STATE OF OHIO
DEPARTMENT OF NATURAL RESOURCES
DIVISION OF GEOLOGICAL SURVEY
Horace R. Collins, Chief

Information Circular No. 43

SUBSURFACE LIQUID-WASTE INJECTION IN OHIO

by

Michael J. Clifford

Columbus
1975

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ABSTRACT

Subsurface waste injection in Ohio began in 1967 following passage of enabling legislation. Ohio law requires an injection permit issued by the Division of Oil and Gas and approved by the Division of Geological Survey, the Ohio Environmental Protection Agency, and in some cases the Division of Mines. Nine permits have been granted to date (March 1974). Seven wells are operating, one is under construction, and one has been plugged and abandoned. Two permit applications have been refused.

Injected waste fluids include spent HCl and H_2SO_4 pickle liquor, acrilonitrile waste, phenols, acetone, and brine. Volumes injected per well range from less than one million to about eight million gallons per month. In most cases the disposal method practiced prior to subsurface disposal was discharge into surface waters. At present, industrial waste is injected into the Mt. Simon Sandstone (Cambrian) at depths ranging from 2,750 feet to 5,600 feet. One well injects natural brine into the Oriskany Sandstone (Devonian). Experience to date indicates that the Mt. Simon is suitable for storage of moderate quantities of waste, but injection pressures sometimes have been high. Other formations are less suitable, principally because they have inadequate confining beds or have been penetrated by numerous wells.

Safety measures include monitoring of waste volume and of casing and annulus pressures. Well construction must include two strings of casing cemented to the surface through fresh-water zones, reserve storage or injection capacity, and surface pretreatment facilities.

Subsurface injection is viewed as an alternative to surface discharge and is useful mainly for long-term storage of "untreatable" wastes.

INTRODUCTION

PURPOSE AND ACKNOWLEDGMENTS

In view of rising demands for cleaner air and water, there is an increasing interest in the use of deep porous formations as permanent storage sites for liquid industrial wastes. This report has been prepared to evaluate the practice of and potential for deep injection in Ohio. Topics of consideration include the requirements for safe injection, benefits and risks, present installations, and geologic formations suitable for injection. It is hoped that this report will place the practice of deep injection in perspective as a possible means of management of industrial wastes in Ohio.

Warren Latimer of Natural Resources Management Corporation and Neilson Rudd of Geo-Engineering Laboratories provided information and discussion which helped to clarify certain facets of deep injection. Thanks are due to Dr. D. C. Bond of the Illinois Geological Survey for his advice on hydrodynamics. In addition the writer wishes to acknowledge the assistance of persons and organizations, too numerous to mention, who have contributed some of the data for this study. The report is based in part on an unpublished M.S. thesis (Clifford, 1972) prepared at The Ohio State University under the direction of Drs. Wayne A. Pettyjohn and Robert L. Bates.

PERSPECTIVE

The technology involved in the injection of unwanted fluids into the subsurface is not new, although techniques are constantly being improved. As early as 1918, attempts were made to force oil from deep beds by the injection of water (Walker and Stewart, 1968, p. 945). Injection of brine began in earnest in the 1940's, and today several *tens of thousands* of wells in the United States are used to inject brine into the subsurface, both to improve recovery of oil (waterflooding) and to dispose of the several *billion* gallons (Piper, 1969, p. 1 and 2) of brine produced each year along with oil and gas. This brine would otherwise be released into surface waters.

Industrial wastes have been injected into wells as early as 1950 (Donaldson, 1964, p. 1). The number of active liquid-waste injection wells in the United States in mid-1973 was 170 (Warner and Orcutt, 1973). In Ohio injection of industrial waste began in 1967 following passage of enabling legislation. Nine permits for wells have been issued; seven injection wells are now (March 1974) in active use, one is being completed, and one has been plugged and abandoned. In addition, one application is awaiting the results of litigation regarding the permit application, which was denied.

The results of this extensive experience with injection have been favorable for the most part. The failures and mistakes have been widely publicized, but out of these problems have come the identification of areas of legitimate concern and the body of knowledge necessary to engineer and control deep injection. For example, a recent bibliography (Rima and others, 1971) lists over 600 scientific papers devoted to various aspects of deep injection. Where the proper engineering and regulatory safeguards have been applied, the risk from deep injection is minimal.

WHY INJECTION WELLS ARE NEEDED

Many liquid wastes pose vexing disposal problems. The cheapest and most common method is discharge into surface waters, but increasingly stringent standards and enforcement have begun to eliminate surface discharge. Disposal into surface ponds or evaporation lagoons is unacceptable in many cases because of infiltration into ground waters, danger of overflow and dike breakage, and esthetic reasons. Surface treatment or recycling operations, even when technologically feasible, can require immense capital expenditure or can impose unacceptable operating expenses. Most surface-treatment methods also generate by-products which can be difficult to dispose of. For example, brines can be evaporated to dryness, using a great deal of heat energy, but the resulting impure solid salt has little market value and remains a disposal problem. Brines, radioactive wastes, and to a lesser extent phenols (from manufacture of plastics) and acid pickle liquors (by-product of steel manufacture) are examples of liquids which are difficult or impossible to treat economically.

Almost any treatment of wastes requires the input of energy. Production of this energy itself creates environmental hazards, and low-cost energy is becoming a thing of the past. There are cases then in which the liquid wastes may be "untreatable," either because the technology doesn't exist or because it is too expensive; environmentally the most acceptable solution seems to be deep-well injection.

BENEFITS OF DEEP INJECTION

Apart from the economic aspects there are certain other benefits to subsurface disposal. (1) Deep wells can be used for short-term disposal in order to "buy time" for the development of surface-treatment technology or to solve a specific nonrecurring problem. (2) Wastes may undergo beneficiation by contact with underground rocks: acids and bases will tend to be neutralized; certain substances, including organic compounds and radioactive elements, may be adsorbed on clays; radioactive substances may be held isolated from contact with plant and animal life until the substances decay; wastes will be diluted by interstitial waters. (3) Wastes emplaced in the subsurface will be isolated in rather localized areas. The rate of movement of fluids in deep formations is very slow, on the order of inches per year; thus wastes could be reclaimed by pumping wells if need be. Where surface discharge has been practiced in the past, dangerous materials such as mercury and pesticides have become dispersed in the environment and may have long-term deleterious effects; the deep-well disposal method would keep such wastes isolated.

CAUTIONS

Two factors restrict the practice of waste injection: (1) suitable reservoirs are few and (2) the volume of waste which can be injected safely into any one reservoir is limited. Subsurface storage space, like any natural resource, is finite and should be used wisely. The best use for deep reservoir space appears to be the storage of wastes which cannot be treated at the surface by the use of existing technology and which are too hazardous to be released into surface waters.

Reservoirs used for deep injection may become unsuitable for alternative uses. In the future, fresh-water storage, liquid or gaseous hydrocarbon storage, brine extraction, radioactive-waste injection, or other uses may compete for the available space in deep reservoirs. As more nuclear power plants are built, radioactive-waste injection may become the most important of these uses.

CRITERIA FOR SAFE INJECTION

RESERVOIR CHARACTER

General nature.—In order for a formation to accept fluid at practical volumes (generally at least 50 gallons per minute for industrial waste) the formation must be thick enough and have sufficient porosity (ratio of void space to total volume) and permeability (ability of the rock to transmit fluid) for the fluid to be forced into the formation at pressures which do not create hazards. The porosity, permeability, and thickness are interrelated; a relatively thin unit with high porosity and permeability serves as well as a thicker body with less porosity and permeability. The rock types likely to have good injection characteristics are sandstones, limestones, and dolomites. In general, sandstones have greater uniformity, greater predictability, and higher injectivity than carbonates. The areal extent of the unit is also important; the formation must be continuous over a wide area (at least hundreds of square miles) so that the pressures resulting from injection may be transmitted away from the well bore. Too great an increase of pressure near the well bore may have unacceptable effects, as discussed in later sections.

Porosity.—Porosity is measured by means of core analysis and geophysical well logs and is expressed as a percent of the total rock volume. Typically, porosity in sandstones ranges from about 30 percent for a well-sorted loosely cemented medium- to coarse-grained sandstone to 5 percent or less in a poorly sorted finer grained well-cemented or dirty sandstone. Porosity in carbonate rocks is extremely variable, ranging from essentially zero in very fine-grained rocks to 40 or 50 percent in cavernous rocks. There is an indirect relationship between porosity and permeability; higher porosity generally indicates greater permeability.

Sandstones of the Appalachian Basin, although they may be at sufficient depth to be suitable reservoirs, tend to have low porosity. Most carbonate rock bodies in Ohio also have low porosity. In some provinces (for example, the Gulf Coast) where sandstones are younger and have undergone comparatively less cementation and compaction, porosities of 20 percent or more are common. Very few of the deep formations in Ohio have sufficient porosity to be considered as reservoirs. In Pennsylvania, which has rocks similar in part to those in Ohio, Rudd (1972, p. 89) concluded that "... there are no known reservoirs of truly good disposal quality."

Permeability.—The unit of permeability is the darcy, defined as that permeability which will allow a fluid of 1-centipoise viscosity (the viscosity of fresh water) to pass through a 1-square-centimeter cross-sectional area at a rate of 1 milliliter per second under a pressure gradient of 1 atmosphere per centimeter. Permeabilities are generally reported in millidarcys (1/1000 of a darcy). In ground-water hydrology the unit equivalent to the darcy is the coefficient of permeability in gallons per day per square foot (1 darcy equals 18.2 gpd/ft^2).

Permeability may be measured from a drill-stem test or from core analysis. A drill-stem test is a short-term flow test through the drill pipe; when properly performed this test gives an accurate reflection of permeability of the unit as a whole. Core analyses for permeability have some shortcomings. Core permeabilities are commonly determined by passing a pressurized inert gas through selected small-diameter (½-inch) plugs taken from the core at 1- or 2-foot intervals. If permeability is high, there tends to be a reasonable correlation between permeability to gas and permeability to water or other liquid. Where permeability is low, especially below 10 md, complex factors such as surface-area effects and polar attraction can cause wide differences between liquid permeability and gas permeability (Neilson Rudd, personal communication). Furthermore, core-plug tests are accurate only if the plugs are representative of the whole rock. Ideally, core analysis should be performed on sections of whole core rather than on small plugs and should be measured relative to water or, better yet, to samples of the effluent liquid.

Sandstone permeabilities range from about 5 to 10 md for a well-cemented fine-grained sandstone to more than 2,000 md for a loosely packed well-sorted sandstone. Permeability of shale is commonly as low as 1 x 10^{-6} to 1 x 10^{-8} md. Permeability of carbonate rocks differs markedly from place to place. Experience has shown that a formation permeability of about 25 md or more is necessary for injection of reasonable volumes of waste on a constant basis (Donaldson, 1972, p. 35). Few Appalachian Basin reservoirs have that permeability. In addition, even the best core analysis or drill-stem test cannot measure the effect which fractures might have on the permeability of the reservoir or of the confining beds.

SALINITY

The salinity of the injection zone should be high, at least above 10,000 mg/l total dissolved solids. Sea water, by comparison, has a salinity of about 35,000 mg/l total dissolved solids. High natural salinity indicates that the reservoir contains slow-moving fluid which is isolated from surface and subsurface sources of fresh water. Reservoirs containing fluid of low to moderate salinity may have future use for potable-water storage or for desalination and should be excluded from injection.

In general, salinity of a formation increases with depth. In Ohio fresh-water-bearing formations occur below 500 feet in only a few places. Information on the names and depths of the lowest local fresh-water aquifers in Ohio can be found in Sedam and Stein (1970). Additional data on depths to saline water are in Stout and others (1943).

MINERAL DEPOSITS

The injection zone should not contain valuable mineral deposits. Under Ohio law a permit application may be denied if oil, gas, or other minerals would be endangered. Figure 1 shows the areas in Ohio in which oil and gas have been produced. Large areas of Ohio not now producing may yield hydrocarbons in the future.

Other mineral deposits in Ohio that might be affected by disposal operations are natural brine, coal, salt, and gypsum. Natural brine from Mississippian and Pennsylvanian beds historically has been a valuable deposit in the lower Ohio River valley, but the brine is not presently a valuable deposit elsewhere. Coal is produced in much of eastern Ohio. Injection operation, if permitted in shallow sandstones, could pose a distinct hazard, especially to deep mines. Rock salt is produced from Silurian beds in northeastern Ohio. Gypsum does not occur at the depths injection is practiced.

CONFINING BEDS

The injection zone must be confined by sufficient thicknesses of relatively impermeable strata so that vertical migration of fluids is negligible. Further safety is assured if there are great thicknesses of rock between the disposal zone and overlying fresh-water aquifers.

Shale, salt, anhydrite, and certain types of limestone and dolomite are good confining rocks. Of these, shale, anhydrite, and salt are the best because they behave in a slightly plastic manner when compressed at depth and are able to flow slightly to seal fractures and small faults.

In order to illustrate the effectiveness of the confining beds, the following example is given: If an attempt is made to force fluid to flow through a 1-foot-square cube of shale of average permeability (1 x 10^{-7} md) by applying a pressure of 100 psi, the resulting flow is only 4 x 10^{-7} gpd. If the shale were 1,000 feet thick, only 4 x 10^{-10} gpd could escape. In an actual disposal operation only a relatively small

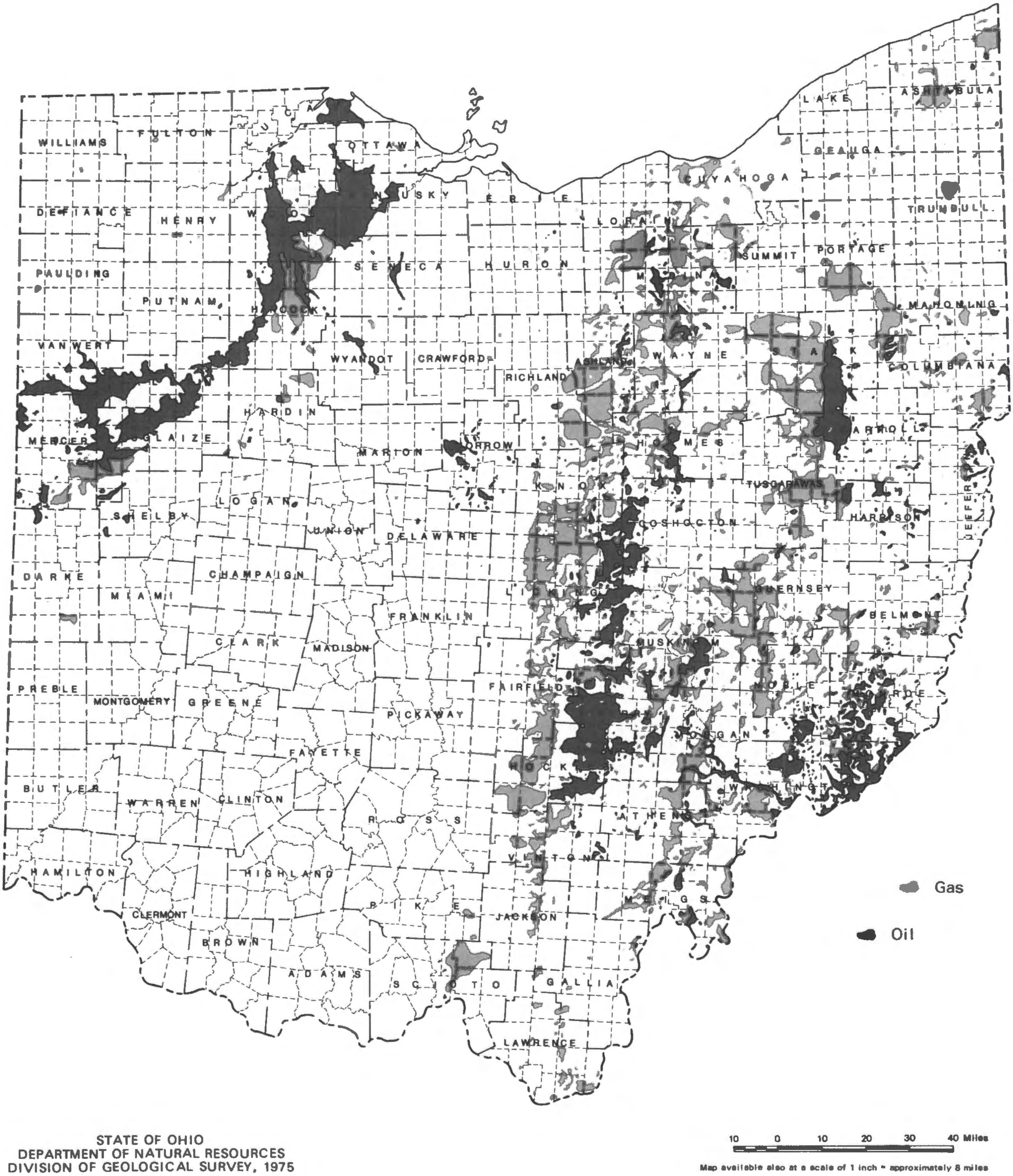

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FIGURE 1.–Oil and gas fields map of Ohio.

area (a few tens of square miles) around the bore hole would be exposed to pressure differentials of 100 psi or more. The volume of fluid which could escape through a square mile of shale 1,000 feet thick, assuming a pressure differential of 100 psi, is about 0.01 gpd. This example does not translate in all respects to the situation of deep disposal, but it does show that wastes can be effectively confined by impermeable strata.

Brittle rocks such as limestone and dolomite are commonly fractured and jointed. It is not clear whether these rocks are effective confining beds, even though their vertical permeability, measured in core plugs, may be low.

STRUCTURE AND SEISMICITY

Faults, folds, fractures.–Geologic structures in the area of disposal wells should be simple and unfaulted. Fracturing, commonly associated with folding of rocks, and faulting may create vertical conduits and paths of weakness through which fluids might escape deep reservoirs. Pressure and cementation are thought to seal most faults and fractures so that they are impermeable. However, it is wise to avoid locating disposal wells where structural disturbances exist.

The general subsurface configuration of Ohio is relatively simple. The major structural feature is the Cincinnati arch, a broad almost flat-topped high area that trends northeast-southwest across the western part of the state. A map (Owens, 1967, pl. 1) of the structure of the basement rocks in Ohio shows that dips near the arch are less than ½°, but increase to almost 1° in Perry County and are slightly higher farther east. Mapping (Owens, 1970) at higher stratigraphic levels, where control is more abundant, shows essentially the same gentle structure on the top of the Columbus (Onondaga) Limestone of Devonian age. The general structural style of the deep beds in Ohio is then one of gentle dips that are interrupted by a few small low-amplitude folds.

Janssens (1973) has mapped most of the few known structural anomalies in deep beds in Ohio. He shows that closure on the Knox Dolomite exceeds 50 feet in only a few places and that closed highs are rarely greater than 1 square mile in area. None of these deep structures are associated with faulting.

Although Ohio has little structural deformation compared with most states, the few known indications of faulting are sufficient to warrant caution in locating disposal wells. A normal fault, down-to-the-lake and with about 50 feet displacement, was noted in a salt mine in Cleveland (Jacoby, 1970). This fault may connect with or be en echelon with a similar fault mapped by Kelley and McGlade (1969) in Erie County, Pennsylvania. In eastern Ohio where salt beds are present the overlying rocks have been disturbed in places by thin-skinned horizontal thrusting and by vertical salt flowage. The competent beds associated with these movements may be extensively fractured and there may be numerous small-displacement faults. In a seismic reflection study of western and central Ohio Mayhew (1969) mapped a few localized small-displacement faults. A structural anomaly in the Bowling Green area (Hancock and Wood Counties) has been interpreted as a fault by some (for example, Farnsworth, cited by Forsyth, 1966, p. 208). The surface evidence regarding the fault is equivocal, and the subsurface control is not definitive. A well in Harlem Township, Delaware County, shows an unusually thin dolomitized Black River-Trenton (Middle Ordovician) sequence; a normal fault is postulated to pass through this well. Where question exists about the possibility of faulting, reflection seismic surveys could be conducted in the vicinity of the well. After disposal wells are drilled, sample- and geophysical-log information should be examined carefully to determine if any abnormal stratigraphic conditions indicative of faulting are present.

Seismicity.–The area of proposed injection should be one of low stress accumulation as evidenced by low levels of seismic activity. Evans (1966, p. 15) has suggested that deep injection in a disposal well at the Rocky Mountain Arsenal near Denver could be correlated statistically with an increase in seismic activity in the vicinity of the well. Since that time several studies have been made to determine whether a cause-and-effect relationship exists. Most investigators (for example, Healy and others, 1968) now believe that deep injection did trigger seismic events. However, Simon (1969) maintains an opposing view. Deep injection was discontinued in the Rocky Mountain Arsenal well in February of 1966, but a lower level of seismicity persists. It has been confirmed (Raleigh, 1972, p. 275-278) that earthquakes were associated also with waterflood injection at the Rangely oil field in northwestern Colorado. Investigators agree that both areas had a previous history of stress accumulation from tectonic shearing, evidenced by faulting and earthquake activity prior to deep injection. The epicenters of the earthquakes at both locations are thought to be located along pre-existing faults. The pressure from injection wells triggered the quakes by relieving a fraction of the frictional resistance to shear along the fault plane. In neither case was the specific fault and shear-stress couple known prior to injection. It has been suggested that the Denver injection well possibly prevented a damaging earthquake by releasing the stress in a series of minor quakes (U.S. Army Corps of Engineers, 1966). Where the hazard of earthquakes is high, this process of intentional injection could be used to produce minor quakes so as to eliminate major ones (Evans, 1966, p. 17).

There are three seismic stations in Ohio (Cleveland, Bowling Green, and Cincinnati) that are capable of detecting quakes of sufficient intensity to be felt by humans. Since waste injection started in 1967, there has been only one shock reported in Ohio; the epicenter was southeast of Columbus, many miles from the nearest injection well. Historically there have been several seismic disturbances in Ohio, fairly well distributed over the state, with an area of high concentration near Anna, in Shelby County (Bradley and Bennett, 1965). The most severe of these reached a magnitude of 5 to 6 on the Richter scale.

From these and other quakes reported by Bradley and Bennett it appears that there probably is stress accumulation in Ohio, although of a low order; this leaves open the possibility that deep injection near shear planes could trigger quakes. Until more evidence is available on this problem, care should be taken to locate injection wells away from seismic epicenters and fault zones. At this time there are no seismic monitoring devices sufficiently close to injection wells to detect *micro*seismic (not detectable to humans) events in Ohio, but it is reasonably certain that no earthquakes greater than about 2 (detectable to humans) on the Richter scale have resulted from deep injection.

COMPATIBILITY

The injected fluid should be compatible with both the fluid in the reservoir and the reservoir rock itself so that hazardous reactions do not occur. There are no likely situations in which such reactions directly create a hazard; the danger arises indirectly in that incompatibility reactions tend to reduce permeability; reduction of permeability in turn causes higher injection pressures. Because there is a limit imposed on injection pressures, it is incumbent on the operator to engineer his operation so that pore-plugging reactions do not occur.

Fluid-fluid reactions.—The various reactions between effluent and reservoir fluid have been summarized by Warner (1965, p. 27-30) and include:

1. Precipitation of alkaline earths such as calcium, barium, strontium, and magnesium as relatively insoluble carbonates, sulfates, orthophosphates, fluorides, and hydroxides;
2. precipitation of heavy metals such as iron, aluminum, cadmium, zinc, manganese, chromium, and others as insoluble carbonates, bicarbonates, hydroxides, orthophosphates, and sulfides;
3. precipitation of oxidation reduction reaction products;
4. polymerization of resin-like materials to solids under aquifer temperature and pressure.

Many common wastes are incompatible to some degree with reservoir fluids. To overcome this problem it has been necessary to inject fresh water, which is generally compatible with both waste and reservoir fluid, as a buffer prior to injecting wastes. Such buffers have been quite successful. Volumes totalling between 1 and 5 million gallons per well have been used on most of the Ohio wells.

Rock-fluid reactions.—Permeability-reducing reactions between injected fluid and reservoirs have been discussed by Warner (1965) and by Hower and others (1972) as summarized below:

1. Acid reaction with limestone or dolomite to produce carbon dioxide gas. The presence of gas may reduce permeability by introducing a second phase of fluid (Rudd, 1972, p. 20). The solution of carbonates may release fine particles which could plug pores. An opposing effect is possible because solution of matrix and cement creates additional permeability. The evolution of gas also could increase the pressure in the reservoir (Warner, 1965, p. 29). However, various acids have been injected successfully into carbonate reservoirs (Donaldson, 1972, p. 28-29). The writer is aware of no evidence that acid injection into carbonates is necessarily unfeasible.

2. Swelling of clay particles. Permeability may be reduced when montmorillonite and some mixed-layer clays absorb water, causing swelling and possibly dispersion and migration. Where the injected fluid is less saline than reservoir fluid, the condition may be severe. Solutions of high pH may also cause clay to expand.

3. Adsorption. Clays, and to a lesser extent quartz, may adsorb polar organic compounds to such an extent that permeability is reduced.

4. Solution of amorphous quartz and feldspar. Under certain conditions of pH and temperature, solution of quartz and feldspar may be sufficient to release fine particles which could cause plugging. In addition, the formation of silica gel is possible.

UNPLUGGED WELLS

A very important criterion for deep injection is that there should be no unlocated or improperly plugged wells penetrating the confining beds within a wide radius of the injection well. The radius within which unplugged wells would constitute a hazard depends upon the volume to be injected and the character of the injection zone, but such radius would be at least 2 miles and possibly up to 20 miles. This may be the most serious constraint on deep injection into many formations in Ohio, because hydrocarbon production dates back well before 1900, and records of old wells are incomplete.

Table 1 is an estimate of the total number of wells drilled to different formations. It is apparent that the potential danger from unplugged wells can be very great, especially in post-Cambrian strata.

The matter of determining what constitutes adequate well plugging is a vexing problem and is one of the least researched in the field of petroleum technology. In the past, various crude devices were used in attempts to plug wells. Such expedients as forcing tree trunks down the bore hole and adding dirt, rocks, limestone screenings, or anything handy were attempted. The producing-casing strings and fresh-water casing were pulled out of some holes, not out of others. In many places disappointed drillers merely walked away from the hole. However, more modern plugging methods involve the placement at several levels in the well of cement plugs, with dense mud between plugs. Such plugging is probably adequate to resist any pressure likely to result from deep injection. One of the most serious problems in deep injection appears to be that of unlocated poorly sealed wells, which can be high-permeability conduits through which fluid—either the waste itself or the highly saline fluid it displaces—can escape the confining beds. For this reason the Mt. Simon is the most favorable injection zone in Ohio.

MOVEMENT OF FLUIDS

Hydrodynamic flow.—Movement of fluids within the

TABLE 1.–*Number, depth, and location of wells in Ohio*

Period	Estimated number of wells	Normal depth (ft)	Area of dense drilling
Mississippian and Pennsylvanian	100,000-150,000	500-2,000	Eastern and southeastern
Silurian and Devonian ("Clinton," "Newburg," and Oriskany)	51,000	1,500-5,000	East-central
Ordovician (Trenton)	75,000	1,100-2,000	Northwestern
Cambro-Ordovician (Knox)	3,000	2,000-3,000	Central
Cambrian (Mt. Simon)	150	3,000-5,000+	Widely scattered

injection zone must be so slow that fluids cannot migrate to outcrops or other areas where they would present hazards in the foreseeable future (Piper, 1969, p. 8-9). In general, velocities of flow in deep reservoirs of low permeability are on the order of inches per year. Rarely do velocities in the deep subsurface exceed a few feet per year under any condition (Galley, 1968, p. 6). In the Appalachian Basin drilling operators do not generally record the sort of pressure data necessary to calculate velocity of flow; consequently, velocities cannot be estimated for any formation but the Mt. Simon Sandstone.

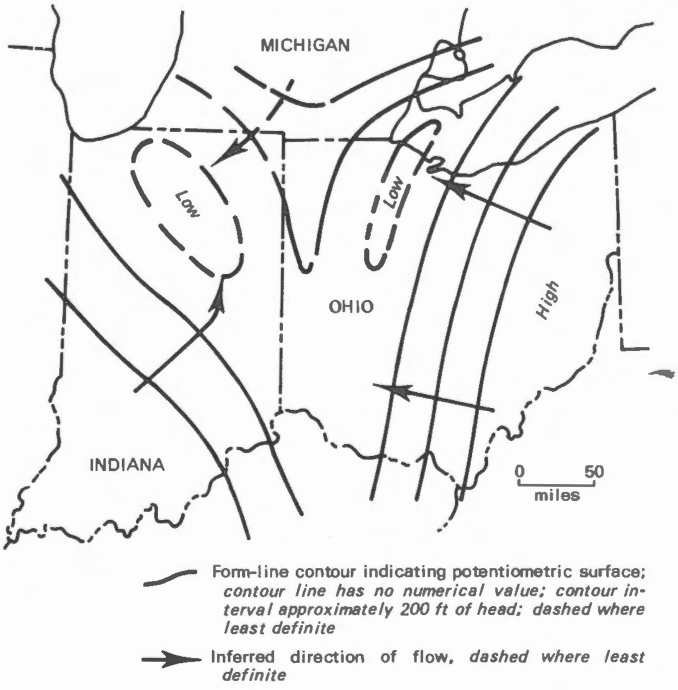

FIGURE 2.–Form-line contour map showing potentiometric surface of the Mt. Simon Sandstone; corrected for density variation.

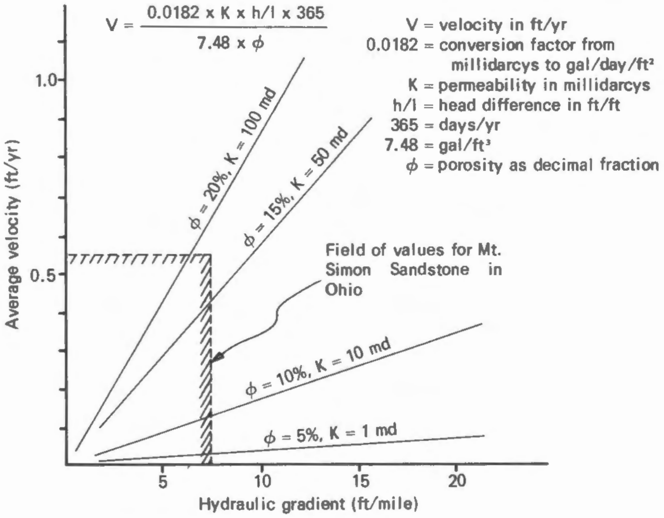

FIGURE 3.–Average velocity of flow as a function of hydraulic gradient for several values of porosity and permeability.

In order to show the possible direction and rate of flow of formation fluids in the Mt. Simon, Clifford (1973) constructed a potentiometric surface map using all available well-pressure data. The resulting map (fig. 2) shows the possible direction of flow (from high- to low-pressure areas) and shows also that head differences between points are slight (less than 7 feet per mile, averaging about 3 feet per mile). Velocity of flow can be estimated by Darcy's law from porosity and permeability data combined with data on head differences. Figure 3 shows the relationship between velocity and head difference for several values of porosity and permeability representative of those found in the Mt. Simon. It can be seen that flow rates would not exceed a few inches per year. Bond (1972) has found that head differences in the Mt. Simon in the Illinois Basin are also slight, indicating slow flow rates there also.

Bond (1972, 1973) shows that deducing flow directions from potentiometric data depends on some assumptions which may not be warranted. When reservoir-fluid density varies greatly, as it does in the Mt. Simon, Bond shows that it may not be possible to make adequate corrections without extensive data on distribution of salinity, data which are not now available. Further, he shows that in some cases flow may not exist even though head differences are present. It appears that the flow directions shown in figure 2 should be treated as tentative until more data are available. However, the conclusion that formation fluid in the Mt. Simon is flowing very slowly, if at all, appears to be valid.

Natural flow is not to be confused with radial flow under pressure of waste fluids. This flow, as discussed in the next section, might be expected to move wastes as much as a mile from the well during a span of perhaps tens of years.

Density contrast.—Additional movement of waste fluids might arise from a downdip or updip flow caused by emplacing a waste fluid which is either heavier or lighter than the reservoir fluid. In most cases the resulting velocity is negligible, either because dip is low or because the density contrast is small. In the U.S.S. Chemicals #1 well in Green Township, Scioto County, the density contrast and dip are more significant. A buoyant force equivalent to a head of 19 ft/mile is created and would yield a velocity of almost 1 foot per year (in a northwest direction). Even this rate is not so high as to cause alarm.

MECHANICS OF INJECTION

PRESSURE EFFECTS

The pore space in deep reservoirs is already filled with saline water. In order to inject waste fluid it is necessary to apply pressure to displace the native fluid. It is not necessary to displace the fluid very far to create an enormous storage space around the well bore. Given an injection formation with a thickness of 200 feet and a porosity of 10 percent, the pore space within a radius of one-half mile of a well in this formation can be calculated from the formula for the volume of a cylinder:

$$V = \pi r^2 h \phi = 4 \times 10^8 \text{ ft}^3$$

where $\pi = 3.14$, $r = 2{,}640$ feet, $h = 200$ feet, and $\phi = 0.10$. One cubic foot of liquid equals 7.48 gallons; thus the storage space is 30×10^8 gallons. If a well were to inject 3 million gallons of waste per month, there would be waste storage for 90 years within a one-half-mile radius of the well.

The effect of injection is to increase the reservoir pressure around the well. The general magnitude of the pressure increase at various distances from the well can be calculated by means of the Theis nonequilibrium formula (discussed by McLean, 1968, p. 25-27). Examples of pressure increase with distance have been calculated for three cases in which reservoir parameters approximate those of the Mt. Simon in Ohio (fig. 4). The calculations are based on an injection rate of 100 gallons per minute continuously for 1- to 10-year periods.

Figure 4 shows several important aspects of deep injection. Note that pressure declines exponentially away from the well. This is heartening for at least two reasons. First, old wells penetrating the injection zone at distances of several miles from the well will not be exposed to high pressures. Second, the amount of cross-formational flow through the aquitard depends on both the pressure and the area. The high pressures are restricted to areas near the bore hole.

Another factor shown on figure 4 is that injection pressures increase with time, but the rate of increase decreases exponentially. In addition, the graph shows that it is possible to estimate the initial injection pressure by calculating head at r = 1. The pressure-decline calculations are based on ideal conditions of isotropic and homogeneous reservoirs and other assumptions. Such calculations should be used only as approximations of actual conditions.

Pressure declines rapidly away from the well bore because the pressure necessary to displace the original reservoir fluid also compresses both waste and native fluid and slightly expands pore space by compressing the rock matrix. Neither water nor rock is very compressible; however, the volume of each upon which the pressure acts is so large that enough additional storage space is created within a relatively short distance of the well bore to absorb much of the pressure increase which would otherwise be transmitted laterally great distances. For additional technical discussion of the mechanism of waste emplacement see McLean (1968), van Everdingen (1968), and Witherspoon and Neuman (1972).

For most operations, beyond about 10 to 20 miles from the site of injection, the pressure theoretically will not be raised above a few pounds per square inch in the injection formation. In addition, as discussed in a later section, the injection pressure has recently been strictly limited by state agencies so that even near the well bore pressure is not high enough to cause foreseeable problems.

FRACTURING

Necessity for limit.—There are four primary reasons for limiting injection pressures: (1) High pressures may lead to failure of the well-head equipment, rupture of tubing, packer failure, or other mechanical failure. (2) High pres-

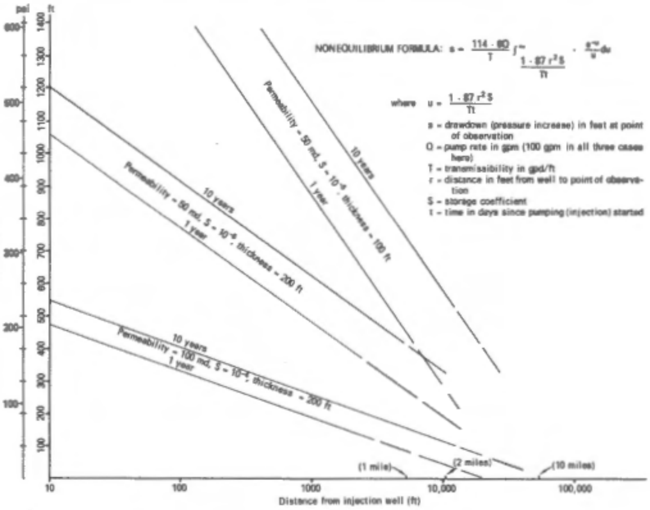

FIGURE 4.—Pressure increase as a function of time and distance; based on continuous injection rate of 100 gpm.

sures may induce artificial fracturing of the receiving formation as well as of confining beds. (3) High pressures increase the rate of cross-formational flow across confining beds. (4) The possibility of initiating seismic activity, although remote, increases with increasing reservoir pressure.

When artificial fracturing is created in the injection reservoir, several undesirable situations are produced. In a normally stressed region such as Ohio, fractures are likely to be vertical at depths below about 1,000 feet (Hubbert and Willis, 1957). Such fractures could, if injection pressure is sufficiently high, rupture the confining beds and allow escape of wastes from the reservoir. Such cases are known to exist (Rudd, 1972, p. 27; Howard and Fast, 1970, p. 169; Felsenthal and Ferrell, 1971, p. 728). Phar (1970) gives an example in which a routine hydraulic fracture of the "Clinton" sandstone (Silurian) reportedly also fractured the underlying shale beds.

If the fluid is transmitted through fractures rather than through pore space, it is not possible to calculate the radius of influence; thus a valuable management control is lost. Fractures tend to propagate in preferred directions, generally parallel to the regional structural strike, and could transmit fluid some distance from the injection well.

Injection pressure limit.—Recognizing the dangers inherent in the injection of wastes at high pressures, the Division of Geological Survey in 1971 recommended a maximum injection pressure of 0.75 psi/ft as an arbitrary limit for injection wells in Ohio. The Division of Oil and Gas has adopted this pressure limit, applied as follows:

$$\text{maximum surface injection pressure} = (d \times 0.75) - (d \times P)$$

where d = depth to highest perforation or top of open hole, and P = the pressure gradient in psi/ft of the effluent. Assuming a well in which the top of the injection zone is 4,000 feet below the surface and the waste fluid has a pressure gradient of 0.5 psi/ft, the maximum allowable surface injection pressure would be:

$$(4{,}000 \times 0.75) - (4{,}000 \times 0.5) = 1{,}000 \text{ psi}$$

Predicting fractures.—At present there is no foolproof method by which the exact pressures necessary to induce fracturing can be predicted. However, some guidelines can be used to provide adequate protection until additional data in a given area are available. When wells are artificially fractured, fluid is pumped into the wells at increasing pressure until there is a sudden increase in injection volume without a pressure increase; in some cases there is an actual decrease in pressure. This is called the breakdown pressure and is assumed to indicate that the formation has ruptured. Breakdown pressures have been compiled and published for different areas of the country (Howard and Fast, 1970, p. 6-8; Matthews and Cesmirosky, 1972, p. 62-63). Breakdown pressures in poorly consolidated high-pressured sands tend to be high, between about 0.75 and 1.0 psi per foot of depth. Carbonates and highly consolidated sandstones tend to have lower breakdown pressures, between about 0.6 and 0.8 psi/ft. The actual data show a wide spread of pressures varying according to regional stress, lithology, condition of the bore hole, number and type of perforations, viscosity of fracturing fluid, and other conditions. There have been no data published on fracture pressures in Ohio, but there are indications that the range is similar (0.6 to 1.0 psi/ft) to those given above. Most breakdown pressures are higher than 0.75 psi/ft.

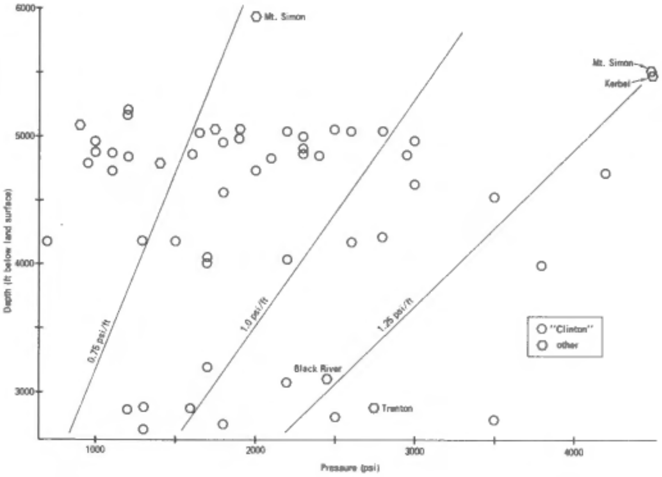

FIGURE 5.—Fracture-breakdown pressure versus depth (based on data from recent Ohio completions).

Breakdown pressures from recent completions in Ohio are shown in figure 5. Almost all data are from the "Clinton" sandstone. It is not certain whether fracture pressures in the "Clinton" would be similar to those in the Mt. Simon or other formations, but regional stress patterns are a causal component of these pressures, and regional stress should be alike for both older and younger units. It is noted that fracture pressures in about 80 percent of the wells are higher than 0.75 psi/ft. In addition, fracture pressures are significantly lower in formations, such as the "Clinton," in which pressure is depleted by production; in undisturbed units the fracture gradients would be much higher (Felsenthal and Ferrell, 1971). The few data from older formations in Ohio show breakdown gradients above 0.75 psi/ft.

In addition to the breakdown pressure, valuable information is gained also from the instantaneous shut-in pressure (ISI) in hydraulic fracturing. At the end of a hydraulic-fracturing treatment, the pumps are turned off, and the pressure declines instantly to a lower pressure (the ISI), from which it then declines more slowly. This instantaneous shut-in pressure, believed to indicate the pressure at which the induced fracture, held open by the injection pressures, closes (Howard and Fast, 1970, p. 98), is a valuable piece of information because it is less affected by the many operational and bore-hole factors that affect breakdown pressures. When this pressure is known, it could be used to regulate injection pressures. If injection pressure is kept below the ISI, the fracture should not open or propagate. Unfortunately, the ISI can only be known *after* fracturing has occurred; the Geological Survey believes that in general wells for waste injection should not be fractured as part of a completion program.

Although data on ISI pressures are rarely reported to the state, the Dowell Corporation (J. L. Norton and G. P. Boland, written communication, May 5, 1972) has kindly supplied ISI values from fracture treatment of some randomly chosen "Clinton" wells representing 25 counties (fig. 6). As expected, the ISI data show less scatter than do breakdown pressures (fig. 5). The average ISI pressure at the perforations is 0.733 psi/ft. Some of the data scatter is probably due to the varying degree of depletion of pressures in the "Clinton" in each location. If the ISI pressures had been taken from wells at original pressure, the average would certainly have been higher than 0.733 psi/ft, probably well over 0.75 psi/ft.

Only two injection wells in Ohio are known to have had fracture treatments as part of the completion program. In the Calhio #1 well in Perry Township, Lake County, the Mt. Simon was fractured at a pressure gradient of 0.77 psi/ft. The Kerbel section fractured at 1.25 psi/ft. In the U.S.S. Chemicals well in Scioto County the Mt. Simon was fractured at a pressure gradient of about 1.24 psi/ft at the top perforation. The ISI pressure was 1,350 psi, which would convert to a gradient of about 0.68 psi/ft.

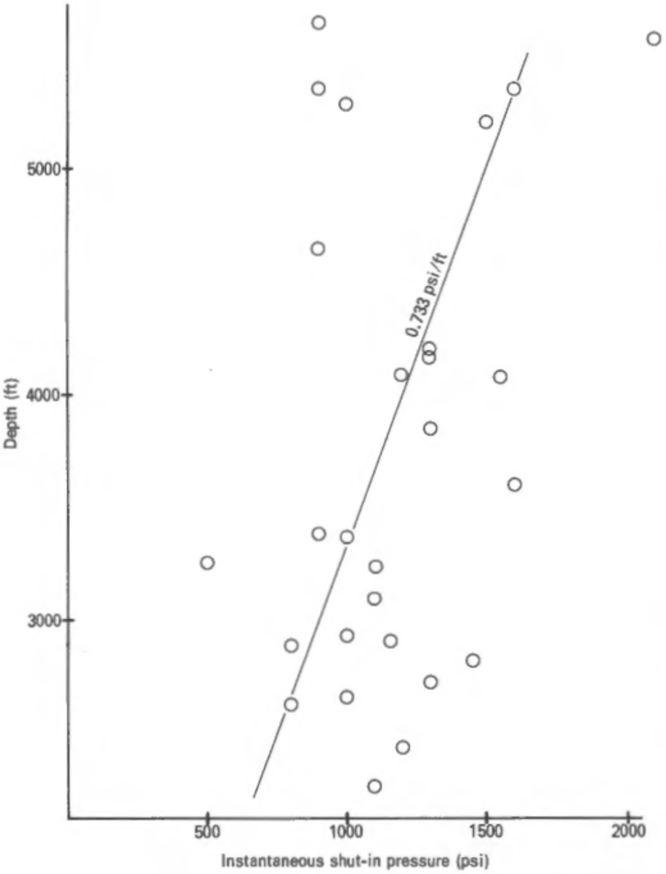

FIGURE 6.—Instantaneous shut-in pressure versus depth, "Clinton" sandstone.

From these limited data, it appears that an injection pressure limited to 0.75 psi/ft at the perforations or top of the open hole provides reasonable assurance that artificial fracturing will be prevented, provided that the formation has not been intentionally fractured as part of the completion program or is not a pressure-depleted formation.

Other states and organizations have adopted or recommended injection pressure limits based on pressure gradient in psi/ft at the formation:

Location	*Pressure limit* (total pressure at formation face in psi/ft)
California	0.75
Kansas	0.60 (Irwin and Morton, 1969, p. 13)
Oklahoma	0.75
Ontario	0.65-0.80 (recommended, McLean, 1968, p. 24)
Pennsylvania	0.75 or 80% of ISI pressure (recommended, Rudd, 1972, p. 43 and 45)
Texas	0.85 approximately (based in part on reservoir pressure)

Ideally the formation should be sufficiently permeable to take fluid at pressures much lower than the fracture pressure. When injection pressures are initially near the fracture pressure, the life of the well will probably be determined by this limit, because injection pressures tend to increase with time.

The arbitrary pressure-injection limit should not be treated inflexibly. There are many anisotropies involved in fracturing, and local conditions should be incorporated wherever possible into the derivation of pressure limits.

DRILLING AND COMPLETION OF WELLS

PERMIT AND FEASIBILITY STUDY

In Ohio, injection is regulated under Chapter 1509 of the Ohio Revised Code, which gives the Division of Oil and Gas authority to permit and regulate deep injection. Under the present law, a permit issued by the Division of Oil and Gas is required to drill and operate a disposal well. To obtain a permit the operator must submit an application along with supporting materials, including a complete feasibility study, to the Chief of the Division. Copies of the feasibility report and application are circulated to the Division of Geological Survey and to the Ohio Environmental Protection Agency. If the proposed well is near mine workings, the Division of Mines also examines the application. If all agencies, including the Division of Oil and Gas, approve the permit, the operator is given approval to drill and test the well. Upon completion of the well, a detailed completion report must be submitted by the operator and again circulated. If it is found that conditions encountered in drilling and testing are essentially the same as those predicted in the application, the operator may proceed with injection. The feasibility study contains extensive engineering and geologic studies dealing with the expected geologic conditions, method of well construction and testing, safety precautions, nature of waste, and surface treatment and handling methods. Suggested outlines of the data which should be included in a good feasibility study and in a thorough completion report are included in the appendixes. Consulting firms are generally engaged by the industry to provide the expertise necessary in designing and operating the disposal well.

CONSTRUCTION AND TESTING OF WELLS

Construction methods for injection wells have been described in the literature by McLean (1968, p. 31-33), Walker and Stewart (1968, p. 952-955), and Donaldson (1964, p. 6-8), as well as several others. Disposal wells in general, and all disposal wells in Ohio, have the following features, as shown in figure 7: (1) Large-diameter casing is placed from the surface and extends below all possible fresh-water-bearing zones; the casing is cemented in place from top to bottom. A depth of 500 feet is adequate in most places for this casing to reach below fresh-water zones, although this depth should not be taken for granted. Proof of good cementation from pressure testing or geophysical bond logs is required by the Division of Oil and Gas. (2) Inside the surface casing another string of pipe is cemented in place from the surface either to the top of the disposal zone or through it. This casing, commonly termed the "long string" in oil field operations, should also be tested for cement bond. One means of testing is the use of a device lowered into the well bore to measure the travel time of an acoustic signal through the cement sheath. A defective area of cement will show an anomalously slow velocity. Another test consists of applying pressure to the casing over a long period of time; if the pressure does not decline, the cement must be providing a good seal. Portland-pozzolan cements normally used in oil-field work can be adapted for use in most disposal operations, although special epoxy-resin cements are advised for use in acid-disposal operations (Ostroot and Ramos, 1972, p. 83). Such cements are highly acid resistant. They do, however, require special handling. The lower part of the long string of casing is commonly constructed of fiberglass or corrosion-resistant steel. (3) Injection tubing of fiberglass or plastic-coated or corrosion-resistant steel is placed inside the long string of casing and either sealed from the casing with a packer at the top of the disposal zone or allowed to hang free. In the former case the annulus between the injection tubing and casing is filled with an inert fluid such as treated water or fuel oil and is pressurized from the surface. The pressure in the annulus is expected to be closely monitored by the operator; leakage from tubing to casing during injection would increase the annulus pressure, and leakage from the casing to surrounding rocks would decrease it. In either case, automatic alarms and shutdown devices are activated to shut off the injection pumps until the cause of the problem is located and corrected. Pressure sensors on the injection system will shut off the pumps also if either high or unusually low injection pressures exist. An additional function of the inert fluid in the annulus is that it protects the outside of the tubing and the inside of the casing from corrosion.

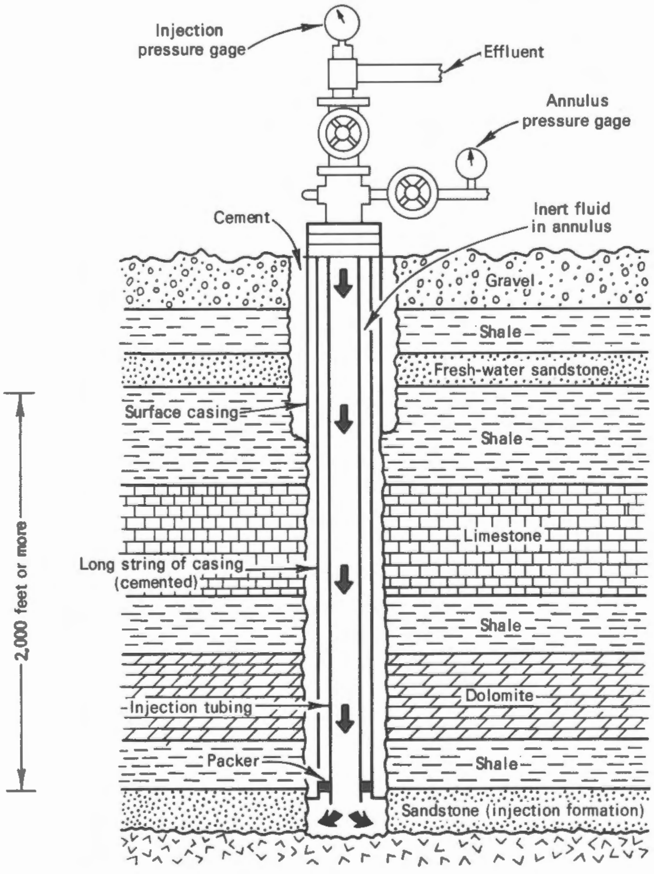

FIGURE 7.–Construction of typical injection well.

Where the injection tubing is allowed to hang free, a system of electrodes is attached to the tubing. These electrodes will indicate any change in the position of the interface between pressurized treated fresh water in the annular space and the effluent; under normal conditions the interface will remain static. Movement of the interface indicates problems, and again appropriate alarms are activated.

During the drilling of the well, it is essential to (1) collect samples of the rock cuttings, (2) take cores of the disposal zone and of the confining beds, (3) run drill-stem tests to determine pressures and permeability, and (4) run geophysical logs to determine correlations, porosity, hydrocarbon indications, and other parameters. These data are submitted also to the state agencies, where they are evaluated to determine if the geologic and hydrologic conditions encountered are essentially those predicted in the approved application. Prior to installing the expensive surface equipment, the operator will usually conduct extensive injection tests to determine whether the well has the capacity to accept the desired volume of waste at safe pressures.

SURFACE EQUIPMENT

Surface installations include lagoons or holding tanks, filters, piping, and monitoring equipment. A lagoon or holding tank is necessary in case it becomes necessary to shut down the well. Such action would require surface storage for days or weeks unless the plant can be shut down or alternative treatment is available. Lagoons are used additionally for cooling, settling of solids, adjustment of composition or pH, oil separation, or merely to accumulate enough waste to warrant starting the injection pumps. Lagoons should be lined or otherwise made watertight.

Filters may consist of metal baskets for coarse particles, sand or cartridge filters for intermediate-sized solids (larger than 60 microns), and diatomaceous-earth filters for particles as small as 2 microns. Cooling towers and equipment to add biocides or other additives may be necessary. The general subject of pretreatment of wastes is discussed by Sadow (1972).

High-quality piping, protected from freezing if necessary, should be used. Monitoring equipment should include: (1) gauge to measure level of fluid in lagoon, with alarm for high levels, (2) gauges to measure pressures of annulus and injection tubing, preferably on strip-chart recorders, (3) alarms and automatic shutdown devices on both annulus and injection tubing in case of unusually high or low pressures, and (4) recorder for injection volume.

Where confining beds are adequate and reservoir conditions are favorable, it is probably an unnecessary precaution to drill monitoring wells around disposal wells. However, if doubt exists that the wastes would be confined, such wells can be installed. The most valuable data would come from a well or wells drilled to the nearest reservoir vertically above the confining beds and equipped to monitor fluid level so as to test the efficiency of the confining beds.

GEOLOGIC FORMATIONS AS RESERVOIRS

MT. SIMON SANDSTONE

Stratigraphy and lithology.—The Mt. Simon Sandstone is a widespread formation of Cambrian age and in Ohio immediately overlies Precambrian igneous and metasedimentary rocks. The formation thickens westward from Ohio into the Illinois Basin, where it is an attractive deep-disposal zone (Bergstrom, 1968, p. 16). Northward from Ohio the Mt. Simon is thick and extensive in the Michigan Basin (Cohee, 1945) and is a suitable injection zone (Briggs, 1968, p. 150). In New York and northern Pennsylvania the Mt. Simon equivalent is the Potsdam Sandstone, which is also a favorable injection zone (McCann and others, 1968, p. 88). In western West Virginia the Mt. Simon is present in Wood County, where it is 282 feet thick in one well (Woodward, 1959, p. 26). In eastern Pennsylvania and southward the Mt. Simon lies at great depths and is not well known, but Colton (1961, fig. 3) believes that the unit passes into a predominantly carbonate sequence that is underlain by older Cambrian clastics not present in Ohio. Wagner (1966, p. 10) states that the Mt. Simon and equivalents can be considered a single rock-stratigraphic unit stretching from the upper Mississippi Valley to New York.

The Mt. Simon is a feldspathic quartzose sandstone that is fine to medium grained in most places, but coarse grained in a few occurrences. Cement is probably silica, although feldspar overgrowths, dolomite, and hematite may also act as cement. Near its base the unit is commonly a conglomeratic pink arkose. Janssens (1973) has examined nearly all available samples of deep tests in Ohio, and readers should refer to his work for detailed sample descriptions.

Figure 8, a cross section based on geophysical logs, shows the Mt. Simon and overlying Cambrian formations in west-central Ohio; the wells on the east and west ends of the section are injection wells. The stratigraphic terminology is that recently introduced by Janssens (1973). The cross section indicates that the top of the Mt. Simon coincides with an increase in natural gamma radiation in most places. Westward, however, the contact is less distinct, and the top is picked at the disappearance of glauconite present in the overlying Eau Claire Formation. The radiation level of the Mt. Simon is about as high as that of marine shales,

FIGURE 9.—Thickness of the Mt. Simon Sandstone (after Janssens, 1973, pl. 1).

abnormally high for a sandstone. Shale and glauconite are common radioactive components of sedimentary rocks, but these are not significant constituents of the Mt. Simon. Basement rocks in many places in Ohio contain large percentages of microcline (potassic feldspar) (McCormick, 1961), and limited data suggest that microcline is also abundant in the Mt. Simon. A small percentage of potassium is normally radioactive (K^{40} decays to Ar^{40}), and this may explain the radioactivity of the Mt. Simon.

Thickness.—The thickness of the Mt. Simon in Ohio ranges from more than 350 feet in the west to less than 100 feet in parts of central Ohio. An isopach map of the formation is shown in figure 9. Thickness of the unit depends partly on the topography of the underlying basement rocks; the sandstone thins over basement highs. In one well in Pickaway County, the Mt. Simon and part of the overlying Rome Formation appear to be absent over a basement high (Janssens, 1973, p. 9), but thickness of the unit is normally predictable with sufficient accuracy to locate injection wells. In general, the wells encountering over 200 feet of Mt. Simon have had good injectivity while those with less than 100 feet have been fair to poor.

Porosity and permeability.—Values of average porosity and permeability derived from core analyses, drill-stem tests, and geophysical-log analyses for six of the injection wells and for other selected Mt. Simon wells are shown in table 2. The relationship between porosity and permeability is graphed in figure 10. Although there is wide scatter in the data, it is suggested that for permeability to reach adequate levels (estimated to be 25 md) for trouble-free injection, porosity must exceed 11 percent. Permeability data are not normally recorded for oil and gas wells, but porosity may be calculated for most wells for which geophysical logs were run. Many such logs are on file at the Ohio Division of Geological Survey.

From the well data at hand, it appears that porosity and permeability of the Mt. Simon tend to decrease eastward, probably owing to increased cementation and compaction associated with deeper burial. Depth to the top of the Mt. Simon greatly increases eastward. Using these facts and histories of the injection wells, figure 11 was prepared to show the relative injection potential of the Mt. Simon. For small volumes of waste, for example 15 gpm, the favorable areas could be shifted farther eastward than the figure indicates.

Confining beds.—Throughout Ohio, at least 2,000 feet and in places more than 10,000 feet of predominantly impermeable strata lie between the Mt. Simon and aquifers bearing fresh water. The Eau Claire, Rome, and Conasauga Formations of Cambrian age directly overlie the Mt. Simon. These units are described by Janssens (1973). The Eau Claire is the western facies of the combined Conasauga and Rome Formations. The facies boundary is gradational, with an arbitrary nomenclatural change along a north-south line

TABLE 2.—*Porosity and permeability data for the Mt. Simon Sandstone*

Well name	Location	Permit number[1]	Average porosity (%)	Average permeability (md)	Interval analyzed (ft)	Source of data
Vistron #1	Allen County Shawnee Township	P-67 (IWDW #4)	14.4	80 (to gas)	334	Core analysis
East Ohio #1 Hoelscher	Auglaize County St. Marys Township	P-71	12.3	- -	148	Density log analysis
			- -	44	127	Drill-stem test
Armco #1	Butler County Lemon Township	P-4 (IWDW #2)	- -	25.1 (to water)	?	Consultant's report
			13.1	over 200 (to gas)	217	Core analysis
Sun Oil #1 Herman	Erie County Florence Township	P-19	13.2	32.6	44	Unpublished consultant's report
Amerada #1 Ullman	Noble County Elk Township	P-1278	2.6	- -	175	Cross-plot log analysis
			- -	very low[2]	159	Drill-stem test
Calhio #1	Lake County Perry Township	P-142 (IWDW #7)	- -	3.0	165	Drill-stem test
			8.4	11.6	102	Core analysis
Empire-Reeves #1	Richland County Madison Township	P-448 (IWDW #1)	- -	24	108	Drill-stem test
			10.4	9	90	Core analysis
Ohio Liquid Disposal #1	Sandusky County Riley Township	P-210	15.5	30	79	Core analysis
			- -	41	122	Drill stem test
U.S.S. Chemicals #1	Scioto County Green Township	P-212 (IWDW #5)	12	27 (to gas)	29	Core analysis

[1] IWDW = industrial waste disposal well.

[2] Drill-stem test of Mt. Simon recovered only 90 feet of drilling mud over interval 11,283-11,442 feet.

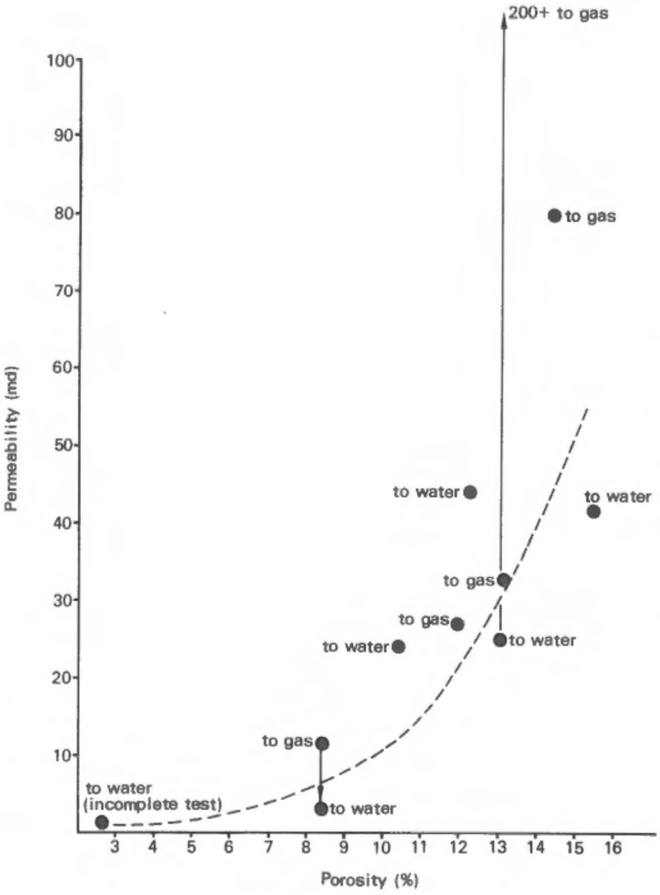

FIGURE 10.—Relationship between porosity and permeability in the Mt. Simon Sandstone.

running approximately along the eastern borders of Hancock, Champaign, and Greene Counties. The Eau Claire consists of glauconitic siltstone and very fine-grained sandstone with thin beds and partings of shale. The unit ranges in thickness from about 300 to 500 feet. Horizontal permeability in such a unit might be significant along porous sand lenses, but the numerous shale beds, partings, and laminations should render vertical permeability negligible. To the writer's knowledge, the only permeability tests made on this unit in Ohio were on core material from the Armco #1 well in Butler County. The interval 2,859-2,881 feet was reported to have vertical permeability to water generally less than 1×10^{-6} md, with one sample as high as 3.43×10^{-2} md. In ground-water terms these permeabilities would be equivalent to less than 2×10^{-8} gpd/ft^2 and 6×10^{-4} gpd/ft^2. The only other permeability data on the Eau Claire known to the author are from an Illinois well which showed vertical permeability less than 1×10^{-3} md for 18 core samples (Bayazeed and Donaldson, 1971, p. 4).

If the average permeability of a 400-foot-thick section of Eau Claire is 2×10^{-8} gpd/ft^2 and the average increase in reservoir pressure due to injection in the Mt. Simon within a quarter-mile radius of the well is 100 psi, then it can be shown that within this radius 0.02 gallon per day of liquid (assuming a viscosity similar to that of water) could pass vertically through the Eau Claire (ignoring density differences). At the higher value, 6×10^{-4} gpd/ft^2, of permeability, 604 gallons per day could leak through the Eau Claire. The actual permeabilities probably average close to the lower value. The significance of these figures is that, although the beds overlying the Mt. Simon are for all practical purposes adequate confining beds, they are only relatively impermeable. If sufficient pressure differential is allowed to exist across the confining beds and if the area affected by pressure elevation is of large areal extent, then the amount of fluid passing through the confining beds could become important. Under present conditions in Ohio, vertical leakage is not thought to be significant.

East of the limit of the Eau Claire facies the Rome Formation overlies the Mt. Simon. The Rome is a pelletal oolitic tight to slightly porous dolomite, more than 700 feet thick in eastern Ohio, but thinning to less than 300 feet in the central part of the state, where it consists of sandy dolomite. The Rome is overlain by shale and glauconitic siltstone of the Conasauga Formation. The Conasauga ranges in thickness from 40 to 439 feet and should be an excellent confining bed.

Many of the formations lying above the Rome and Conasauga are confining beds, notably the Ordovician shale sequence, which is as much as 1,500 feet thick, and the Devonian and Mississippian shales of central and eastern Ohio. These strata are not discussed in detail in relationship to the Mt. Simon because it is believed that sufficient confinement is afforded by the sub-Knox units.

Mineral deposits.—The Mt. Simon Sandstone contains

FIGURE 11.—Generalized injection potential of the Mt. Simon Sandstone.

no known economically valuable mineral deposits. There are no wells producing hydrocarbons from the formation, and only two wells (in Mercer and Allen Counties) have reported shows of gas. At this time the connate brines have no known commercial value. In general, the waters in the "Clinton" and "Newburg" formations (Silurian) are of higher concentration and are shallower, but even these are not generally considered valuable.

Salinity.—A contour map showing the salinity (as total dissolved solids, TDS) of the fluid in the Mt. Simon is shown in figure 12. The increase in salinity (as specific gravity) with depth in Ohio is graphically illustrated in figure 13. The values falling to the left of the dashed line may be caused by erroneously low specific gravities resulting from possible contamination of the recovered drill-stem-test fluids by relatively fresh filtrate from the drilling mud.

The lowest salinity reported for the Mt. Simon in Ohio is about 67,000 ppm TDS recorded in the East Ohio #1 Hoelscher well in Auglaize County. This value is probably erroneously low. The sample was reported to be muddy and thus may have been contaminated by fresh mud and mud filtrate. The next lowest value is for a sample about four times saltier than seawater; it is unlikely that any desalination or fresh-water storage project would be feasible in the Mt. Simon.

OTHER RESERVOIRS

General comments.—Several other potential injection zones exist in Ohio, but all are less attractive than the Mt. Simon. The generalized reservoir characteristics of post-Mt. Simon strata which might be considered to have injection potential are discussed below.

FIGURE 12.—Concentration of total dissolved solids in fluid of the Mt. Simon Sandstone.

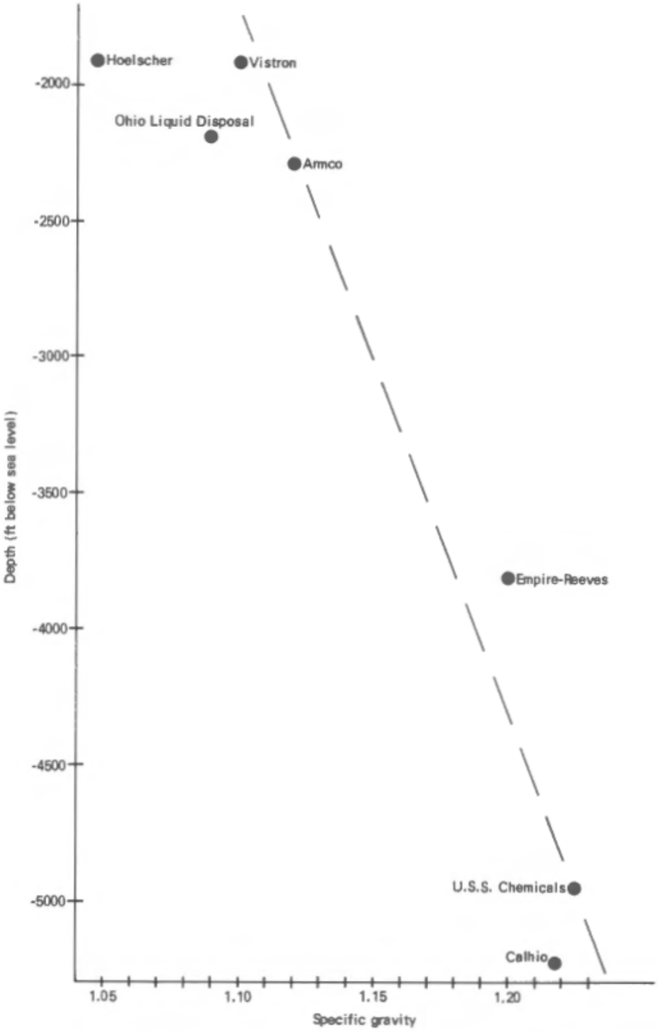

FIGURE 13.—Fluid specific gravity versus depth in the Mt. Simon Sandstone.

Kerbel Formation.—The Kerbel Formation (Cambrian), recently named by Janssens (1973), is a fine- to coarse-grained deltaic sandstone that coarsens upward. The unit lies between the Conasauga Formation below and the Knox Dolomite above and ranges in thickness from 0 to 150 feet (fig. 14). Permeability is probably at a maximum where the sandstone is thickest. The formation becomes dolomitic eastward from central Ohio, dolomitic and argillaceous southward, and silty and argillaceous westward. Flows of water and shows of oil and gas have been reported from wells reaching the Kerbel, but the formation is not presently productive.

The Kerbel was tested as a disposal zone in the Calhio well in Lake County. Preliminary reports indicate a fair injection potential, but the well is not yet being used for injection. Data are insufficient to describe the hydrodynam-

FIGURE 14.–Thickness of the Kerbel Formation (from Janssens, 1973, pl. 5).

ics of the unit.

Confining beds for the Kerbel include the overlying Knox Dolomite and stratigraphically higher units. The Knox is absent by erosion in extreme northern Ohio; here shale, representing post-Knox clastics (Glenwood or Chazy equivalent), directly overlies the Kerbel. The Knox is a dolostone and as such is a brittle unit, probably fractured; porous zones are present in places. In addition, the Knox has been penetrated by about 3,000 wells in Ohio; thus on a regional basis the unit should be considered a questionable confining bed. If the Knox is to be considered the confining bed, any future injection into the underlying Kerbel should be in areas where the Knox is relatively thick and/or undrilled (fig. 15). The amount of fluid injected into the Kerbel Formation over a long term should be restricted because the Kerbel is not as thick or extensive as the Mt. Simon (hence pressures regionally would increase more rapidly) nor are the confining beds as good as for the Mt. Simon.

Knox Dolomite.–The Knox is a widespread generally thick dolostone containing sandy and oolitic zones. With few exceptions it does not contain zones of persistent mappable porosity. The Knox is truncated by an unconformity in Ohio; the unit ranges in thickness from a featheredge to about 1,500 feet (fig. 15). Permeability is developed locally at the unconformity surface, most notably in central Ohio, where production of oil, gas, and water from buried erosional hills has been prolific.

Areas in which the Knox is too shallow or has been too densely drilled to be considered for injection are shown in figure 15. An additional area in northwestern Ohio should be proscribed because of dense drilling to the overlying Black River-Trenton strata; this area is shown also in figure 15. In northwestern Ohio, generally where the Knox is structurally high and relatively shallow, the overlying Black River-Trenton sequence is dolomitized and the Glenwood or Chazy equivalent may be absent. In the latter situation the units would be in lithologic continuity, and the Knox might be in hydrologic continuity with the Trenton. A great number of old wells penetrate the Trenton; therefore the Knox would be a poor injection zone.

In eastern Ohio, where the Knox is sparsely drilled and relatively deep, potential exists for injection if porous beds are encountered. With present information, this would be strictly a wildcat proposition.

Within the Knox, and subcropping along a northeast-southwest line running through Coshocton County, is a sandstone and sandy dolomite member informally called the Rose Run sandstone. The unit has produced water and gas, especially near the subcrop, but it does not appear that sufficient porosity for injection of large volumes of waste would normally be present in eastern Ohio.

Black River and Trenton formations.–In central and eastern Ohio the Black River-Trenton strata (Ordovician) are composed primarily of tan lithographic limestone. In western Ohio the limestone becomes irregularly dolomitized, ranging from patches to complete replacement. Thickness of the total sequence is fairly uniform at 500 to 600 feet. Where dolomitized, the zone is very porous; unfortunately these areas tend to be densely drilled, hence unsuitable for injection.

FIGURE 15.–Generalized thickness of the Knox Dolomite, areas of extensive drilling, and injection potential.

Eastward the dense limestone may be a fair confining bed, although it may be extensively fractured. A series of thin bentonite beds at the base of the Trenton would seem to offer additional confining potential.

"Clinton" sandstone.—The "Clinton," an informally named Silurian sandstone, has been a producer of oil and gas for many years and has been drilled extensively over much of east-central Ohio. Where permeability is highest, some water is produced with the oil, but at most places the sand is too tight to be very permeable to water. Because of low permeability (usually 1 md or less) and the great number of old wells reaching the "Clinton," the unit appears to have very slight injection potential, except perhaps for small volumes of oil-field brines produced from the same strata. The Rochester Shale, which overlies the "Clinton" sandstone, is 100 feet or more thick in eastern Ohio and could be a good confining unit except for numerous penetrations by wells.

"Newburg" porous zone.—"Newburg" is a drillers' term for a porous dolomite usually at or near the top of the Lockport Dolomite (Middle Silurian). The name originated in a gas field at Newburg, near Cleveland; the rock was incorrectly called a sandstone. The name was never rigidly defined and has been used in various ways by different operators, but commonly is applied to the first sugary porous vuggy brown dolomite below the Cayugan Salina rocks or to any zone producing abundant water, oil, or gas about 600 to 800 feet below the top (Delaware Limestone of Devonian age) of the "Big Lime." A description of the "Newburg" from a producing field in Wayne County is given by Multer (1963).

Flows of highly saline water which rapidly fill the bore hole have been reported from wells reaching the "Newburg" in nearly every county in eastern Ohio. The large number of cable-tool holes in which the zone yields water is reflected by the fact that the zone is also called "Second Water" or "Big Water" by drillers.

As is true with most carbonate reservoirs, permeability in the "Newburg" is neither uniform nor predictable. In any given area, well cards and geophysical logs indicate that some "Newburg" wells lack porosity. The permeable zones are so discontinuous that this writer was not able to identify a specific porous zone within the "Newburg" and could not construct a map to delineate good injection potential; thus any injection site bears the risk that porosity will be inadequate. Within the Salina Group good confining beds of halite and anhydrite overlie the "Newburg" zone in eastern Ohio.

Although the unit may have good reservoir characteristics, the use of the "Newburg" as a disposal zone will be greatly limited, if not contraindicated, by the large number of wells drilled into the underlying "Clinton." The areas in which "Clinton" drilling has been extensive are outlined in figure 16, which also shows the generalized structure on top of the "Newburg." As is apparent from the map, the "Newburg" is deep enough (about 2,000 feet) for injection and lies outside of closely spaced drilling only in southeastern Ohio to the east of current drilling. Potential problems are seen in siting injection wells in this area. "Clinton" drilling historically has progressed deeper into the basin. If disposal is allowed where the "Clinton" is prospective, can or should oil and gas operators be prevented from drilling nearby? If they are allowed to drill, who should bear the additional expense of properly casing the oil wells and, more important, the expense of adequately isolating the "Newburg" when the well is plugged? In a sense, usage of this potential injection zone above a potential producing zone would constitute a risk to the production of oil and gas. Under present law, such injection might not be permissible.

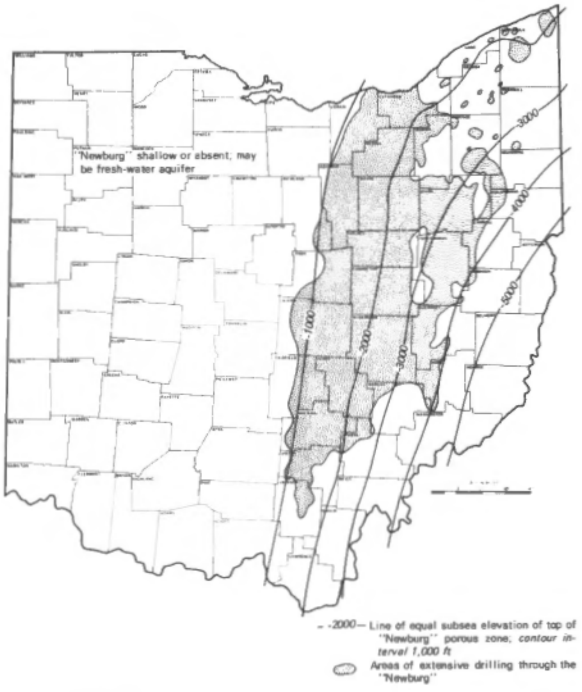

FIGURE 16.—Generalized structure on top of the "Newburg" porous zone and areas of extensive drilling to or through the "Newburg."

Oriskany Sandstone.—The Oriskany Sandstone (Devonian) is described by Hall (1952, p. 39) as white to brownish gray and fine to medium-coarse grained. The cement is generally calcareous, although it is dolomitic or siliceous in a few wells. The sandstone thins westward in Ohio from about 100 feet along the Ohio River to a featheredge along an irregular pinchout line running approximately north-south through Morgan, Holmes, and Medina Counties. Drillers' names that have been applied to the unit include "Austinburg" (northern Ohio), "Cambridge" (southern Ohio), and "First Water" (general usage). The sand has produced oil, gas, and water over large areas of eastern Ohio. The locations of producing fields, line of sand pinchout, and structure contours are shown by Hall (1952, p. 44, 53).

Where thick the sandstone generally has sufficient permeability to be attractive as a disposal zone. As is the case with the "Newburg," however, dense drilling may eliminate the most favorable areas from consideration. Two core analyses provide some permeability data. The Ashland

#1 Canton Refinery well in Canton Township, Stark County, showed a permeability to water of 106 md, with an average porosity of 10.3 percent within an 8-foot interval. Near the sandstone limit in Union Township, Muskingum County, the Oxford #3 Morrison tested 5.3 feet of sand, with an average permeability of 10.7 md (to water?) and a porosity of 6.9 percent. From these limited data it appears that the sand must have good sorting in order to have high permeability with relatively low porosity. Farther east, where the sand is thicker, the Oriskany should have reasonable injectivity.

The most favorable injection area of the Oriskany appears to be in northeastern Ohio east of the dense drilling of the "Clinton," "Newburg," and Oriskany. Because the Oriskany is a sandstone of regional extent, its permeability should be more predictable than that of the "Newburg."

Overlying the Oriskany is the Columbus Limestone (Devonian), which is about 100 to 150 feet thick. The Columbus is probably too porous and fractured to be considered a confining bed; however, overlying the Columbus is the thick Ohio Shale (Devonian), which is an excellent confining bed.

A disposal permit was issued for injection into the Oriskany at the International Salt Company Mine at Whiskey Island in Cleveland. The injected fluid is Oriskany brine, which seeps into the mine shaft.

Mississippian and Pennsylvanian sandstones.–Disposal in the shallow sands of eastern Ohio involves considerable hazard. Some 120,000 to 200,000 wells have been drilled in the area since the late 1800's, and the locations of many of these are unknown. Wildcatting was in its heyday, regulations were weak or absent, and early cable-tool rigs were quite capable of reaching the 2,000-foot depths necessary to penetrate the Berea Sandstone (Mississippian). Thus it will never be known, even approximately, how many holes were drilled and where they are. Possible structural complexities involving the shallower beds in eastern Ohio may present an additional hazard. Anticlines and closures mappable on shallow or surface beds are commonly not present at depth.

With due caution for possible faults and unlocated wells, and perhaps with suitable monitoring wells, some minor injection potential conceivably may exist in the Berea Sandstone. Unlike most of the shallow sands the Berea tends to be a widespread continuous unit ranging in thickness from 5 to 80 feet in eastern Ohio (Pepper and others, 1954, pl. 1). Permeability reported from 21 core analyses in Hancock County, West Virginia, and Carroll and Harrison Counties, Ohio (Whieldon and Pierce, 1965, p. 4), ranges from 2.4 md to 443.0 md, with an average porosity of 16.6 percent. A core of the Berea in the U.S.S. Chemicals well in Scioto County had an average permeability of 1.5 md and an average porosity of 12.1 percent over a 23-foot interval. Where the sandstone is thick, it appears that injectivity may be adequate.

A very generalized map (fig. 17) shows (1) the area in which the Berea is below 2,000 feet in depth, (2) structural contours on the top of the sandstone (R. E. Lamborn, unpublished data), and (3) the area where the Berea is a fresh-water aquifer. In the deep area in Washington and Monroe Counties and adjacent areas the sandstone is shown by Pepper and others (1954, pl. 1) to be only between 5 and 20 feet thick, which is probably not enough for injection.

FIGURE 17.–Generalized structure on the Berea Sandstone and locations of deep areas and fresh-water-bearing areas.

Even less potential is present in the shallower Mississippian sandstones. At least four of these, the "Keener," "Big Injun," "Squaw," and "Weir," in descending order, have produced significant amounts of oil, gas, and water, but all are probably discontinuous and too shallow to be considered as injection zones.

Pennsylvanian sandstones generally do not lie below 1,000 feet, are heavily drilled, and are discontinuous. For these reasons, and because of the additional hazard of deep coal mines at the same general stratigraphic level, these sandstones are not believed to have safe injection possibilities.

INJECTION WELLS IN OHIO

GENERAL STATEMENT

The locations of wells drilled for the purpose of industrial injection are shown in figure 18. Also shown in the figure is the approximate depth required to drill through the Mt. Simon. Table 3 is a summary of the major facts concerning the injection wells. The following section discusses these wells in more detail.

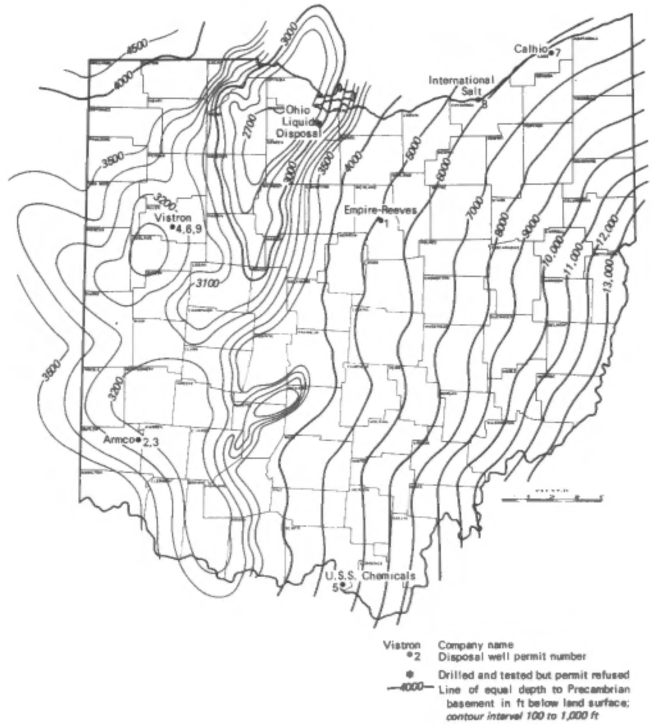

FIGURE 18.—Locations of wells drilled for industrial waste disposal and approximate depth to top of the Precambrian (after Hennington, 1973).

ARMCO STEEL CORPORATION

Armco Steel Corporation operates two wells in Butler County near Middletown. The wells are 1,300 feet apart and each penetrates about 300 feet of the Mt. Simon Sandstone. Neither well has reached basement rocks. Each well was equipped with 13⅜-inch O.D. surface casing cemented through all fresh-water zones to a depth of about 300 feet. The long string of 9⅝-inch O.D. inner casing was set in both wells at the top of the Mt. Simon at a depth of about 2,950 feet and cemented to surface. In 1972, corrosion of the 9⅝-inch casing required that a 7-inch liner be cemented inside the casing in the second well.

Each well originally injected through steel tubing, but corrosion problems have forced a switch to fibercast tubing of 3½-inch diameter. Tubing is set on a packer with oil under pressure in the annular space. Normal monitoring devices and surface equipment, including filters capable of removing solids down to 2 microns in size, have been installed.

Injected fluid is spent hydrochloric acid with the following reported characteristics (Cleary and Warner, 1969): HCl, 1 percent; $FeCl_2$, 25 percent; and $FeCl_3$, 1½ percent. Prior to injection of wastes a fresh-water buffer was injected into each of Armco's disposal wells; the buffer served to isolate the reservoir fluid from the effluent to prevent precipitation of solids. The volume of fresh-water buffer was 3 to 5 million gallons per well.

Injectivity testing on the first well indicated that the formation would accept approximately 200 gpm at 600 psi, 500 gpm at 750 psi, and 740 gpm at 800 psi. Operational injection pressures are normally quite low, ranging from 0 to 80 psi at the surface when injection is at a rate of 70 gpm or less. Only one well at a time is used for injection, the other remaining on standby.

Cost of one well is reported to be as follows: well installation, \$179,000; surface equipment, \$145,000; average annual operating expense, \$50,000.

Cumulative injected volume as of May 1973 was 33 million gallons for well #1 and 42 million for well #2. This seems an immense volume. However, when area of invasion is calculated as follows, it appears that the volume injected in well #2 could be contained within a radius of about 262 feet. The calculation is based on the formula for the volume of a cylinder:

$$r = \left(\frac{V}{7.48\,\pi h \phi}\right)^{1/2}$$

where r = radius of influence, V = volume of injected fluid (42,000,000 gallons), 7.48 = number of gallons per cubic foot, π = 3.14, h = thickness of porous formation (200 feet net), and ϕ = average porosity (0.13). Figure 19 shows a comparison between volumes of injected waste for each of the disposal wells.

The first Armco well was cored through a portion of the Eau Claire Formation (Cambrian) and through the Mt. Simon. Average porosity and permeability of the Mt. Simon are discussed in a previous section. Unfortunately, original reservoir pressure and temperature were not recorded in either well. Samples of reservoir fluid were obtained, and the following analysis was reported by the operator:

pH	6.1
Specific resistance	7.8 ohm-cm
Density	9.35 lb/gal (1.120 g/cc)
Iron, total	24.4 mg/l
Iron, soluble	7.1 mg/l
Total dissolved solids	189,000 mg/l
Sodium	40,200 mg/l
Potassium	940 mg/l
Calcium	20,400 mg/l
Magnesium	2,500 mg/l
Chloride	110,000 mg/l
Sulfate	790 mg/l
Acidity (phenolphthalein) $CaCO_3$	40 mg/l
Alkalinity (methyl orange) $CaCO_3$	7 mg/l

Prior to the establishment of the deep disposal system, it is reported that the effluent from this plant was released untreated into the Great Miami River.

VISTRON CORPORATION

Vistron Corporation, a division of Sohio, operates an acrilonitrile plant near Lima, in Allen County. The waste consists of a complex mixture of ammonia, sulfate, cyanide, aldehydes, organic acids, nitriles, and amides. Reportedly,

TABLE 3.–*Industrial injection wells in Ohio*

Industrial waste disposal well permit number	Operating company	Well number	Location	Permit number	Depth (ft)	Year drilled	Waste	Remarks	Injection rate (gpm)
2 3	Armco Steel Corp.	1 2	Butler County Lemon Township	4 5	3200 3200	1967 1967	Spent HCl pickle liquor	Low injection pressure	30 (one well used at a time
7	Calhio Chemicals Inc., Stauffer Chemical Co.	1	Lake County Perry Township	142	5600	1971	NaCl, 25,000 ppm, organics 4,200 ppm	Injection in Kerbel (Cambrian) as well as Mt. Simon, testing 7/73	60-100 (proposed)
1	Empire-Reeves Steel Div. of Cyclops Corp.	1	Richland County Madison Township	448	5000	1967	Spent H_2SO_4 pickle liquor	Abandoned February 1971 owing to corrosion	15
8	International Salt Co.	1	Cuyahoga County City of Cleveland	744	1435	1959?	Natural brine reinjected into Oriskany	Fluid from Oriskany seeps into mine shaft; first injection in May 1972	15
5	U.S.S. Chemicals, Div. of U.S. Steel Corp.	1	Scioto County Green Township	212	5600	1968	Phenols, acetone, sodium sulfate solution	High injection pressure; completed by setting casing through Mt. Simon and perforating	90
4 6 9	Vistron Corp., Sohio Petroleum Co.	1 2 3	Allen County Shawnee Township	67 71 84	3200 3200 3200	1968 1969 1971	Acrilonitrile waste, sulfate solution with HCN	High injection pressure	300-400 (three wells used)
Permit refused	Ross Laboratories		Franklin County City of Columbus		200?		Cooling water with soap	Fresh-water aquifer was target zone	150 (proposed)
Permit refused	Ohio Liquid Disposal Corp.	1	Sandusky County Riley Township	210	3000	1971	Liquid effluent from many sources	Drilled and tested as stratigraphic test	70 (proposed)
Permit pending	Columbia LNG Corp.		Seneca County Pleasant Township		3200		Cooling, wash, and backflush water; moderate amount of dissolved solids	Two wells proposed	100-200

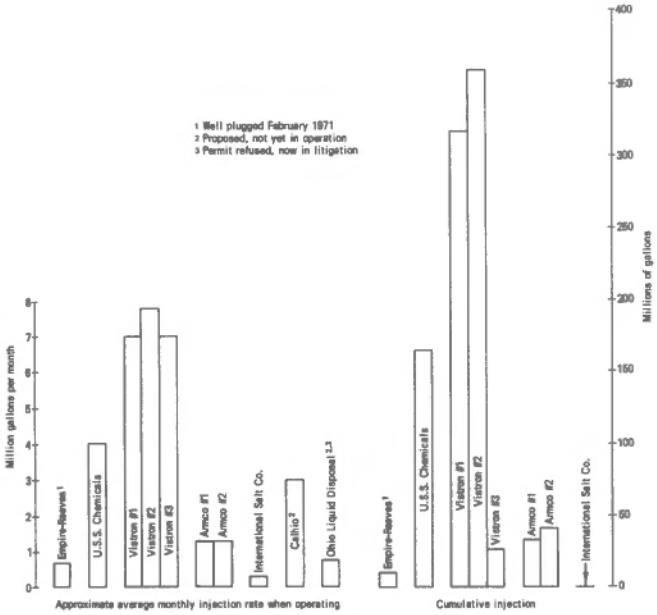

FIGURE 19.–Average and cumulative volumes of injected industrial waste in Ohio as of May 31, 1973.

attempts have been made to treat this waste by incineration and by biological degradation, but both methods were reportedly uneconomical and produced effluents that were unable to meet standards for water or stack emissions.

The company has installed three injection wells. The first and second wells drilled through 352 and 382 feet, respectively, of Mt. Simon strata; neither reached basement rocks. The third drilled through 390 feet of Mt. Simon and reached granite at 3,170 feet.

All three wells are reported to have used 10¾-inch surface casing, extending to a depth of about 500 feet, and 7-inch O.D. inner casing, which terminates at the top of the Mt. Simon, about 2,800 feet below land surface. All casing is cemented to surface. Injection tubing in the first well is 3-inch O.D., in the second, 4-inch O.D., and in the third, 4½-inch O.D. All three wells use steel tubing set on packers at the top of the Mt. Simon at about 2,800 feet. Chemically inhibited water under pressure is used as the annulus fluid. Monitoring and filtration equipment are used in conjunction with special cooling towers. The effluent from the plant is reported to be difficult to handle in warm weather because certain solids will not precipitate above the filters. Consequently, downhole precipitation of these solids may have caused somewhat high injection pressures, especially in the first well. The addition of the cooling equipment reportedly has alleviated the problem. The first well had been operational for some time before the problem was identified, and it has been necessary to treat the well several times with acetonitrile solvent to maintain injectivity at safe pressures. Injection pressures in well #1 have been as high as 1,250 psi. Since late 1971, injection pressures have been held below about 840 psi by direction of the Ohio Division of Oil and Gas. Injection pressures for wells #2 and #3 average about 700 psi and 600 psi, respectively. No problems have been reported for these wells.

The radius of invasion of the effluent injected in well #2 should be about 600 feet, based on an effective thickness of 300 feet and 14.4 percent average porosity. A cumulative volume of over 317 million gallons has been injected in well #1 and 360 million in well #2 as of May 1973 (fig. 19).

An estimate of the costs involved in using the well disposal system have been provided by the company: cost of drilling and completing one well, $124,000; surface equipment (including monitoring devices, filters, pumps, piping, building, heat exchangers), $245,000; annual operating expenses, $60,000. Prior to installation of the injection system, the company had incinerated the wastes at a cost of $600,000 per year (Environmental Science and Technology, 1968). The stack emissions reportedly did not meet effluent standards.

Injection testing performed prior to the completion of well #1 indicated good reservoir potential. At a pressure of 700 psi, 380 gpm (16 million gallons per month) were injected.

A fresh-water buffer pad was not used in well #1. In well #2, about 6 million gallons of fresh water were injected; well #3 has been treated similarly.

The Mt. Simon reservoir fluid taken from well #1 was analyzed by the operator and the composition is reported as follows:

pH	7.3
Alkalinity to pH 8.2 as $CaCO_3$	0 mg/l
Alkalinity to pH 4.6 as $CaCO_3$	70 mg/l
Chloride as Cl	57,500 mg/l
Sulfate as SO_4	1,450 mg/l
Calcium as Ca	7,200 mg/l
Magnesium as Mg	1,400 mg/l
Sodium as Na	65,000 mg/l
Barium as Ba	low
Hydrogen sulfide as H_2S	negligible
Conductivity	81,200 µmhos

U.S.S. CHEMICALS

The disposal well drilled in 1968 near Haverhill, in Scioto County, by the U.S.S. Chemicals Division of U.S. Steel reached a total depth of 5,608 feet, ending in granite. The Mt. Simon was encountered at a depth of 5,514 feet and is about 66 feet thick. Reservoir fluid recovered from a drill-stem test was analyzed as reported below:

Specific gravity	1.225
pH	5.5
Total alkalinity as $CaCO_3$	28.0 mg/l
Calcium	50,600 mg/l
Magnesium	7,080 mg/l
Sodium	58,300 mg/l
Barium	0 mg/l
Sulfate	140 mg/l
Chloride	200,000 mg/l
Silica	2 mg/l
Total iron	39 mg/l
Aluminum	0.5 mg/l
Turbidity as SiO_2	>150 mg/l

Iodide	1.3 mg/l
Bromide	2,160 mg/l
Total dissolved solids	316,000 mg/l
Carbon dioxide	240 mg/l
Resistivity	.047 Ωm at 77°F

In this well 10¾-inch O.D. surface casing was set through fresh-water zones to a depth of 477 feet. Seven-inch casing was run through the Mt. Simon and cemented to the surface in five stages. Injection tubing is 3½-inch O.D. set on a packer at a depth of 5,422 feet. The annular space is reported to be filled with inverted oil-emulsion mud. Unlike other disposal wells in Ohio, completion was accomplished by running the long string of casing *through* the injection zone, then perforating it in the interval 5,517-5,599 feet. The first attempt to inject through these perforations failed, probably because of inadequate perforation cleanout. After notching the casing at three places, the well was fractured with acid, water, and sand.

Injection tests performed through the casing showed the following rates: 21 gpm at 389 psi, 102 gpm at 590 psi, and 252 gpm at 990 psi. A total of about 2 million gallons of fresh-water buffer was injected. The average injection rate has been about 90 gpm during operation. The surface pressures from injection of this volume have been near 1,700 psi, a pressure gradient of 0.77, which is considered to be very slightly above the safe injection-pressure limit. The company has recently lowered injection pressures.

The effluent at this plant consists of phenolic wastes resulting from the manufacture of phenol, acetone, and alpha methyl styrene. A typical analysis is reported as follows:

Component	*Component flow* (lbs/hr)
Water (condensate)	32,144
Phenol	44
Acetone	91
Sodium sulfate	1,315
Sodium bicarbonate	24
Sodium carbonate	218
Sodium formate	22
Cumene hydroperoxide	50
Total	33,908
Temperature (°F)	120
Density (lbs/gal)	8.61
Flow rate (gpm)	65.6

The theoretical radius of the area occupied by the waste fluid is 1,078 feet; this figure is based on an average effective thickness of 50 feet and 12 percent porosity and a cumulative injected volume (May 1973) of 164 million gallons.

This injection well was installed as part of the original design of the plant, consequently there was no previous disposal method for the operation.

EMPIRE-REEVES

The Empire-Reeves Steel Division of Cyclops Corporation drilled the first industrial disposal well in Ohio in the fall of 1967. It was abandoned in 1971. The well, located near Mansfield, Richland County, reached a total depth of 5,085 feet. The top of the Mt. Simon was reported at 4,982 feet and granite at 5,061 feet.

Surface casing was 10¾-inch O.D. and bottomed 675 feet below land surface. It was cemented to surface. The bottom of the long string of casing, 7 inches in diameter, was set at 4,975 feet and the string was cemented to surface in two stages. Injection tubing was 3½-inch O.D., lined with Penton and set on a packer at 4,974 feet.

The effluent at the Empire-Reeves plant is spent sulfuric acid pickle liquor with the following characteristics:

Iron as Fe	43,750 ppm
Copper as Cu	7.87 ppm
Zinc as Zn	1.58 ppm
Insoluble residue	4,705 ppm
Acid content	10.8%
pH	<2.0
Specific gravity	1.195
Freezing point	6°C
Particle size	20μ-200μ (50% <50μ)

Prior to establishment of the deep-well system, the waste was reportedly released into Rocky Fork Creek at a controlled rate.

The disposal well experienced problems with the pressure in the annulus after a few months' operation and underwent extensive reworking. It appears that both casing and tubing were extensively corroded by acid, which had deteriorated the cement around the casing annulus. Because the casing and tubing were corroded beyond salvage, the well was plugged early in 1971. Plugging was accomplished by removing as much of the injection tubing as possible and filling the hole to the surface with cement. Despite the failure of the well, there is no reason to believe that any waste fluid was brought into contact with fresh-water zones. Unverified reports indicate that the waste effluent is now being stored in surface pits.

The injection pressures were somewhat erratic in this well, making it impossible to arrive at a meaningful average. The injection volume also ranged within wide limits, but the cumulative volume over the life of the well was about 10.3 million gallons. A fresh-water buffer of 3 million gallons was emplaced prior to waste injection. Injectivity tests indicated the following: 42 gpm at 1,200 psi, 168 gpm at 1,600 psi, and 300 gpm at 1,800 psi. No fracturing was reported at the highest test pressure, 1,800 psi, which exceeds the injection-pressure limits now set by the state for a well of this depth.

The operator's analysis of the Mt. Simon fluid is reported below:

pH	5.4
Specific gravity	1.200 at 73°F
Bicarbonate	24 mg/l
Chloride	183,000 mg/l
Sulfate	0 mg/l
Calcium	37,500 mg/l
Magnesium	3,950 mg/l

Sodium	67,900 mg/l
Total dissolved solids	292,000 mg/l
Total iron	145 mg/l

CALHIO CHEMICALS

Calhio Division of Stauffer Chemical Co. has a plant in Lake County near Perry. Plant effluent, as reported below, is a byproduct of the manufacture of the agricultural fungicides Captan and Phaltan.

Sodium chloride	25,000 ppm
Sodium sulfate	2,000 ppm
Ferrous ion	300 ppm
Calcium ion	100 ppm
Magnesium ion	10 ppm
Hexane soluble	10 ppm
Chloroform soluble	3,000 ppm
Methyl ethyl ketone soluble	1,200 ppm
Suspended soluble	nil
Biological oxygen demand	3,000 ppm
Chemical oxygen demand	4,000 ppm
Specific gravity	1.025
pH	7.0-7.5

A well was drilled at the plant in March 1971. Top of the Mt. Simon was reported at 5,930 feet and granite basement at 6,060 feet. Total depth was 6,072 feet. Surface casing is 10¾-inch O.D. and was set at 512 feet; 7-inch-diameter long string was run to 5,950 feet and cemented to surface in three stages.

The Mt. Simon was tested for injection in April 1971. Initial tests indicated inadequate injectivity; the formation was acidized and fractured, but extensive additional testing was negative. During drilling, a drill-stem test of the Kerbel Sandstone had indicated good reservoir characteristics. The Kerbel was perforated, acidized, and fractured. Fresh-water buffer was emplaced in both the Mt. Simon and the Kerbel in conjunction with injectivity testing. After experimenting with injection into the Kerbel and the Mt. Simon separately and in combination, it was decided that the Kerbel had adequate injectivity, and the Mt. Simon was plugged off. The well is not yet (February 1974) in operation.

INTERNATIONAL SALT COMPANY

International Salt operates a salt mine on Whiskey Island in Cleveland. The mine is in the Salina Group (Silurian) at a depth of about 1,900 feet. The mine shafts are reported to be leaking fluid from the Oriskany Sandstone (Devonian) at a depth of about 1,350 feet. The briny fluid was collected in the mine, pumped to the surface, and discharged into the Cuyahoga River. A permit was granted in June 1971 to convert to a disposal well an Oriskany well drilled in 1959 for observation purposes. This well is about 600 feet from the mine shafts. The brine from the mine shafts is, in a sense, recycled by injection back into the Oriskany. Preliminary injection began in May 1972.

Problems with corrosion of surface equipment and perhaps plugging by downhole biological growth have hampered injection, but these problems are being solved.

Cumulative injection as of May 1973 was 259,000 gallons at an average pressure of about 125 pounds. Injection rate is about 15 gpm.

POTENTIAL FOR CONTINUED INJECTION

GENERAL STATEMENT

Deep injection of industrial liquid wastes is not a free ride. It serves only as a means of placing wastes in locations where they present no immediate hazard and an acceptable long-term hazard. The locations and formations in Ohio that meet the rigorous injection criteria are limited. The result of subsurface waste storage is an increase in the reservoir pressure of underground formations. The pressure increases are cumulative and are inherently hazardous, although the hazard is not necessarily unacceptable. The problem is to identify the safest locations and then to determine whether the benefit is worth the risk. For limited volumes of waste, there are probably numerous safe injection sites, provided that the best engineering practices are incorporated in well design. However, for large volumes of waste, injected over a long term, there is a strong possibility that the risks would outweigh the benefits.

The major risk associated with deep injection results from the rise in reservoir pressures. At higher pressures the native fluid and the effluent will tend to migrate to lower pressure areas until equilibrium is restored. The avenues of migration will be along the formation toward the outcrop, across the confining beds to higher formations, and through old wells, either to the surface or to adjacent beds. In the process fresh waters may become contaminated or displaced by the wastes.

If the injected volume is small, the time required for the fluid system to reach equilibrium and affect shallow fresh waters could be measured in terms of hundreds of thousands of years. The effect could be undetectably small, in which case it would probably be unwise *not* to practice injection if some significant benefit is gained thereby. On the other hand, it would be foolish indeed to abet a policy that encouraged injection to the extent that fresh-water aquifers were damaged within a few years. The potential hazard from seismic activity triggered by injection is not possible to evaluate in a quantitative manner, but certainly the risk increases with an increase in reservoir pressure.

In a sense, the amount of reservoir space that can safely be devoted to injection is an exhaustible natural resource which should neither be denied usage nor needlessly exploited. Clearly, injection of wastes which can be treated at the surface would constitute needless use.

The proper evaluation of potential benefits versus risk for deep injection is very complex and difficult and requires the close cooperation of several disciplines. It is necessary to determine, first, if the waste is suitable for injection. This requires primarily a judgment, which is necessarily a matter of technology and economics, as to the treatability of the waste at the surface. Next, the mechanics of well construction and operation must be evaluated. Third, an evaluation of the short- and long-term effects on the pressure system within the reservoir must be made. This lies in the field of reservoir engineering with a necessary input of geologic data. Last, the effect and possible hazards must be balanced against the need.

The matter of deep injection is too complex to be handled by rule of thumb. Health officials or others concerned with surface conditions recognize the need and may tend to encourage deep injection. Geologists, aware of the risks more than the need, tend to be cautious. Some individuals, sensitive to the sensational aspects of deep-well hazards, would ban injection altogether. Others, equally well meaning, feel that any potential hazard of deep injection is preferable to the obviously hazardous existing practice of dumping noxious wastes into the nearest river. The writer believes that deep injection of industrial wastes has a definite place in waste management, provided that subsurface storage space is treated as an exhaustible resource and carefully rationed to assure future as well as present use.

MODEL FOR LONG-TERM INJECTION

The quantity of liquid waste now injected and the volume of reservoir space available to accept the waste are both so large that it is very difficult to attain an intuitive grasp of the potential magnitude and effects of deep injection. The following simple hypothetical model, designed to clarify the relationship between volume of effluent, size of the reservoir, and pressure increase, attempts to answer, at least in an intuitive way, the following questions: What are the long-term effects of injection? Are these effects acceptable?

The model considers only the area within Ohio (41,263 square miles) and assumes (1) an average thickness of 100 feet and 10 percent porosity for the Mt. Simon, (2) injection at the present rate (about 200 x 10^6 gallons per year) for 100 years, and (3) that the pressure increase from injection is spread out evenly over the entire area rather than concentrically and exponentially decreasing around each well bore. In order to accommodate the injecta within the formation, the connate fluid is compressed and the pore space within the rock matrix is expanded (by compression of the rock). The compressibility of water is about 3 x 10^{-6} volumes/volume/psi, and the space made by expansion is about the same (Katz and Coats, 1968, p. 93, 182). The volume of pore space involved is 115 x 10^{11} cubic feet (thickness x area x porosity). The volume of the waste fluid is 27 x 10^6 cubic feet (gallons x cubic feet per gallon). Multiplying pore space times compressibility gives volume created by a 1-psi pressure increase; it can be shown that a 78-psi increase would accommodate the entire waste volume by compression of connate fluid alone. Because expansion of pore space in the rock matrix as well as compression of the connate fluid is involved, the pressure increase is reduced by half to 39 psi.

A pressure increase of 39 psi, spread out over the entire formation, would be so small that it could be detected only by the most sensitive measurements. Such a pressure increase would not affect drilling operations and likely would not affect plugged wells. It must be understood that there are many invalidating assumptions involved in this model: reservoir-pressure increases initially would be highest around each well and would decline exponentially away from the well; either higher or lower pressures may be encountered at state lines, depending on whether or not injection is occurring in neighboring areas; compressibilities vary with pressure, composition, and other parameters. The model does show that the long-term pressure increase could be a detectable phenomenon over wide areas, although it is probably an acceptable one. It cannot be positively stated that a pressure rise of 100 or even several hundred psi in any reservoir would necessarily produce unacceptable effects over a relatively short term. Over a longer term or at higher injection rates the effects could become serious. It is very difficult to quantify the limiting volume of waste that can be injected safely, for two reasons: (1) We can engineer deep-injection systems so that the effects on the biosphere take a very long time (thousands to hundreds of thousands of years) to appear; not knowing the expected span of mankind, however, we don't know if this is long enough. (2) We cannot say what effects from deep injection might be "acceptable" to future generations.

Another factor that should enter into a consideration of the potential for future injection is the possibility that growing dependence on nuclear power may make it necessary to inject large quantities of radioactive waste. Of all substances, radioactive liquids have the least possibility of surface treatment and may prove to have the strongest call on the limited subsurface storage space. To fill that space now with less hazardous liquids may not be wise.

In Ohio less than 0.03 percent of all industrial waste is currently being injected. Under carefully controlled conditions it might be possible to increase that volume by an order of magnitude. The effects of such an increase might be tolerable within a short time span, say 100 years. It is clear, however, that such usage would constitute a major exploitation of a limited natural resource and that deep injection is no panacea for the overall problem of industrial waste management.

SUMMARY AND CONCLUSIONS

Subsurface injection has been practiced in Ohio in a relatively safe manner. Injection has been confined primarily to the Mt. Simon Sandstone at depths ranging from 2,800 to 5,600 feet. Injection has been successful in that there have been no known instances of pollution resulting from its use and in that it has served as an attractive alternative to releasing the wastes into surface waters.

The Mt. Simon meets all the criteria for a safe injection zone. The unit is sparsely drilled, relatively unfaulted, and has sufficient permeability in the western two-thirds of Ohio. The sandstone is overlain by reasonably good confining beds, although additional testing of these beds should be done. No oil, gas, or other minerals are produced from the Mt. Simon; regional fluid flow is so slow as not to be a hazard, and the risk of hazardous seismic activity resulting from injection is not thought to be significant.

The Knox, Trenton, "Newburg," Oriskany, and Berea strata lie at sufficient depth and have suitable reservoir characteristics in places in Ohio, but the presence of numerous unlocated or poorly plugged wells penetrating their confining beds greatly reduces the potential usage of these beds for injection.

At the present rate of injection, reservoir-pressure increase in the Mt. Simon in 100 years will probably be acceptable. If the rate of injection is increased by an order of magnitude, or if a longer time period is considered, it is not certain that the effects will be acceptable. The subsurface storage space is created by compression of the rocks and fluid already present in the reservoir. The compressed system will tend to return to equilibrium because of the migration of fluids to areas of lower pressure. Eventually the migration will affect fresh waters; if the injected volume is small enough, the effect will not be significant within a foreseeable time.

The goal of proper management would seem to be a balance between the need to inject untreatable liquids such as radioactive wastes and the possible long-term effects of the resulting pressure increases.

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APPENDIX A

Outline of feasibility report to accompany application for an industrial disposal well

- A. Location
  - 1. Plat showing locations of plant and proposed well and property line with relation to cultural and topographic features. A 7½-minute topographic base showing all wells within 5 miles of injection site.
  - 2. Surveyed plat showing location of well(s) with respect to lot and property lines to conform with NRo-5-05c of Oil and Gas Rules and Regulations.
- B. Geology
  - 1. Stratigraphy–discussion of stratigraphic section to be encountered in well: thickness, depth, and general description of each unit; depth and nature of fresh-water aquifers in the area.
  - 2. Injection horizon and confining beds–description of estimated lithology, thickness, permeability, and porosity of proposed injection zone; calculation of theoretical pressure buildup with time in the reservoir at various distances from the well at the proposed injection rate; description of thickness, lithology, and predicted permeability of proposed confining beds; any data bearing on fracture-breakdown pressures from nearby wells to be included.
  - 3. Structure–contoured structure map of injection zone or other mappable zone showing structural configuration of at least 100-square-mile area; illustration and discussion of any indications of folding and/or faulting.
  - 4. Mineral resources–discussion of any indications of mineral occurrence, including hydrocarbons, salt, or brines, in vicinity of well.
- C. Well design and testing
  - 1. Drilling, coring, and testing program–cores of disposal zone and aquitard advisable; drill-stem test of injection zone or other means of determining reservoir quality, fluid characteristics, original reservoir pressure, and temperature advisable; geophysical-logging program to be included.
  - 2. Reservoir analysis–type of testing, including core analysis and injectivity tests, to be performed to establish character of aquifer and aquitard(s).
  - 3. Casing program–weight, diameter, length, and type of downhole components; description of method of cementation and testing for bond and type and character of cement.
  - 4. Tubing–size, length, and nature of injection tubing; method of setting; fluid to be placed in annulus.
- D. Surface equipment
  - 1. Well-head equipment.
  - 2. Injection pumps and flow lines.
  - 3. Holding tanks–type, capacity, and number of days capacity; if surface pit or lagoon, type of lining; if not lined, discussion of permeability of substrate.
  - 4. Filtration equipment
  - 5. Pre-injection treatment, including settling, neutralization, and additives.
  - 6. Monitoring devices, including complete description of annulus and injection pressures and volume gauges and recorders, automatic alarms and shut-down devices.
- E. Waste fluid
  - 1. Industrial process from which waste derived.
  - 2. Complete chemical analysis of waste and expected range of variation.
  - 3. Volume of waste and variation in volume; expected life of plant or process or time limitation expected for need to inject.
  - 4. Compatibility of waste with subsurface rocks and fluids; effect of and steps taken to control any incompatibility.
- F. Alternative waste handling–discussion of actions to be taken with regard to waste if well is unable to receive fluid for short or extended periods.
- G. Alternative treatment methods
  - 1. Discussion of present treatment method and reason it is not acceptable.
  - 2. Discussion of other possible disposal methods, including those practiced in similar industries.

APPENDIX B

Outline of well-completion report

- A. Division of Oil and Gas completion form (attached)
- B. Additional information
  - 1. Drilling, casing, and cementing record
    - a. Chronological drilling record–hole size, dates of significant operations, unusual occurrences, elevation.
    - b. Casing–size, depth, and characteristics of all casing and tubing.
    - c. Cement–amount, type, and method of cementation. Record of cementing and how cement quality was assured (bond logs, pressure testing, etc.) to be included.
  - 2. Core, sample, and log record
    - a. Cores–intervals cored and names of units; core description; copy of results of lab tests; disposition of core.
    - b. Sample record–description of samples and identification of formations encountered; description of any mineral resources such as coal, salt, oil, or gas; disposition of samples.
    - c. Copies of all geophysical logs run in hole, logs to be sufficient to determine porosity, water saturation, lithologic identification, and correlation.
  - 3. Testing record
    - a. Drill-stem tests–copies of all DST charts and interpretations.
    - b. Initial reservoir temperature and pressure and method of determination.
    - c. Analysis of uncontaminated reservoir fluid.
    - d. Injectivity test results–note: injection pressure should be below 0.75 psi/ft pressure limit. Indications of artificial fracturing to be reported if such occur during testing.
    - e. Compatibility studies; if not compatible, steps to assure injectivity.
    - f. Buffer zone–describe type, rate, and volume of fluid.
  - 4. Summary
    - a. Character of injection zone and confining beds; suitability of system for injection.
    - b. Estimates of injection pressure and calculation of theoretical pressure buildup at several distances from well bore at various times and based on all data.
    - c. Identification of significant departures of drilling data from feasibility report.