FEASIBILITY OF DEEP-WELL INJECTION OF
INDUSTRIAL LIQUID WASTES IN OHIO

A Thesis
Presented in Partial Fulfillment of the Requirements
for the Degree Master of Science

by

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The Ohio State University
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Approved by

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ERRATA

Page 2  para. 2, line 5: Should read about 2800 feet instead of 3000 feet.

Page 4  third line from bottom: Stuart should read Stewart.

Page 53  para. 2, line 1: The Mt. Simon fluid from the Hoelscher well has a lower salinity than that from the Sandusky County well. This is correctly shown on the graph on page 54 (Figure 14). Fluid samples from both wells are believed to be contaminated by mud-filtrate and the salinities probably should be higher.

Page 65  last para., line 1: Warner (1964) should read Warner (1965).
FEASIBILITY OF DEEP-WELL INJECTION OF LIQUID INDUSTRIAL WASTES IN OHIO

INTRODUCTION

Purpose and Scope

The purpose of this investigation is to review the existing practice of deep-well injection of industrial wastes in Ohio, to evaluate the effects, and to assess the future potential of injection based on the geology and geohydrology of disposal zones. Because most of the injected industrial waste in Ohio has been, and probably will continue to be, directed into the Mt. Simon Sandstone of Cambrian age, this formation is given extensive treatment in this report. Coring and testing of the Mt. Simon Sandstone prior to injection operations have provided very good reservoir information, whereas reservoir data for other porous units are sparse.

The practice of injecting brines produced with oil and gas is not considered in this report, although many of the problems and requirements are similar.

General History of Injection in Ohio

Subsurface injection of industrial wastes has been practiced in Ohio since 1967 when enabling legislation was passed to allow and regulate deep injection in response to a growing demand from industry. Administration of the waste-injection law was placed within the
Division of Oil and Gas of the Department of Natural Resources. At this writing, nine applications have been approved, seven wells are in operation, and one is testing prior to operation. One well has been abandoned following corrosion problems.

Injected wastes in Ohio include spent acids from steel pickling lines, brines, and mixed organics from the manufacture of plastics and insecticides. Except for two minor cases, discussed later, all injection has been restricted to the Mt. Simon Sandstone at depths ranging from 3000 to 5600 feet below land surface.

Subsurface injection in Ohio has been successful in that there have been no known instances of pollution resulting from its use, and in general it has served industry as a practical, economically attractive alternative to the previously practiced disposal method, which consisted of releasing the wastes, usually untreated, into surface waters or into pits. Time has been too short to evaluate the possible long-term effects of deep injection.

Increasingly stringent standards of effluent quality will continue to force industry to consider deep injection. For several classes of wastes, notably brines, certain organics, and radioactive liquids, there are presently no technologically feasible treatment methods. For other wastes, such as pickling liquors and phenols, treatment methods exist, but are so expensive as to exclude their use for all but a few plants. For many of these liquid wastes, it appears to be less hazardous to place them remotely underground, under proper conditions, than to release them to surface waters. Consequently, the practice of deep-well injection will probably continue for many years.
Legal Aspects of Waste Injection

Ohio. The legal operation of waste injection wells in Ohio is covered in Chapter 1509 of the Ohio Revised Code. Chapter 1509 deals also with oil and gas operations in general. The sections of the Code which deal specifically with waste injection are reproduced in Appendix A. Under the law, an operator must obtain a permit from the Division of Oil and Gas of the Department of Natural Resources prior to drilling an injection well. Before the permit is issued it must also be approved by the Division of Geological Survey, Department of Health, and Ohio Water Pollution Control Board. If the well is near underground mines, the Division of Mines must also give approval. The Division of Water serves as an advisory body on all permits.

Note, however, that the Division of Oil and Gas and Geological Survey are given very narrow criteria by which to judge the application (1509.081, par. 1 and 2). The Division of Water has no specific authority. The broadest authority appears, to this writer, to lie with the Department of Health and the Ohio Water Pollution Control Board.

The Chief of the Division of Oil and Gas is given authority to adopt rules and regulations for the administration and implementation of the law (1509.081, par. 7), but no rules have been formulated as yet. A potential weakness of the Ohio injection law lies in the fact that no agency is given the specific authority or responsibility of determining if a proposed injection project has sufficient benefit to outweigh the risks involved, and to reject any concerning wastes which
might be more safely treated at the surface. Many states and the Federal Environmental Protection Agency have passed laws or issued policy statements which oppose waste injection unless alternatives have been considered and found less safe in terms of environmental protection. Ohio should have such a policy, but unless the present law is very broadly interpreted, there may not be legal grounds for rejecting applications which would inject treatable wastes underground.

The permit applications are accompanied by extensive engineering and geologic reports dealing with the expected geologic conditions, method of well construction and testing, safety precautions, and surface waste handling facilities. Consulting firms are usually engaged by industry to provide the necessary expertise in designing the injection well, partly because construction and operation are somewhat different than for oil and gas wells.

**General Questions.** Injection of wastes into deep wells is a relatively new development. There have been very few instances of loss or damage due to the practice of injection, consequently many questions regarding damage and liability are not settled. For example, no body of law exists at present to clearly determine whether injected wastes are considered to trespass if they pass beneath the land of another, or whether the law of capture prevails, by which the first user of the reservoir gains precedence. These questions are discussed more fully by Walker and Stuart (1968) and Trelease (1971).

In some cases of deep-well injection, it can be shown that, at least theoretically, the wastes will not pass beyond the limits of the
land owned or leased by the injector, yet reservoir pressure increases will extend for a much larger radius. Has an operator damaged the land of another by causing a pressure increase in underlying deep strata? These questions are largely unanswered at present.

Previous Work

Only a few reports deal with deep-well injection in Ohio. Of these, Smith (1969) and Water Well Journal (1968) briefly describe the Armco Steel operation at Middletown. The two Vistron wells at Lima are mentioned in Environmental Science and Technology (1968). A general overview of deep-well disposal in the Ohio River basin, which includes technical considerations and regional geology, was published by the Ohio River Valley Sanitation Commission (Cleary and Warner, 1968). The document had limited distribution and is now out of print. There is a fairly large body of literature dealing with deep injection, which has been made the subject of a U.S. Geological Survey bibliography (Rima, et al, 1971).

Studies of feasibility of injection have been published for several states including Illinois (Bergstrom, 1968) and Pennsylvania (Rudd, in press); and also for Ontario, Canada (McLean, 1968).

Many papers describe the geology of Ohio, but one bears special mention in regard to deep-well injection. A lithologic study based on nearly one-hundred oil and gas well samples by Janssens (in press) has been completed, which details the stratigraphy of the Sauk Sequence of Cambro-Ordovician age, including the Mt. Simon and its overlying confining beds. Parts of that report have been used herein with the
author's permission. There are no published papers dealing with the hydrodynamics of the Mt. Simon Sandstone in Ohio. A recent paper by Bond (1972), however, describes the hydrodynamics of the Mt. Simon and other deep aquifers of the Illinois Basin.

CONSTRUCTION OF INJECTION WELLS AND OPERATIONAL CONSTRAINTS

Well Construction

Construction methods for injection wells have been described in the literature by McLean (1968), Walker and Stewart (1968), and Donaldson (1964), as well as several others. Disposal wells in general, and all disposal wells in Ohio, have the following features as shown in Figure 1: (1) Large diameter casing is placed from the surface so that it extends below all possible fresh-water bearing zones; it is cemented in place from top to bottom. A depth of 500 feet or less is adequate in most places to reach below fresh-water zones, although this should not be taken for granted. Proof of good cementation from pressure testing or bond logs is usually requested by the Division of Oil and Gas. (2) Inside the surface casing, another string of pipe is cemented in place from the surface to either the top of the disposal zone or through it. This casing, often termed the "long-string" in oil field operations, should also be tested for cement bond. 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 run inside the long string of casing and either sealed from the
Figure 1. Construction of typical injection well.
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 since a leak 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 shut-down devices are activated to shut off the injection pumps until the cause of the problem is located and corrected. Pressure sensors on the injection tubing will also shut off the pumps if either high or unusually low injection pressures exist.

Where the injection tubing is allowed to hang free, a system of electrodes is attached to the injection tubing. These electrodes will indicate any change in the position of the interface between fresh water in the annular space and the effluent, since under normal conditions the interface will remain static. Movement of the interface indicates problems and again appropriate alarms are activated. (4) Surface equipment related to the injection system includes filters, settling and holding tanks, cooling devices if needed, injection pumps, and monitoring equipment. The construction plans must be submitted to the various state agencies as part of the permit application.

During the drilling of the well, it is normal practice to (1) collect samples of the rock cuttings, take cores of the disposal zone, and run drill-stem tests to determine pressures and permeability; and (2) to run geophysical logs to determine correlations, porosity, hydrocarbon indications, and other parameters. These data are also submitted 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.

Volume Limits

The volume of injected effluent is limited to that monthly rate specified in the permit application. Volumes have ranged from less than one to more than eight million gallons per month per well. Each month the well operator is required to report monthly volume, rate, and cumulative volume to the Division of Oil and Gas.

As yet no permit approval has been issued with a limitation on total volume or with a time limit. It may prove to be necessary to make such limitations in order to (1) encourage the development of surface treatment facilities; (2) limit the radius occupied by the liquid, perhaps to the land owned in fee or leased by the operator; (3) limit the build-up of reservoir pressure to a specified value.

Pressure Limits

Recognizing the dangers inherent in injection of wastes under high pressures, the Division of Oil and Gas has instituted a policy of defining a maximum injection pressure for each well. There are three 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 pressures may induce artificial fracturing of the receiving formation as well as confining beds.

3. 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 1000 feet (Augenbaugh and Pullen, 1970; Howard and Fast, 1970; and 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, in press; Howard and Fast, 1970, p. 169; Felsenthal and Ferrell, 1971, p. 728). An additional example is given by Phar (1970) in which a routine hydraulic fracture of the Clinton Sandstone of Silurian age in Ohio is reported to have 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 and, thus, a valuable management control is lost. Fractures tend to propagate in preferred directions, usually parallel to the regional strike, and could transmit fluid great distances from the injection well.
Figure 2. Average fracture breakdown pressure with depth. Pressure gradients are indicated. (After Howard and Fast, 1970, p.7).
Vertical fractures could lead to the transmission of effluent through the casing cement, possibly causing premature corrosion problems, and increasing hazards of contaminating higher beds.

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 and sometimes with an actual decrease in pressure. This is called the breakdown pressure and is assumed to indicate that the formation has ruptured. Breakdown pressures, shown in Figure 2, have been compiled by Howard and Fast (1970) for the Gulf Coast and Mid-Continent. These data show that breakdown normally occurs at a pressure between 0.75 and 1.0 psi/ft (pounds per square inch per foot) of depth at the perforations. The actual data show a wide spread of pressures caused by such variables as regional stress, lithology, condition of the bore hole, number and type of perforations, viscosity of fracturing fluid, and other conditions. The lower limit of 0.75 psi/foot has been chosen to serve as an arbitrary maximum injection pressure limit in Ohio. It is derived as follows:

Maximum surface injection pressure = (depth times 0.75) less (depth times pressure gradient in psi/ft. of the effluent).

Assuming a well in which the top of the injection zone is 4000 feet and the waste fluid has a pressure gradient of 0.5 psi/ft., the maximum allowable surface injection pressure would be:

\[(4000 \times 0.75) - (4000 \times 0.5) = 1000 \text{ psi.}\]
Extensive data like that recorded by Howard and Fast are not available for the Appalachian area, but there are a few indications that the breakdown pressures may fall within the same range. Almost all Ohio data are from the Clinton sandstone. It is not certain that fracture pressures in the Clinton would be similar to those in the Mt. Simon or other formations, but regional stress patterns are a strong causal component of these pressures, and they should be alike for both older and younger units. Breakdown pressures from recent completions reported to the Division of Geological Survey show wide scatter for reasons previously mentioned (Figure 3). It is noted, however, that a 0.75 gradient would have prevented fracturing in about 80 percent of the wells. In addition, fracture pressures are significantly lower in pressure-depleted formations such as the Clinton, hence in undisturbed units the fracture gradients would be much higher (Felsenthal and Ferrell, 1971). The few data from older formations, as noted in Figure 3, show breakdown gradients well above 0.75 psi/ft.

In addition to the breakdown pressure, valuable information is also gained in hydraulic fracturing from the I.S.I. (instantaneous shut-in pressure). At the end of a hydraulic fracturing treatment, the pumps are turned off, and the pressure declines instantly to a lower pressure (the I.S.I.) from which it then declines more slowly. This instantaneous shut-in pressure is believed to indicate the pressure at which the induced fracture, held open by the injection pressures, closes. It is a valuable piece of information because it is seemingly not affected by the many operational and bore-hole factors
Figure 3. Fracture breakdown pressure versus depth, based on data from recent Ohio completions.
that affect breakdown pressures and is not dependent on rock strength. When this pressure is known, it should be used as a basis on which to regulate injection pressures. If injection pressure is kept below the I.S.I., it should assure that the fracture will not open or propagate. Unfortunately, the I.S.I. can only be known after fracturing has occurred, and this writer believes that wells for waste injection should not be fractured as part of a completion program.

Although data are rarely reported to the State on I.S.I. pressures, the Dowell Corporation (letter of May 5, 1972) has kindly supplied I.S.I. values from fracture treatment of some randomly chosen Clinton wells representing 25 countries (Figure 4). As expected, the I.S.I. data show much less scatter than would be expected for breakdown pressures alone. The average I.S.I. 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 I.S.I. pressures had been taken from wells at original pressure, the average would certainly have been higher than 0.733, probably well over 0.75 psi/ft.

Only two injection wells in Ohio are known to have had fracture treatments attempted as part of the completion program. In the Lake County well the Mt. Simon was treated with about 50,000 gallons of water and 15,000 pounds of sand at a maximum pressure of 2500 psi at the surface (about 0.88 psi/ft). Records indicate no breakdown at this pressure. Either the formation was not fractured at this point or, less likely, parting pressure and propagation pressure were the same, allowing injection without a distinct break. The Haverhill well in
Figure 4. Instantaneous shut-in pressure versus depth, Clinton sandstone, Ohio.
Scioto County was fractured at a pressure gradient of about 1.24 psi/ft at the top perforation. The I.S.I. pressure was 1350 psi, which would convert to a gradient of about 0.68 psi/ft.

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 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. Some of these are as follows:

<table>
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<th>Location</th>
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<tr>
<td>Texas</td>
<td>0.85 (approx.)</td>
</tr>
<tr>
<td>California</td>
<td>0.75</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>0.75 or 80 percent of instantaneous shut-in pressure (recommended)</td>
</tr>
<tr>
<td>New York</td>
<td>0.65 (recommended)</td>
</tr>
<tr>
<td>Interstate Oil Compact Commission (Ives and Eddy, 1968)</td>
<td>0.65</td>
</tr>
<tr>
<td>Ontario</td>
<td>0.65 to 0.80 (recommended)</td>
</tr>
<tr>
<td>Kansas</td>
<td>0.60</td>
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Ideally the formation should be sufficiently permeable to take fluid at pressures much less 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, since injection
pressures tend to increase with time. Were it not for an arbitrary
limit, many operators would have a tendency to push injection as far
as possible, since any additional injection is economically very
attractive once the well system is in operation.

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

DESCRIPTION OF INJECTION INSTALLATIONS IN OHIO

General Statement

The major facts concerning the existing industrial injection
wells in Ohio are shown in Table 1. Additional data are presented in
the following section. The location of the wells and the approximate
depth to the top of the Mt. Simon are shown in Figure 5. Data on the
disposal wells are from the files of the Ohio Division of Geological
Survey.

Injection Wells

Armco. Armco Steel Company operates two wells in Butler County
near Middletown. The wells, drilled 1300 feet apart, each penetrate
about 300 feet of the Mt. Simon Sandstone. Neither well reached base-
ment rocks. Each well was equipped with 13-3/8-inch O.D. surface
casing cemented through all fresh-water zones to a depth of about 300
feet. The long-string of 9-5/8-inch O.D. inner casing was set in both
<table>
<thead>
<tr>
<th>Industrial Disposal Well</th>
<th>COUNTY</th>
<th>TOWNSHIP</th>
<th>PERMIT NUMBER</th>
<th>NAME</th>
<th>WELL NUMBER</th>
<th>DEPTH</th>
<th>DATE DRILLED</th>
<th>LIQUID</th>
<th>REMARKS</th>
<th>INJECTION RATE (GALLONS PER MINUTE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 •</td>
<td>Butler</td>
<td>Lemon</td>
<td>4</td>
<td>Armeo Steel</td>
<td>1</td>
<td>3200</td>
<td>1967</td>
<td>Spent MCL pickle liquor</td>
<td>low injection pressure</td>
<td>30 gpm (one well used at a time)</td>
</tr>
<tr>
<td>3 •</td>
<td></td>
<td></td>
<td>5</td>
<td>&quot;</td>
<td>2</td>
<td>1</td>
<td></td>
<td>&quot;</td>
<td>(proposed)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Lake</td>
<td>Perry</td>
<td>142</td>
<td>Calbio Div. of Stauffer Chemical</td>
<td>1</td>
<td>5600</td>
<td>1971</td>
<td>NaCl-25,000 ppm, Organics 4,200 ppm</td>
<td>Injection in Kewel (Cambrian) as well as Mr. Stew., testing 6/72</td>
<td>60-100 gpm (proposed)</td>
</tr>
<tr>
<td>X</td>
<td>Richland</td>
<td>Madison</td>
<td>448</td>
<td>Empire-Reeves Div. of Cyclops Corp.</td>
<td>1</td>
<td>5000</td>
<td>1967</td>
<td>Sr135 H2SO4 pickle liq.</td>
<td>Abandoned February, 1971 due to corrosion</td>
<td>15 gpm</td>
</tr>
<tr>
<td>8 •</td>
<td>Cuyahoga</td>
<td>City of Cleveland</td>
<td>744</td>
<td>International Salt Co.</td>
<td>1</td>
<td>1435</td>
<td>1959 (?</td>
<td>Natural Brine re-injected into Oilskany</td>
<td>Fluid from Oriskanyweep into mine shaft, First injection in Aug., 1972</td>
<td>15 gpm</td>
</tr>
<tr>
<td>5 *</td>
<td>Scioto</td>
<td>Green</td>
<td>212</td>
<td>U.S.S. Chemical Div. U.S. Steel</td>
<td>1</td>
<td>5600</td>
<td>1968</td>
<td>Phormols, Acetone, sodium sulfure solution</td>
<td>high injection press. Completed by wetting casing through Mr. Simon and perf.</td>
<td>90 gpm</td>
</tr>
<tr>
<td>4 *</td>
<td>Allen</td>
<td>Shawnee</td>
<td>67</td>
<td>Vistron Div. of Sohio</td>
<td>1</td>
<td>3200</td>
<td>1968</td>
<td>Antimoninite waste, Sulfate sol'n. w/HCN</td>
<td>high injection press. — testing 6/72</td>
<td>300-400 gpm (three wells used)</td>
</tr>
<tr>
<td>6 •</td>
<td></td>
<td></td>
<td>71</td>
<td>&quot;</td>
<td>2</td>
<td>1969</td>
<td></td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>84</td>
<td>&quot;</td>
<td>3</td>
<td>1971</td>
<td></td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Franklin</td>
<td>Columbus</td>
<td>Ross Labs.</td>
<td>Permit Refused</td>
<td>2007</td>
<td>Cooling water w/soap</td>
<td>Fresh water aquifer was target zone</td>
<td>150 gpm (proposed)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sandusky</td>
<td>Riley</td>
<td>Ohio Liquid Disposal Corp.</td>
<td>Permit Pending</td>
<td></td>
<td></td>
<td>Drilled and tested as stratigraphic test</td>
<td>70 gpm (proposed)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Active well
X Abandoned well
Figure 5. Depth to top of Mt. Simon Sandstone in feet below land surface and locations of injection wells. Depths ignore topography, hence are only approximate.
wells at the top of the Mt. Simon, at a depth of about 2950 feet, and cemented to surface. Each well contains 3-1/2-inch Penton (plastic) coated steel tubing that is set on a packer with oil in the annular space under pressure. Normal monitoring devices and surface equipment, including filters capable of removing solids down to two microns in size, are installed.

Injected fluid is spent hydrochloric acid with the following reported characteristics (Cleary and Warner, 1969): HCl, one percent; FeCl₂, twenty-five percent; and FeCl₃, one and one-half percent.

Prior to injection of wastes, a fresh-water buffer was injected in each of Armco's disposal wells, the purpose of which was 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 (gallons per minute) at 600 psi, 550 gpm at 750 psi, and 740 gpm at 800 psi. Operational injection pressures until just recently have been quite low, ranging from 0 to 80 psi at the surface when injecting at a rate of about 70 gallons per minute or less. Latest reports (May, 1971) show pressure reaching 500 psi for both wells, which is still reasonably low for the depth. Only one well is used for injection at a time, the other remaining on standby. If all is as reported, this operation seems to be a model system with adequate excess injection capacity, low injection pressures, moderate volumes, and no operational problems other than periodic replacement of tubing and packer elements.
Cumulative injected volume as of January 1, 1972, was about 20 million gallons per well. This seems an immense volume. However, when the area of invasion is calculated as follows, it appears that the entire volume theoretically can be contained within a radius of about 216 feet around each well. The calculation is based on the formula for the volume of a cylinder.

\[ r = \frac{V}{\pi h \phi (1 - S_w)} \left[ \frac{1}{2} \right] \]

where

\[ V = \text{volume of injected fluid (20,000,000 gallons)} \]
\[ r = \text{radius of influence} \]
\[ 7.48 = \text{number of gallons per cubic foot} \]
\[ \phi = \text{average porosity (0.13)} \]
\[ S_w = \text{irreducible water saturation (assumed to be 0.30)} \]
\[ \pi = 3.14 \]
\[ h = \text{thickness of porous formation (200 feet net).} \]

Figure 6 shows a comparison between volumes of injected wastes for each of the disposal wells.

The first Armaco well was cored through a portion of the Eau Claire Formation of Cambrian age and through the Mt. Simon. The core is stored at the Ohio Division of Geological Survey. Average porosity and permeability of the Mt. Simon are discussed in a later 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:
Figure 6. Average and cumulative volumes of injected industrial wastes in Ohio as of January, 1972.
<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pH</strong></td>
<td>6.1</td>
</tr>
<tr>
<td><strong>Specific resistance, OHM/CM</strong></td>
<td>7.8</td>
</tr>
<tr>
<td><strong>Density:</strong></td>
<td></td>
</tr>
<tr>
<td>Iron, total</td>
<td>24.4 mg/1</td>
</tr>
<tr>
<td>soluble</td>
<td>7.1</td>
</tr>
<tr>
<td>Dissolved solids</td>
<td>189,000 &quot;</td>
</tr>
<tr>
<td>Sodium</td>
<td>40,200 &quot;</td>
</tr>
<tr>
<td>Potassium</td>
<td>940  &quot;</td>
</tr>
<tr>
<td>Calcium</td>
<td>20,400 &quot;</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2,500 &quot;</td>
</tr>
<tr>
<td>Chloride</td>
<td>110,000 &quot;</td>
</tr>
<tr>
<td>Sulfate</td>
<td>790  &quot;</td>
</tr>
<tr>
<td>Acidity (Phen.) CaCO</td>
<td>40   &quot;</td>
</tr>
<tr>
<td>Alkalinity (M.O.) CaCO₃</td>
<td>7    &quot;</td>
</tr>
</tbody>
</table>

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

**Vistron.** Vistron Division of Sohio operates an acrilonitrile plant near Lima. The wastes consist of a complex mixture of ammonia, sulfate, cyanide, aldehydes, organic acids, nitriles and amides. Reportedly, attempts have been made to treat this waste by incineration and biological degradation, but both methods were uneconomical and produced effluents that were unable to meet standards for water and stack emissions.

The company has installed two injection wells and has completed construction on a third, which will soon be in operation. The first and second wells drilled through 352 and 382 feet of Mt. Simon strata respectively; neither reached basement rocks.

All three wells are reported to have used 10-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 2800 feet below land surface. All casing is cemented to the surface. Injection tubing in the first well is 3-inch O.D., and the second is 4-inch O.D. Both are steel tubing set on packers at the top of the Mt. Simon at about 2780 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 high injection pressures. 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.

The volume of effluent injected in the two operational wells is quite large. Average injection for well No. 1 is about 7 million gallons per month and for the second well is about 8 million gallons per month. Average injection pressures range from about 950 psi to 700 psi respectively, with well No. 1 having essentially reached the injection pressure limit set by the State. The third well, now under construction, appears to be an absolute necessity for continued operation.

The radius of invasion of the effluent injected in well No. 1 should be about 600 feet, based on an effective thickness of 300 feet and 14.4 percent average porosity. A cumulative volume of over 250
million gallons has been injected in well No. 1 and 110 million in well No. 2 as of January 1972. An estimate of the costs involved in constructing well No. 1 was reported in Environmental Science and Technology (1968) as $270,000.

Wells No. 2 and 3 will be able to share much of the surface equipment, but will add at least another $120,000 to the cost of the system. Operational costs were estimated at $100,000 per year. The costs of incinerating the wastes had been reported at $600,000 per year and the company has stated that it could not meet stack effluent standards with that system. The deep-well system appears not only more economical, but may be the only environmentally acceptable solution.

Injection testing performed prior to the completion of well No. 1 indicated good reservoir potential. At a pressure of 700 psi, 380 gallons per minute (16 million gallons per month) were injected. Well No. 1 can still inject as much as seven million gallons per month at about 950 psi.

A fresh-water buffer pad was not used in well No. 1, which may in part account for some of the initial high injection pressures. In well No. 2, about 6 million gallons of fresh water were injected; well No. 3 will be treated similarly.

The Mt. Simon reservoir fluid taken from well No. 1 was analyzed by the operator and is reported as follows:

| Parameter                   | Value  
|-----------------------------|--------
| pH                          | 7.3    
| Alkalinity to pH 8.2 as CaCO₃ | 0 mg/l 
| Alkalinity to pH 4.5 as CaCO₃ | 70 "   
| Chloride as Cl              | 57,500 " 
| Sulfate as SO₄              | 1,450 " 
| Calcium as Ca               | 7,200 " |
Magnesium as Mg
Sodium as Na
Barium as Ba
Hydrogen sulfide as H2S
Conductivity

1,400 mg/l
65,000 "
10w "
negligible "
81,200 μmhos

U.S.S. Chemicals. A disposal well was drilled near Haverhill in Scioto County by the U.S.S. Chemicals Division of U.S. Steel in 1968. The well reached a total depth of 5608 feet, ending in granite. The Mt. Simon, encountered at a depth of 5514 feet, was about 66 feet thick. Reservoir fluid recovered from a drill stem test was analyzed as reported below:

Specific gravity @ 60/60 F
pH
Total alkalinity as CaCO3
Calcium
Magnesium
Sodium
Barium
Sulfate
Chloride
Silica
Total iron
Aluminum
Turbidity as SiO2
Iodide
Bromide
Resistivity, M @ 77°F
Total dissolved solids
Carbon dioxide

1.225
5.5
28. mg/l
50,600 "
7,080 "
58,300 "
0 "
140 "
200,000 "
2 "
39 "
5 "
>150 "
1.3 "
2,160 "
.047 "
316,000 "
240 "

In this well, 10-3/4-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 3-1/2-inch O.D. set on a packer at a depth of 5422 feet. The annular space is reported to be filled with inverted oil emulsion mud. Because the casing was set through the injection zone,
it was perforated in the interval 5517-5599. The first attempt to inject through these perforations failed, probably because of inadequate perforation clean-out. 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 1700#, which is considered to be very slightly above the safe injection-pressure limit at a pressure gradient of 0.77. The company has recently lowered injection pressures. Additional pressure increase could signal the need for an additional well. No operational problems have been reported for the Haverhill well other than high surface 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:

<table>
<thead>
<tr>
<th>Component</th>
<th>Flow, lbs/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (Condensate)</td>
<td>32,144</td>
</tr>
<tr>
<td>Phenol</td>
<td>44</td>
</tr>
<tr>
<td>Acetone</td>
<td>91</td>
</tr>
<tr>
<td>Sodium sulfate</td>
<td>1,315</td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td>24</td>
</tr>
<tr>
<td>Sodium carbonate</td>
<td>218</td>
</tr>
<tr>
<td>Sodium formate</td>
<td>22</td>
</tr>
<tr>
<td>Cumene hydroperoxide</td>
<td>50</td>
</tr>
<tr>
<td>Total</td>
<td>33,908</td>
</tr>
<tr>
<td>Temperature, °F</td>
<td>120</td>
</tr>
<tr>
<td>Density, lbs/gal</td>
<td>8.61</td>
</tr>
<tr>
<td>Flow rate, gal/min</td>
<td>65.6</td>
</tr>
</tbody>
</table>
The theoretical radius presently occupied by the waste fluid is 1056 feet around the bore hole, based on an average effective thickness of 50 feet and 12 percent porosity. The cumulative injected volume on January 1, 1972, was about 110 million gallons.

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

**Empire-Reeves.** The Empire-Reeves Division of Cyclops Corporation drilled the first industrial disposal well in Ohio in the fall of 1967, following passage of enabling legislation. It was abandoned in 1971. The well, located near Mansfield, reached a total depth of 5085 feet. The top of the Mt. Simon was reported at 4982 and granite at 5061 feet.

Surface casing was 10-3/4-inch O.D. which 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 4975 feet and the string was cemented to surface in two stages. Injection tubing is 3-1/2-inch O.D., lined with Penton and set on a packer at 4974 feet.

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

| Iron as Fe  | - 43,750 ppm | pH     | - < 2-0 |
| Copper as Cu | - 7.87 ppm  | SpG    | - 1.195 |
| Zinc as Zn  | - 1.58 ppm  | Freezing Pt | - 6°C |
| Insoluble Residue | - 4,705 ppm | Particle Size | - 20-200 microns |
| Acid Content | - 10.8      |        | 50% <50 microns |
Prior to the establishment of the deep well system, it is reported that the waste was released into Rocky Fork Creek at a controlled rate.

The disposal well experienced problems with the pressures in the annulus after a few months' operation, and underwent extensive reworking. It appears that both casing and tubing were extensively corroded from acid, probably originating from deterioration of the cement around the annulus. During the life of the well, careful attention was given to the possibility that fluid might escape from the disposal system. There is no reason to believe that the waste fluids were brought into contact with overlying fresh water zones, although a strong possibility exists that the Newburg Formation of Silurian age may have accepted some waste.

Because it was determined that the casing and tubing were corroded beyond salvage, the well was plugged early in 1971. Unverified reports indicate that the waste is being stored in surface pits in Sandusky County awaiting attempts to gain approval for an injection well. Plugging was accomplished by removing as much of the injection tubing as possible, and filling the hole with cement.

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 three million gallons was emplaced prior to waste injection. Injectivity tests indicated the following: 42 gpm at 1200 psi, 168 gpm at 1600 psi, and 300 gpm at 1800 psi. No
fracturing was reported at the highest test pressures, 1800 psi, which exceeds the injection-pressure limits now set by the state for a well of this depth at a gradient of about 0.80 psi/ft.

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>5.4</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.200 @ 73 F</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>24 mg/l</td>
</tr>
<tr>
<td>Chloride</td>
<td>183,000 &quot;</td>
</tr>
<tr>
<td>Sulfate</td>
<td>0 &quot;</td>
</tr>
<tr>
<td>Calcium</td>
<td>37,500 &quot;</td>
</tr>
<tr>
<td>Magnesium</td>
<td>3,950 &quot;</td>
</tr>
<tr>
<td>Sodium</td>
<td>67,900 &quot;</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>292,000 &quot;</td>
</tr>
<tr>
<td>Total Iron</td>
<td>145 &quot;</td>
</tr>
</tbody>
</table>

Calhio Chemicals. Calhio Division of Stauffer Chemicals drilled a well in Lake County near Perry for deep disposal in April 1971. As of June, 1972, the well was still being tested, and surface equipment was being installed. The Mt. Simon was topped at about 5930 feet and granite at 6060 feet. Total depth of the well is 6072 feet.

Effluent of the Calhio plant is from the manufacture of the agricultural fungicides Captan and Phalan. The current disposal method is by way of the Grand River via Red Creek. An analysis of the effluent is shown below.

<table>
<thead>
<tr>
<th>Description of Waste Fluid</th>
<th>Chloroform solubles</th>
<th>Methy-ethyl-ketones</th>
<th>Suspended solids</th>
<th>Biological Oxygen Demand</th>
<th>Chemical Oxygen Demand</th>
<th>Specific Gravity</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride - 25,000 ppm</td>
<td>Chloroform solubles</td>
<td>1,200 ppm</td>
<td>nil</td>
<td>3,000 ppm</td>
<td>4,000 ppm</td>
<td>1.025</td>
<td>7.0 to 7.5</td>
</tr>
<tr>
<td>Sodium Sulfate - 2,000 ppm</td>
<td>Methy-ethyl-ketones</td>
<td>nil</td>
<td>Biological Oxygen Demand</td>
<td>3,000 ppm</td>
<td>4,000 ppm</td>
<td>1.025</td>
<td>7.0 to 7.5</td>
</tr>
<tr>
<td>Ferrous Iron - 300 ppm</td>
<td>Biological Oxygen Demand</td>
<td>Chemical Oxygen Demand</td>
<td>Specific Gravity</td>
<td>pH</td>
<td>7.0 to 7.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calcium ion - 100 ppm</td>
<td>Chemical Oxygen Demand</td>
<td>Specific Gravity</td>
<td>pH</td>
<td>7.0 to 7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnesium ion - 10 ppm</td>
<td>Specific Gravity</td>
<td>pH</td>
<td>7.0 to 7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hexane Soluble - 10 ppm</td>
<td>pH</td>
<td>7.0 to 7.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In this well, surface casing is set at 512 feet and cemented to surface. Details of the completion efforts have not been released, but it has been reported that the Mt. Simon appears to have limited permeability and is possibly inadequate as an injection zone. Approval was given for the operators to test the Kerbel Sand, a Cambrian unit overlying the Conasauga Formation. This sandstone has been fractured and initial testing may indicate sufficient injection capacity when it is used in conjunction with the Mt. Simon.

Formation characteristics of the Mt. Simon and the Kerbel have not been fully reported as yet.

_International Salt Company_. International Salt operates a salt mine on Whiskey Island in Cleveland. The mine is in the Salina Formation of Silurian age at a depth of about 1900 feet. The mine shafts are reported to be leaking fluid from the Oriskany sandstone of Devonian age at a depth of about 1350 feet. The briny fluid was collected in the mine, pumped to the surface, and discharged into the Cuyahoga River. Legal action against the company has forced consideration of a disposal well. A permit was granted in June 1971 to convert an Oriskany well drilled for observation purposes in 1959 to a disposal well. The brine from the mine shafts will actually be recycled by injection into the Oriskany. Operation of the disposal well had awaited construction of pumps and filters, but in May 1972, preliminary injection was started. Injection pressures will not be allowed to exceed 50 psi at a rate of about 15 gpm.
GEOHYDROLOGY OF POTENTIAL INJECTION ZONES

Suitability for Injection

In order for a formation to be suitable for deep-well injection of wastes, the following conditions are identified as being essential.

1. The unit must be thick enough and have sufficient areal extent to receive large volumes of fluid without an unacceptable rise in reservoir pressure.

2. Permeability and porosity must be high enough so that the desired volumes may be injected at useful rates and acceptable pressures.

3. The 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.

4. Geologic structures in the area of the well must be simple and unfaulted, and the area should be one of low stress accumulation as evidenced by low levels of seismic activity.

5. The injection zone normally should not contain valuable mineral deposits, such as oil and gas. It is possible, however, that in some cases the benefits of subsurface injection would outweigh the value of the possible minerals in the formation.
6. Salinity of fluid in the disposal zone should be high, at least above 10,000 mg/l total dissolved solids. High natural salinity is a good argument in itself that the reservoir is confined and that the fluids therein are relatively stagnant. Reservoirs containing fluid of low to moderate salinity should be reserved for future use as sources of potable-water storage or desalination.

7. A very important criterion is that there should be no likelihood of unlocated or improperly plugged wells reaching or penetrating the confining beds within a wide radius of the injection well. The radius will depend on the volume to be injected but it should be at least two miles. This may be the most serious constraint on deep injection in Ohio, where hydrocarbon production dates back well before 1900 and where records of old wells are very incomplete. Figure 7 indicates the areas of extremely dense drilling associated with oil and gas production.

8. Movement of natural fluids within the injection zone must be so slow that waste fluids cannot migrate to outcrops or other areas where they would present hazards in the foreseeable future.

9. The injected fluids should be compatible with the formation itself and its contained fluid so that hazardous reactions would not occur.

Each of these factors is discussed in the following section with regard to the Mt. Simon and other potential disposal zones.
Mt. Simon Formation

**Thickness and Distribution.** The Mt. Simon Formation is a widespread sandstone of Cambrian age, which immediately overlies Precambrian igneous and meta-sedimentary rocks in Ohio. The formation thickens westward from Ohio into the Illinois Basin, where it exceeds 1500 feet in thickness in many places and is an attractive deep-disposal zone (Bergstrom, 1968). Northward from Ohio, the Mt. Simon is thick and extensive in the Michigan Basin (Cohee, 1957). In New York and northern Pennsylvania, it is equivalent to the Potsdam Sandstone. In western West Virginia, the Mt. Simon is present in Wood County, where it is about 280 feet thick (West Virginia Geol. Survey R.I. 18). In eastern Pennsylvania and southward, the Mt. Simon lies at great depths and is not well known, but Colton (1961) believes that it passes into a predominantly carbonate sequence that is underlain by older Cambrian clastics not present in Ohio. Wagner (1966) states that the Mt. Simon and equivalents can be considered as a single rock-stratigraphic unit stretching from the Upper Mississippi Valley to New York State.

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 8 (Janssens, in press). Thickness of the unit depends partly on the topography of the underlying basement rocks; the sandstone thins markedly over basement highs. Because many of the deep wells were drilled in attempts to encounter high areas, the data may be biased in favor of anomalously thin Mt. Simon sections. If wells had been randomly located, the normal thickness
Figure 8. Thickness of the Mt. Simon Sandstone in Ohio. (from Janssens, in press)
would probably tend to be somewhat greater than is shown in Figure 8. The most striking example of thinning is in a well in Pickaway County, where the entire Mt. Simon and part of the overlying Eau Claire are absent, probably as a result of nondeposition over a granite high (Janssens, personal communication).

In general, wells encountering less than 100 feet of Mt. Simon have been marginally successful at receiving wastes with reasonably low pressures, while those with more than 200 feet of section have had good injection characteristics.

Figure 9 is a cross section of the Mt. Simon and associated formations in west-central Ohio. The top of the Mt. Simon is relatively easy to locate on geophysical logs in eastern and central Ohio. The contrast in radioactivity levels between the carbonates of the Rome formation and the more highly radioactive Mt. Simon provides a ready differentiation on gamma ray logs. Westward, however, the contact is less distinct and is usually determined from well cuttings or cores at the disappearance of glauconite which is present in the overlying Eau Claire. There is some indication that the top of the Mt. Simon, on the basis of lithology, is picked stratigraphically higher westward than it would be if log correlations were used. Note the log correlations (dashed line) between wells P-79 and P-139 shown on Figure 9. Younger strata seems to be included in well P-139 in the Mt. Simon on the basis of lithologic correlation (solid line).

Porosity, Permeability, and Lithology. Janssens' study, in press, of the Sauk Sequence includes examination of nearly all available
Figure 9. Cross-section showing Mt. Simon and sub-Knox stratigraphy in west-central Ohio (tops and terminology after Jassenko, in press; names in parentheses after Calvert, 1963); lines dashed where correlations are uncertain or where alternate correlations or terminology are possible.
samples of the deep tests in Ohio. This work, along with examination of the cores from the disposal wells, has provided a good picture of the Mt. Simon. The sandstone is fine- to medium-grained, with some coarse-grained beds. It is hematitic and slightly glauconitic. Cement is generally silica, although dolomite and hemetite are present in places. Near the base the sandstone is often very arkosic and conglomeratic.

On gamma ray logs, the Mt. Simon appears to be abnormally radioactive for a sandstone. Its natural radiation is about as high as that of marine shales. The common explanation for this phenomenon is that the sandstone contains either glauconite or potassium minerals, but glauconite is not a significant constituent. Basement rocks in Ohio contain large percentages of microcline (potassic feldspar) in many places (McCormick, 1961), and limited unpublished data suggest that microcline is also abundant in the Mt. Simon.

Values of average porosity and permeability derived from core analysis, drill stem tests, and geophysical log analysis for the injection wells and other selected Mt. Simon tests are shown in Table 2. Most permeabilities derived from drill stem tests are quite accurate, but core analysis for permeability has some shortcomings. Permeability tests are usually performed on selected, small-diameter plugs (1/2-inch) taken from the core at one- or two-foot intervals. The tests are only accurate if the plugs are representative of the whole rock. Analysis of sections of the whole core can be done and are preferable.

Core permeabilities are commonly determined by passing an inert gas under pressure through the core. If permeability is high, there
<table>
<thead>
<tr>
<th>Well Name</th>
<th>County</th>
<th>Permit</th>
<th>Average Porosity</th>
<th>Average Permeability</th>
<th>Interval Analyzed</th>
<th>Source of Data</th>
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<tr>
<td>Vistron #1</td>
<td>Allen</td>
<td>P-67</td>
<td>14.4%</td>
<td>80 md (in.²/ft.²)</td>
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<td>East Ohio</td>
<td>Auglaize</td>
<td>P-71</td>
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<td></td>
<td>148'</td>
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<tr>
<td>#1 Hoelscher</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>127'</td>
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<tr>
<td>Arco #1</td>
<td>Butler</td>
<td>P-4</td>
<td>13.1%</td>
<td>25.1 md (in.²/ft.²)</td>
<td>7</td>
<td>Consultants Report</td>
</tr>
<tr>
<td></td>
<td></td>
<td>IWDW #2</td>
<td></td>
<td></td>
<td>217'</td>
<td>Core Analysis</td>
</tr>
<tr>
<td>Sun Oil #1</td>
<td>Erie</td>
<td>P-19</td>
<td>13.2%</td>
<td>32.6 md.</td>
<td>44'</td>
<td>Unpublished</td>
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<tr>
<td>Herman</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Consultant's Report</td>
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<tr>
<td>Amerada #1</td>
<td>Noble</td>
<td>P-1278</td>
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<td></td>
<td>175'</td>
<td>Cross-plot log analysis</td>
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<tr>
<td>Ullman</td>
<td></td>
<td></td>
<td></td>
<td>very low*</td>
<td>159'</td>
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<tr>
<td>Calhio #1</td>
<td>Lake</td>
<td>P-142</td>
<td>8.4%</td>
<td>3.0 md</td>
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<tr>
<td></td>
<td>IWDW #7</td>
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<td>27 md (in.²/ft.²)</td>
<td>29'</td>
<td>Core Analysis</td>
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</table>

*Note - Drill Stem Test of Mt. Simon recovered only 90 feet of drilling mud over interval 11,283-11,442

Table 2. Porosity and permeability data for the Mt. Simon Sandstone.
tends to be a reasonable correlation between permeability to gas and permeability to water or other liquid. When permeability is low, especially below 10 md, complex factors such as surface-area effects and polar attraction can cause wide differences between liquid and gas permeability (Neilson Rudd, personal communication). Some permeabilities listed in the table are based on the movement of gas only, and could be as much as 50 percent lower with respect to a polar liquid such as water.

Ideally, core analysis should be performed on sections of the whole core, rather than on small plugs, and should be measured relative to water, or, better yet, to samples of the effluent liquid. Even the best core analysis cannot measure the effect fractures might have on the permeability of the reservoir or the confining beds.

The unit of permeability measured in the oilfields is the darcy, defined as that permeability which will allow a flow of one millimeter per second per each square centimeter, of a fluid of 0.01 poise viscosity (fresh water) under a pressure drop of one atmosphere. Permeabilities are almost always reported in millidarcies (1/1000 of a darcy), with the range being about 5 to 10 md for a well-cemented, fine-grained sandstone to more than 2000 md for a loosely-packed, well-sorted sand. Permeability of shale is frequently as low as $1 \times 10^{-6}$ to $1 \times 10^{-8}$ md. In ground-water hydrology, the unit equivalent to the darcy is the coefficient of permeability in gallons per day per square foot (one darcy equals 18.2 gpd/ft$^2$).

A graph was prepared showing the relationship between porosity and permeability in the Mt. Simon (Figure 10). The data suggest that for
Figure 10. Relationship between porosity and permeability in the Mt. Simon Sandstone, Ohio.
permeability to reach adequate levels for injection into an average thickness of the Mt. Simon, the average porosity should exceed 11 percent. Work is now in progress at the Geological Survey to determine more accurately the porosity distribution in the Mt. Simon, using porosity cross-plots from geophysical logs.

From the well data now at hand, it appears that porosity and permeability of the Mt. Simon tend to decrease eastward. Thickness decreases toward central Ohio, then increases further east. Depth to the top of the Mt. Simon increases greatly in that direction. From these facts, and the histories of the injection wells, Figure 11 was constructed to show the relative injection potential of the Mt. Simon. For small volumes of waste—for example, less than 15 gpm—the areas could be shifted somewhat further eastward.

Confining Beds. Throughout Ohio, at least 2000 feet and in places more than 10,000 feet of predominantly impermeable strata lie between the Mt. Simon and aquifers bearing fresh water. A typical stratigraphic column for Ohio, giving lithology, thickness, and aquifer information is shown in Figure 12.

In Ohio, fresh-water-bearing formations rarely occur below 500 feet. Detailed information on the depth and name of the lowest fresh-water-bearing unit in each area of Ohio can be found in Sedam and Stein (1970).

The Eau Claire, Rome, and Conasauga formations of Cambrian age are the confining beds overlying the Mt. Simon. These are shown in Figure 9 and are fully described by Janssens, in press. The Eau Claire
Figure 11. Areas of good, fair, and poor injection potential in the Mt. Simon of Ohio. Line of cross-section also shown.
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 running approximately along the eastern borders of Hancock, Greene, and Champaign Counties. The Eau Claire is a glauconitic siltstone and very fine-grained sandstone with thin beds and partings of shale. It ranges in thickness from 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 were on core material from the Armco No. 1 well in Butler County. The interval 2859-2881 feet was reported to have permeability in a vertical direction to water generally less than $1 \times 10^{-6}$ md, with one sample as high as $3.43 \times 10^{-2}$ md. In ground-water terms, these permeabilities would be equivalent to less than $2 \times 10^{-8}$ gallons per day per square foot, up to $6 \times 10^{-4}$ gpd/ft$^2$. If the average permeability of a 400-foot-thick section of Eau Claire were $2 \times 10^{-8}$ gpd/ft$^2$, and the increase in reservoir pressure due to injection in the Mt. Simon within a quarter-mile radius of the well were 100 psi, then it can be shown that within this radius 0.05 gallon per day of liquid (assuming a viscosity similar to that of water) could pass vertically through the Eau Claire. At the higher value of permeability, 1950 gallons per day would leak from the injection zone. The actual permeabilities probably average close to the lower value. The point of this exercise is that while 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 con-
fining beds, and if the area affected by pressure elevation is of 
large areal extent, then the amount of fluid passing through the con-
fining beds could be significant.

It must also be realized that if the confining beds are brittle 
enough to contain vertical fractures, then permeability along these 
planes may be more important than the intergranular passages. Shale, 
being slightly elastic under conditions of deep burial, is a favorable 
confining bed, because it can flow and seal fractures. It is believed 
that there are adequate shale beds to perform this function in the Eau 
Claire.

To the writer's knowledge, the only conclusive method of deter-
mining the sealing ability of the Eau Claire and other confining beds 
would be by monitoring the fluid level in a well drilled near a dis-
posal well. The monitor well should be drilled to the aquifer nearest 
vertically to the disposal zone. If a fluid level increase in the 
monitor well is detected as injection progresses, the confining beds 
between the aquifer and the disposal well may not be adequate. The 
interpretation of the data would be difficult because part of any 
detectable pressure rise in the monitor well could be due to compres-
sion of the rocks rather than direct leakage. As yet, no studies of 
this type have been done in Ohio.

East of the Eau Claire facies, the Rome and Conasauga Formations 
overlie the Mt. Simon. The Rome is a pelletal, oolitic, tight to 
slightly-porous dolomite. It is more than 600 feet thick in eastern
Ohio but thins 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 100 to 150 feet. It should be an excellent confining bed.

The formations lying above the Rome and Conasauga are described briefly in the columnar section (Figure 12, in pocket). Many of these units are confining beds, notably the Ordovician shale sequence, which is as much as 1500 feet in thickness, and the Devonian and Mississippi shales of central and western Ohio. These are not discussed in detail because it is believed that sufficient confinement is afforded by the sub-Knox units.

**Structure and Seismicity.** The general subsurface configuration of Ohio on the top of the basement rocks is relatively simple. The major structural feature is the Cincinnati Arch, a broad, almost flat-topped, relatively high area that trends northeast-southwest across the western part of the state. The approximate configuration of the Arch is apparent in Figure 5. A map showing the structure on the top of the basement rocks was published by Owens (1967). He shows that dips on the top of the Arch are less than a half-degree, but increase to about one degree in Perry County and are slightly higher further east.

Janssens (in press) has mapped many of the known structural anomalies in the state. He shows that closure at the Knox level rarely exceeds 50 feet, and that closed highs are rarely greater than one square mile in area. Mapping at higher stratigraphic levels, where
control is more abundant, shows essentially the same gentle structure on the top of the Columbus Limestone of Devonian age (Owens, 1970).

None of the deep structures is associated with known faulting. A flexure in the Bowling Green area has been interpreted as a fault by some (e.g., Farnsworth, cited by Forsyth, 1966), but the surface evidence is equivocal and the subsurface relationships may be accounted for by postulating dips of no more than six degrees, rather than faults. The writer knows of no firm evidence for deep faulting anywhere in Ohio, although Lockett (1947) cites confidential seismic indications of faulting in eastern Ohio.

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. Except possibly for the Bowling Green area, and the Serpent Mound (astrobleme ?) disturbed area in Adams County, there appear to be no areas where the Mt. Simon Sandstone should be excluded from waste injection because of structural conditions. Geophysical logs and other evidence from injection wells should nevertheless be carefully examined for evidence of faulting before injection is begun.

Evans (1966) has suggested that deep injection in a disposal well at the Rocky Mountain Arsenal near Denver could be statistically correlated 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 now believe that deep injection did trigger seismic events. However, for opposing
views see Simon (1969). Deep injection was discontinued in the Rocky
Mountain Arsenal well in February of 1966, but a lower level of seis-
micity persists. It has been confirmed (Raleigh, 1971) that earthquakes
were also associated with water-flood injection injection at the Rangeley
oil field in northwestern Colorado. Investigators agree that both areas
had a previous history of stress accumulation from tectonic shearing, as
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 (Raleigh, 1971). The injection wells
triggered the quakes by relieving a fraction of the frictional resistance
to shear along the fault plane. In neither case, however, was the 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
Engrs., 1966). This process could be used where the hazard of earth-
quakes is high, to intentionally produce minor quakes so as to eliminate
major ones (Evans, 1966).

There are three seismic stations in Ohio that are capable of
detecting any quakes of sufficient intensity to be felt by humans.
Since waste injection started in 1967, there has been only one shock
reported in Ohio; it had an epicenter near Columbus, which is about 60
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, 1965). The largest of these reached a magnitude of about 5
to 6 on the Richter scale.
From these and other quakes reported by Bradley, it appears that there probably is stress accumulation in Ohio and this leaves open the possibility that deep injection near shear planes could trigger quakes. Until more evidence is available on this problem, it would be well to carefully locate injection wells away from seismic epicenters and fault zones. At this time there are no seismic monitoring devices sufficiently close to the injection wells to detect micro-seismic events in Ohio, but it is reasonably certain that no earthquakes greater than about 2 on the Richter scale have resulted from deep injection.

**Mineral Deposits.** The Mt. Simon Sandstone contains no known economically valuable mineral deposits. There are no wells producing hydrocarbons from the formation, and only one well has reported a show of gas. At this time, the connate brines have no known commercial value. In general, the water in the Clinton and Newburg Formations (Silurian) are of higher concentration and are shallower, but even these are not considered valuable. The only commercial natural brine production in Ohio is from shallow Mississippian and Pennsylvanian sandstones in Meigs County, which produce less than 1 percent of the salt made in Ohio.

**Salinity.** A contoured map showing the salinity, as total dissolved solids, of the fluid in the Mt. Simon is shown in Figure 13. The increase in salinity (as specific gravity) with depth is graphically illustrated in Figure 14. The values falling to the left of the dashed line may be caused by erroneously low specific gravities resulting from
Figure 13. Salinity of fluid in the Mt. Simon Sandstone.
the fact that fluids recovered from drill-stem tests possibly are contaminated with relatively fresh filtrate from the drilling mud. It is believed that the dashed line represents an approximately accurate average salinity for any given depth (Figure 14).

The lowest recorded salinity in the Mt. Simon is 126,000 ppm of dissolved solids. Because this concentration is about 4 times greater than that of seawater, it is unlikely that any desalination or freshwater storage project in the Mt. Simon would be feasible in Ohio.

**Unplugged and Unlocated Wells.** Because the Mt. Simon is the deepest sedimentary unit in Ohio, and because it has not been productive of oil and gas, there has been relatively little drilling to this zone. Only about 140 of the estimated 120,000 to 200,000 total wells in the state reach the Mt. Simon. Each Mt. Simon test was a wildcat, and was unusually deep for its area; therefore a much better record was generally kept than for a shallow test. It will almost certainly be possible to locate all Mt. Simon wells near any proposed injection site, but whether or not some of these wells were adequately plugged may be difficult or impossible to determine.

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 an attempt to plug wells. Such expedients as forcing tree trunks down the bore hole, followed by dirt, rocks, limestone screenings, or anything handy, were attempted. The producing casing strings and fresh
Figure 14. Fluid specific gravity versus depth in the Mt. Simon Sandstone.
water casing were sometimes pulled out of the hole, sometimes not. Too often the disappointed drillers merely walked away from the hole.

Even where careful attempts are made to provide a long-lasting plug to isolate all reservoir zones, it is not certain that any given method is adequate. The art of adequately plugging wells is very poorly developed. For instance, a commonly approved practice is to plug wells with mixtures of locally acquired clay and water, yet no standards of acceptable mud characteristics such as weight, viscosity, or water loss have been applied. Nor is it known what long-term changes these mud slurries undergo in contact with subsurface fluids. Whether or not cement plugs, wooden plugs, or other solid devices emplaced in well bores are actually effective in resisting upward pressure is also uncertain.

The most serious problem 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 alone the Mt. Simon is the most favorable injection zone in Ohio.

**Hydrodynamics.** It has been suggested that naturally occurring patterns of fluid flow may exist in deep reservoirs, and that fluids injected into such reservoirs may be incorporated into this regional flow and be carried to outcrops or other areas where they could present hazards (e.g., Piper, 1969). In order to determine the significance of deep flow as related to injection into the Mt. Simon in Ohio, the following study was undertaken.
The indicated direction of fluid flow is determined from potentiometric surface maps (Hubbert, 1953). The potentiometric surface is described by determining the elevation to which fresh water would rise in a bore-hole open to the surface at the pressure encountered in the formation. This is done for each well, and the points are contoured. Flow, if any, is normal to the contours and in the direction of lower potential.

Pressure data for the Mt. Simon were available from seven drill-stem tests and from two static water levels from wells in Ohio and surrounding states (Table 3). The pressures recorded from the drill stem charts were extrapolated to infinite time by the service companies or by the writer, or had essentially flat curves which could be read directly; the data are felt to be reliable. No attempt was made to verify the two reported static water levels. The potentiometric surface of the Mt. Simon in Ohio and adjacent areas is shown in Figure 15.

It has long been known that part of the apparent difference in potential head from one area to another is due to the variation in salinity of the reservoir fluid and does not reflect actual difference in head (Hubbert, 1953, p. 1995). Bond (1972) discusses both the problem and the effects of the salinity variation.

A method suggested by Dr. Bond of the Illinois Geological Survey (personal communication, May, 1972) was used to correct the potentiometric surface data. Basically, a model of the pressure system in a deep aquifer can be considered as a U-tube that is open at both ends. The tube is filled with water that increases in salinity and density
### POTENTIALMATIC SURFACE DATA

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<th>State</th>
<th>Well</th>
<th>Elevation</th>
<th>Reservoir Pressure</th>
<th>Gage Depth</th>
<th>Gage Elevation</th>
<th>Top Mt. Simon</th>
<th>Specific Gravity</th>
<th>Potentiometric Surface</th>
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<td>-100</td>
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<td>(-4614)</td>
<td>1.166 (.497)</td>
<td>992</td>
<td></td>
<td>Published static str.</td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>level (Hundley, 1963)</td>
</tr>
<tr>
<td>Michigan</td>
<td>Consumers Gas</td>
<td>616</td>
<td>2145</td>
<td>4498</td>
<td>(-3882)</td>
<td>4576</td>
<td>(-3960)</td>
<td>1.195 (.517)</td>
<td>DST (Extrapolated)</td>
</tr>
<tr>
<td>Kentucky</td>
<td>Louisville (DuPont)</td>
<td>462</td>
<td>2571</td>
<td>5397</td>
<td>(-4335)</td>
<td>5408</td>
<td>(-4946)</td>
<td>1.14 (.494)</td>
<td>DST (not extrapolated,</td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>curve reported flat</td>
</tr>
</tbody>
</table>

1. Depths measured from Kelly bushing
2. Depth measured from ground surface
3. Top in feet below land surface
4. Elevation of top of Mt. Simon in feet below sea level
5. Potentiometric surface = (Reservoir pressure x 2.31) + gage datum

Table 3. Potentiometric-surface data
Figure 15. Potentiometric-surface map of the Mt. Simon Sandstone. Not corrected for density variations.
with depth, so that the pressure at the bottom of the tube is greater than it would be if only fresh water filled the tube. This difference in salinity affects the interpretation of a potentiometric-surface map unless it is somehow eliminated. Bond suggests comparing data from pairs of wells and by assuming that salinity, hence density, varies directly with depth, subtracting an appropriate pressure from the well which taps the reservoir affected by the most dense column of water (Figure 16). When these corrections are made between all combinations of pairs of wells, a form-line map styled after the uncorrected potentiometric surface map can be constructed (Figure 17). This map will more accurately depict the actual head difference between any areas. The correction is only valid if density varies directly with depth, and data shown in Figure 18 suggests that it does.

Potentiometric surface data based on pressures at the bottom of a well are also slightly affected by variations in density caused by the compressibility of fluid. Unlike the salinity variation, this change in density is negligibly small for the area under consideration.

The theoretical velocity of natural hydrodynamic flow in the Mt. Simon can be calculated between any two points in Ohio on the basis of Darcy's Law. It is necessary to know the average porosity and permeability, and the average thickness of the formation, and to assume that the formation is isotropic and homogeneous. A fluid viscosity equal to that of fresh water is also assumed. Using average porosities and permeabilities from Table 2 and head differences determined from Figure 17, velocities expected to occur in the Mt. Simon are calculated as shown in
$P_1(\text{corrected}) = P_1 + \frac{(D_1 - D_2) \times (G_1 - G_2)}{2} \times \frac{.433}{.511 - .478}$

$= P_1 + \frac{(-4000 - (-2000)) \times (.511 - .478)}{2} \times \frac{.433}{.511 - .478}$

$= P_1 - 79 \text{ feet}$

Where: $P$ = Potentiometric surface value in feet  
$D$ = Datum of pressure recording gage in p.s.i.  
$G$ = Pressure gradient of reservoir fluid in p.s.i. per foot  
$.433$ = Conversion factor from p.s.i. to feet

Figure 16. Method of correcting potentiometric-surface data for fluid density variation between two wells.
Figure 17. Form-line map showing potentiometric surface corrected for salinity variations. Contour interval 100 feet of hydraulic head.
Figure 18. Pressure versus depth, Mt. Simon Sandstone.
Figure 19. The theoretical highest velocity in Ohio, neglecting effects of viscosity and irreducible water saturation, should not exceed seven inches per year, and will average much less. The fluid will actually travel slightly faster and farther than is indicated because it will travel preferentially in zones of highest porosity. Still, the velocity of the natural fluid is so low that it can be neglected as a consideration in deep-well injection practices in the Mt. Simon in Ohio. The effects of pressure increases due to injection on the velocity are not considered in detail here, but could locally affect the flow velocity, even reversing the direction. Unless injection is continued for a very long time at rates much greater than at present, the changed velocities due to injection should not constitute a significant hazard.

Compatibility. The various reactions between effluent and reservoir fluid have been reviewed by Warner (1965) 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.
Figure 19. Theoretical velocity of flow versus head difference for various values of porosity and permeability.
If these reactions occur, they will tend to reduce permeability and may cause increased injection pressure. Since there is a limit placed on injection pressure by the Ohio Division of Oil and Gas, it is incumbent on the operator to engineer his technique in order to avoid incompatibility reactions. Many of the common wastes have proven to be incompatible with the reservoir fluids and it has been necessary to inject fresh water, which is compatible with both fluids, as a buffer prior to injection of wastes. Such buffers may total between 2 and 4 million gallons per well.

The Mt. Simon is a sandstone, composed of probably at least 60 percent quartz and lesser amounts of feldspar, and dolomite cement. The quartz is essentially nonreactive. No hazardous reaction of feldspar to any common industrial effluent is known to the writer.

Acid reaction with dolomite can cause evolution of carbon dioxide. The presence of gas may reduce permeability because of the Jamin effect (Rudd, in press), which applies to the presence of two phases of fluid moving through pore spaces. An opposing effect is possible because permeability may be increased through the dissolution of matrix and cement by the acid. The total effect of these two conditions in an average reservoir is unknown.

Evolution of gas may also cause an increase in pressure (Warner, 1964, p. 29). However, various acids have been successfully injected into carbonate reservoirs for many years (Donaldson, 1964) under gravity flow, with no apparent ill effects. The writer knows of no evidence that acid injection into carbonate reservoirs is necessarily unfeasible.
No hazard resulting from incompatibility from most liquid wastes is indicated for the Mt. Simon other than perhaps early abandonment of the well system due to high injection pressures.

Other Potential Injection Zones

General Comments. Several other potential injection zones exist in Ohio, but all are less attractive than the Mt. Simon for one reason or another and all would require extremely careful investigation prior to approval. The most difficult obstacle is the presence of numerous old wells drilled to the post-Cambrian strata. Most of these were development wells, for which records are poor or nonexistent. In order to use the shallower zones, an operator might have to re-enter and properly plug all known wells within a wide radius of the disposal well. He would probably also need to show good evidence that he had actually located all the wells. In some areas, this would be a difficult task. Rough estimates from several sources concerning the number of wells drilled to various zones are given below:

<table>
<thead>
<tr>
<th>Pennsylvanian and Mississippian Sandstones</th>
<th>100,000 to 150,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silurian (Oriskany and Newburg)</td>
<td>51,000</td>
</tr>
<tr>
<td>Silurian (Clinton)</td>
<td>50,000</td>
</tr>
<tr>
<td>Ordovician (Trenton)</td>
<td>75,000</td>
</tr>
<tr>
<td>Cambro-Ordovician (Knox)</td>
<td>3,000</td>
</tr>
<tr>
<td>Cambrian (Kerbel)</td>
<td>160</td>
</tr>
<tr>
<td>Cambrian (Mt. Simon)</td>
<td>140</td>
</tr>
</tbody>
</table>

It is apparent that the potential danger of effluent leakage through unplugged wells increases immensely in post-Cambrian strata. In order for an operator to gain approval for injection in any formation that has
Figure 20. Thickness of Kerbel Sandstone. From Janssens, in press.
been penetrated by numerous wells, it may be necessary that plans for
one or more monitoring wells in overlying reservoirs be included in the
permit application.

The generalized reservoir characteristics of the post-Mt. Simon
strata which might be considered to have injection potential are dis-
cussed below (refer to Figure 2, in pocket).

**Kerbel Formation.** The Kerbel Formation of Cambrian age, recently
named by Janssens (in press) is a fine- to coarse-grained deltaic sand-
stone that stratigraphically higher becomes coarser. It lies between
the Conasauga Formation and the overlying Knox Dolomite. The Kerbel
ranges in thickness from 0 to 150 feet in central Ohio (Figure 20).
Permeability is probably at a maximum where the sandstone is thickest.
The formation becomes dolomitic eastward, and dolomitic and argillaceous
southward from central Ohio. Flows of water and shows of oil and gas
have been reported from wells reaching the Kerbel, but it is not pres-
ently productive.

The Kerbel was tested as a disposal zone in the Calhio well in
Lake County. Preliminary reports indicate a fair injection potential,
but detailed information has not been released. Data are insufficient
to describe the hydrodynamics or reservoir character in detail.

Confining beds for the Kerbel include the overlying Knox Dolomite
and stratigraphically higher units. The Knox was removed by erosion in
extreme northern Ohio, and here the Chazy-Glenwood Formation, a shale,
directly overlies the Kerbel. The Knox is a dolostone, and as such is
a brittle unit, probably containing many fractures. In addition, it has
Figure 21. Generalized thickness of Knox Dolomite, areas of extensive drilling, and injection potential.
been penetrated in about 3000 wells in Ohio, thus it should be considered a poor confining bed. Because of this, any future injection into the Kerbel should be in areas where the Knox is relatively thick and undrilled (Figure 21). As a matter of policy, the amount of fluid injected into the formation should be restricted. If reservoir pressure were allowed to increase substantially, fluids very likely would migrate upward through the Knox, laterally toward a probably low-pressure area in Morrow County, thence upward through unplugged wells.

**Knox Formation.** The Knox is a widespread, generally thick dolostone that contains sandy and oolitic zones. With few exceptions it does not contain zones of persistent mappable porosity. The Knox is truncated to various degrees in Ohio, ranging in thickness from a feather edge to about 1500 feet (Figure 21). Permeability is locally developed at the unconformity surface, most notably in central Ohio where production of oil, gas, and water from erosional traps 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 21. An additional area in northwestern Ohio also should be proscribed because of dense drilling to the overlying Trenton-Black River Interval (also shown in Figure 21). In places, usually where the Knox is structurally high and relatively shallow, the overlying Trenton-Black River is dolomitized and the underlying Chazy is absent. Here the units would be in lithologic continuity and would lack effective confining beds.
In eastern Ohio, where the Knox is sparsely drilled and relatively deep, there exists potential 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 would normally be present in eastern Ohio.

**Trenton-Black River.** In central and eastern Ohio, the Trenton-Black River interval of Ordovician age is primarily composed of tan lithographic limestone. In western Ohio, the limestone becomes irregularly dolomitized, ranging from patches to complete replacement. Thickness of the total interval is fairly uniform at 500 to 600 feet. Where dolomitization is present the zone is very porous, but unfortunately these areas tend to be densely drilled, hence unsuitable for injection.

Eastward, the dense limestone is probably a fair confining bed, although it may be extensively fractured. A series of thin bentonite beds at the base of the Trenton would appear 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 extensively drilled 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 millidarcy or less), and great number of old wells reaching the Clinton, it appears to have virtually no injection potential, except perhaps for small volumes of oil field brines produced from the same interval.

**Newburg.** The Newburg is a driller's term for a porous dolomite usually at or near the top of the Lockport (Niagaran) Dolomite of Middle Silurian age.

The name originated in a gas field at Newburg near Cleveland, where 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 it is applied to the first brown sugary porous vuggy, dolomite below the Cayugan Salina rocks, or to any zone producing abundant water, oil, or gas about 600 to 800 feet below the top of the Big Lime (Columbus Limestone of Devonian age). A good 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 frequency with which the zone yields water in cable-tool holes is reflected by the fact that the zone is also called Second Water or Big Water by drillers. Information from scattered core and drill-stem tests confirms that good reservoir potential is present in this unit in much of eastern Ohio.

As is true with most carbonate reservoirs, permeability 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 absent.

The use of the Newburg as a disposal zone will be greatly hampered, if not prevented, by the large number of wells drilled into the underlying Clinton. The areas in which Clinton drilling has been extensive are outlined in Figure 22, which also shows generalized structure. As is apparent from the map, the only area in which the Newburg is deep enough for injection (say 2000 feet) and lies outside of closely spaced drilling, is in eastern Ohio to the east of current drilling. Potential problems are seen in siting injection wells in this area. Clinton drilling has historically 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.

**Oriskany Sandstone.** The Oriskany Sandstone of Devonian age is described by Hall (1952) as a white to brownish-gray, fine- to medium coarse-grained sandstone. The cement is usually calcareous, although
Figure 22. Generalized structure on top of "Newburg" porous zone, and areas of extensive drilling to or through the Newburg.
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 feather edge along an irregular pinch-out line running approximately north-south through Morgan, Holmes, and Medina Counties. Driller’s 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 locating of producing fields, line of sand pinch-out, and structure contours are shown by Hall (1952, pp. 44 and 53).

Where thick, the sandstone usually 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 representative permeability data. The Ashland No. 1 Canton Refinery in Stark County, Canton Township showed a permeability to water of 106 md, with an average porosity of 10.3 percent within an 8-foot interval. Near the sand limit in Union Township, Muskingum County, the Oxford No. 3 Morrison tested 5.3 feet of sand, which had 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 to have high permeability with relatively low porosity. Where the sand is thicker, it should have reasonable injectivity.

The most favorable injection areas of the Oriskany appear to be in northeastern Ohio east of the dense drilling of the Clinton, Oriskany,
and Newburg zones. Because it is a sandstone of regional extent, the presence of permeability should be more predictable than in the Newburg.

Injection of liquid into the Oriskany should be limited because it may interfere with future production of oil and gas in eastern Ohio, and because large pressure increases will create fluid migration toward areas containing numerous unplugged wells.

A disposal permit was issued for injection into the Oriskany at the International Salt Company Mine at Whiskey Island. The injected fluid will be Oriskany brine that has seeped into the mine shaft. Injection operations have just begun, and data are not yet available.

Pennsylvanian and Mississippian 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. Early cable-tool rigs were quite capable of reaching the 2000-foot depths necessary to penetrate the Berea in most places, wildcatting was in its heyday, and regulations were weak or absent. Thus it will never be known, even approximately, how many holes were drilled and where they are.

An additional hazard arises from the fact that there may be structural complexities involving the shallower beds in eastern Ohio. Anticlines and closures, easily mapped on shallow or surface beds, are commonly not present at depth.

The most reasonable explanation is that "thin-skinned" thrusting and sliding has warped only the shallow or strata. A well-documented example of such thrusting is the Burning Springs anticline in northern
West Virginia and southern Washington County, Ohio. The abundance of shallow structures in eastern Ohio leads one to believe that thrusting, jointing, and folding may be common. The resulting fault zones and fractures could provide avenues of escape for injected fluids.

With due caution for the possibility of unlocated wells and possible faults, and perhaps with suitable monitoring wells, some minor injection potential may nevertheless exist in the Berea Sandstone. Unlike most of the shallow sands, the Berea tends to be a widespread, continuous unit and its thickness ranges between 5 and 80 feet in eastern Ohio (Pepper, et al., 1954). Average permeability reported from 21 core analyses in Hancock County, West Virginia, and Carrol and Harrison Counties, Ohio (Whieldon and Pierce, 1965) range from 2.4 md to 443.0 md with an average porosity of 16.6 percent. A core of the Berea in the Haverhill 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 sand is thick, it appears that injection potential may be adequate.

A very generalized map shows the area in which the Berea is below 2000 feet in depth, structural contours on the top of the sand (from Lamborn, unpublished), and fresh water bearing areas (Figure 23).

In the deep area in Washington and Monroe Counties, the sand is shown by Pepper, et al. (1954) to be only between 5 and 20 feet thick, which is probably not enough for injection. Control in the area is rather sparse, however, and thicker sands could be present.
Figure 23. Generalized structure on the Berea, deep areas and fresh-water bearing areas.
Even slighter 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 discontinuous and probably too shallow to be considered as injection zones.

Pennsylvanian sandstones generally do not lie below 1000 feet, are heavily drilled, and are discontinuous. For these reasons, and because of the additional hazard of deep coal mines in the same general stratigraphic interval, they are not believed to have safe injection possibilities.

EVALUATION OF INJECTION POTENTIAL

**General Statement.** Deep injection of industrial liquid wastes is not a free ride. It serves only as a means of placing wastes in a location where they present no immediate hazard and an acceptable long-term hazard. The locations in Ohio that meet the rather rigorous injection criteria are limited. The price paid for this means of waste storage is an increase in the reservoir pressure of underground formations. The pressure increases are cumulative and are inherently hazardous. 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 volumes of waste approaching a significant percent of total industrial effluent, say 10 percent, over a long term, say 100 years, 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 to reach equilibrium and affect shallow fresh waters could be measured in terms of hundreds of thousands of years. The volume of fresh water affected could be undetectably small. In this case it would probably be foolish not to practice injection if some significant benefit is thereby gained. On the other hand, it would be foolish indeed to abet a policy that encouraged injection to the extent that the 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 waste.

The proper evaluation of potential benefits versus risk for deep injection is very complex and difficult, requiring the close cooperation
of several disciplines. It is necessary to determine, first, if the waste is suitable for injection. This requires primarily a judgment as to the treatability of the waste at the surface which is necessarily a matter of technology and economics. Next, the mechanics of well construction and operation must be evaluated. Thirdly, 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 advanced 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 rules-of-thumb. Health officials or others concerned with surface conditions, recognizing the need, tend to encourage deep injection. Geologists, aware of the risks but not of the need, tend to be cautious. Some, 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.

**Pressures from Injection.** A complete discussion of the pressure increases resulting from injection involves fluid mechanics and is beyond the scope of this report; see McLean, 1968, and van Everdingen, 1968, for more information. The injected fluid is accommodated in the
formation in this manner: First, the native fluid in the immediate vicinity of the bore hole is radially displaced. A pressure differential of several hundred psi is usually required to accomplish this. As the fluid is forced outward, it is slightly compressed and the rock framework slightly expanded, thus the pressure at the fluid front is decreased. At some distance from the bore hole, depending upon several factors, the pressure increase diminishes to zero. The pressure increase declines exponentially, so that within a few miles of the injection site, there will not be a noticeable increase for several years. Over a long enough time, of course, the pressure near the bore hole and away from it will equalize as the fluid moves toward the lower pressured areas.

Potential for Continued Injection. The quantities of liquid waste now injected, and the volume of reservoir space available to accept it, 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 discussion sets up a model designed to clarify the relationship between volume of effluent and size of the reservoir.

What are the long-term effects of injection into the Mt. Simon at the present rate? First consider that not all pore space in a given formation is available to receive fluid since the pore space is already totally occupied by connate brines. In order to receive the effluent, the connate fluid must ultimately be compressed and the pore space dilated. Unfortunately, neither the liquid nor the rocks are very
compressible. According to Katz and Coats (1968, p. 93), the compressibility of water is about $3 \times 10^{-6}$ volumes/volume/psi.

The present volume of waste being injected is about $250 \times 10^6$ gallons per year ($33 \times 10^6$ ft$^3$), as shown in Figure 6. In 100 years the volume would be $33 \times 10^8$ ft$^3$.

The volume of pore space in the entire Mt. Simon is estimated from the following assumptions: average effective thickness, 100 feet; average porosity, 10 percent; areal extent of Mt. Simon (Ohio only), 41,263 square miles. The total pore space (thickness x area x percent porosity) is $115 \times 10^{11}$ cubic feet. If the Mt. Simon pore fluid ($115 \times 10^{11}$ ft$^3$) is compressed to accept this liquid, the resulting pressure increase is about 100 psi throughout the reservoir. If half of the fluid is accepted by dilation of pore space rather than compression of the liquid (Katz and Coats, 1968, p. 182), then the corresponding pressure increase is reduced by half to about 50 psi. It must be understood that there are significant assumptions involved in this model: reservoir pressure increases initially would be highest around each well and would decline exponentially away from the well; the model does not consider either higher or lower pressures at state lines depending on whether or not injection is occurring in neighboring areas; compressibilities vary with pressure and composition; etc. The model does show that the long-term pressure increase will be a detectable phenomena.

The effects of a pressure increase of the amount postulated (50 psi) would not likely be dramatic. Such a rise would increase the fluid level in all unplugged bore holes reaching the zone by about 100 feet.
It is conceivable that the rise might bring saline waters opposite a fresh-water aquifer, but the odds are highly against this happening near enough to a water user that it would be noticed. Dilution would also tend to mask the effect. If wells had been plugged with a heavy enough clay mixture, no flow would occur. For example, a well bore filled with clay mud having a weight of 10 lbs per gallon would exert a pressure of about 0.52 psi/ft. The normal pressure in the Mt. Simon is about 0.51 psi/ft (Figure 18). At 3000 feet there would be an excess of pressure of 30 psi, almost enough to balance the effect of overpressuring by injection. Unfortunately, nothing is known about the weights of muds used to plug wells in Ohio, especially in years long past.

Another effect of the pressure rise would be to increase the rate of leakage across the confining beds. Where the confining beds are adequate, the leakage would be so slow that detectable effects are not likely; however, if faults or other potential high-permeability zones are present, migration could be significant.

The possibility that a rise in pressure could initiate seismic activity cannot be quantitatively evaluated at present, but the chance exists, and should be noted.

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 volume of waste that can be safely injected, for two reasons. First, we know that injection will ultimately displace
fresh waters. We can engineer the process so that it takes a very long time for this to happen, but not knowing the expected span of mankind, we don't know how long is long enough. Secondly, with our weak predictive tools we cannot say exactly what effects will arise from a given pressure increase, or whether these effects will 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 are 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

Subsurface injection has been practiced in Ohio in a relatively safe manner. Injection has been confined primarily to the Mt. Simon Formation at depths ranging from 3000 to 5500 feet. Injection has been successful in that there have been no known instances of pollution resulting from its use, and it has served as an attractive alternative to releasing the wastes to surface waters.

The Mt. Simon meets all the criteria for a safe injection zone. It is sparsely drilled, relatively unfaulted, and has sufficient permeability in the western two-thirds of Ohio. It 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 in the Mt. Simon 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 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 by 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

Ohio Oil and Gas Law
Revised Code Section 1509

1509.051 Liquid disposal permit.

No person shall use a well for the injection of sewage or any liquid used in or resulting from any process of industry, manufacture, trade, business, or agriculture, without having a liquid disposal permit issued by the chief of the division of oil and gas, and the original permit or a true copy thereof displayed in a conspicuous and easily accessible place at the well site.

A permit to drill a new well, drill an existing well deeper, or to reopen a well, is a liquid disposal permit if the permit was issued in satisfaction of the requirements of section 1509.081 of the Revised Code, or if a permit authorizing such use has been issued under section 1509.21 of the Revised Code, or if such use is approved by the chief under section 1509.22 of the Revised Code.

(132 v S 228. Eff. 6-28-67)

Penalty, 1509.99

1509.06 Application for permit.

An application for a permit to drill a new well, drill an existing well deeper, reopen a well, plug back a well to a different source of supply, or use a well for injection of a liquid for which a permit is required by section 1509.051 of the Revised Code, shall be filed with the chief of the division of oil and gas upon such form as the chief prescribes and shall contain the following information:

(A) The name and address of the owner;
(B) The signature of the owner or his authorized agent. When an authorized agent signs an application it shall be accompanied by a certified copy of his appointment as such agent.
(C) The names and addresses of all persons holding the royalty interest in the tract upon which the well is to be drilled or within a proposed drilling unit;
(D) The location of the tract or drilling unit on which the well is to be drilled identified by section or lot number, city, village, township, and county;
(E) Designation of well by name and number;
(F) The geological formation to be tested or used and the proposed total depth of the well;
(G) The type of drilling equipment to be used;
(H) The name and address of the corporate surety and the identifying number of the bond;
(I) The plan for disposal of water and other waste substances resulting, obtained, or produced in connection with exploration, drilling, or production of oil or gas.
(J) If the well is for the injection of a liquid, identity of the geological formation to be used as the injection medium and the composition of the liquid to be injected.
Each such application shall be accompanied by a map, on a scale not smaller than four hundred feet to the inch, prepared by an Ohio registered surveyor, showing the location of such well and containing such other data as may be prescribed by the chief. If the well is or is to be located within the excavations and workings of a mine the map shall also include the location of such mine, the name of the mine, and the name of the person operating the mine.

Each application to drill or reopen a well, except a well drilled or reopened for purposes of section 1509.22 of the Revised Code, shall also be accompanied by a fee of thirty-five dollars for a well two thousand feet or more in depth, or twenty dollars for a well less than two thousand feet in depth or for a well for injecting gas into or removing gas from an underground gas storage reservoir. If for any reason the permit is denied, such fee shall be returned to the applicant. (132 y 8 226, Eff. 6-26-67. 131 y H 234)

1509.081 Approval of application for liquid disposal permit; suspension or cancellation; appeal.

Upon receipt of an application for a permit to drill a new well, drill an existing well deeper, reopen a well, or use a well for injection of a liquid for which a permit is required by section 1509.051 of the Revised Code, other than one for which he is within the requirements of sections 1509.21 or 1509.22 of the Revised Code, the chief of the division of oil and gas shall determine whether the proposed injection would present an unreasonable risk that waste or contamination of oil or gas in the earth will occur. If he determines such risk to exist, he shall make an order rejecting the application. If he determines such risk not to exist, he shall transmit copies of the application and the map required by section 1509.06 of the Revised Code to the water pollution control board, the director of health, the chief of the division of geological survey, the chief of the division of water and, if so required by section 1509.08 of the Revised Code, to the chief of the division of mines.

The chief of the division of geological survey shall approve the application unless he determines that the proposed injection would present an unreasonable risk of loss or damage to valuable mineral resources.

The chief of the division of water shall make a report and recommendation to the director of natural resources.

The water pollution control board shall approve the application if it determines that the proposed injection will not cause pollution as defined in division (A) of section 6119.01 of the Revised Code.

Upon approval by the water pollution control board, the department of health under section 3701.19 of the Revised Code, the chief of the division of geological survey, and by the chief of the division of mines if required by section 1509.08 of the Revised Code, the chief of the division of oil and gas shall issue a liquid disposal permit with such conditions as may be necessary to protect health, safety, or the conservation of natural resources, including all conditions appended by the water pollution control board and the department of health.

If the chief is unable to obtain the required approv-
als, he shall issue an order denying the application. In an appeal from such an order where the application was denied because of lack of approval by an agency or agencies other than the division of oil and gas, the appeal shall be taken under section 119.12 of the Revised Code as if the order had been made by the agency whose approval is lacking.

The chief of the division of oil and gas may adopt rules and regulations for the administration and implementation of this section as may be necessary to protect health, safety, or the conservation of natural resources.

The chief may order that a liquid disposal permit be suspended and that operations cease if he determines that the well is being operated in violation of law, regulation, order, or condition of the permit. Upon service of a copy of the order upon the permit holder, his agent, or assignee, the permit and operations thereunder shall be immediately suspended without prior hearing, and shall remain suspended until the violation is corrected and the order of suspension is lifted. If a violation is the second within a one-year period, the chief may, after hearing, revoke the permit.

The chief may order that a liquid disposal permit be suspended and that operations cease if he has reasonable cause to believe that the permit would not have been issued if information available at the time of suspension had been available at the time a determination was made by one of the agencies acting under authority of this section. Upon service of a copy of the order upon the permit holder, his agent, or assignee, the permit and operations thereunder shall be immediately suspended without prior hearing, but a permit may not be suspended for such reason without prior hearing unless immediate suspension is necessary to prevent waste or contamination of oil or gas, pollution as defined in division (A) of section 6111.01 of the Revised Code, damage to valuable mineral resources, or danger to human life or health. If after hearing the chief determines that the permit would not have been issued if the information available at the time of the hearing had been available at the time a determination was made by one of the agencies acting under authority of this section, he shall revoke the permit.

A revocation of permit shall not prejudice the right of the holder to obtain another permit. When a permit has been revoked, the permit holder or other person responsible therefor shall immediately plug the well.

In an appeal from an order of suspension or revocation where the order was made because of objection of an agency or agencies named in this section other than the division of oil or gas, the appeal shall be taken under section 119.12 of the Revised Code as if the order had been made by the agency upon whose objection the order was based.


Penalty, 1500.99