waste is injected into one well in Hinds County in central Mississippi (fig. 1). Mississippi currently has no Class III or IV wells and hundreds of Class II and V wells. The focus of this report primarily is on Class I wells; however, the material presented in this report concerning Class I wells can be applied with some variation to wells in other classes.

Class I Injection Wells

Class I injection wells are defined as wells used to inject hazardous or non-hazardous liquid waste below a formation containing the lowermost underground source of drinking water (USDW) located within one-quarter mile of the well bore (U.S. Environmental Protection Agency, 1990, p. 683). A typical geologic setting that can be used for a Class I injection operation is shown in figure 2. Wilson and Holland (1984) developed a system to classify aquifers as potential injection zones for the purpose of compliance to UIC regulations for New Mexico. A flow chart (fig. 3) is used to classify an aquifer into one of the following categories.

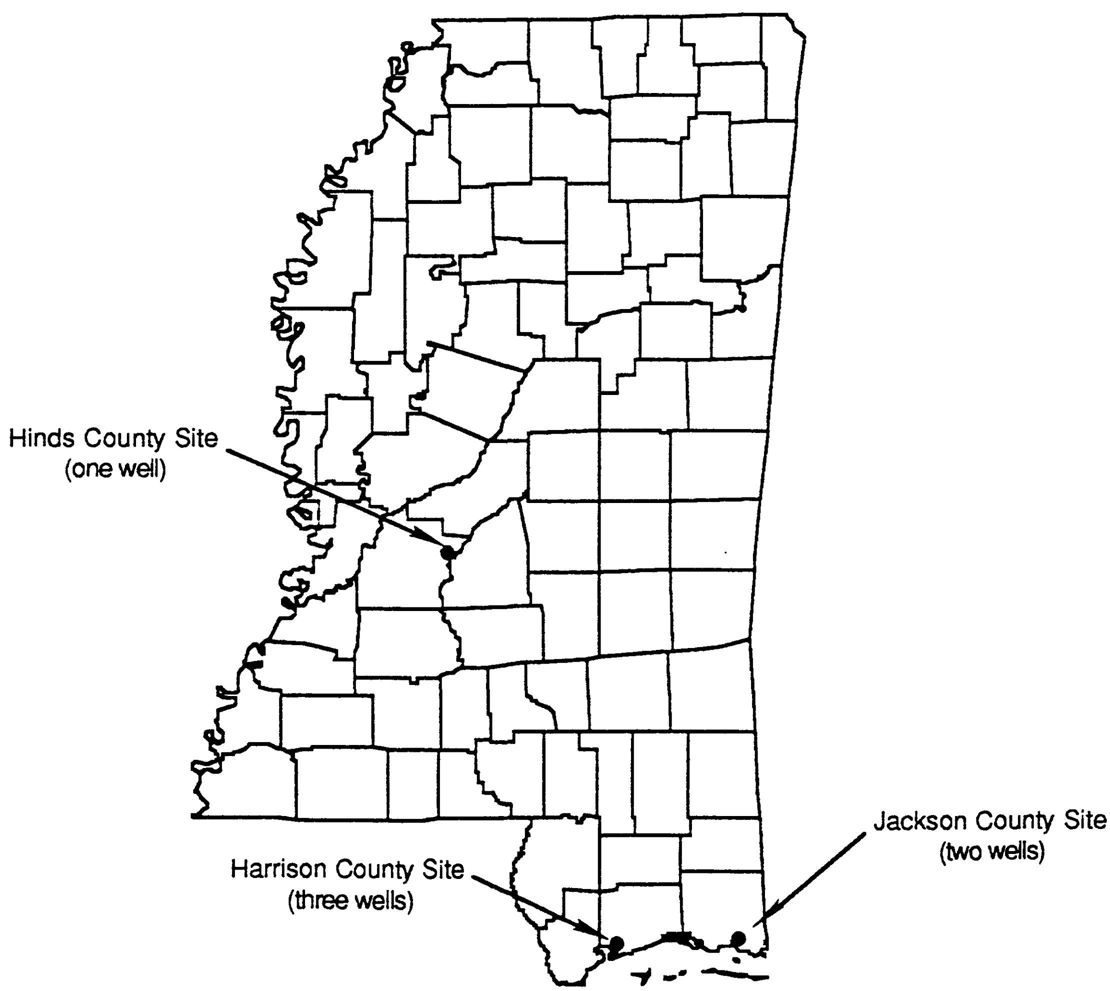

Figure 1.-- Class I injection well locations in Mississippi.

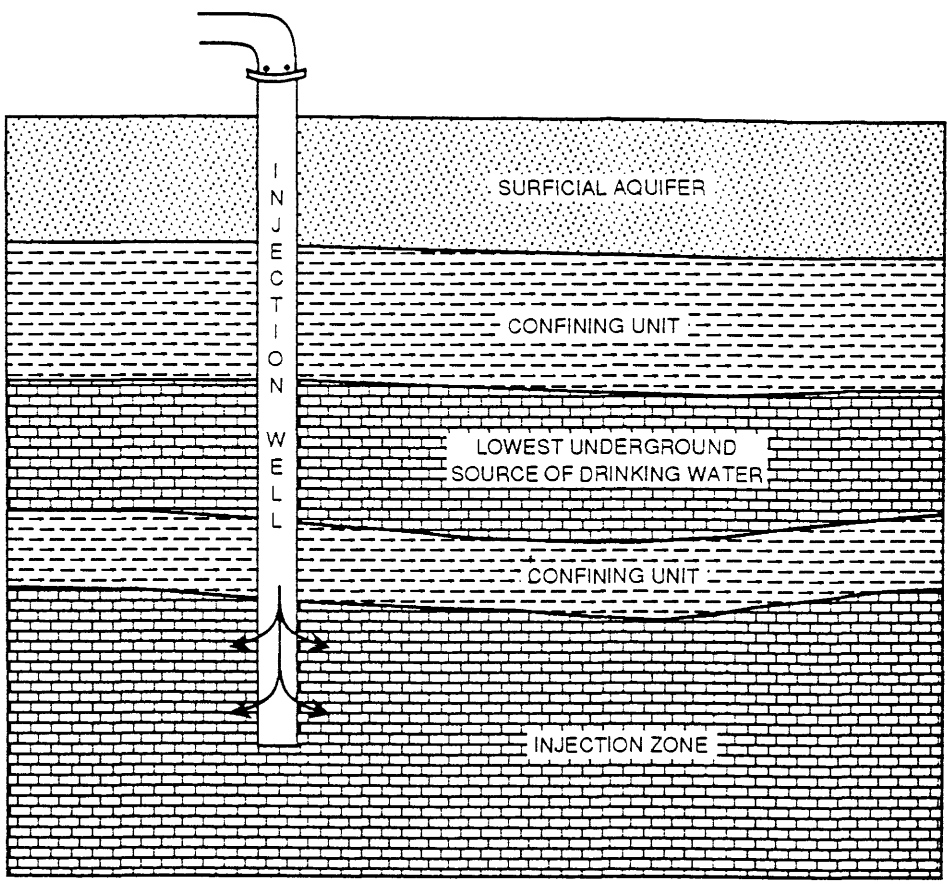

Figure 2.--Typical geologic setting that can be used for a Class I injection operation (modified from Hickey and Vecchioli, 1986, p. 8).

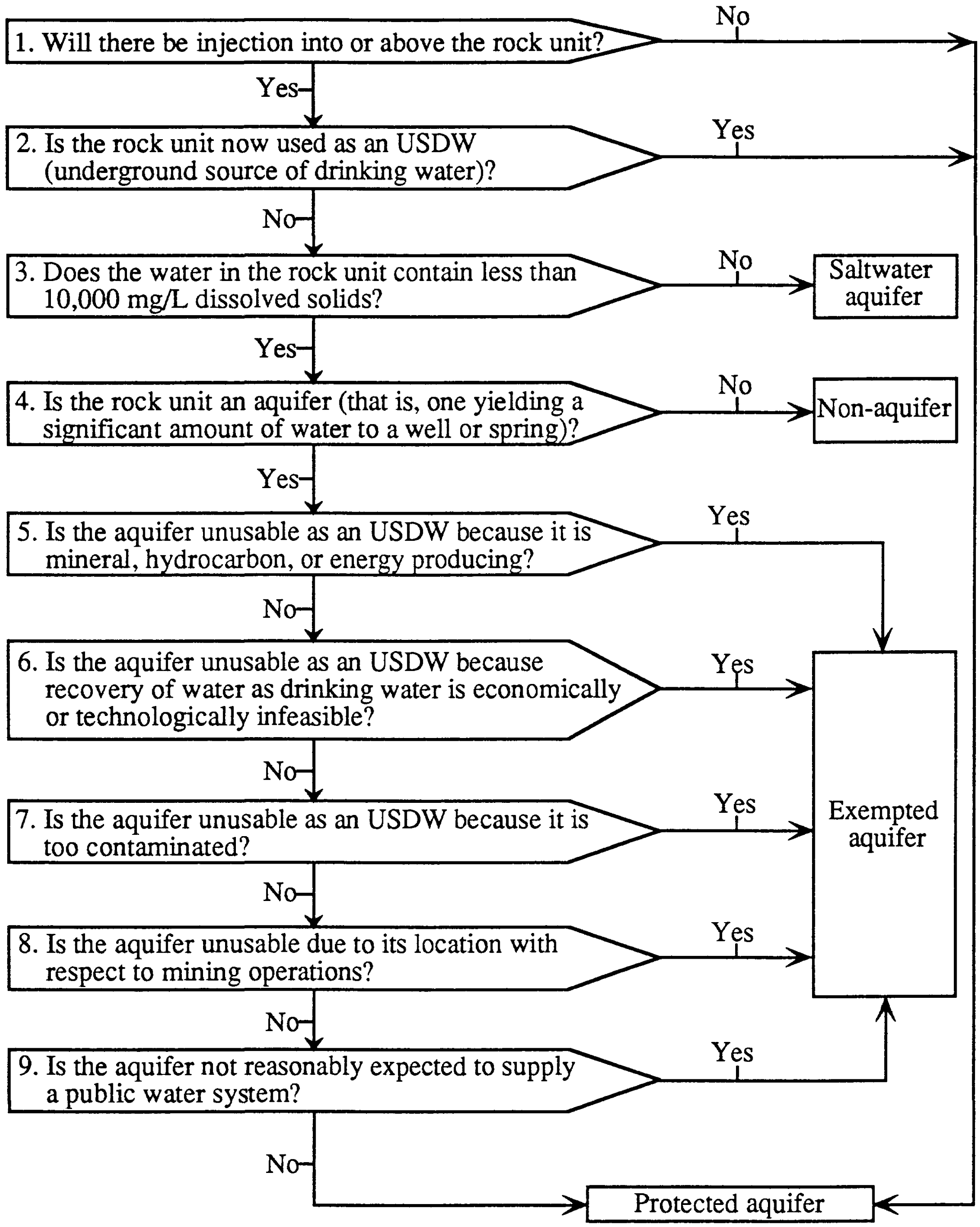

Figure 3. -- Process developed for New Mexico to classify aquifers for the purpose of compliance with underground injection control regulations [modified from Wilson and Holland, 1984, p.707].

- Protected aquifer - Applies to any geologic unit that is a present or potential source of drinking water.

- Saltwater aquifer - Rock units that contain water having a dissolved-solids concentration in excess of 10,000 mg/L. Aquifers which contain water having a dissolved-solids concentration less than 10,000 mg/L are currently protected under UIC regulations.

- Non-aquifer - Rock units that cannot yield usable amounts of water to a well or spring.

- Exempted aquifer - Rock units that are potential sources of drinking water but are excluded as protected aquifers for economic or technological reasons.

Saltwater aquifers, non-aquifers, and exempted aquifers are not required to be protected and can be considered potential injection zones. Therefore, for all Class I wells, "the base of the confining layer immediately below the deepest protected aquifer represents the shallowest interval at which injection of a non-potable water would be allowed" (Wilson and Holland, 1984, p. 710).

The area of review of a Class I well is defined as that area surrounding an injection well at a specified distance, which is established by calculating a "zone of endangering influence" or established by a fixed radius (U.S. Environmental Protection Agency, 1990, p. 748). Fundamental requirements for the area of review are directed toward three geologic features: the injection zone, the confining unit, and the formation fluid. The injection zone is required to have adequate porosity and permeability and is required to have sufficient areal extent. If the injection zone has adequate porosity and permeability, then it will accommodate all of the waste either by available void space or by displacing formation fluid. Typical geologic strata having adequate porosity and permeability for injection include sandstone, some limestone, and some dolomite strata. If the injection zone has sufficient areal extent, then it will not "pinchout" or outcrop and is free of natural faults or folds, which can provide a conduit for waste to either reach the surface or other geologic layers.

Confining units are also required to have large areal extent. Payne (1970) describes the confining units in a particular hydrogeologic setting as "semi-infinite." Semi-infinite means that "the horizontal extent of the confining layer is very large with respect to vertical thickness and injection volume * * * " (Payne, 1970, p. 14). Confining units need not necessarily be semi-infinite but have enough areal extent to contain the injection volume through time from both upward and downward migration, thus limiting the use of lenticular or discontinuous confining units. Confining units with large areal extent will provide adequate separation from "usable-quality groundwater" (Klempt, 1985, p. 404). McKenzie (1976) describes a hot, acidic wastewater that was injected below a confining unit having a 100-ft thickness. This unit did not confine the industrial waste adequately, and the waste migrated into overlying freshwater zones. McKenzie states that migration occurred both as a result of inadequate confinement and due to the nature of the injected waste.

The third fundamental requirement for the area of review concerns the formation fluid. The formation fluid in the injection zone is required to have a dissolved-solids concentration greater than 10,000 mg/L to protect all current and potential drinking-water supplies (U.S. Environmental Protection Agency, 1990, p. 746). However, Hernandez (1977) proposes that an aquifer with a dissolved-solids concentration less than 10,000 mg/L could be used for injection if the aquifer is oil-producing, too contaminated for use as a drinking-water supply, or has an impractical or economically infeasible location as a drinking-water supply. The formation fluid in the injection zone is also required to have little or no apparent value. The formation fluid is thoroughly tested for mineral or petroleum resources prior to injection because such resources cannot be extracted after injection begins.

Class I Injection Well Design

An important aspect of underground injection is the proper design of the injection well. Generally, Class I wells are designed to prevent the movement of liquid waste into any geologic zones other than the injection zone, to permit the use of proper testing devices, and to permit continuous monitoring of the well construction (U.S. Environmental Protection Agency, 1990, p. 765-767). Most injection wells have similar features: a surface casing, a well casing, injection tubing, a packer, and annulus fluid (Buttram, 1986; Miller and others, 1986b; and Klempt, 1985). The surface casing is set from the surface to a distance below the base of protected ground water (USDW) (fig. 4). The surface casing usually is made of stainless steel to prevent corrosion and to protect the formation from any potential leakage. The entire length in the annular space between the formation and the surface casing is then cemented. The well casing or "long string" is cased within the surface casing and extends into the injection zone (fig. 4). This well casing usually is made of stainless steel and is completed within the injection zone using casing perforation or well screens to allow fluid to enter the injection zone. The annular space between the well casing and the surface casing is then cemented along the entire length, thereby assuring that the injection well is doubly cased in the USDW.

The injection tubing is then placed inside the well casing (fig. 4). Waste enters the injection zone through this injection tubing. The tubing typically

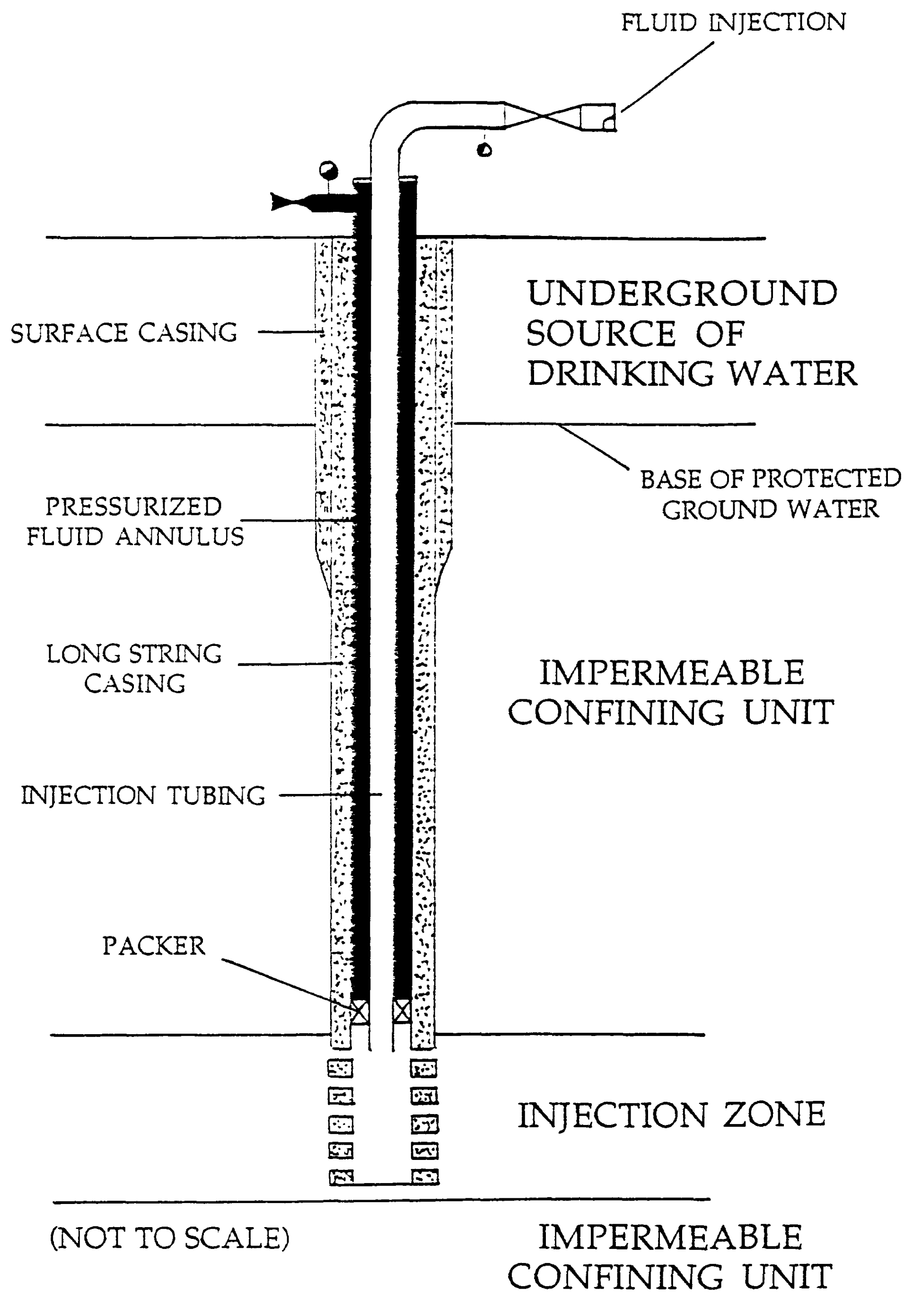

Figure 4.--Typical Class I injection well (modified from Miller and others, 1986b, p. 38).

is made of corrosion-resistant material such as carbon steel, internally plastic-coated steel, fiberglass, or stainless steel, to prevent the waste from corroding the well casing. A sealing device called a "packer" is then placed above the injection zone between the injection tubing and well casing. Above this packer, the annular space between the injection tubing and well casing is filled with fluid, typically a non-corrosive, non-toxic liquid such as an oil or a corrosion-inhibiting brine (fig. 4). This "annular fluid" is maintained at a higher pressure than the injected waste to monitor tubing integrity. If a failure occurs, the annular fluid will leak into the injection tubing rather than injected waste leak out.

Mechanical integrity testing of an injection well is required for new injection wells and for all injection wells every 5 years. Mechanical integrity for injection wells is demonstrated when no significant leaks in the surface casing, well casing, injection tubing, or packer can be detected and when no significant fluid movement can be detected in a USDW through vertical channels adjacent to the injection well-bore (Thornhill and Benefield, 1987).

In 1981, the U.S Environmental Protection Agency conducted a study to develop methods for detecting leaks or fluid movement in the cement casing surrounding the injection well-bore (Thornhill and Benefield, 1987). This study initially was conducted on Class II wells; however, the results can be applied to other class injection wells. The study compared well-logging techniques used to evaluate the cement bond between cement and well casing and between cement and formation, and to evaluate the integrity of the casings, tubing, and packer materials. The techniques that were compared included various combinations of "down-hole" ultrasonic transmission and reception devices, as well as variations of spacing between these devices. Each technique was used to detect controlled fluid movement through pre-installed polyvinyl chloride (PVC) "channels" in the cement casings of a test injection well. Results of the comparison indicated that a single combination of the devices and spacing between the devices was inadequate to detect all of the fluid movement in the pre-installed channels. Rather, the results of the study indicated that several combinations of the devices and spacings between the devices was necessary to detect most of the fluid movement, thus providing a more complete evaluation of the integrity of the cement bonds and well materials.

LITERATURE OVERVIEW OF METHODS TO EVALUATE CLASS I INJECTION SITES

Findings of the literature overview indicate that methods used to evaluate the area of review of a potential Class I injection site can be divided into three common steps: collection of comprehensive site data, identification of potential hydrogeologic problems, and injection simulation using mathematical models. These three common steps of evaluation are explained in the following paragraphs.

Collection of Comprehensive Site Data

The first common step to evaluate a potential Class I injection site is to collect data that adequately and accurately describe the area of review. "Appropriate logs and tests shall be run to determine or verify the depth, thickness, porosity, permeability, and rock type of * * * all relevant geologic units to ensure conformance * * * and to establish accurate baseline data against which future measurements may be compared" (U.S. Environmental Protection Agency, 1990, p. 767). Data-collection techniques include geophysical logging and core testing. Geophysical logs are used to evaluate geologic strata, waste movement, and the structural integrity of the injection well. For example, resistivity logs can be used to identify geologic layering such as freshwater aquifers, saltwater aquifers, and confining units (Keys and Brown, 1973). Caliper and gamma-ray logs can be used to identify highly permeable aquifers and to construct cross sections of complex geologic systems. Well logs can be used to describe the structure and thickness of the injection zone and to define the distribution of waste in the injection zone. Horizontal movement of the wastewater can be traced using temperature and fluid-resistivity logs, and vertical movement can be traced using flowmeter logs. Resistivity, spontaneous potential, and caliper logs are required before well casings are set. Cement bond, variable density, and temperature logs are required after the casings are set and cemented to prevent well leaks.

In addition to geophysical logging, core tests and well tests are used to identify more specific parameters of the area of review. Characteristics such as fluid temperature, pH, conductivity, pressure, and static fluid level of the injection zone are measured and recorded from core tests from the injection well. Core tests from nearby wells may be used if they are representative of the injection site. Drill-stem tests are used to record fracture pressure and other physical and chemical characteristics prior to well completion for the injection zone and confining units. After well completion, pumping tests or injection tests are required prior to operation to verify hydrogeologic characteristics in the injection zone (U.S. Environmental Protection Agency, 1990, p. 767). Brief examples of site information necessary to describe the areas of review of the two hazardous waste injection facilities in Jackson and Harrison Counties in southeastern Mississippi are presented in the following paragraphs.

Jackson County - A liquid hazardous waste is injected into two wells at a site in southern Jackson County. The first well is completed approximately 3,950 ft below the surface in the Wilcox Group, upper part of the Meridian-upper Wilcox aquifer (table 1). The injection zone is composed of sandstone containing saltwater with a dissolved-solids concentration greater than

Table 1. – Geologic units and principal aquifers in Mississippi
[modified from Slack and Darden, 1991, p. 21]

Erathem	System	Series	Group	Geologic unit	Principal aquifer or aquifer system
				Quaternary alluvium	
	Quaternary	Holocene and Pleistocene		Mississippi River valley alluvium	Mississippi River alluvial aquifer
		Pleistocene		Loess	
				Terrace deposits	
		Pliocene		Citronelle Formation	Citronelle aquifer
				Graham Ferry Formation	
				Pascagoula Formation	
				Hattiesburg Formation	
		Miocene		Catahoula Sandstone, upper part	Miocene aquifer sysetm
				Catahoula Sandstone, lower part	
				Deposits of Miocene age	
				Bacutunna Formation	
				Waynesboro sand lentil	
				Byram Formation	
				Glendon Limestone	
		Oligocene	Vicksburg Group	Marianna Formation	Oligocene aquifer system
				Mint Spring Formation	
	Tertiary			Forest Hill Formation	
				Yazoo Clay	
			Jackson Group	Moodys Branch Formation	
				Cockfield Formation	Cockfield aquifer
Cenozoic				Cook Mountain Formation	
				Sparta Sand	Sparta aquifer
				Zilpha Clay	
		Eocene		Winona Sand	
			Claiborne Group	Tallahatta Formation	Winona-Tallahatta aquifer
				Neshoba Sand Member	
				Basic City Shale Member	
				Meridian Sand Member	
				Meridian Sand Member	Meridian-upper Wilcox aquifer
				and Wilcox Group, upper part	
				Wilcox Group, upper part	
				Hatchetigbee Formation	
			Wilcox Group	Tuscahoma Formation	
				Wilcox Group, middle part	
				Nanafalia Formation	
		Paleocene		Fearn Springs Member	Lower Wilcox aquifer
				Wilcox Group, lower part	
				Naheola Formation	
			Midway Group	Porters Creek Clay	
				Matthews Landing Marl Member	
				Clayton Formation	
				Prairie Bluff Chalk	
				and Owl Creek Formation	
	Cretaceous			Ripley Formation	Ripley aquifer
			Selma Group	Demopolis Chalk	
Mesozoic				Coffee Sand	Coffee Sand aquifer
				Mooreville Chalk	
				Arcola Limestone Member	
		Upper Cretaceous		Eutaw Formation	
				Tombigbee Sand Member	
				Eutaw Formation, lower par	Eutaw-McShan aquifer
			Tuscaloosa Group	McShan Formationt	
				Gordo Formation	
				Coker Formation	Tuscaloosa aquifer system
				Massive Sand	
		Lower Cretaceous		Undifferentiated	
Paleozoic				Undifferentiated	Paleozoic aquifer system
				Paleozoic Erathem	

10,000 mg/L. Freshwater does not occur in the upper Wilcox formation at this location; the downdip limit of freshwater occurs approximately 100 mi north (Wasson, 1986). The injection zone is bounded above by confining units approximately 160 ft thick composed of shales of the Claiborne Group (Basic City Shale Member, table 1).

The second well is completed approximately 2,500 ft below the surface in the Hattiesburg Formation of the Miocene aquifer system (table 1). The Miocene aquifer system is composed of clay, silt, sand, sandstone, and gravel, and may have beds of limestone at depth. The injection zone in the Hattiesburg Formation of this system is composed primarily of sandstone. In contrast to older geologic units along the Gulf Coast, the sediments composing the Miocene aquifer "lack regional lithologic layering and tend to be areally discontinuous and variable in thickness" (Sumner and others, 1989, p. 3). The lack of lithologic layering indicates that adequate, regionally extensive confining units may not exist for injection purposes; however, small-scale layering due to lenticular formations of clay or shale may form confining units. Hydraulic conductivities in the Miocene aquifer average about 100 ft/d, whereas storage coefficients range from 0.0001 to 0.001. Dissolved-solids concentrations approach 10,000 mg/L, and chloride concentrations are probably greater than 1000 mg/L (Sumner and others, 1989).

<u>Harrison County</u> - Liquid hazardous waste is injected through three wells in southern Harrison County. The wells are completed in an injection zone of Early Cretaceous age consisting primarily of undiffferentiated sandy sediments approximately 9,800 to 10,000 ft below the surface. Locally, a 170 ft thick confining unit separates the overlying Tuscaloosa aquifer system from the injection zone (table 1). The injection zone also contains some small layers of clay or shale typically ranging from about 5 to 10 ft in thickness. Porosity in the sand layer averages about 24 percent. Horizontal permeability between a depth of 9,800 and 9,900 ft averages about 400 millidarcies, whereas vertical permeability averages about 180 millidarcies.

Permeability data for these wells are expressed in units of millidarcies. Permeability is a measure of the relative ease with which a porous medium can transmit a liquid (Lohman, 1979). It is a property of the medium alone and is independent of the fluid in the medium. The darcy (and smaller unit, millidarcy) is widely used in the literature of the petroleum industry because of the wide range of fluids-of-interest in that industry. Permeability is also expressed in units of length squared, and one millidarcy is approximately equal to 1.06×10^{-14} ft^2.

Hydraulic conductivity is related to permeability in that hydraulic conductivity is a measure of the ability of a material to transmit ground water. Hydraulic conductivity includes the properties of ground water in its definition (Lohman, 1979). A permeability of one millidarcy is equivalent to a hydraulic conductivity of 2.44 x 10^{-3} ft/d for an aquifer containing freshwater at 60°F.

Examples of data-collection activities necessary to properly evaluate the area of review of a Class I injection site similar to those presented here for Jackson and Harrison Counties in Mississippi are described in reports by Klempt (1985), Hickey (1989a), Hanby and others (1973), McKenzie (1976), and Pascale and Martin (1977).

Identification of Potential Hydrogeologic Problems

After site data have been collected, the second step in the evaluation of a potential Class I injection site is the identification of potential hydrogeologic problems within the area of review. Four problems common to many Class I injection sites include chemical compatibility between the injected waste and the injection zone materials, abandoned wells, seismic activity, and subsurface migration of the injected waste out of the injection zone. Results of research directed toward the resolution of these problems are presented as follows:

Chemical Compatibility - Many chemical reactions can occur between the injected waste and the injection zone materials during and after the injection process. During the injection process, chemical compatibility can prevent mechanical problems such as clogging. Research concerning clogging was conducted by Oberdorfer and Peterson (1985) who detected geochemical and biogeochemical processes near an injection well. Their literature search indicated that the major cause of clogging was filtration of suspended solids from the injected waste by the porous injection zone materials. Other causes of clogging included microbial growth at the well bore and within the aquifer, chemical precipitation within the aquifer, and entrapped air and gas bubbles in the injected waste. The literature search also indicated that most of the clogging activity occurred at the injection well - aquifer boundary. Using the information from their literature search, Oberdorfer and Peterson (1985) then injected a secondary-treated sewage effluent into a carbonate receiving formation. They found that filtration of suspended solids was not the major cause of clogging in this case; rather, the most significant clogging was caused by microbial activity, principally in the form of denitrifying bacteria. At first, this microbial activity eliminated clogging problems caused by suspended solid accumulation adjacent to the injection well by metabolizing all of the available organic matter at that location. However, the bacteria farther out in the injection zone became well established and began producing significant amounts of nitrogen gas. This gas then acted as a barrier and drastically reduced injection capacity close to the well, thus clogging the system.

After a waste has been injected into a particular geologic unit, other chemical reactions can take place which can be beneficial or non-beneficial. Research was conducted by Scrivner and others (1986) to develop a generalized model that simulates and predicts chemical scenarios for an injection operation. The approach to this model included: identifying the chemical characteristics of a particular injected waste; listing all possible chemical reactions during post-injection that would influence the waste, injection zone, or confining unit; quantifying these reactions using kinetic and thermodynamic equations; then developing a model that incorporates material transport with the most relevant chemical reactions. The most significant chemical reactions simulated by the model with respect to the injected wastes included neutralization, hydrolysis, co-precipitation, ion exchange, and microbial degradation. These reactions were combined with a simple one-dimensional flow model to determine gross effects on flow. Preliminary results using the generalized chemical model and data from two operating injection wells indicated that the injected hazardous wastes underwent many chemical reactions, even those reactions that could change hazardous wastes into non-hazardous forms over time.

In a report by Hickey and Ehrlich (1984), a study was conducted to document water quality changes over time of a municipal waste stored underground by means of injection with the intention of recovery for spray irrigation. The most significant water-quality change occurred as a result of constant mixing between the highly saline formation fluid and the injected waste. The mixing was primarily caused by buoyant forces in the injection zone moving the injected waste both upward and outward after injection. Consequently, this mixing caused an unacceptable level of saline concentration in the injection zone preventing the recovery of the injected waste for the purposes of future spray irrigation.

<u>Abandoned Wells</u> - Wells of any type that penetrate the confining unit or the injection zone can provide an "avenue of escape" for the injected waste to migrate out of the injection zone in response to pressure buildup. These wells can include those currently operating or those abandoned within the area of review. Prior to operation of a Class I injection well, the locations of currently operating or abandoned wells are documented and their construction records examined (U.S. Environmental Protection Agency, 1990, p. 764-765). However, records do not exist for many abandoned wells, and some of these wells have been buried. Also, many abandoned wells are improperly plugged (according to current standards), which may cause leakage into other zones. Problems associated with abandoned or improperly plugged wells have accounted for many ground-water contamination incidents (Javandel and others, 1988).

Javandel and others (1988) discussed current methods and a proposed hydrologic method for the detection of abandoned wells. Current methods include reviewing records, aerial photography, and geophysical and hydrologic methods. However, all of the current methods have shortcomings which may produce incomplete or inaccurate results. For example, records and aerial photography may not exist, especially for wells drilled many years ago. Also, geophysical methods such as magnetic, electrical resistivity, and electromagnetic surveys can be used to detect wells but will not indicate if a well is properly plugged. The proposed hydrologic method is developed to avoid these shortcomings. Generally, the proposed method is the use of a model simulating an injection zone, a confining unit of sufficiently low permeability, and another aquifer above the confining unit. Hydraulic head (or pressure buildup) values are recorded over time in the injection well while water is injected at a constant rate. Then, hydraulic head values are calculated using the hydraulic properties of the injection zone. The difference between the calculated and recorded hydraulic head value is then obtained. Through a series of equations, plots, and curves specified in the report, a radial distance from the injection well to an abandoned well can then be determined. This proposed method is based on the theory that the rate of leakage from the injection zone to the overlying aquifer through the abandoned well is proportional to the difference between the hydraulic head in the injection zone and the other aquifer above the confining unit and inversely proportional to the resistance of flow. This method cannot be applied under conditions of a leaky aquifer or where an abandoned well is filled with materials of low permeability.

Seismic Activity - Seismic activity is another "avenue of escape" caused by injection in which the injected waste may leak through pre-existing faults, or injection may cause hydraulic fracturing due to excessive pressure buildup. The area of review is required to be free of "transecting, transmissive faults or fractures" (U.S Environmental Protection Agency, 1990, p. 763-764). According to Kazmann (1981), faults usually are considered barriers to flow; however, density variations between the injected waste and formation fluid can cause fluid movement through these faults in some situations. If the injected waste is less dense than the formation fluid, both upward and outward migration of the waste from the point of injection can occur. As the waste moves, dispersion and dilution cause mixing with the formation fluid. This mixed fluid will vary in density ranging from the density of the injected waste to that of the formation fluid. The mixed fluid can then continue to move up the fault until it reaches and possibly contaminates another overlying aquifer.

Injection can also induce hydraulic fracturing in the injection zone due to excessive pressure buildup. The excessive pressure buildup increases pore water pressure in the injection zone possibly causing sliding along pre-existing faults. The most publicized seismic disturbance related to underground injection occurred at an injection facility at the Rocky Mountain Arsenal in Colorado (Klempt, 1985). During a 3-year period in the early 1960's, a number of small seismic disturbances occurred in the Denver area where only a few events had been recorded prior to the operation of the injection well. These types of disturbances can be assessed before locating an injection well by means of a seismic risk map and a comprehensive geologic evaluation of the area.

Subsurface Migration - Subsurface migration is probably the most significant hydrogeologic problem in terms of long-term effects of injection. Subsurface migration exists in two possible forms: vertical migration through confining units, and horizontal migration in the injection zone during and after injection. In the case of vertical migration through confining units, waste movement through avenues of escape such as abandoned wells, faults, or fractures have been previously discussed. However, vertical migration can still occur in the absence of such obvious physical features. In research conducted by Chen (1989), solute transport is approximated in a leaky aquifer system during injection. A leaky aquifer is defined as an aquifer bounded by low-permeability confining units which allow some ground-water movement to other aquifers. These leaky aquifers are often part of a multiple aquifer system that includes a pumped aquifer where waste is being injected; a confining unit adjacent to the pumped aquifer; and an unpumped aquifer adjacent to the confining unit. In Chen's research, a model was proposed to provide both analytical and semi-analytical solutions approximating solute transport for injection into a leaky aquifer system. This model was then solved analytically using steady-state conditions and semi-analytically using transient conditions. The semi-analytical results compared well with numerical results and were considered reasonable solute transport approximations in a leaky aquifer system.

The concern for horizontal migration of the injected waste in the natural ground-water flow system is comparable to the concern for vertical migration of the injected waste into overlying geologic units. Generally, injected waste will move in the downdip direction of the regional flow system. The rate of movement is determined by the hydraulic gradient and the permeability in that flow system (Klempt, 1985). An adequate estimate of waste movement over time is necessary to prevent both present and future contamination problems near the injection well and any other locations affected after a well ceases operation. Both vertical and horizontal migration of waste in the ground-water flow system typically are evaluated by simulating injection using available mathematical modeling techniques, which are explained in the next section.

Injection Simulation Using Selected Mathematical Modeling Techniques

After site data have been collected and hydrogeologic problems identified, mathematical models may be then used in the evaluation of a potential Class I site by simulating injection over time. Most models developed for injection simulation combine theories of ground-water pressure and flow with ground-water transport. Pressure caused by injection is considered a source of stress in the injection zone, and effects of this stress are interpreted with respect to pre-existing potentiometric surfaces and regional flow patterns. Typically, injection causes a mound in the potentiometric surface, which is opposite the response of a producing well (fig. 5). This mound of pressure would ideally follow a cylindrical pattern outward from the well (Miller and others, 1986b). However, the mound usually extends "unsymmetrically in the direction of regional flow" in the injection zone due to density variations and other transient conditions in the formation (Freeze and Cherry, 1979, p. 454; see also Merritt, 1985).

The injected waste ideally would also enter from the well into the injection zone in an even, cylindrical pattern. The diameter of this cylinder is determined by the cumulative volume of the injected waste and the height and porosity of the formation (Miller and others, 1986b). However, due to transient conditions in the injection zone (such as variable densities, varying temperatures, and so forth), one-dimensional flow analyses are inadequate. Flow-analysis techniques suitable for evaluating the injection rate from an injection well generally involve an equation for unsteady flow in a horizontal, confined aquifer (Remson and others, 1971). In 1935, Theis developed a solution for the radial equation of unsteady flow in a horizontal, confined aquifer (Freeze and Cherry, 1979). To use the Theis solution for production wells, the hydraulic head at a specified distance and time is calculated to determine drawdown effects around the well. However, to use the Theis solution for injection wells, the change in hydraulic head typically is pre-measured from pressure buildup tests or pumping tests, and the expression is solved for radial distance, which is the location of the waste migration front (Freeze and Cherry, 1979). The Theis solution for unsteady flow in a confined aquifer is a standard solution used in many mathematical models to evaluate the present and future locations of injected waste movement. The mathematical models then refine the Theis solution for specific transient conditions. Research involving the Theis solution and its applications in areas related to injection include: "Unconfined Aquifer Characteristics and Well Flow" by Esmaili and Scott (1968) which presents graphical solutions of unsteady flow in unconfined aquifers ; and "Cold-Water Injection into Single- and Two-Phase Geothermal Reservoirs," by Garg and Pritchett (1990) which presents analytical solutions of reservoir properties for injection of cold water into geothermal aquifers.

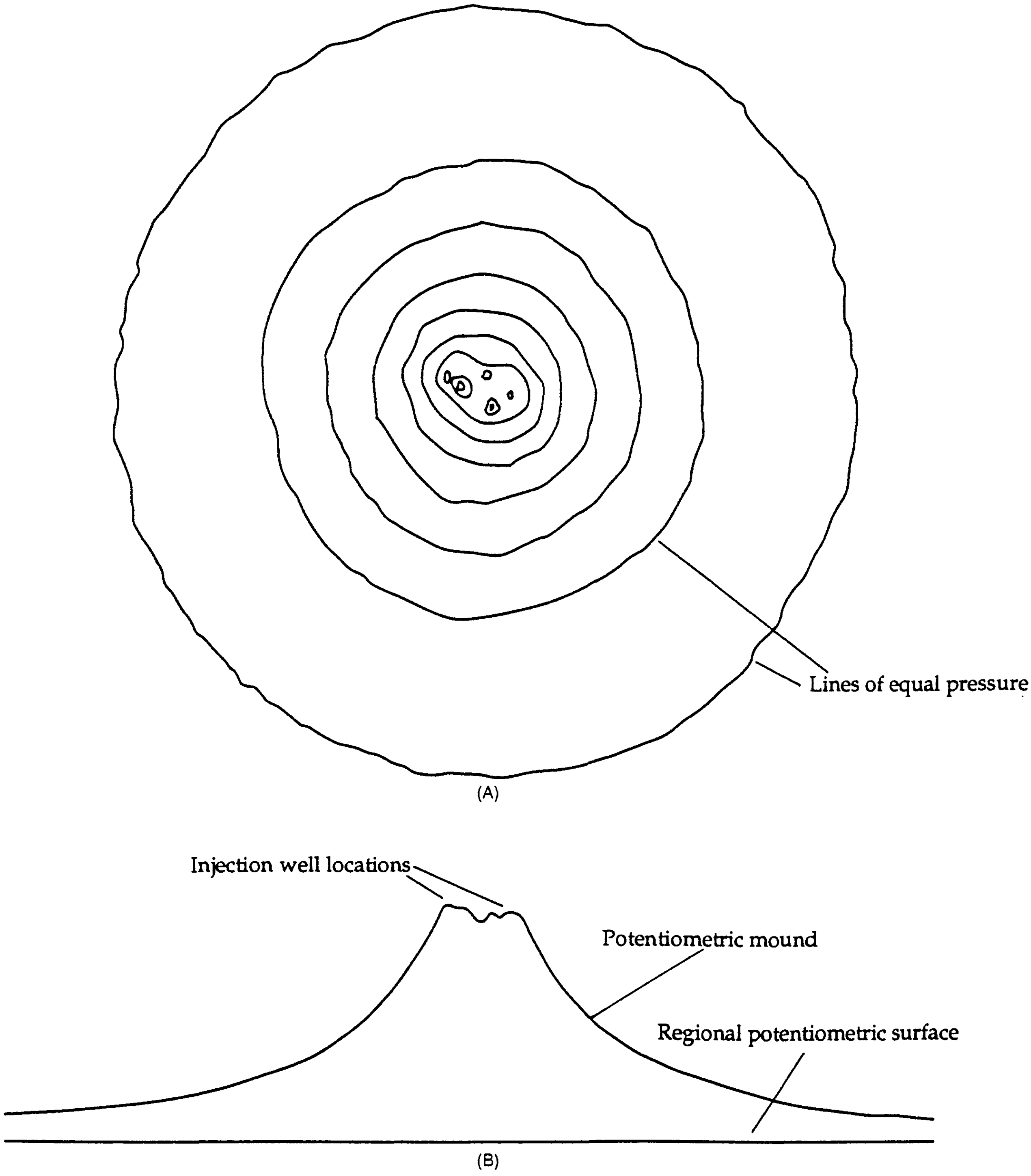

Figure 5.--Conceptual potentiometric mound caused by pressure buildup during injection operations. (A) Top view. (B) Profile view.

Many mathematical models are available that can simulate Class I injection. Brief summaries of four mathematical models including the Basic Plume Method (Miller and others, 1986b), the Intercomp model (Intercomp, 1976), the Heat and Solute Transport model (HST3D) (Kipp, 1987), and the Saturated-Unsaturated Transport model (SUTRA) (Voss, 1984) are presented in the following paragraphs. These four models were selected for this report at the discretion of the author. Consideration was given to the availability of the models to local regulatory agencies and the wide-acceptance of applying these models to injection simulations.

<u>Basic Plume Method</u> -

BASIC THEORY - The "Basic Plume Method" is a series of numerical models developed by the chemical industry to estimate horizontal and vertical movement of injected waste (Miller and others, 1986b). The method is based on similar techniques developed by the petroleum industry, which used numerical methods to simulate hydrogeologic processes at sites where injection wells enhanced oil production (Chester Miller, E.I. DuPont de Nemours and Co., Inc., oral commun., 1992). The method is not intended to estimate the exact waste front location, but rather to estimate where the waste front will not be located. The overall method is named the "Basic Plume Method" for the purposes of this report after the Basic Plume Model, which is a primary model within the overall method that estimates horizontal movement. The Basic Plume Method is composed of six models: the Basic Plume and the 10,000-Year Waste Plume Models, which are used to estimate horizontal waste movement; and the Multilayer Vertical Permeation, the Molecular Diffusion, the Multilayer Pressure, and the Flow-Resistance Models, which are used to estimate vertical waste movement (fig. 6) (State of Mississippi, 1990).

The Basic Plume Model simulates horizontal movement of the injected waste for time periods during injection and immediately following shut down of the injection operation. The model neglects the vertical exchange of fluids between geologic layers and can include the effects of a multi-well operation. Although the model was primarily based on calculations for a uniform homogeneous aquifer, it was later modified using a multiplying factor concept to account for nonuniformities in the injection zone. The multiplying factor is used as a scaling parameter to increase injection rates by a constant factor greater than or equal to 1; therefore, when this factor is used, a margin of safety is guaranteed in the calculations. The Basic Plume Model is structured as a single-layer calculation requiring separate calculations for each layer affected by the injected waste. The solution of the Basic Plume Model is a two-part process

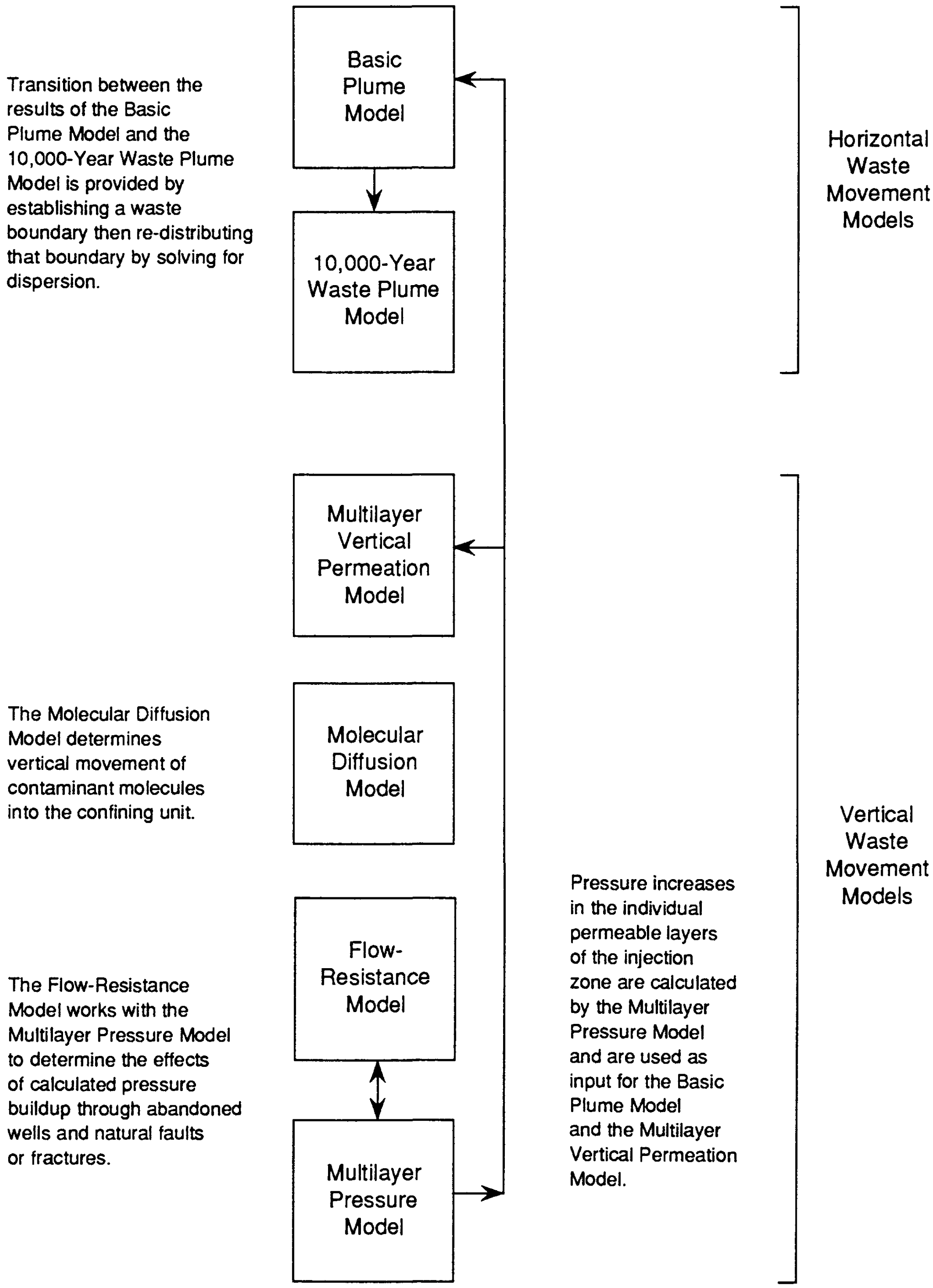

Figure 6.--Model structure of the Basic Plume Method.

that includes calculating lateral velocity distributions in the injection zone and then integrating these velocity distributions with the movement of the diffuse boundary existing between the waste and formation fluids (State of Mississippi, 1990).

Long-term horizontal waste migration after injection operations cease is simulated using the 10,000-Year Waste Plume Model. This model analyzes natural background flow patterns, density-driven flow, and hydrodynamic dispersion. Natural background flow refers to regional ground-water movement before and after injection takes place, typically driven by low hydraulic gradients. Density-driven flow occurs during injection when horizontal components of buoyant forces drive the injected waste up-dip of the injection well if the waste is less dense than the formation fluid, and downdip if the waste is more dense than the formation fluid. A result of natural and density-driven flow in the injection zone is hydrodynamic dispersion, which is a "mixing" process generating a diffuse boundary between the injected waste and the formation fluid. The 10,000-Year Waste Plume Model is a two-dimensional estimate of horizontal flow and transport in the injection zone based on Darcy's Law and laws of conservation of mass. Transition between the results of the Basic Plume Model for short-term horizontal movement and the 10,000-Year Waste Plume Model for long-term horizontal movement is provided by first establishing the waste boundary and then redistributing that boundary by a dispersion transport solution in radial flow (fig. 6) (State of Mississippi, 1990).

Vertical movement of the injected waste into other geologic layers is modeled using four smaller models: the Multilayer Vertical Permeation, the Molecular Diffusion, the Multilayer Pressure, and the Flow-Resistance Models. The Multilayer Vertical Permeation Model calculates the vertical movement of the injected waste that may permeate through the confining unit or other geologic layers driven by pressure buildup created during injection. The extent of permeation is estimated for short-term effects during or shortly after injection and long-term effects many years later.

The Molecular Diffusion Model estimates distance of waste movement due to diffusion, which is defined as the ability of the molecules of the injected waste, driven by random thermal movement, to diffuse into the confining unit. The Molecular Diffusion Model determines the vertical movement of contaminant molecules from areas of high concentration to areas of low concentration in the confining unit (fig. 7). First, the model calculates the magnitude of concentration reduction necessary to

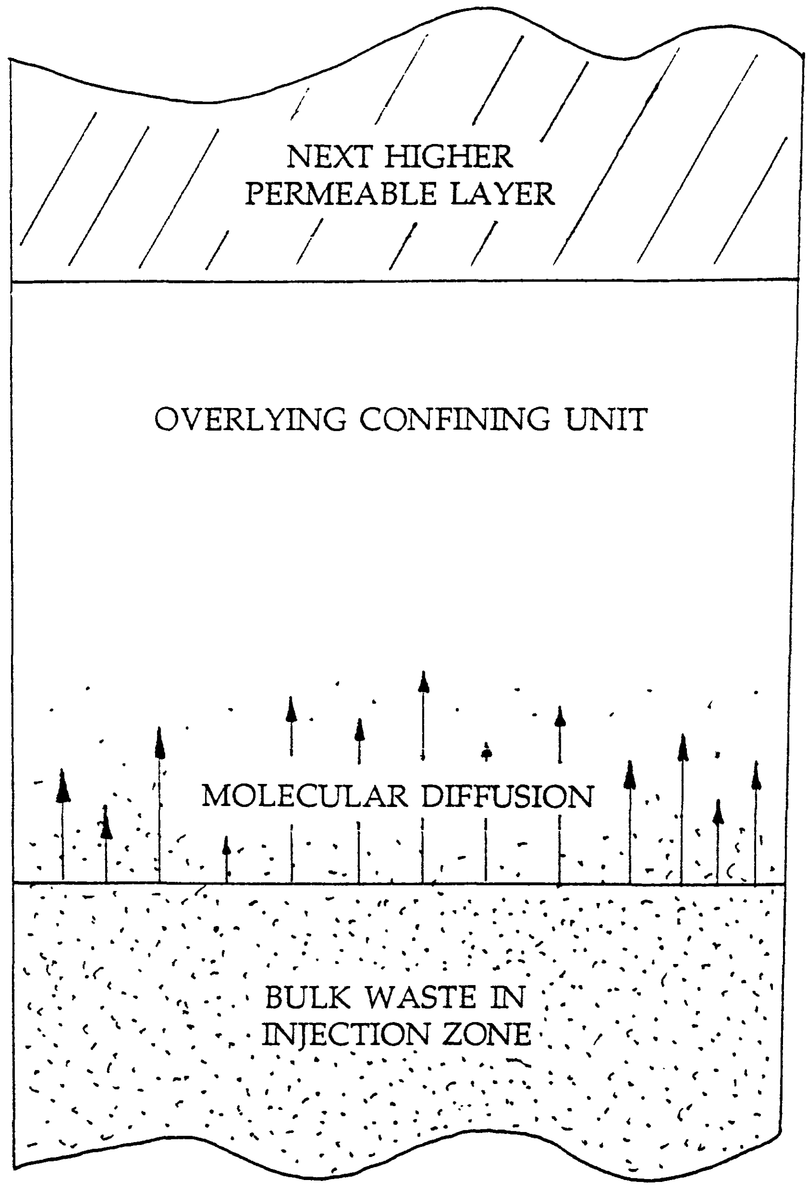

Figure 7.–Molecular diffusion process.

render the most toxic or mobile contaminant non-hazardous. Secondly, the model calculates the vertical distance into the confining unit necessary to obtain this reduction after 10,000 years of diffusion. The calculations make use of an effective diffusion coefficient, which is selected based on conditions for a free aqueous solution; however, a geometric correction factor based on the geologic characteristics of the confining unit is applied which reduces the diffusion coefficient to account for complexities in the pore channel geometry of the confining unit (State of Mississippi, 1990).

The Multilayer Pressure and Flow-Resistance Models evaluate the potential for leakage through abandoned wells and natural faults or fractures. The Multilayer Pressure Model calculates the pressure increases in the individual permeable layers of the injection zone and includes calculations for multiple wells and multiple layers. The model structure consists of alternating high- and low-permeability layers which correspond to the particular layering scheme in the injection zone. The model output is used in the Multilayer Vertical Permeation and the Basic Plume Models as input data (fig. 6). The Flow-Resistance Model works in conjunction with the Multilayer Pressure Model to determine the effects of this calculated pressure buildup through abandoned wells and natural faults or fractures (fig. 6) (State of Mississippi, 1990).

INPUT DATA REQUIREMENTS AND ASSUMPTIONS - Input data requirements for the Basic Plume Method can be divided into four general categories: hydrogeologic parameters, fluid parameters, molecular diffusion parameters, and operating parameters. Specific data in these categories and the models they may affect are presented in the following paragraphs (State of Mississippi, 1990):

A. Hydrogeologic Parameters -

1. Layer Thickness - Layers defined for the model do not necessarily coincide with the formal layering of the stratigraphic column; rather, layers are specified according to their behavior as functional hydrogeologic units. The models are developed based on the use of uniform layer thickness.

2. Layer Permeabilities - Injection zone permeability data are important for the Basic Plume, 10,000-Year Waste Plume, and Multilayer Pressure Models. Confining unit permeability data are important for the Multilayer Vertical Permeation Model.

3. Layer Porosities - Injection zone porosity data are minor input parameters for the Basic Plume and 10,000-Year Waste Plume Models. Confining unit porosity data are important for the Multilayer Vertical Permeation and Molecular Diffusion Models.

4. Layer Compressibilities - Injection zone and confining unit compressibility data are minor input parameters to the various models in the method.

5. Layer Dispersion Characteristics - Dispersion in the Basic Plume Model is accounted for in the Multiplying Factor Concept, which is based on permeability, porosity, and thickness.

B. Fluid Parameters -

1. Viscosity - Formation fluid and injected waste viscosity data are used in the various models of this method. In addition, temperature measurements at depth are important for viscosity calculations.

2. Density - The density of the formation fluid and the injected waste are primary input parameters for the 10,000-Year Waste Plume Model.

3. Fluid Compressibility - Formation and injected waste fluid compressibility are minor input parameters to the Multilayer Pressure Model.

4. Original Formation Pressure - The original formation pressure of the injection zone is not a direct input to any of the models. During pressure calibration, measured formation pressures are compared with modeled formation pressures. Therefore, a valid approximation of the original formation pressure for the injection zone is essential.

C. Molecular Diffusion Parameters -

1. Required Concentration Reductions - These reductions are defined for each contaminant in the waste stream as the health-based standard concentration (or detection limit) of a particular contaminant divided by the actual concentration of that contaminant in the waste stream.

2. Molecular Diffusion Coefficients - Diffusion coefficients of key contaminants in the injected waste are determined for free aqueous solutions. These coefficients are then corrected using a Geometric Correction Factor, which is based on lithology and porosity, to determine an effective diffusion coefficient for the confining unit.

D. Operating Parameters - The Basic Plume Method requires the location and completion zones of all injection and monitor wells, the monthly and yearly injection history for each well, the record of monitor well pressures, and injection rates.

Assumptions associated with the models of the Basic Plume Method, as well as assumptions associated with any other numerical method, limit the effectiveness of a particular method to simulate injection. The Basic Plume Model includes six key assumptions. First, the fluid is assumed incompressible. Compressibility is important to determine overall pressure distributions; however, local compressibility is considered minimal and, therefore, unnecessary to estimate horizontal waste movement. Second, seepage from the injection zone into adjacent confining units is neglected for this model. Any seepage that does occur only decreases lateral velocities, thus slowing horizontal movement. Third, physical properties such as thickness, permeability, and porosity do not vary with position. The Multiplying Factor Concept accounts for these variations. The fourth and fifth assumptions state that the densities of the injected waste and formation fluid are assumed equal, and fluid viscosity is assumed uniform. Flow variations caused by varying densities or viscosities are included in the Multiplying Factor Concept. Sixth, the injection well is assumed perforated evenly across the entire saturated thickness of the injection zone (State of Mississippi, 1990).

The 10,000-Year Waste Plume Model has two key assumptions related primarily to contaminant concentration with respect to flow. First, density is proportional to relative species concentration. Relative species concentration is defined as the ratio of the difference between formation concentration (or density) and species concentration (or density) over the difference between formation concentration (or density) and waste concentration (or density). The second assumption, related to the first, states that the relative concentrations of all species are about equal and are transported identically (State of Mississippi, 1990).

The Multilayer Vertical Permeation Model has five key assumptions. The first assumption states that flow is horizontal in high-permeability layers (such as the injection zone) and vertical in low-permeability layers (such as the confining units). Secondly, properties and thicknesses of the layers do not vary with position. Using pressure as a driving force in the injection zone, vertical variations in material properties have little effect on the pressure distributions. However, some horizontal variations, such as those caused by faults or pinch-outs, can be simulated by the model. Third, fluid viscosity is assumed uniform within each layer. Fourth, viscosity variations in the injection zone typically are minimal and can be considered incorporated into the margins of safety built into this model. Fifth, the injection zone thickness is assumed fully penetrated and completed, and hydrodynamic dispersion is assumed negligible (State of Mississippi, 1990).

For the Molecular Diffusion Model, key assumptions are associated with the effective diffusion coefficient calculation. First, the waste concentration during injection is assumed equal to the waste concentration at all other times. Secondly, chemical reactions that accelerate or impede movement in the confining unit are assumed negligible. Third, horizontal movement of the waste plume is assumed negligible after injection ceases, but the waste can remain in contact with the overlying confining unit for an extensive period of time. Fourth, chemical decomposition of the injected waste is negligible to provide a conservative estimate of vertical movement (State of Mississippi, 1990).

The Multilayer Pressure Model contains six key assumptions. Four of these assumptions are similar to the Multilayer Vertical Permeation Model: flow is horizontal with high-permeability layers and vertical with low-permeability layers; material properties and thicknesses do not vary with position; viscosities of the waste and formation fluid are uniform and equal; and the injection zone is fully penetrated and completed. This model also assumes that waste density and formation fluid density are equal, and that compressive storage in the confining unit is negligible (State of Mississippi, 1990).

MODEL SUMMARY AND CASE STUDIES - A review of the literature indicates that the Basic Plume Method is an effective method for evaluating injected waste movement in a multilayer environment. The method is divided into several models to estimate both vertical and horizontal waste movement over time. The assumptions, boundary conditions, and input data are then structured in each model to provide a conservative estimate of movement. This method is most effective for "typical" injection practices involving geologic environments where a large porous injection zone is "sandwiched" between highly impermeable confining units.

A disadvantage of this method is its inability to respond to heterogeneities in the geologic setting. Several of the models of this method assume homogeneous conditions, and property variations in density, viscosity, and so forth, are accounted for using margins of safety, such as the Multiplying Factor Concept. Overall, this type of approach can provide a conservative estimate of waste movement by "engulfing" the property variations; however, the method cannot address specific problems caused by property variations. For example, in areas of variable density flow in the injection zone, convection cells or pockets of waste may exist as a result of injection. The user has no flexibility to evaluate these cells and local effects caused by the cells using this model.

The Basic Plume Method has been documented extensively in permit applications of chemical and petroleum industries that request the use of injection wells as a means of liquid waste disposal. However, few documented case studies other than permit applications are available in which the Basic Plume Method was used to simulate injected waste movement. In reports by Miller and others (1986a, 1986b), who are the principal writers of the method code, the method was used to simulate the effects of injection for an injection practice in Texas. The results of using the method indicated that the estimated extent of horizontal migration was in close agreement with an estimation based on using a three-dimensional numerical method. Also, the results of using this method to simulate vertical migration indicated that the injected waste would barely penetrate into the overlying confining unit for the life of the well.

<u>Intercomp Model</u> -

BASIC THEORY - The Intercomp Model was developed by Intercomp Resource Development and Engineering, Inc., and published under contract with the U.S. Geological Survey in 1976 (Intercomp, 1976). This model was later revised and appended by Intera Environmental Consultants, Inc. (1978). In many publications, the initial model has been nicknamed "SWIP", which stands for Subsurface Waste Injection Program (Merritt, 1984). The model provides a three-dimensional transient simulation of waste injection in the subsurface environment by solving for specific fluid properties or flow patterns in terms of pressure, temperature, and waste concentration. The results of the model simulations can then be interpreted with respect to regional ground-water flow patterns.

The SWIP model is developed as a numerical solution of partial differential equations describing flow in porous media in three dimensions. The model actually is a combination of two separate sub-models: a reservoir model, which can be solved for flow and energy transport in the injection zone and adjacent confining units; and a well-bore model, which can be solved for flow and energy transport for vertical flows in the injection well. The reservoir model is a combination of three partial differential equations, which simulate temperature, pressure, and concentration patterns in the injection zone. The three equations include a single-phase flow equation, an energy equation, and a solute transport equation. The well-bore model simulates well conditions such as energy losses, bottom-hole pressure and temperatures, and pressure declines between the well and a particular location in the injection zone. The results from simulations using the well-bore model are expressed in terms of pressure and temperature changes and then used as initial values for the reservoir model. By combining these two sub-models, simulations can include nonuniformities in the flow system such as physical displacements (stratified permeabilities) and flow variations (variable densities which can form convective cells). Therefore, the combination of these two sub-models gives this method additional flexibility to evaluate very complex details associated with an injection operation. A general representation showing how this model simulates underground injection is given in figure 8.

The Intercomp model basically was revised to update the original code (Intera, 1978). These updates included: use of water-table conditions when the solution of the energy equation is not necessary; inclusion of vertical recharge rates at specified points of the injection site; calculation and printing of hydraulic heads; simulation of an infinite or large finite system; initialization of regional temperature; and use of radioactive decay and adsorption functions.

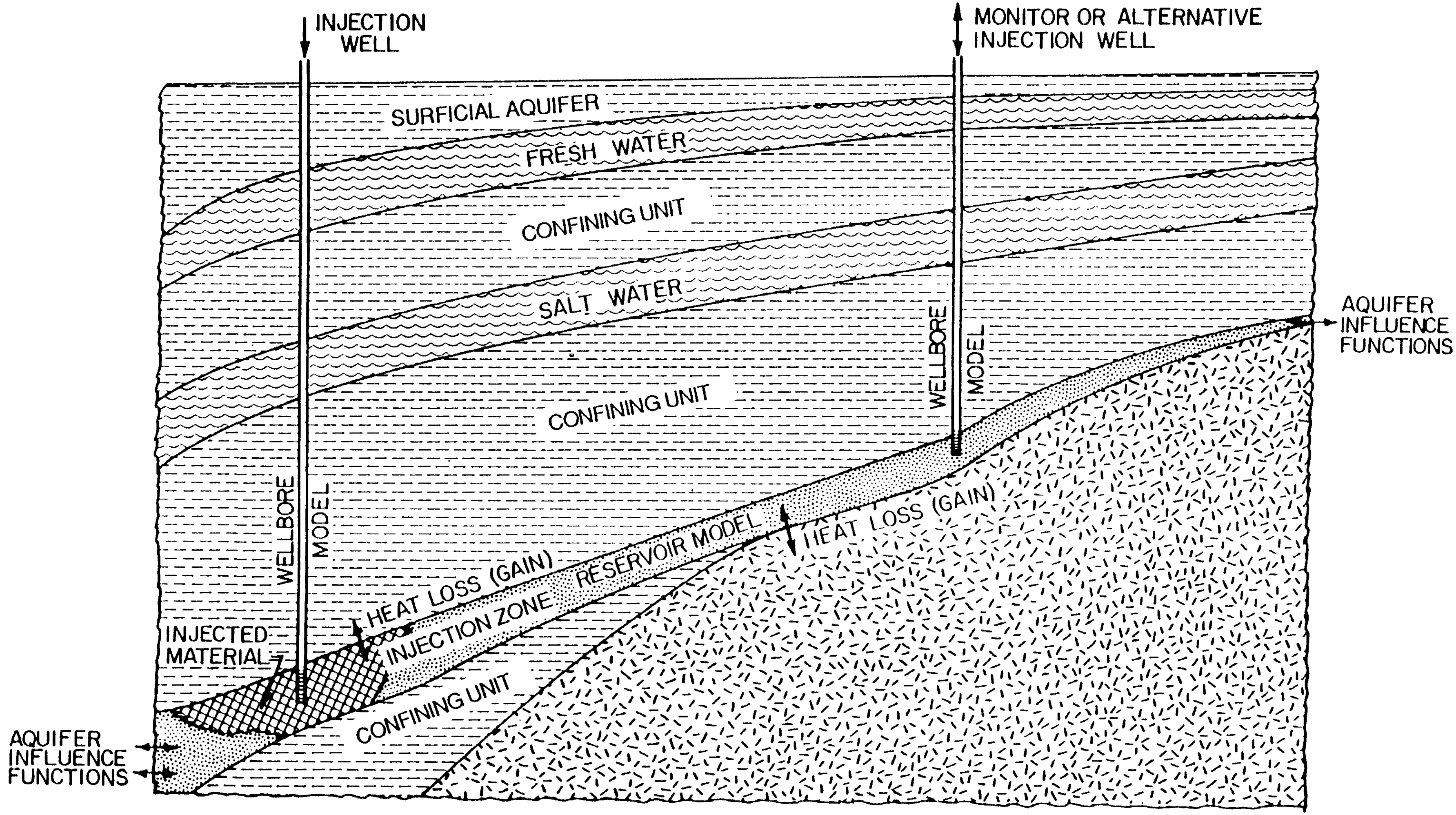

Figure 8.--Specific components of the Intercomp model used to simulate injection operations for a particular geologic setting (modified from Intercomp, 1976, p. 2.5).

INPUT DATA REQUIREMENTS, ASSUMPTIONS, AND BOUNDARY CONDITIONS - Input data requirements for the Intercomp model can be divided into two general categories: fluid and aquifer properties data, and well data. Specific data requirements for these two categories are presented as follows:

A. Fluid and Aquifer Properties - These data are generally expressed as functions of pressure, temperature, and concentration. However, these data may be assumed constant or expressed in terms of other constant properties.

1. Compressibility - Fluid compressibility is required and is entered at the reference pressure and temperature. The reference pressure is the initial pressure at the top of the injection zone. The reference temperature is user specified and is used to calculate fluid density and internal energy. Rock compressibility is required and is entered as an average value over the expected range of pressure and temperature (Intercomp, 1976).

2. Thermal Expansion Factor - This factor is used to calculate fluid density when necessary and is specified at the reference pressure and temperature.

3. Heat Capacities - Total heat capacity is the heat required to raise the fluid and injection zone material temperatures 1° F. Heat capacity is a function of temperature and pressure but assumed to be consistent in the reservoir model calculations.

4. Fluid Density - Injected waste and formation fluid densities are entered at the same pressure and temperature conditions.

5. Fluid Viscosity - The model requires extensive viscosity information. Injected waste and formation fluid viscosities may be entered as functions of temperature. Also, a reference viscosity may be entered as a function of concentration at a reference temperature. If any fluid viscosity is to be independent of temperature, then the same value of viscosity is entered at two temperatures.

6. Dispersivity - Longitudinal and transverse dispersivity are required for the model to calculate nine dispersion coefficients. Thermal conductivities are required for the porous injection zone, and a value for molecular diffusivity is required representing a net value to include the effects of porosity and tortuosity.

7. Transmission Coefficients - Fluid velocity in the reservoir model are expressed in terms of spatial pressure gradients by means of Darcy's Law for flow in porous media. The transmission coefficient is the hydraulic conductivity and is entered at reference conditions. Permeability is entered in units of darcies and assumed to be constant in the injection zone (Intercomp, 1976).

8. Intera Revision - When the Intercomp model was revised by Intera Environmental Consultants, Inc. (1978), the revision included several input data requirement updates. For example, water-table conditions may be entered if the solution of the energy equation is not desired; vertical recharge rates may be entered for the uppermost layer of the modeled system where recharge occurs; and, initial temperatures may be entered on a regional basis for the modeled system.

B. Well Data - If well-bore calculations are not conducted, then bottom-hole conditions are specified. If well-bore calculations are to be performed, then the wellhead conditions and well specifications are specified including well depth, internal diameter of the tubing inside of the well, outer diameter of the casing, inner tubing roughness, and the overall heat transfer coefficient between the fluid inside the tubing and the outside surface of the casing. Also, model requirements include entering a well index, which is used to calculate the pressure drop between the well bore and the grid block center (Intercomp, 1976).

The limiting assumptions associated with this model are used primarily to reduce the partial differential equations developed for flow, energy, and solute transport. Assumptions associated with the reservoir model are as follows (Intercomp, 1976):

1. The reservoir model assumes three-dimensional, laminar, transient flow.

2. Fluid density can be expressed in terms of pressure, temperature, and concentration.

3. Fluid viscosity can be expressed in terms of temperature and concentration.

4. The injected waste and formation fluid are miscible.

5. Aquifer properties vary with position, which means that aquifer properties can be different in specific areas of the grid system.

6. Hydrodynamic dispersion is a function of fluid velocity.

7. The energy equation in this model is expressed as "enthalpy in minus enthalpy out equals change in internal energy."

Assumptions associated with the well-bore model equations are as follows:

1. Heat dissipation in the well bore can be ignored.

2. The initial ground temperature surrounding each well bore is known and can be expressed as a function of depth only.

3. Flow in the well is assumed incompressible and steady-state.

4. Fluid properties are allowed to vary with pressure and temperature in the well bore.

5. The enthalpy of the injection fluid is proportional to the enthalpy of pure water at the same temperature and pressure. (For the purposes of this report, "pure water" is defined as water with a dissolved solids concentration of less than 5 mg/L.)

The reduced equations are then approximated using finite-difference expressions, which are solved with the aid of boundary conditions. Boundary conditions represent pre-existing conditions such as ground-water gradients or seismic zones and represent properties associated with the injection activity such as sources of heat loss, injection well locations, or monitor-well locations. Boundary conditions may be supplied by the user or calculated by the model for a specific location or locations across the grid network. For example, the user may supply surface properties, injection rates, or bottom-hole pressures. If the user specifies surface properties and an injection rate only, the model can calculate the appropriate bottom-hole pressure (Intercomp, 1976).

The model also offers the choice of using "aquifer influence functions," which are applied to the periphery of the grid system. Typically, model iterations are performed for a specific length of time with no changes in temperature, pressure, or concentration along the edges of the grid system. For these iterations, the periphery of the grid is considered impermeable. However, changes in temperature, pressure, or concentration can occur for iterations involving longer times. Aquifer influence functions are then used to simulate the changes along the periphery over time. The user can choose among three aquifer influence functions available in the model. The first aquifer influence function is a type of "superposition" function where the exterior boundaries of a finite aquifer are surrounded by an infinite aquifer. Therefore, normally rectangular grid boundaries are now replaced by circular grid boundaries, and peripheral influences are evaluated in terms of an effective radius. The second aquifer influence function available in the model is a "pressure" function. This influence function first assumes impermeable external boundaries to limit waste migration out of the aquifer. When the waste is completely contained in the aquifer, pressure increases occur as a result of additional injection. Average pressures and pressure gradients are then calculated when flow through the external boundaries is reestablished. The third aquifer influence function included in the model is a "steady-state" function. This function first calculates the cumulative water inflows to the aquifer. A steady-state pressure distribution is then established when the rate of outflow equals the rate of inflow.

MODEL SUMMARY AND CASE STUDIES - The Intercomp model is a numerical method for evaluating the effects of injection. The model is divided into two separate sub-models, the reservoir model and the well-bore model, to evaluate most of the major influences on waste movement. Assumptions are used to help reduce the theoretical equations describing flow and transport, and boundary conditions are used to help solve these equations by representing specific features associated with a particular injection site. The main advantage of using this model is the flexibility of using a numerical method to describe a geologic environment. Critical details in the geologic setting can be described in the grid system. However, the task of developing this grid system and accurately calibrating the model with any available data can be very cumbersome and tedious. Yet, this model proves valuable for those injection practices requiring such detail.

The Intercomp model has been used in several case studies to simulate waste migration fronts and for describing other details associated with an injection site. The Intercomp model was used in a study to simulate the effects of injection on the regional flow system of the lower limestone of the Floridan aquifer near Pensacola, Florida (Merritt, 1984). The objectives of the study generally were to simulate the regional flow system, to simulate injection zone water-level changes at various observation wells, and to incorporate transport calculations into the regional flow model. Results of the study indicated that the regional flow system and injection zone water-level changes were successfully simulated by a two-dimensional flow model. Also, the Intercomp model successfully replicated the regional flow system simulated by the two-dimensional flow model. However, the Intercomp model was unsuccessfully calibrated when transport calculations were incorporated into the injection simulation due to time-step and grid-size constraints.

In another study by Merritt (1985), the Intercomp model was used to investigate the storage and recoverability of freshwater in brackish artesian aquifers in southern Florida. Merritt's model study involved using a hypothetical aquifer representative of the permeable zones in southern Florida. Sensitivity analyses were performed by varying hydrogeologic parameters to determine how efficient the permeable zones could be with respect to storage and recoverability of freshwater. Results of this study indicated that recovery efficiency was lowered by processes that cause mixing of the injected freshwater with formation fluid, irreversible displacement of the freshwater from the well, and dissimilar injection and withdrawal flow patterns. However, recovery efficiency was improved during successive cyclic injection, in which freshwater is injected during the wet season of a particular year followed by a short storage period and then withdrawal of the freshwater during the dry season of the same year. Cyclic injection was most effective when injecting into low permeability and low salinity aquifers, and when withdrawal ended when the chloride concentration of the withdrawn water exceeded potability requirements. Related articles by Merritt include "Recovering Fresh Water Stored in Saline Limestone Aquifers" (Merritt, 1986); "A Review of Factors Affecting Recovery of Freshwater Stored in Saline Aquifers" (Merritt, 1988); and "Nonunique Simulations of the Quality of Water Recovered Following Injection of Freshwater into a Brackish Aquifer" (Merritt, 1991). In addition, the Intercomp model was used in a study by Miller (1989) to evaluate cyclic injection, storage, and withdrawal of heated water in a sandstone aquifer at St. Paul, Minn.

The Intercomp model was used in a study to determine flow characteristics for injection into baroclinic fields, which are defined as formations where densities vary laterally as well as vertically, and surfaces of equal density do not coincide with surfaces of equal pressure (Hickey, 1989b). Such conditions can lead to the development of circular convection cells in the flow field. The hypothesis of circular convection is based on theory advanced by

Cooper (1959), Hubbert (1957), and de Josselin de Jong (1969), which states that circulation may occur in variable density ground-water flow as a result of density gradients related to salinity variations. In Hickey's research, chloride concentrations in observation wells located near an injection well were significantly greater than in the injected waste, but less than in the formation fluid. Therefore, the hypothesis was that density-induced circular convection with landward saltwater flow caused increased chloride concentrations in the injection zone penetrated by the observation wells. The Intercomp model was used to simulate the velocity patterns in the injection zone. Data from a 91-day test were used to calibrate the model, and the model successfully simulated a 366-day test. The model results showed that circular convection contributed substantially to the flow patterns in the injection zone causing increased chloride concentrations in observation wells near the injection well due to counterflow with saltwater.

<u>Heat and Solute Transport (HST3D) Model</u> -

BASIC THEORY - The Heat- and Solute- Transport Model (HST3D) "simulates heat-and solute-transport in three-dimensional saturated ground-water flow systems (Kipp, 1987, p. 3)." This model is a "descendent" of the Intercomp model and its revision by Intera Environmental Consultants, Inc. (1978), previously presented. For ground-water flow and transport, the HST3D model solves three basic equations similar to the Intercomp model: a saturated flow equation, a heat-transport equation, and a solute transport equation. These equations are combined and reduced using independent variables of fluid velocity in relation to advective transport; temperature and solute concentration with respect to fluid viscosity; and pressure, temperature, and solute concentration with respect to fluid density. The dependent variables are then solved numerically using finite-difference approximations.

The HST3D model also includes a well model to simulate flow and energy transport contributed by the injection well. The well model is composed of two sub-models: a well-bore sub-model for the lower part of the well, measured from the bottom of the well to the top of the uppermost screened part; and a well-riser sub-model for the upper part of the well, measured from the top of the screened part to the surface (fig. 9). The well-bore sub-model calculates heat and solute-injection rates and heat and solute-withdrawal rates. These rates are calculated by inflow rate allocation, which is based on fluid mobility and pressure differences across the entire length of the screened well-bore between the well and a pre-determined exterior radius. After the well-bore model calculations are performed with

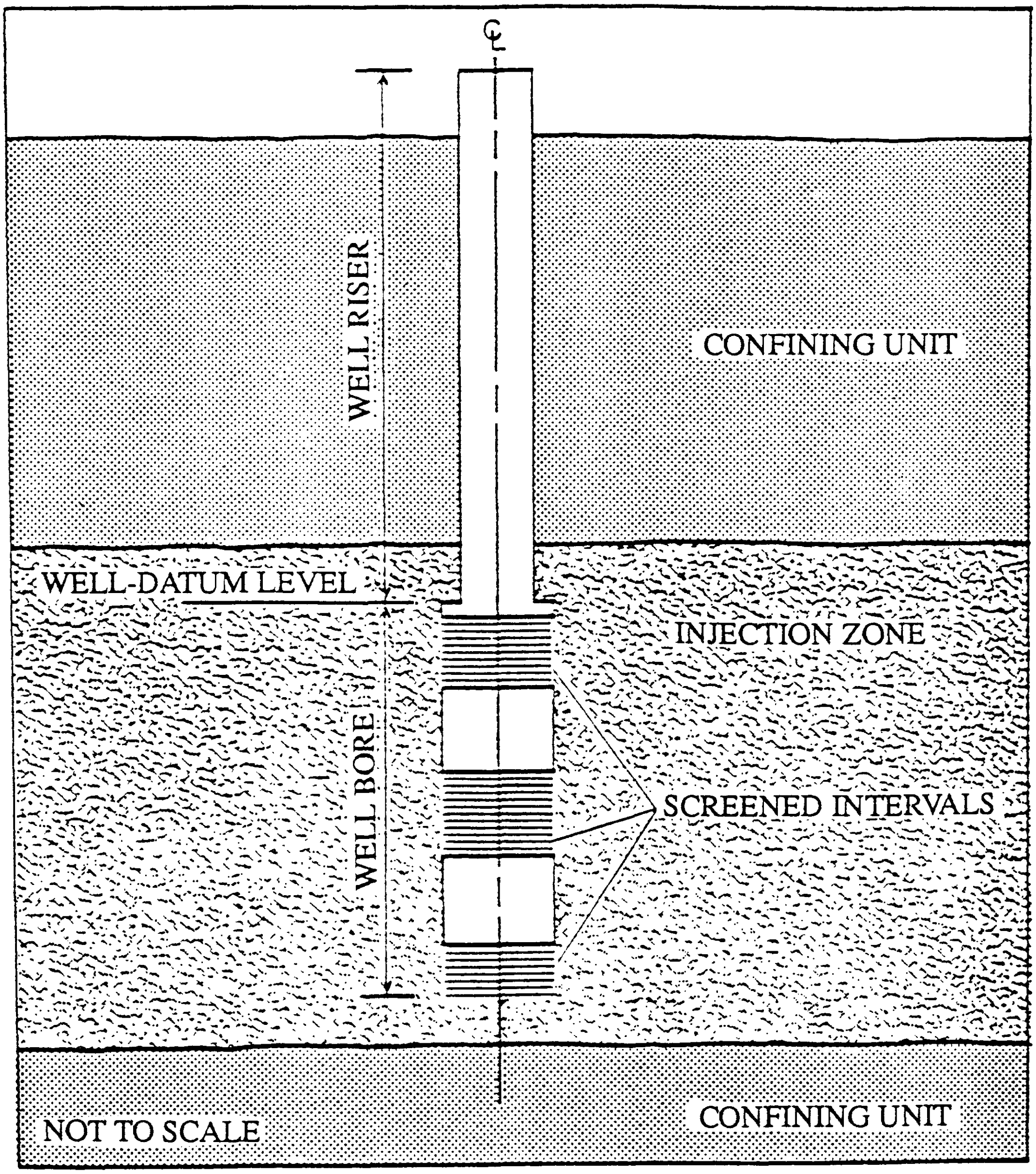

Figure 9.–Well-bore and well-riser subdivisions used in the well model calculations of the Heat and Solute Transport (HST3D) model (modified from Kipp, 1987, p. 32).

the appropriate flow-rate allocations, the well riser sub-model then calculates pressure and temperature changes across the well riser length by solving simultaneous equations of total energy, momentum, and mass.

The HST3D model uses solution techniques similar to the Intercomp model and improved techniques developed as a result of improving or modifying the Intercomp model. A few of these improved techniques are as follows (Kipp, 1987):

1. In terms of boundary condition features, the user can specify flow, heat-flux, solute-flux, leakage, and heat conduction boundary conditions at periphery locations.

2. Geologic properties may vary spatially.

3. Temperature, pressure, and mass-fraction boundaries can be specified to calculate flow, heat, and concentration balances.

4. Heat losses to adjacent strata can be determined using a general heat-transfer calculation.

5. Flow and heat/solute-transport calculations can be performed separately.

6. Solution techniques include an alternating, diagonal direct equation solver or a two-line successive over-relaxation (L2SOR) technique, which was used in the Intercomp model.

7. Programming features include free formatting and logical organization for the input file, a read-echo file for locating input errors, and a variety of output and plotting options.

Despite its features, the HST3D model also includes several limitations, which are comparable to those of the Intercomp Model. For example, finite-difference techniques are difficult to apply to space and time-derivatives. Small dispersivities or non-uniform solute transport represented by these derivatives can require an increase in grid sizes or node amounts, which drastically increases computer storage and time requirements rendering a simulation infeasible. Also, grid-orientation errors can occur in cases where the natural geologic setting has little dispersion or has variations in viscosity, specifically, when the viscosity of the injected fluids is much less than the viscosity of the formation fluid. Grid-orientation errors can produce separate solutions when miscible displacement (or mixing) is simulated (Kipp, 1987).

INPUT DATA REQUIREMENTS, ASSUMPTIONS, AND BOUNDARY CONDITIONS - Data required to use the HST3D model to simulate injection include flow, transport, and injection well information. Data required to solve the ground-water flow equation include fluid and injection zone properties and transport coefficients. Data used to solve the energy and solute transport equations are optional if the solution of these equations is specified by the user. Similarly, data used in the well model are optional if well-model simulations are specified by the user. General data requirements for the HST3D model are as follows (Kipp, 1987):

A. Fluid Properties - Fluid density, viscosity, heat capacity, thermal conductivity, reference-state enthalpy, and compressibility data are required. Fluid density and viscosity data are functions of pressure, temperature, and solute-mass fraction.

B. Geologic Properties - Porosity, compressibility, permeability, heat capacity, thermal conductivity, and reference-state enthalpy data are required.

C. Transport Coefficients - Longitudinal and transverse dispersion coefficients for the injection zone, the effective molecular diffusion coefficient for the contaminant, and decay and sorption coefficients for the contaminant are required.

D. Well Model Data - All well locations, inside and outside diameters, injection rates, well length, well-bore roughness coefficients, and all other well dimensions are required to simulate activities of the injection well(s) and monitor wells using the well model.

E. Boundary Conditions - Other data are required for optional boundary conditions available in the HST3D model and are included in the model documentation (Kipp, 1987).

The limiting assumptions associated with this model are primarily used to reduce the partial differential equations simulating flow and transport. The assumptions associated with the ground-water flow equation can be divided into three basic categories: fluid and injection zone properties, ground-water flow, and the coordinate system. Concerning fluid and injection zone properties, the porous medium and fluids are assumed compressible. Also, porosity and permeability are functions of space, and fluid viscosity is a function of space and time. For ground-water flow, the injection zone is assumed fully saturated, and flow is described by Darcy's Law. In addition, density-gradient diffusion and bulk fluid dispersion are negligible. The coordinate system is assumed right-handed with the z-axis located vertically upward. The system is aligned orthogonally along the principal directions of permeability (Kipp, 1987).

The assumptions associated with the heat transport equation can be divided into two categories, which are the equation's identity - heat and transport. Concerning heat (and the associated energy), fluid kinetic energy, radiant-energy transfer, and chemical reaction energy are neglected. Also, gravitational energy and heating from viscous dissipation are ignored. Thermal conductivities and heat capacities are not considered functions of temperature or solute concentration, and thermal equilibrium exists between the fluid and solid phases. Concerning transport, only a single fluid phase exists, and a pressure equilibrium exists between the fluid and porous media phases. Also, energy transport due to diffusion and the thermal expansion of the porous medium are neglected. Finally, fluid enthalpy with pressure during fluid movement is neglected, and the dependence of enthalpy on solute concentration is determined using a heat-capacity adjustment (Kipp, 1987).

The assumptions associated with the solute-transport equation can be divided into two categories: diffusion and solute concentration. Concerning diffusion, the model ignores certain types of diffusion including thermal, pressure, and forced (gravitational and electrical) diffusion. Concerning the solute concentration of the injected waste, certain types of solute transport are described by a hydrodynamic dispersion coefficient. Also, the only solute reaction mechanism is linear decay or disappearance, and the only interaction mechanism is sorption. Finally, no solute concentration sources can occur in fluid or solid phases (Kipp, 1987).

The reduced differential equations are then approximated using finite-difference expressions, which are solved with the aid of boundary conditions. General boundary conditions include: pressure, which is specified for the ground-water flow equation; temperature, which is specified for the energy transport equation; and a mass fraction, which is specified for the solute-transport equation. The user can then specify other boundary conditions to represent particular aquifer features including leaky aquifers, heat conduction, and unconfined aquifers. In addition to these boundary conditions, the HST3D model also includes aquifer influence functions (similar to Intercomp model). Explanations of these influence functions appear in the Intercomp model summary, "Assumptions and Boundary Conditions" section, previously presented.

MODEL SUMMARY AND CASE STUDIES - The Heat and Solute-Transport (HST3D) model is similar in theory to its predecessor, the Intercomp model. The model is composed of flow and transport equations describing ground-water flow, heat-transport, and solute-transport. These equations are combined using similar independent variables, reduced using similar reduction techniques for ease of solution, and solved using similar matrix operator solution techniques. The HST3D model updates the Intercomp model by resolving some theoretical calculations and by improving or including certain features. The model includes more user-specified boundary conditions, including leakage (leaky aquifers), pure heat-conduction, and unconfined aquifers. Other features of the model include the ability to vary fluid properties spatially (such as hydraulic conductivity); a more sophisticated well-bore model for source or sink evaluations; improved matrix operator solution techniques such as the alternating diagonal, direct equation solver; and improved programing operators such as free formatting, logical organization for the input file, and efficient input error warnings.

This model is still limited by certain natural and numerical problems, which also limits the Intercomp model. Such limitations include finite-difference applications to space and time derivatives and grid orientation errors. Yet, the effects of these limitations are reduced by the HST3D model through the updated features and boundary conditions. The updated features and boundary conditions provide the user more flexibility to incorporate more site-specific details into the injection simulation.

The HST3D model has been used in a few case studies to simulate injection. In a report by Hutchinson (1992), the HST3D model was used to evaluate injection-well design and injected-waste migration for seven injection sites in southwestern Florida, where treated-municipal and reverse-osmosis wastewater is injected into the Avon Park permeable zones of the Floridan aquifer. Model simulations were based on using a hypothetical, representative injection well. Initial simulations indicated the formation of a convection cell near the injection well where the injected waste rose to the top of the permeable zone and was in immediate contact with the confining unit. Results of other simulations indicated that the type of well construction and completion had little effect on the areal spread or rate of upward movement of the injected waste. However, the results of the simulations indicated that the rate of upward movement of the injected waste increased for injection zones located below well fields.

In a study by Weihu and Ahmad (1991), the HST3D was used to simulate the fate and transport of hazardous waste injection into both shallow and deep aquifers through 18 wells for 5 industries located in southeastern Louisiana. In this study, the model simulations indicated that waste injected into the shallow aquifer had moved vertically into an overlying USDW, and also indicated that waste injected into the deep aquifer had also moved vertically threatening a USDW unless injection operations cease.

The HST3D model has also been used in other contaminant transport research that did not involve injection wells but can be related to injection studies. For example, the HST3D model was used in a study by Ahmad and others (1991) to simulate contaminant transport for the purpose of a wellhead protection plan to protect public water supplies for a city in Ohio. The HST3D model was more capable than other wellhead protection models to predict first arrival times of a potential contamination plume and to approximate the behavior of the plume in the hydrogeologic environment.

<u>Saturated-Unsaturated Transport (SUTRA) Model</u> -

BASIC THEORY - The Saturated-Unsaturated Transport Model (SUTRA) is a numerical model that simulates ground-water flow and either energy or solute transport (Voss, 1984). However, unlike the other numerical models previously discussed, the SUTRA model simulates flow and transport using a combination of a two-dimensional finite-element method and an integrated-finite-difference method. The ground-water flow equation used by the model is based on a density-dependent fluid mass balance relation for saturated or unsaturated flow conditions. Although the model can simulate some unsaturated flow conditions, the unsaturated flow capabilities of the model are intended for incidental analyses and are not used as the primary application of the model. After the ground-water flow equation is solved, the model can be solved for either solute or energy transport using a unified transport equation.

The primary variable in the ground-water flow model is pressure; however, varying densities may also drive fluid flow. In pressure-driven flow, ground-water flows from areas with pressures greater than hydrostatic pressure to areas with pressures less than hydrostatic pressure. Density-driven flow occurs when higher density fluids move across regions of less dense fluids, usually downward by means of gravity. Actual flow simulation, however, is based on a fluid mass balance. Fluid-mass changes at every point in the ground-water simulation region are described by the model over time including normal ground-water inflows and outflows, injection or withdrawal wells, and flows caused by changes in density or saturation.

The solution of the ground-water flow model is fundamental to the solution of the transport model because energy and solute transport also depend on pressure and density. SUTRA only models energy or solute transport in a given simulation; therefore, if energy is modeled, a constant value of solute concentration is assumed (and the reverse is true for modeling solute transport in which a constant value of temperature is assumed). Energy is transported both by ground-water flow and by "thermal conduction from higher to lower temperatures through both fluid and the solid (Voss, 1984, p. 35)." Energy transport is actually simulated by the model as a calculation of the rate of change of energy in the injection zone materials over time. These changes in energy in the injection zone materials include temperature changes in the natural flow system, temperature differences in the injected waste, changes in the total fluid mass, changes in thermal conduction, and changes in energy dispersion.

Solute transport occurs within the injection zone by ground-water flow and by molecular or ionic diffusion. The model simulates solute transport by describing a single species mass in fluid solution and a single species mass adsorbed onto the surface of the formation materials over time. Changes in solute concentration in fluid solution are a result of different solute concentrations entering the system from natural ground-water flow; different solute concentrations entering the system as a result of injection; total fluid mass changes; transfer of dissolved solute species to adsorbed solute species (or reverse); or a chemical or biological reaction causing production or decay. Changes in solute concentration as adsorbed species on formation materials are a result of adsorption gains from fluid solution or a chemical or biological reaction causing production or decay. All of these changes are then quantified mathematically and summed for the total change in solute concentration over time.

Both the solute and energy balance equations are solved for a particular quantity per unit volume of formation material and fluid. In addition, fluxes in energy and solute mass in the injection zone can be attributed to similar physical processes. For example, fluxes in both energy and solute mass undergo diffusion, both are analogous in production or decay, and both undergo similar adsorption processes. Therefore, the balance equations representing energy and solute transport are combined into a unified balance equation developed in terms of a unified variable, which represents temperature for energy transport or concentration for solute transport. This unified equation is modified to remove any duplicate terms and then solved using finite-element methods for the flux terms and finite-difference methods for the non-flux terms (Voss, 1984). The code has recently been updated (1991) to include error corrections, revisions, and modifications.

The SUTRA model is an extremely flexible model for evaluating flow and transport in an underground injection system. The model is most accurate for simulations that are well-defined and well-discretized; however, the model can be used in less-defined simulations by providing an overall concept of the underground system. For example, the model can be used to indicate the need to collect additional data to better represent the injection site. In addition, the computer code is a modular design that allows for direct modifications or additions to the code to improve efficiency. Other options in the code include pinch nodes, which change mesh sizes to refine specific areas of interest and upstream weighting, which simulates special conditions such as extreme temperature or solute concentration variations.

INPUT DATA REQUIREMENTS, ASSUMPTIONS, AND BOUNDARY CONDITIONS - Data requirements necessary to use the SUTRA model to simulate underground injection generally are similar to the other models previously presented. Because the SUTRA model uses a unified transport equation approach, however, data requirements necessary to simulate energy or solute transport are optional depending on which is specified. A general listing of hydrogeologic data required to code the SUTRA model is presented as follows (Voss, 1984):

A. Flow Parameters - General data requirements used to solve the flow equation include fluid compressibility and density, and injection zone compressibility, porosity, and permeability. Individual pressure and fluid source data at specified locations in the simulated region are required as necessary for initial and boundary conditions in the model.

B. Energy Transport - Data requirements used to solve the unified transport equation for energy transport include a coefficient of fluid density change with temperature; longitudinal and transverse dispersivity; a base temperature for density calculations; thermal conductivity of the fluid and injection zone media; and the specific heat capacity of the fluid and injection zone media. Temperature data for any fluid entering the simulated region are required as necessary for initial and boundary conditions in the model.

C. Solute Transport - Data requirements used to solve the unified transport equation for solute transport include a coefficient of fluid density change with concentration; longitudinal and transverse dispersivity; a base concentration for density calculations; and the molecular diffusivity of the contaminant in the fluid. Concentration data for any fluid entering the simulated region are required as necessary for initial and boundary conditions in the model.

The primary mathematical procedures involved in this model are finite-element solutions to the ground-water flow and transport equations previously presented. The assumptions associated with the model aid in reducing the complexity of these finite-element solutions; therefore, some of these assumptions are included from a theoretical standpoint rather than physical. The injection zone volume is divided into a single layer mesh of many adjacent blocks called finite-elements (fig. 10) (Voss, 1984). Typically, an element is two-dimensional in the x-y plane with a finite thickness in the z-direction. The element is composed of 12 straight sides forming a quadrilateral with 4 sides parallel in the z-direction (fig. 10). Two x-y planes intersect the parallel sides of the z-direction so that the top and bottom surfaces form mirror images. Along each parallel side, a node is formed at the midpoint between the two x-y planes. Aquifer properties are assigned to these nodal points from one end of the aquifer to the other in any direction. Aquifer properties are assumed to vary and be representative of a particular location in the injection zone. These properties (or coefficients) can be assigned a constant value for an entire element or assigned a particular value at each node. In addition, properties can be assigned a particular value at each cell of the mesh (Note: a cell is defined here as a part of an element centered on a node with boundaries centered halfway between nodes, fig. 11). The SUTRA code depends on these types of assignments; therefore, the model assumes that certain properties be assigned according to cells, elements, or nodes to properly perform calculations (fig. 11). For example, a constant-density, water-table aquifer simulation would probably require the assignment of hydraulic conductivity to elements; storage coefficient to cells; and hydraulic head to nodes (Voss, 1984).

When the assumed aquifer properties have been assigned, the flow and transport equations are reduced to a form most descriptive of a particular injection site. Then, boundary conditions are specified to solve the reduced equations. Primary boundary conditions for the finite-element mesh include head and initial flows at exterior boundary surfaces. For example, either fluid fluxes are specified across boundaries, or particular heads are specified at node locations

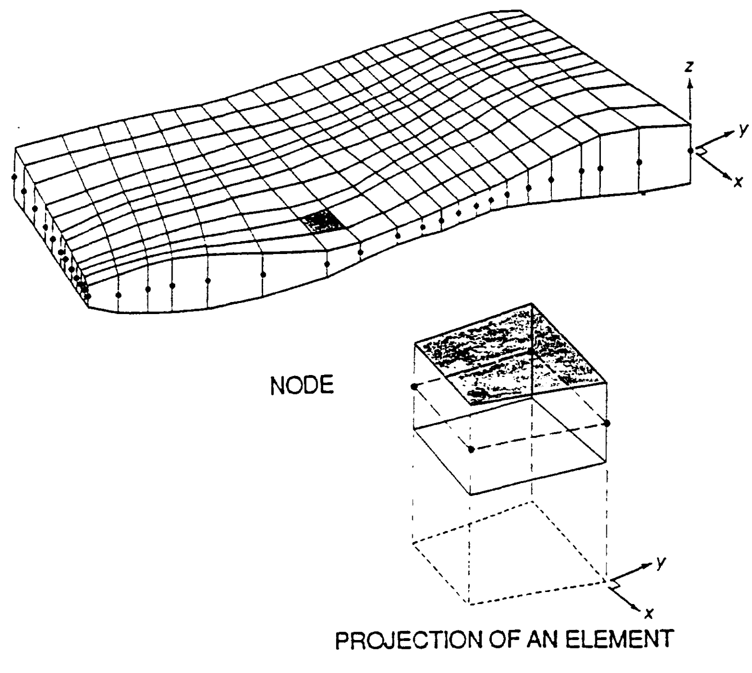

Figure 10.--Conceptual two-dimensional finite-element mesh and quadrilateral element for the Saturated-Unsaturated Transport (SUTRA) model (modified from Voss, 1984, p. 67).

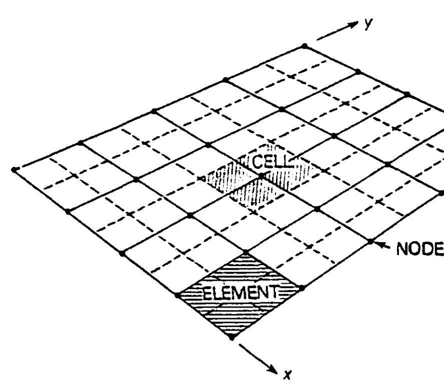

Figure 11.--Cells, elements, and nodes for a conceptual two-dimensional finite-element mesh composed of quadrilateral elements for the Saturated-Unsaturated Transport (SUTRA) model (from Voss, 1984, p. 72).

when solving for hydraulic head. Secondary boundary conditions are then assigned in the finite-element mesh similar to the aquifer properties, according to cells, elements, or nodes.

MODEL SUMMARY AND CASE STUDIES - The SUTRA model simulates flow and transport for either saturated or unsaturated conditions. The model simulates ground-water flow using a flow equation based on pressure and density, and the model simulates transport using a unified transport equation. This transport equation can be solved for either energy or solute transport, but not for both; one is held constant, while the other is solved. The unified transport equation is based on a unified variable, which can be solved as temperature for energy transport or concentration for solute transport. The equations themselves are based on mass balances to include nearly every mass entering or leaving the system.

A finite-element approach is used to solve mass balance equations for the entire system. The system is divided into a mesh of small individual elements of finite thickness and shape. Aquifer properties are then assigned according to elements, cells or nodes within the mesh system. Some of these properties are actual data or assumed values representative of the particular geologic setting. Then, boundary conditions are used to help solve the simultaneous equations involved in the problem. Finite difference methods are used to solve non-flux parameters in the system as boundary conditions.

The model includes certain features that increase its flexibility as a tool to evaluate subsurface flow and transport, including pinch nodes, upstream weighting, and a modular design; however, the model also has several limitations that could limit its use to evaluate an injection site. First, the model only solves for one type of transport, energy or solute. If a user requires results for both types of transport at an injection site, then separate simulations are conducted thus increasing time requirements. Next, solutions of the model are highly dependent on how well a problem is defined and how well data are discretized within the mesh system. If only limited hydrogeologic data are available to describe a particular injection site, then SUTRA is best used to provide an approach to evaluate waste flow and transport at that particular site.

The SUTRA model has been used in very few case studies to simulate the fate and transport of injected waste. The SUTRA model is presently being used in a study in southern Florida to evaluate the efficiency of injecting freshwater into a deep saline aquifer for the purposes of storage and recovery (Vincente Quinones, U.S. Geological Survey, written commun., 1992). The freshwater is expected to mix with the saline formation fluid due to natural mixing processes and other geochemical problems once injected. However, the freshwater is intended for irrigation and purposes other than public drinking-water supply, and therefore, is not required to have a very high quality once recovered.

The SUTRA model was also used by Hutchinson (1992) as a method of evaluating the severity of potential numerical problems associated with a particular finite difference technique used in HST3D simulations of injection operations in southwestern Florida. If the two different models produced similar results, then the numerical problems were considered minimal, and credibility was gained for a particular finite difference method used in the HST3D simulations. Results of the comparison indicated that the finite element results in the SUTRA simulations were most similar to the centered-in-space, backward-in-time (CIS-BIT) finite difference methods in the HST3D simulations. The CIS-BIT finite difference methods were then used for the remaining HST3D simulations.

Mathematical Model Comparison -

Four mathematical models that can be used to simulate injection for the purposes of evaluating Class I injection sites are summarized in the previous paragraphs. Specifically, these models estimate the short and long-term effects of injection in the subsurface environment, such as the extent of both vertical and lateral waste movement, pressure responses, and energy transfer. However, the application of a specific model depends on the amount of detail necessary to accurately simulate an injection operation. For example, the Basic Plume Method provides a conservative estimate of horizontal movement of the injected waste over time if a greater degree of detail concerning local effects of injection is unnecessary. However, the Intercomp, HST3D, or the SUTRA models provide greater detail if local effects of injection cannot be neglected. Representative features associated with each model presented are listed in table 2.

The literature overview indicates that more case studies are available in which the Intercomp model has been used to simulate the fate and transport of injected waste than the other three models, probably because the Intercomp model has been available approximately 10 years longer than the other three models. The literature overview indicates that very few case studies are available in which the Basic Plume Method and the SUTRA model have been used to simulate injection, and that only a few case studies are available in which the HST3D model has been used to simulate injection.

Table 2. -- Summary of features associated with the Basic Plume method, Intercomp model, Heat and Solute Transport model, and Saturated-Unsaturated Transport model

Representative feature method	Injection simulation model			
	Basic Plume model	Intercomp model	HST3D model	SUTRA
Ground-water flow is described by Darcy's Law to some extent	X	X	X	X
Accounts for density-driven flow	X	X	X	X
Solves separately for ground-water flow, solute transport, and energy transport	X	X	X	
Accounts for regional flow patterns	X	X	X	X
Aquifer properties may vary		X	X	X
Can be used to describe inhomogeneities in the geologic setting		X	X	X
Uses sub-model approach to describe specific components of an injection operation	X	X	X	X
Accounts for multi-well operation	X	X	X	X
Accounts for leakage through abandoned wells or faults/fractures	X	X	X	X
Finite-difference methods are used	X	X	X	X
Uses combination of finite-element and finite-difference methods				X
Primarily three-dimensional		X	X	
Option for two-dimensional cylindrical coordinates		X	X	
User has a choice of iterative techniques to solve matrix equations		X	X	
Frequency of use in injection studies	very few	several	few	very few

LITERATURE OVERVIEW OF METHODS TO MONITOR CLASS I INJECTION SITES

In addition to a comprehensive site evaluation, a monitoring program is also required for Class I injection wells. A monitoring program is developed to prevent or detect contamination problems within the area of review during the operation of the injection well and after operations cease. A monitoring program for a Class I injection site includes minimum requirements common to all Class I operations and may include additional monitoring based on site-specific evaluations. Findings of the literature overview concerning required monitoring and possible additional monitoring for a Class I injection site are presented in the following paragraphs.

Required Monitoring

The minimum requirements for monitoring Class I injection wells primarily address the injection well operation only (U.S. Environmental Protection Agency, 1990). For example, the injected waste is monitored continuously to provide information concerning both temperature and chemical compatibility between the injected waste and injection zone materials. In addition, injection pressure, flow rate and volume, and annulus pressure are also monitored. By monitoring the injection pressure, flow rate, and volume, induced seismic activity due to pre-existing or potential faults and fractures in the injection zone may be prevented. By monitoring the annulus pressure, mechanical failures such as ruptures in the injection tubing can be detected to prevent leakage into overlying geologic layers, particularly formations containing an underground source of drinking water (U.S. Environmental Protection Agency, 1990, p. 691-696). Data from required monitoring are recorded on a 24-hour schedule, and any non-compliances during operation are reported to the State UIC agency (Office of Pollution Control) immediately. Periodic inspections of the injection facilities and records are also permitted to verify the monitoring programs.

The extent of required monitoring is determined by site-specific hydrogeologic settings. In Alabama for example, highly toxic injected wastes and injection practices located in seismic zones required more stringent monitoring programs (Hanby and others, 1973). The monitoring programs included continuous monitoring devices with alarms and automatic shut-down systems for cases of system malfunctions. In Florida, monitor wells located near an injection well were required to measure water-level changes in permeable zones above the injection zone in response to injection volume changes and were also used to sample for ground-water quality constituents (Wilson, 1976). For injection wells in Illinois, similar monitor wells were required; however, these monitor wells were enhanced by periodic integrity testing using pressure tests and geophysical logging (Visocky and others, 1986).

Monitor wells were required to detect contamination for an injection practice near Belle Glade, Fla. (McKenzie, 1976). A hot, acidic industrial waste was injected into the lower part of the Floridan aquifer, which is primarily composed of highly permeable carbonate rock. Two monitor wells were located near the injection well to detect potential upward migration problems. Both wells were used primarily to monitor hydraulic and geochemical changes within their respective completion areas. Upward migration of the waste, primarily due to dissolution of the formation materials and density differences between the injected waste and the formation fluids, was detected in the upper part of the Floridan aquifer approximately 3 years after injection began. Injection operations were temporarily halted to improve the design of the injection practice. However, upward migration of this particular waste continued, and the injection practice was shut down. The monitor wells were used primarily to detect upward migration of the waste; however, lateral or horizontal extent of contamination was unknown at that time. Additional monitoring that included monitor wells in the regional flow system was suggested to detect lateral waste movement (McKenzie, 1976).

Additional Monitoring

Injection permits may be modified to include additional monitoring activities if necessary (U.S. Environmental Protection Agency, 1990, p. 702-703). For example, if extensive contaminant movement is suspected, or if contaminant movement of any type is considered a significant threat to drinking-water supplies, additional monitor wells may be required. Additional monitoring is based on a site-specific assessment and on the potential value of using monitor wells to detect the contaminant movement. Additional monitor wells can be required to measure pressure buildup changes in the injection zone; pressure and ground-water quality changes in the overlying aquifer; and ground-water quality changes in the lowermost underground source of drinking water. Additional monitoring can continue for a specified time beyond well-closure, during which corrective action may be required if additional monitoring indicates contaminant movement not previously assessed.

Additional monitoring was included in a monitoring program developed by the U.S. Geological Survey near Milton, Fla. (Pascale and Martin, 1977). The monitoring program consisted of a standby injection well; a deep-test well, originally drilled to assess the potential of the site location for an injection well; a deep-monitor well, to monitor regional pressure effects and to detect any waste migration; and a shallow monitor well to detect local upward migration. The first three monitor wells were completed in the injection zone, and the shallow monitor well was completed above the upper confining unit. Data collected at these wells included injection rates, wellhead pressures in the injection and monitor wells, and water sample analyses (Pascale and Martin, 1977). After 1 year of injection, pressure increases were detected in the three wells monitoring the injection zone, and geochemical changes were detected only in the deep-test monitor well.

Long-term regional effects of injection may require monitor-well placement at distances beyond the proximity of the injection well. The location of additional monitor wells primarily depends upon the regional hydraulic gradient. When injection ceases and pressure buildup dissipates, the injected waste will migrate out of the injection zone in the downdip direction of the regional flow path. However, location of these additional monitor wells may also depend on other critical factors such as the potential to affect nearby drinking-water sources. Mathematical models can be used to help locate these regional monitor wells by supplying "worst-case" scenarios of waste migration. The Intercomp model was calibrated and used to estimate flow patterns of an industrial waste injected into the lower part of the Floridan aquifer for six injection practices near Tampa, Fla. (Hickey, 1981). Pressure and velocity changes were computed for 20 years of projected wastewater injection at these sites. The results of the model simulation were then interpreted with respect to regional flow patterns to estimate the most probable waste front location. Although the report indicated minimal regional impact from the injection activity, the results were used to propose three regional monitor well locations for the purposes of additional monitoring.

SUMMARY

Underground injection of industrial wastewater is a disposal process in which liquid waste is injected and stored below the surface of the earth. This report is a literature overview of methods used to evaluate and monitor Class I underground injection sites. Under current Underground Injection Control regulations (1993), Class I wells are used to inject hazardous or non-hazardous wastes below the lowermost formation containing a current or potential underground source of potable drinking water. Mississippi has six Class I wells: hazardous waste is injected into two wells in Jackson County and three wells in Harrison County; and non-hazardous waste is injected into one well in Hinds County.

The area of review surrounding a Class I well is composed of the injection zone, the confining units, and the formation fluid. The injection zone is required to have sufficient thickness, adequate porosity and permeability, and sufficient areal extent. The confining units are also required to have sufficient areal extent to contain the injected waste from upward or downward migration. The formation fluid is required to have a

dissolved-solids concentration greater than 10,000 mg/L, have little value, and be chemically compatible with the injected waste. Class I wells are designed to prevent movement of the waste into any geologic zone other than the injection zone. Typical Class I well designs include a surface casing, a well casing, injection tubing, a packer, and annulus fluid.

Methods used to evaluate the area of review of a potential Class I site can be divided into three common steps: collection of comprehensive site data, identification of potential hydrogeologic problems, and injection simulation using mathematical models. Data-collection techniques include geophysical logging and core testing. Geophysical logs are used to evaluate geologic strata, waste movement, and the structural integrity of the injection well. Core tests are used to identify more specific parameters of the area of review such as fluid temperature, pH, and pressure, and fluid levels in the injection zone.

After site data have been collected, potential hydrogeologic problems are then identified. Four common problems associated with Class I wells include chemical compatibility between the injected waste and the injection zone materials, abandoned wells, seismic activity, and subsurface migration of the injected waste out of the injection zone.

Mathematical models may be used in the evaluation of a potential Class I site by simulating injection over time. Four mathematical models summarized in this report include the Basic Plume Method, the Intercomp model, the Heat and Solute Transport model, and the Saturated-Unsaturated Transport model. Consideration was given to the availability of the models to local regulatory agencies and the wide-acceptance of applying these models to injection simulations. The application of a specific model depends on the amount of detail necessary to accurately simulate the injection operation. More case studies are available in which the Intercomp model has been used to simulate the fate and transport of injected waste than were the other three models, probably because the Intercomp model has been available approximately 10 years longer than the other three models.

In addition to a comprehensive site evaluation, a monitoring program is required for Class I injection wells to prevent or detect contamination problems within the area of review. A monitoring program includes minimum requirements common to all Class I injection operations and may include additional monitoring based on site-specific evaluations. Minimum requirements for the monitoring program primarily address the injection well operation only. Requirements include monitoring the nature of the injected fluid, the injection pressure, the flow rate, and the annulus pressure. Additional monitoring, such as monitor wells in the regional flow system, may also be required if potential contaminant movement is suspected or if contamination is considered a significant threat to potable drinking water supplies.

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