Potential Effects of Deep-Well Waste Disposal in Western New York

GEOLOGICAL SURVEY PROFESSIONAL PAPER 1053

Prepared in cooperation with the New York State Geological Survey

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By ROGER M. WALLER, JOHN T. TURK,
and ROBERT J. DINGMAN

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ABBREVIATIONS AND CONVERSION FACTORS

[Factors for converting English units to International System (SI) units and abbreviations of units]

English units	Multiply by	SI units
	Length	
inches (in)	25.4	millimeters (mm)
	2.54	centimeters (cm)
feet (ft)	.3048	meters (m)
miles (mi)	1.609	kilometers (km)
	Area	
square miles (mi^2)	2.590	square kilometers (km^2)
	Volume	
gallons (gal)	3.785	liters (L)
	3.785×10^{-3}	cubic meters (m^3)
million gallons (Mgal)	3,785	cubic meters (m^3)
cubic feet (ft^3)	.02832	cubic meters (m^3)
	Flow	
feet per day (ft/d)	0.3048	meters per day (m/d)
gallons per minute (gal/min or gpm)	.06309	liters per second (L/s)
gallons per day (gal/d)	3.785	liters per day (L/d)
million gallons per day (Mgal/d)	.04381	cubic meters per second (m^3/s)
millidarcy-feet (mD-ft)	----	----------
darcy (D)	----	----------
	Mass	
pounds per square inch (lb/in^2)	0.07031	kilograms per square centimeter (kg/cm^2)
pounds per cubic inch (lb/in^3)	.01602	grams per cubic centimeter (g/cm^3)
	Time	
hours (h)	----	----------
minutes (min)	----	----------
seconds (s)	----	----------
	Temperature	
degrees Fahrenheit (°F)	(°F−32)5/9	degrees Celsius (°C)
degrees Celsius (°C)	9/5 °C+32	degrees Fahrenheit (°F)
	Hydraulic conductivity	
cubic feet per day per square foot (ft/d)	0.305	meters per day (m/d)
	Transmissivity	
cubic feet per day per foot (ft^2/d)	0.0929	square meters per day (m^2/d)
	Gradient	
feet per mile (ft/mi)	0.1894	meters per kilometer (m/km)
	Viscosity	
centistokes	$1{,}000{,}000 \times 10^{-6}$	square meters per second (m^2/s)
	Pressure	
atmosphere (atm)	----	----------

POTENTIAL EFFECTS OF DEEP-WELL WASTE DISPOSAL IN WESTERN NEW YORK

By Roger M. Waller, John T. Turk, and Robert J. Dingman

ABSTRACT

A deep waste-disposal well was drilled at Lackawanna, N.Y., for proposed disposal of a highly acidic, iron-rich waste solution (waste pickle liquor) from a steel mill into a dolomitic sandstone. This report evaluates the hydraulic, seismic, and geochemical aspects and the feasibility of such disposal. Hydraulic reactions under field pressure and field temperatures were simulated by mathematical models, and chemical reactions by laboratory models. The mathematical results are compared with 1968 freshwater injection-test data obtained from State records.

During the middle stages of the 1968 injection of freshwater into the injection zone that contains high-density brine, the rock probably was hydraulically fractured in the immediate vicinity of the well bore. The permeability of the Cambrian sandstone and dolomite sequence is attributed mainly to natural fractures in the strata. Transmissivity of the entire 457-foot sequence is 13 feet squared per day. Calculations indicate that the proposed rate of injection (72,000 gallons per day) of waste pickle liquor into a total of 42 feet of "effective" permeable sections of the rocks would exceed a wellhead pressure of about 580 pounds per square inch, causing the rocks to be hydraulically fractured. Fractures at the well depth would probably be vertical and might extend into the confining beds of dense carbonate rock. On the basis of an average storage coefficient (fluid expansion only) estimated to be 5.87×10^{-6} for the "effective" unit and an injection rate of 72,000 gallons per day, the measurable cone of influence would extend about 22 miles after injection for 1 year.

The sandstone and fractured dolomite rocks of the disposal unit would theoretically accept the waste pickle liquor. Within a year, however, at an injection rate of 50 gallons per minute, the wellhead pressure would be about 600 pounds per square inch. Chemical reactions between acidic wastes and brine-saturated, unfractured dolomite would create precipitates that would drastically reduce the already low permeability of the unfractured part of the dolomite. Fractures in the dolomite would probably not become plugged by chemical precipitates, however. Nondolomitic sandstone permeability may not be affected. In general, the fractured dolomite and the sandstone parts of the sequence would probably maintain their present permeability so that the effective injection rate could be sustained. Generation of carbon dioxide may be a problem in that excessive pressures could develop.

The digital model, constructed with assumed values of hydrologic and geologic characteristics, can be used for qualitative predictions on a regional scale, but hydrologic and geologic data for an individual site would be required before reasonable predictions could be made of the effects of waste injection at any particular site.

Field tests under operating conditions are needed to insure reliable predictions of long-term effects of injecting industrial wastes in any part of the region. In addition, all oil- and gas-test or production wells and deep water wells within the affected radius of injection should be monitored to detect possible upward migration of brine.

INTRODUCTION

Waste disposal into lakes and streams has become a critical problem in many places. International agreements on use of boundary waters have been designed to prevent further pollution of the Great Lakes. Also, the Finger Lakes in western New York have begun to accumulate wastes. Because streams in western New York have a greatly reduced flow in summer, discharge of waste to streams during the summer causes vast deterioration in stream quality. Subsurface disposal is being used for the disposal of some wastes that otherwise would be discharged into streams, but underground water resources are susceptible to pollution also. One of the first considerations in deep-well disposal is that underground space is almost always filled with native brine at depth and with freshwater at shallower depths. The brine must be displaced in order to emplace additional liquid and the freshwater must be protected.

The State of New York has received requests from industries for permission to dispose of liquid industrial wastes into the subsurface by means of deep wells. The New York State Geological Survey is responsible for evaluating the geologic and hydrologic aspects of specific deep-well injection sites in New York.

PREVIOUS STUDIES

The possibilities of subsurface disposal in New York were studied in 1963 by McCann, Privrosky, Stead, and Wilson (1968) and in 1967 in less detail by Kreidler (1968). The method, experience, problems, and implications of disposal were noted by Piper (1969) and were the subject of symposiums in 1971 (Cook, 1972) and 1973 (Braunstein, 1973). A discussion of deep-well disposal by Mokha (1974) covers many aspects of the current situation. A technical paper on hydraulics of deep-well waste disposal was recently published (van Everdingen, 1974). The possibility of creating seismic effects has been considered—increased fluid pressures in incipient fault fractures have caused earthquakes (Evans, 1966; Pakiser and others, 1969; Sykes and others, 1972). Two annotated bibliographies have been compiled in preparation for investigations of techniques and problems of deep-well disposal (Rima and others, 1971; U.S. Environmental Protection Agency, 1972).

PURPOSE AND SCOPE

The purpose of this study by the U.S. Geological Survey in cooperation with the New York State Geological Survey was to evaluate the hydrologic aspects of disposal of industrial liquid wastes in deep wells. Of immediate concern was the planned disposal of acidic steel-pickling wastes (commonly called waste pickle liquor, or pickling liquor) from an iron- and steel-processing plant in Lackawanna, N.Y. Of long-range concern was the feasibility of this type of waste disposal anywhere in New York west of Cayuga County (fig. 1).

The study involved two formations beneath the Knox unconformity—the Cambrian Potsdam Sandstone and Theresa Formation—which McCann, Privrosky, Stead, and Wilson (1968) considered to be the best potential disposal rocks. Objectives included determination of (1) the feasibility of injecting acidic iron-bearing wastes into the dolomite and sandstone, based on an understanding of chemical reactions between the wastes and the formation rock and native fluid, (2) a prediction of the pressure buildup in the disposal formation, (3) the potential of hydraulic fracturing, and (4) the feasibility of using additional disposal wells elsewhere in the receiving system.

Determination of the hydrologic feasibility of deep-well injection involved two main efforts. Injection of acidic steel-pickling liquor into rock cores under simulated field conditions was done by the U.S. Geological Survey laboratory in Denver, Colo. A computer-oriented mathematical model of the disposal formation simulated the response of the formation fluid pressure to stress around the injection well. Two models were designed—one to determine

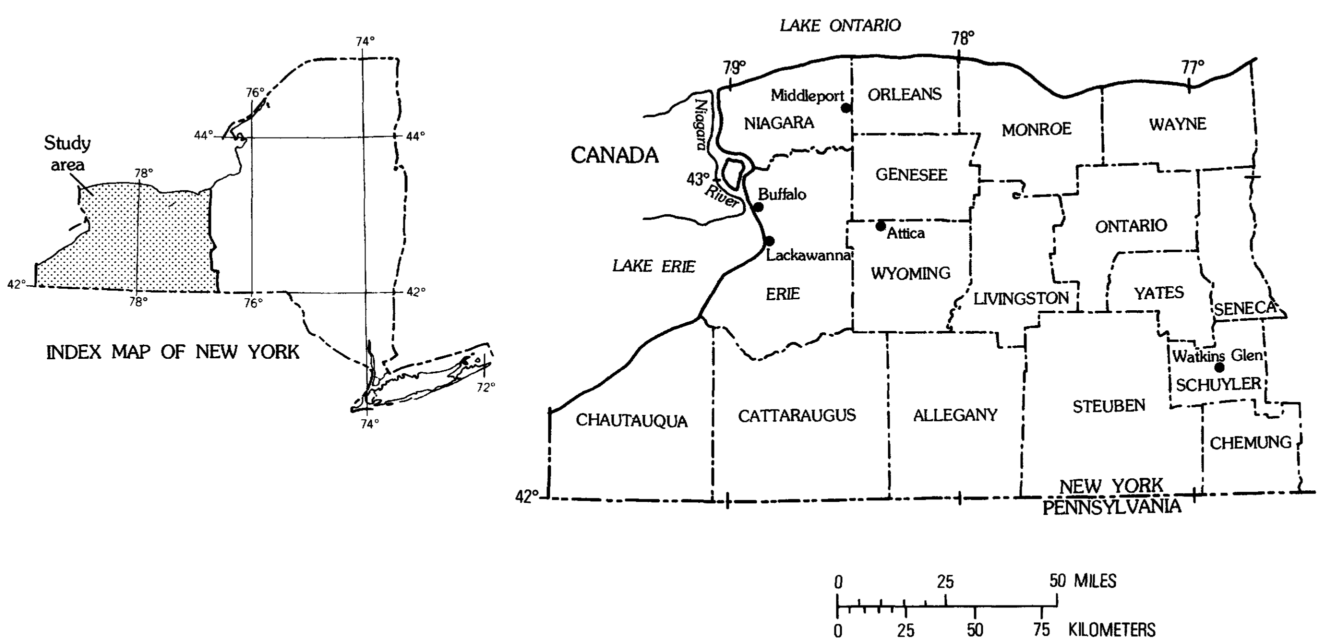

FIGURE 1.—Location of study area.

TABLE 1.—*Data on wells in Cambrian formations*

[Data from New York State Geological Survey; altitudes and depths in feet]

Well				Formation						
							Reported brine			
					Altitude [3]					
No.	Name	Altitude [1]	Total depth [1]	Name [2]	Top	Base	Depth [1]	Static level [1]	Yield (gal/min)	Temperature (°C)
Canada										
7S	Smith 1	305	2,313	Po	1,887	2,265	2,233	809	----	----
8	Pearson	613	3,197	Po	2,437	3,215	3,064	1,200	1.6	27.5
8W	Welland	617	4,104	Th-Po	2,989	4,072	3,798	----	----	29
9	Erco 2	589	3,569	Po	2,636	3,555	3,239	800	----	----
9H	Haldimand	599	4,693	LF-Th-Po	3,491	4,670	4,058	+26?	----	34
United States										
58	Kennedy	599	6,385	LF-Th-Po	4,929	----	5,650	----	----	----
59	McClurg	1,001	5,644	Po	3,879	5,560	5,150	----	7	----
61	Johnson	795	4,839	Po	3,448	4,740	4,690	3,290	21	----
63	Hazen	312	2,185	Th	1,851	1,858	----	----	----	----
64	Wilson	1,483	7,144	LF-Th-Po	4,712	----	6,375	1,540	----	----
65	Veith	1,573	7,182	LF-Th-Po	4,687	----	6,375	----	5.5	----
66	Werner	1,608	5,722?	Th	5,568	----	5,646	3,436	----	----
67	Fisher	1,504	5,718	Th	4,019	----	5,420	----	----	----
71	Page	1,508	6,237	Th-Po	3,689	5,790	5,206	3,459	2	----
72	Cox	1,166	5,620	Th-Po	3,684	4,209	----	----	----	----
73	Tyler	713	4,000	Th-Po	2,807	3,813	3,722	----	24	----
74	Naylor	668	3,410	Th-Po	2,489	----	3,284	2,609	----	----
75	Klotzbach	870	3,962	Th-Po	2,683	2,987	----	100?	----	----
76	Brundage	727	3,560	Th-Po	2,593	2,833	----	125?	----	----
77E	Emil Camp	664?	3,030	Th?	2,063?	----	----	----	----	----
78	Kelly	658	3,044	Po	2,222	3,020	2,972	----	.3	----
79	Domay	634	3,152	Th-Po	2,331	3,105	2,965	----	----	----
80	Cook	625	2,983	Th	2,213	2,346	----	35?	----	----
81	Thaxter	504	2,664	Th-Po	2,100	2,137	2,604	----	Slight	----
82	Stevens	382	2,450	Th	1,998	2,062	----	0?	----	----
83	Herman	325	2,259	Po	1,823	2,197	2,120	----	----	----
84	Nowak	362	2,325	Th	1,900	1,946	----	0?	----	----
85	Malone	436	2,567	Po	1,999	----	2,518	----	Large	----
88	Woolston	372	2,345	Po	1,882	1,946	----	27?	----	----
89	Morrison	335	2,760	Th	1,825	1,840	----	----	----	----
92	Searles	354	2,225	Po	1,823	2,208	2,225	1,225	----	----
94	Ellis	1,332	6,528	Th-Po	4,289	6,460	5,681	----	Large	----
94ET	ET-1	2,294	11,683	LF-Th-Po	6,955	8,765	9,800	9,200	----	----
96	Harrington	1,773	7,692	LF-Th-Po	4,985	----	6,836	----	----	----
100	LaScala	1,413	5,911	Th	4,437	----	5,910	----	.6	----
101	Bethlehem	[4]592	4,310	Th-Po	3,202	4,251	3,818	380	6	40
103	FMC Corp	[4]549	3,189	Th	2,111	2,765	3,130	----	----	31?
104	Hooker	[4]582	3,060	Th-Po	2,254	3,026	2,848	----	2	27

[1] From derrick floor, approximately 15 ft above leveled land surface.
[2] LF, Little Falls Dolomite; Th, Theresa Formation; Po, Potsdam Sandstone.
[3] Below sea level.
[4] From land surface.

the pressure buildup in the vicinity of the injection well, and the other to determine the regional effects of pressure buildup in the formation.

Geologic information for western New York was compiled by the New York State Geological Survey. Data were available on deep gas, oil, and salt wells that penetrated the proposed disposal zones (Kreidler and others, 1972). Data on drilling, testing, and completion of the principal disposal well by American Industrial Disposal Systems, Inc. (AIDS, Inc., 1968) and on two other disposal wells were available in the State Geological Survey files. Pertinent data on Cambrian wells are presented in table 1, and the well locations are shown in figure 4. Interpretation of the geology of the disposal formations is based on work by McCann, Privrosky, Stead, and Wilson (1968), Kreidler (1968), and Rickard (1973).

HYDROGEOLOGIC CONDITIONS

GEOLOGY

Geologic conditions in the study area are summarized from McCann, Privrosky, Stead, and Wilson (1968) and Kreidler (1968). Western New York lies in the north end of the Appalachian Synclinorium. The geologic setting consists of a series of gently dipping sedimentary formations overlying the basement complex. The sedimentary-rock surface is mantled by glacial deposits. The outcrop pattern of the major bedrock units is shown in figure 2. A generalized geologic column, using New York State Geological Survey nomenclature with U.S. Geological Survey variances, for western New York follows:

System	Formation or group	U.S. Geological Survey designation
Pennsylvanian	Pottsville Group	(Pottsville Formation)
Mississippian	Pocono Group	(Knapp Formation)
Devonian	A sequence of shale sand and limestone units.	
Silurian	Bertie Limestone	(Bertie Limestone of Salina Group)
	Salina Group	
	Lockport Group	(Lockport Dolomite)
	Clinton Group	
	Medina Group	(Albion Group)
Ordovician	Queenstown Shale	
	Oswego Sandstone	
	Lorraine Shale	
	Trenton Group	
	Utica Shale	(overlies Trenton Group)
	Black River Group	
	Beekmantown Group	
Cambrian	Little Falls Dolomite	
	Theresa Formation (=Galway Formation)	
	Potsdam Sandstone	
Precambrian	Crystalline rocks	

STRATIGRAPHY AND LITHOLOGY

The sequence of sedimentary rocks overlies the crystalline Precambrian rocks. The lowermost sedimentary rocks are part of the Cambrian System. The Potsdam Sandstone has an average thickness of 100 ft and is composed of fine to medium quartzitic and dolomitic sand. The Potsdam lies unconformably on the Precambrian and grades upward into the Theresa Formation (Galway Formation of Fisher and Hanson, 1951) of interbedded dolomite and sandstone. The Theresa is as thick as 1,500 ft. The Potsdam Sandstone is differentiated from the basal part of the Theresa sandstone by a higher feldspar content. Overlying the Theresa in the southern half of the region is the Little Falls Dolomite. The relatively dense Little Falls contains much quartz sand and is as much as 950 ft thick. The above-named formations, particularly the Potsdam and the Theresa, are of immediate concern to this study.

Ordovician rocks, nearly 2,000 ft thick, overlie the Cambrian System and, with the exception of the lowermost unit—Beekmantown Group—lie above an erosional surface called the Knox unconformity. From the lowermost units, they are the Beekmantown Group (largely shales), Black River Group and Trenton Group (both carbonates), Lorraine Shale, Oswego Sandstone, and the Queenstown Shale, the oldest rock exposed in the area. The Knox unconformity is considered a significant horizon that controls oil and gas accumulation and the hydrodynamics of the underlying Cambrian rocks and the Beekmantown Group.

The Silurian System overlies the Ordovician and consists, from oldest to youngest, of the following groups: Medina Group (name abandoned and designated Albion Group by U.S. Geological Survey), Clinton Group, Lockport Group (designated Lockport Dolomite by U.S. Geological Survey), Salina Group, and Bertie Limestone (included in Salina Group by U.S. Geological Survey). The units consist of sandstone, carbonates, and shales.

Devonian rocks make up the surficial bedrock in more than half the area of this study. The system largely consists of major groups of carbonates and shales near the bottom and then a succession of numerous shale, sand, and limestone units.

Mississippian and Pennsylvania rocks occur in isolated patches on hilltops in the extreme south part of western New York.

Glacial drift mantles most of the area in varying thickness. In most areas the drift is less than 25 ft thick, but in bedrock valleys it may be several hundred feet. In general, the drift is composed of fine-grained lacustrine sediments in the northern third of the area, with till capping most of the highlands, and sand and gravel outwash in the valley floors. Modern streams have reworked the drift and deposited alluvium adjacent to the streams.

STRUCTURE

The sedimentary rocks above the Knox unconformity dip gently to the south at about 20 ft/mi in the west to 60 ft/mi in the east. The Cambrian units dip on the average 100 ft/mi to the south. Most of the units thicken to the south also. A generalized north-south section (fig. 3) illustrates the structural relationship of the rocks. Thickness of the section approaches 20,000 ft at the New York-Pennsylvania border. The Beekmantown Group is present only in this area, south of section *A–A′*.

The sedimentary sequence has a gentle undulating structure. A fault system, the Clarendon-Linden, occurs in the north-central part of the region (fig. 2) as high-angle thrust faults associated with a north-trending anticline. Large anticlines are common near the surface in the southern part of the area but apparently do not extend into the deeper formations.

SEISMICITY

Earthquakes of minor to intermediate intensity have occurred in western New York (Coffman and von Hake, 1973); those of greatest intensity have been in the Attica area. Seismic areas of moderate to major risk have been delineated for the region (Coffman and von Hake, 1973, p. 1). In general, the area of major risk parallels the northeast trend of Lake Erie and Lake Ontario. Of immediate interest to this study are the earthquakes apparently induced from a water-injection system of salt-mining activities southeast of Attica (fig. 1) near the Clarendon-Linden fault (Sykes and others, 1972). Waste disposal by deep-well injection is of concern in this area because of the potential for inducing earthquakes.

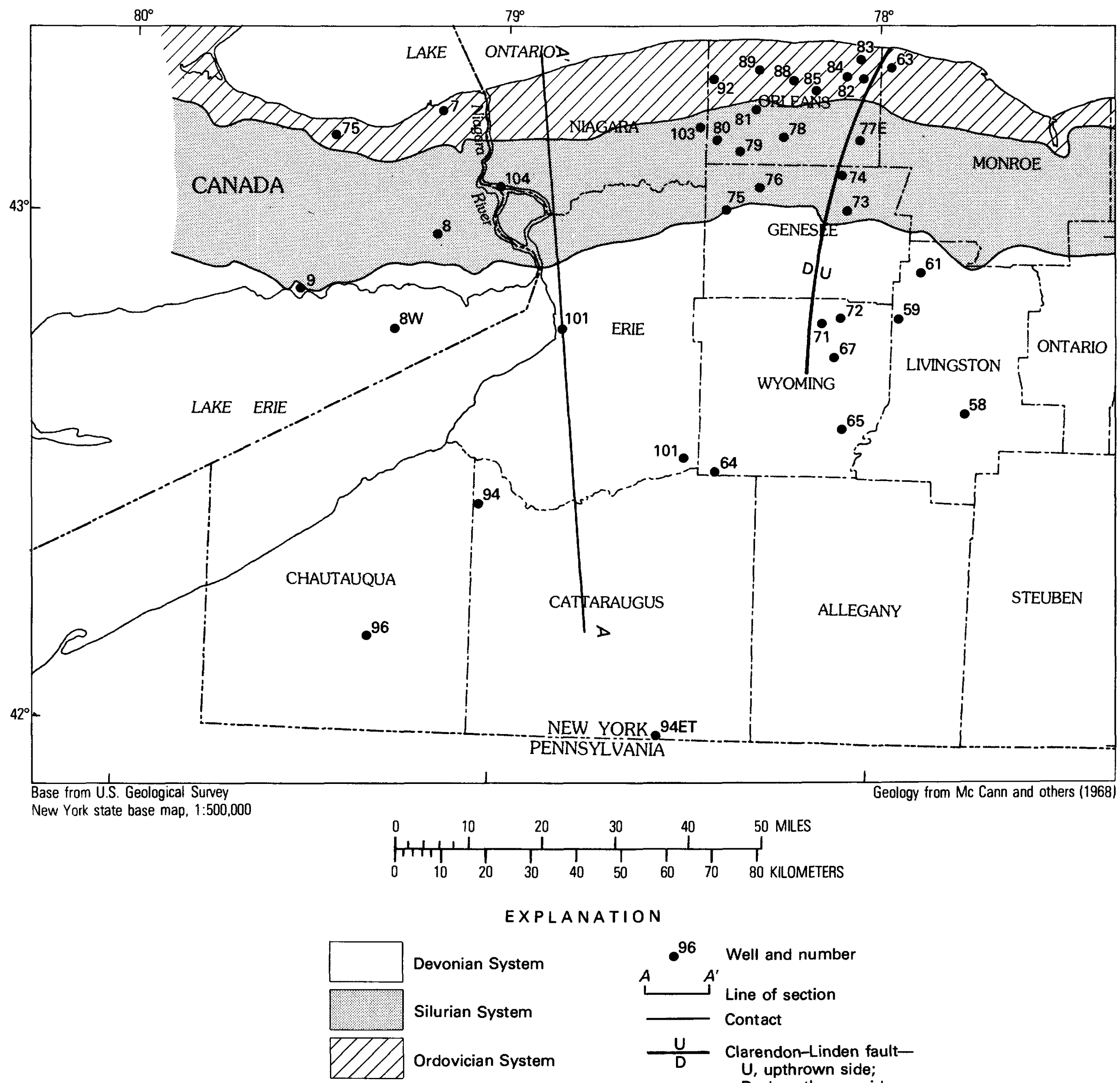

FIGURE 2.—Bedrock geology for part of western New York and Canada and location of wells used in study.

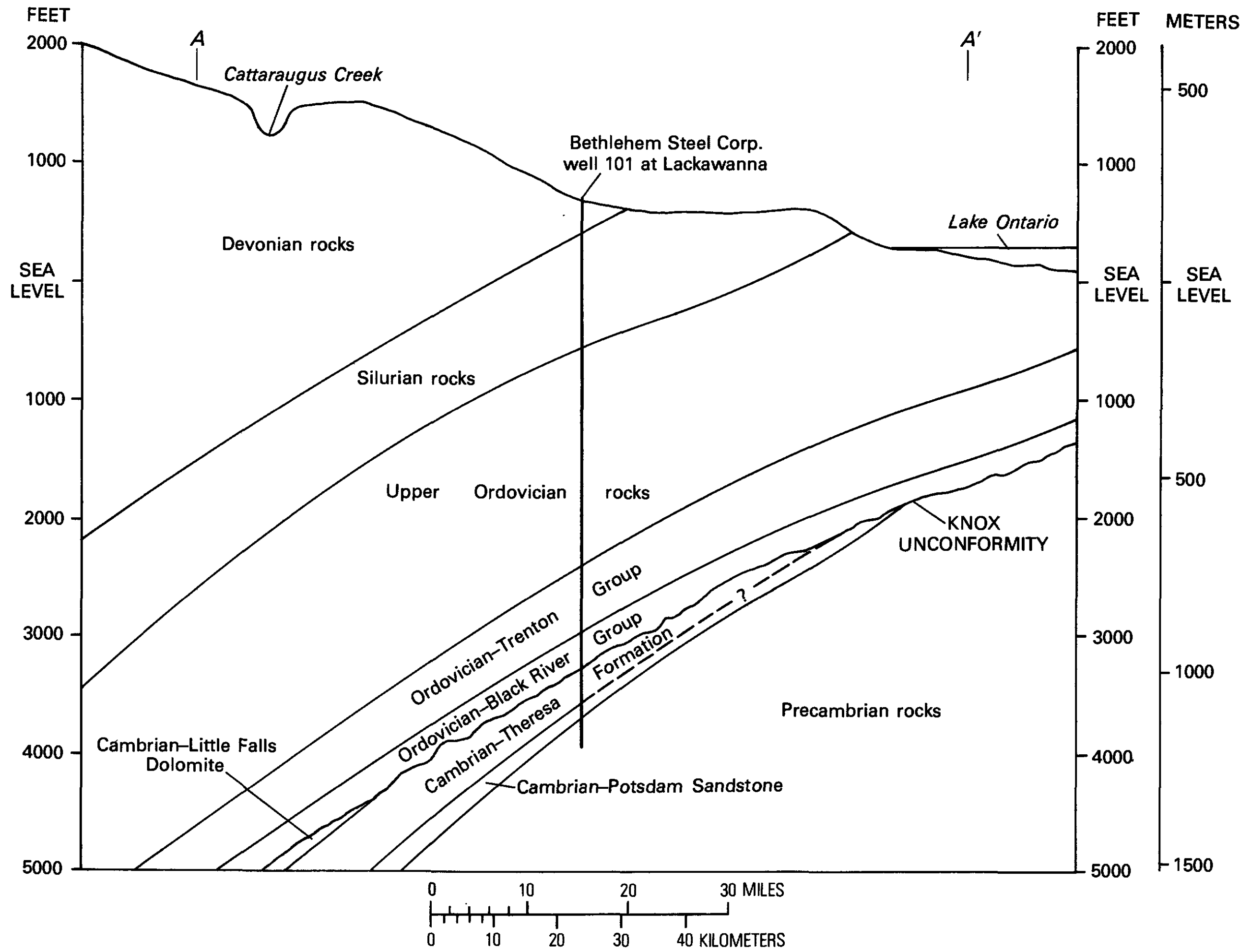

FIGURE 3.—Generalized geologic section through western New York. Line of section shown in figure 2.

PETROLEUM AND NATURAL-GAS RESOURCES

The basal part of the Potsdam Sandstone has produced natural gas 12 mi west of Buffalo in Canada, and the Potsdam pinchout beneath the Lake Ontario shoreline probably contains gas (W. L. Kreidler, oral commun., 1974). Natural gas is produced from the Theresa Formation in Wyoming County.

Methane is produced in minor amounts from the Utica Shale. Many gas fields in western New York are producing from Silurian Medina rocks. Devonian formations yield gas and oil in the southern part of the study area.

SUBSURFACE HYDROLOGY

Water, gas, or oil occupies most voids below the water table, permeability permitting. Freshwater occurs near the surface, but, in general, the dissolved-solids concentration of ground water increases with depth. Deep formations usually contain brine. The U.S. Geological Survey classifies the salinity of water as follows:

Type of water	*Concentration (mg/L)*
Fresh	0– 1,000
Slightly saline	1,000– 3,000
Moderately saline	3,000–10,000
Very saline	10,000–35,000
Brine	35,000 and above

Of principal concern in this study are native fluids in prospective disposal formation of the Cambrian System and freshwater in the overlying near-surface rocks that constitute usable aquifers.

SALINE WATER

OCCURRENCE AND CHARACTERISTICS

Occurrence of water in the Cambrian System in western New York is not well documented. Occurrences are reported in logs of some oil and gas tests, mostly in sandstone; these logs are on file

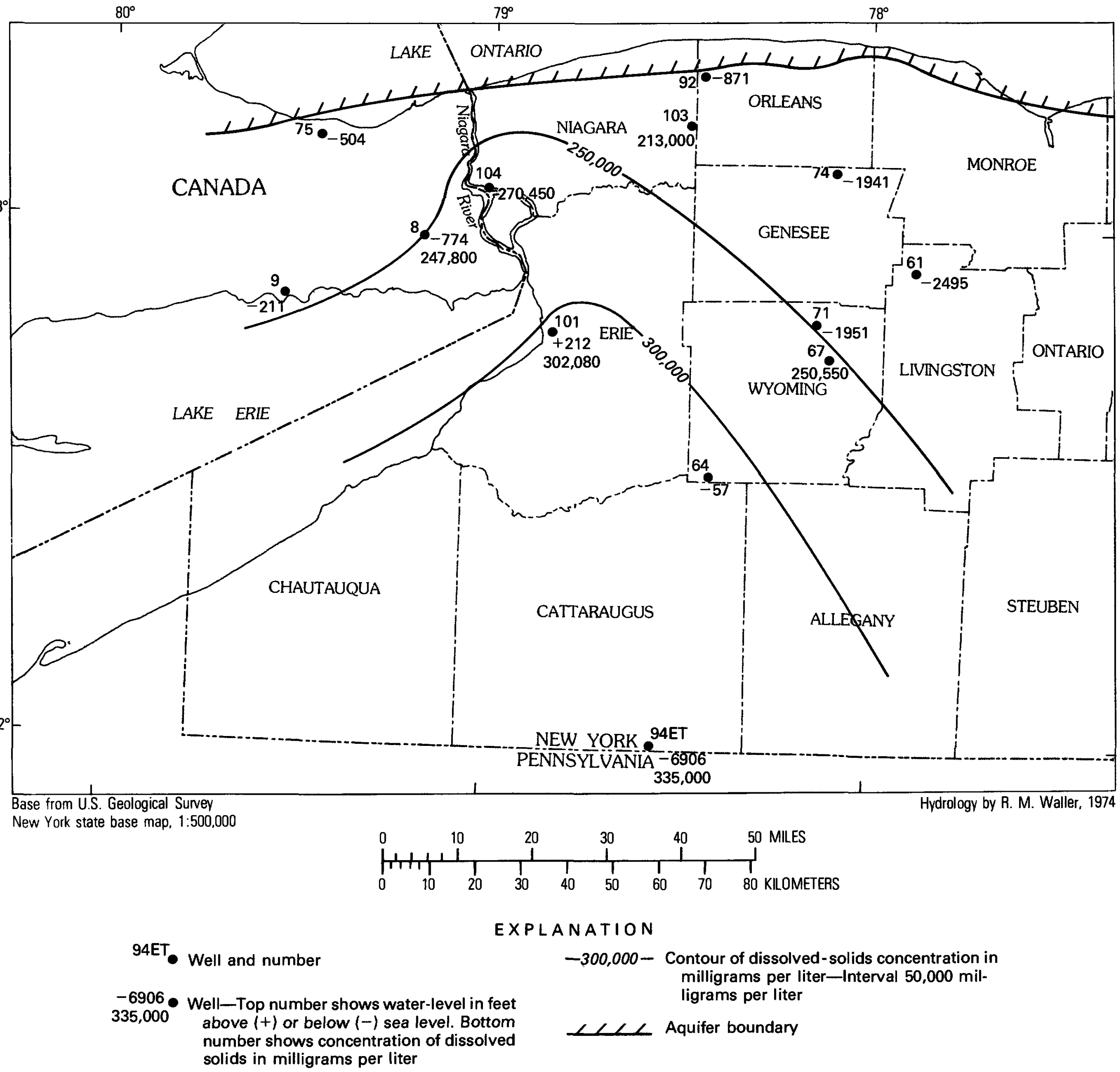

FIGURE 4.—Pressure head and dissolved-solids concentration of Cambrian brine in western New York.

with the New York State Geological Survey. Logs of the few injection wells in the study area contain the most accurate information on occurrence of water in the Cambrian.

In general, dissolved-solids concentration of water in the Cambrian unit ranges from 213,000 to 335,000 mg/L (table 2). Water temperatures of as much as 40°C are on record. Sodium chloride-type water is dominant in the Cambrian. Chloride concentration ranges from about 62,000 to 192,000 mg/L.

Data to show the areal variance in the dissolved-solids concentration of the brine are inadequate, but, in general, the dissolved-solids concentration of Cambrian brine increases from north to south (downdip) and with depth below land surface (fig. 4) in the study area.

HYDRAULICS

Fluid movement in rocks depends on intrinsic permeability (k). Interconnected pore spaces or fractures provide for movement if a gradient or pressure differential exists. Permeability data for the Cambrian rocks are sparse. Drill-stem tests, coring and laboratory determinations, or pumping tests are means of obtaining information on permeability, or hydraulic conductivity, which involves intrinsic permeability and type of fluid. Hydraulic conductivity is defined by Lohman (1972, p. 4) as follows: "If a porous medium is isotropic and the fluid is homogenous, the hydraulic conductivity of the medium is the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow."

Permeability of the Cambrian rocks undoubtedly varies considerably in areal as well as vertical extent. Few data are available on permeability because drill-stem tests of deep exploration holes are not made unless gas or oil is indicated. Rates of inflow of brine give a measure of permeability, but only qualitatively.

The authors attempted to relate permeability, as known from three laboratory studies and two injection tests, to lithology, but the meager data seem to indicate contradictory relationships. An intuitive interpretation is that greater permeability results from fractured dolomite than from primary porosity of sandstone (or dolomite), but laboratory determinations are, of necessity, made on unfractured cores. In general, as the percentage of sandstone in the section increases, permeability increases. Injection tests determine the gross permeability of the exposed section and would include fracture permeability.

Average hydraulic conductivity of the formations exposed to the uncased parts of a well can be determined from injection tests. Data on "flow-capacity" were available for two injection-test wells, including well 101 (fig. 4) at Lackawanna, N.Y., the one of concern in this report. Flow capacity was apparently the term used for permeability multiplied by the effective porous zone, and is equated herein to transmissivity (T), which is defined as the rate at which water is transmitted through a unit width of a formation. Transmissivity is the product of the field, or average, hydraulic conductivity (K) times the saturated thickness at the prevailing viscosity and temperature of the water.

Well 101 had a flow capacity that converts to an average hydraulic conductivity of about 26×10^{-3} ft/d for the Cambrian Potsdam-Theresa unit. Similarly, the calculated hydraulic conductivity of the Cambrian rocks at well 104 (fig. 4) is 7×10^{-3} ft/d.

Laboratory determination of hydraulic conductivities of cores taken at well 101 ranged (table 4) from 0 to 23×10^{-3} ft/d. The hydraulic conductivity of most cores was less than 2×10^{-3} ft/d. Comparison of these hydraulic conductivities with flow-capacity data from two injection tests indicates that fracture permeability is dominant in the Cambrian System. Because regional permeability data were lacking, hydraulic conductivity of the Cambrian rocks was assumed to be comparable with that of cores from well 101 and was used in a subsequent analysis. Actual test data at proposed injection sites will be needed to reappraise hydraulic effects.

The amount of fluid in storage in rocks depends on porosity. Some of the regional well data indicate high porosities, but most of the Cambrian unit probably has a low porosity. Additional storage within a confined aquifer is available from expansion of the aquifer or compression of the formation fluid. The volume of fluid that can be released or taken into storage per unit area of a formation per unit change in the component of head normal to that surface is called the storage coefficient (S). Specific storage, or storage coefficient per foot of aquifer thickness, is similarly defined, but for a unit volume of formation rather than for a unit surface area. Because of the apparent "tightness" of the Cambrian System, a specific storage of 1.3×10^{-8} was used in the studies reported in this paper. An analysis of this figure is given in the section, "Transmissivity and Storage Coefficient."

Hydrostatic pressure of the Cambrian rocks is rarely recorded in New York State. Scattered reported data on unstabilized water levels were not reliable enough to allow construction of a potentiometric map of the brine pressure head. The reported levels are included in table 1 and figure 4. The pressure head of Bethlehem Steel Corp. well 101 may be the only true static level of the brine. Direction of natural fluid movement in the Cambrian was not determined because data were lacking.

Clifford (1973, figs. 1 and 5), in a study of the hydrodynamics of the Cambrian Mount Simon Sandstone west of the study area (equivalent to the Potsdam Sandstone of New York), indicates a reverse pressure gradient in relation to the slope of the underlying Precambrian surface. If this condition extends into New York (the Bethlehem Steel Corp. well pressure level "fits" the extension), the potentiometric surface in western New York probably slopes northwestward. A gradient of the potentiometric surface does not necessarily imply movement of the brine. Among other factors, regional density differences of the brine may prevent flow downgradient.

FRESHWATER AQUIFERS

UNCONSOLIDATED ROCK

Freshwater occurs at shallow depth in almost all unconsolidated deposits (glacial drift and alluvium) in the region. Domestic and municipal water supplies are obtained from aquifers in major stream valleys. Recharge to the aquifers is principally from precipitation. Some recharge comes from deeper circulation of ground water that seeps upward into shallow aquifers and into streams from bedrock aquifers.

BEDROCK

Some parts of the bedrock formations have void spaces—formed by fractures, bedding planes, or solution channels—which allow water to move. Generally, these openings are most numerous in the upper 200 ft of the rock. Such rocks constitute aquifers and provide water to wells and springs and supply base flow of streams. In some areas, the water is highly mineralized from contact with rocks that readily dissolve or from long contact with rocks during deep circulation. Recharge to rock aquifers is usually by water infiltrating from the overlying unconsolidated material.

CONFINING BEDS

A formation that restricts fluid movement is called a confining bed. In subsurface disposal, a confining bed is needed to restrict vertical movement of wastes. Ideal confining beds are thick, tight shales.

The Cambrian formations considered for disposal in this study lie beneath the limestone of the Ordovician Black River and Trenton Groups; the erosional Knox unconformity separates the Ordovician, except the Beekmantown Group, and the Cambrian rocks (fig. 3). The limestones, which are generally thick (nearly 800 ft), massive, and nearly void of permeable zones, have been considered good confining beds for deep-well disposal with the possible exception of disposal of acidic wastes. The Knox unconformity is indicated as a permeable zone in some well records. Because the unconformity is an erosional surface, it overlies rocks that have been weathered and whose permeabilty is probably greater than that of the original rock.

DEEP-WELL INJECTION POTENTIAL

GENERAL PRINCIPLES

Disposal of wastes to the subsurface requires an injection well constructed of material resistant to corrosion and capable of withstanding high injection pressures. In addition, type and character of the rock and the native fluid of the disposal zone are of vital importance to chemical-reaction and fluid-transmission characteristics within the receiving formation.

Permeabilty of the formation and viscosity of injection fluid largely determine the pressure needed to inject the wastes and displace the native fluid. If the permeability is great enough, low pressure or even gravity flow may handle the required amount of waste. Or, permeability at required disposal depths may be so low that wastes have to be pumped under pressure, especially where the receiving formation does not have adequate transmissivity. Chemical reactions can precipitate solids or form gases that plug voids and thus reduce permeability.

EXISTING INJECTION WELLS

In early 1974, only one deep waste-disposal well other than those involved in oil and gas operations was known to be operating in western New York. This was a brine-disposal well for a salt company near Watkins Glen on Seneca Lake. Other wells have been completed or are nearing completion for disposing of industrial wastes or brine from salt mining. Some have never been put into operation because of State permit denial or industrial changes. In general, State law requires that industrial wastes be disposed of at depths greater than that required for waste brine.

BRINE DISPOSAL

Brine disposal in New York is generally associated with salt mining. Antipollution laws are gradually forcing mining companies to stop surface disposal of highly mineralized water. Salt processing involves small amounts of highly mineralized waste water. The salt-producing companies are permitted to inject mineralized waste water into the first subsurface saline-water zone having a confining bed. Depths of about 1,000 ft are required in the Seneca Lake area.

Salt is mined by both excavation and solution methods in the east and central parts of the study area. At present, only the eastern mining is involved with deep-well waste disposal. One additional well began operation and two additional disposal wells approached completion during 1974. The disposal formations are Devonian limestone and dolomite confined by a thick sequence of shale.

ACIDIC-WASTE DISPOSAL

Three wells have been drilled in western New York specifically for proposed disposal of industrial wastes. Data in the files of the New York State Geological Survey indicate that the wells were initially tested by injecting freshwater to determine well response and formation characteristics. The data included probable flow rates and pressures expected for injection of the waste fluid. Aquifer characteristics identified from these data in 1973–74 were used in this report to evaluate the region's potential for disposal of liquid industrial wastes.

FMC CORPORATION WELL

The FMC Corp. at Middleport, N.Y., drilled a well (103, fig. 4) in 1968 to dispose of wastes containing pesticides. The well was drilled to 3,189 ft into Precambrian rocks and was cased and cemented to 2,655 ft. Water was found at 3,130 ft, but the head was not reported. The 534 ft of open hole in the well is exposed to Cambrian sandstone and dolomite beds and produces a brine having a dissolved-solids concentration of 213,000 mg/L (table 2).

An injection test on the FMC well, after acidizing, involved injection of freshwater at rates of as high as 336 gal/min and maximum wellhead pressure of 2,300 lb/in ^{2}. The receiving rocks were probably hydraulically fractured at this injection pressure. The contractor who injected the freshwater estimated that the completed well would accept water at 40 gal/min and a wellhead pressure of 1,000 lb/in ^{2}. No data on the length of test, buildup of pressure, or stabilized pressures were available in the State files. Permission to use the well for waste disposal was denied by the State.

HOOKER CHEMICAL AND PLASTICS CORPORATION WELL

Hooker Chemical and Plastics Corp., Niagara Falls, N.Y., drilled a disposal well in 1968 to dispose of hydrochloric acid wastes. The well (104, fig. 4) was drilled into Precambrian rock to a depth of 3,063 ft and was cased to 2,829 ft. Cambrian rocks consisting of dense oolitic dolomite and sandstone are exposed in the 207 ft of open hole. Water was found in the disposal zone at 2,848 ft. In a test, the formation yielded 2 gal/min of brine having a dissolved-solids concentration of more than 270,000 mg/L (table 2). The low pH (3.1) possibly indicates that acid from well treatment may not have been flushed from the formation. A temperature log run after the test showed a formation-water temperature of 27°C.

In a test on well 104, 1.9 Mgal of city water was injected into the well in 10 days. A maximum injection rate of 500 gal/min produced a wellhead pressure of 1,650 lb/in ^{2}. This well, just as FMC well 103, was probably hydraulically fractured by the high injection pressures. An analysis of test data by the testing firm indicated that the receiving formations had a flow capacity of 600 mD-ft, and conclusions by the firm indicated that fractures were the most permeable parts of the formations. (A darcy is the flow, in milliliters per second, through each square centimeter, of a fluid of 0.01-poise viscosity under a pressure of 1 atm.)

BETHLEHEM STEEL CORPORATION WELL

American Industrial Disposal Systems (AIDS, Inc.) drilled and tested a disposal well for Bethlehem Steel Corp. at Lackawanna, N.Y., in 1968. The well (101, fig. 4) was drilled to 4,310 ft into Precambrian rocks and was cased to 3,783 ft. Open hole in the Theresa Formation, Potsdam Sandstone, and Precambrian units totals 527 ft. Brine was found in the Theresa Formation at 3,818 ft. The brine head after completion of drilling was 380 ft below land surface. Two analyses of the brine are included in table 2. Bottom-hole temperature was 40°C in 1968. After the well was acidized, more than 1 Mgal of freshwater was injected at various rates during a 10-day period. The proposed disposal of waste pickle liquor into well 101 is the basis for the study described here. Details of the formation at the well, the injection test, and probable effects if the well is put into operation are discussed in sections that follow.

EFFECTS OF INJECTION TEST AT LACKAWANNA SITE

HYDROLOGIC CONDITIONS OF DISPOSAL UNIT

Brine in the Cambrian rocks (well 101, table 2) has a reported dissolved-solids concentration of about 300,000 mg/L. A static level of 380 ft below land surface was reported at the time of the injection test. The high dissolved-solids content of the brine indicates that brine movement is probably very slow under natural conditions.

GEOLOGIC CONDITIONS OF DISPOSAL UNIT

The geologic section beneath the Lackawanna disposal site is shown as Bethlehem Steel well 101 in figure 3. The Theresa Formation, consising mainly of dolomite with sandstone layers, occurs at depths of 3,794 to 4,131 ft. Potsdam Sandstone lies below the Theresa to 4,251 ft, and then Precambrian is present to the bottom of the well at 4,310 ft. The well is cased and cemented to 3,783 ft, apparently 11 ft above the Theresa contact. The remainder of the well, 527 ft of open hole, can transmit injected fluid.

A map showing thickness of Cambrian formations beneath the Knox unconformity in western New York was made from data in Rickard (1973). Thicknesses were taken from this map to construct a hydraulic model of the geologic sequence (fig. 5). The map shows a wedge-shaped unit of Cambrian

TABLE 2.—*Chemical analyses of Cambrian brines in western New York and Canada*

[Analyses by several laboratories; copies obtained from New York State Geological Survey. Chemical constituents, dissolved-solids concentration, and hardness for samples from wells 78, 8, 9H, and 94ET are in milligrams per liter; those for remaining samples, in parts per million, not equivalent at density greater than freshwater]

Characteristic or constituent	Well number and date of sample collection								
	Western New York						Canada		
	Well 67 (1969)	Well 94ET (10-4-72)	[1] Well 101 (1968)	[2] Well 101 (1968)	Well 103 (1968)	Well 104 (1968)	Well 7S (1963)	Well 8 (8-11-55)	Well 9H (7-19-70)
Specific conductance (μmho/cm at 25°C)	--	229,000	--	--	--	--	--	--	--
Resistivity (ohm-meters at 20°–21°C)	0.054	--	--	--	--	--	--	--	0.197
Silica (SiO_2)	--	28	1.9	2.1	--	9.3	--	--	--
Iron (Fe)	3.5	2.5	--	--	--	--	--	--	[3] Trace
Manganese (Mn)	--	.21	--	--	--	--	--	--	--
Calcium (Ca)	29,550	36,000	30,827	31,713	27,600	72,490	[3] 71,640	--	3,320
Magnesium (Mg)	3,880	5,100	4,640	3,965	100	14,486	0.7	--	--
Sodium (Na)	60,150 (Na + K)	78,000	84,200	80,400	69,960	9,840	[3] 102,200	--	10,200
Potassium (K)		8,200	3,030	3,148	--	892	--	--	--
Bicarbonate (HCO_3)	--	307	14.5	<.5	20	0	--	--	37
Sulfate (SO_4)	3	--	[4] 57	[4] 43	136	[4] 500	[4] 15,130	--	412
Chloride (Cl)	156,600	200,000	192,300	185,450	118,000	61,820	[3] 164,240	[3] 154,447	22,600
Dissolved-solids concentration	250,550	335,000	321,722	302,080	213,000	270,450	[3] 261,300	[3] 247,800	40,900
Hardness, as $CaCO_3$	83,500	110,907	84,676	85,770	--	241,670	--	--	--
pH	5.1	6.0	7.0	4.5	10.5	3.1	6.1	--	7.6
Temperature (°C)	--	--	--	40	--	27	--	27.5	33.9
Specific gravity (15.6°/15.6°C)	1.21	--	--	1.22	1.15	--	1.22	[5] 1.21	1.03

[1] Sample depth 3,818 ft.
[2] Sample depth 4,300 ft.
[3] Calculated by U.S. Geological Survey.
[4] Sulfite (SO_3).
[5] 20°/20°C.

rocks (pre-Knox unconformity) thickening southward from its northern limit near Lake Ontario. Near the south edge of the model limit, thickness of the unit is more than 2,000 ft. The top of the unit is an erosional unconformity that transects the underlying geologic formations.

The three geologic formations (Little Falls, Theresa, and Potsdam) in the sequence (disposal unit) within the model limits consist of sandstone, dolomite, and shale units. The lowermost part of the sequence is the Potsdam Sandstone, which rests unconformably on Precambrian rocks. Generally, the Potsdam is a quartzitic and dolomitic sandstone with dolomite stringers. The upper part of the unit is absent in the north, where the Potsdam wedges out.

Above the Potsdam is the Theresa Formation. The Theresa consists primarily of dolomite and interbedded sandstone and shale. In places, the basal sandstone beds are differentiated from the underlying Potsdam Sandstone by the lack of feldspar. The Theresa wedges out to the north.

The Little Falls Dolomite overlies the Theresa in the extreme south part of the model area.

Permeability, or hydraulic conductivity, of the individual sandstone and dolomite beds differs greatly. Primary porosity and permeability occur principally in the sandstone and to a lesser degree in the dolomite. Fracture and joint systems provide secondary permeability in some zones. Some zones of the dolomite have vuggy permeability.

Porosity and permeability determinations of Cambrian cores from well 101 were made available through the New York State Geological Survey. Porosity generally ranged from 1 to 13 percent and, in the sandstone cores, was usually highest. The greatest horizontal hydraulic conductivity (K) reported was about 9×10^{-3} ft/d for a core of Potsdam Sandstone. Of 105 determinations in a 342-ft interval, K averaged 1.5×10^{-3} ft/d. Hydraulic conductivity of 73 cores of the Theresa Formation averaged 0.8×10^{-3} ft/d, whereas that of 32 cores of the Potsdam Sandstone averaged about 3×10^{-3} ft/d.

As part of this study, splits of the cores from well 101 were made available to the U.S. Geological Survey, which used simulated brine to determine hydraulic conductivity of five of the Potsdam Sandstone cores (table 4). For horizontal flow, K ranged from 21.6×10^{-3} ft/d to 4.3×10^{-5} ft/d. For vertical flow, K was generally lower by one order of magnitude.

The injection test on well 101 provided data that can be used to interpret the average K of the rocks penetrated in the open borehole. Flow capacity of 4,736 mD-ft was based on "pressure fall-off data following the injection test at 400 gpm," the fifth stage of the injection test (AIDS, Inc., 1968). This flow capacity, or transmissivity (T), is a measure of the rate of flow through the 527-ft thickness of the open hole. Average permeability (K), calculated by dividing T by thickness, is about 9 mD. Conversion of 9

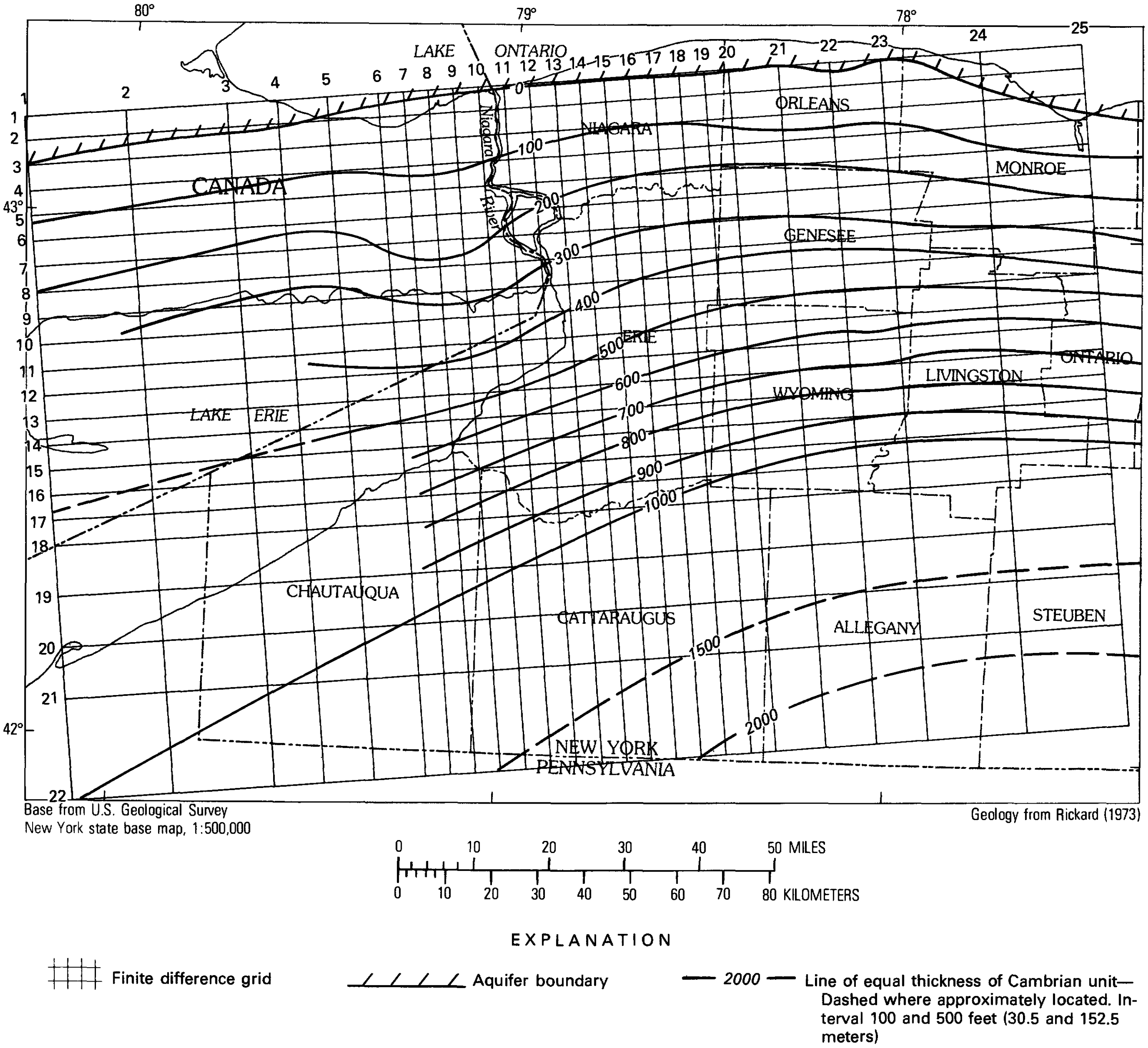

FIGURE 5.—Thickness of Cambrian unit underlying Knox unconformity, and grid overlay for hydraulic model.

mD to hydraulic conductivity units gives 26×10^{-3} ft/d, about comparable to the highest laboratory determination of hydraulic conductivity of cores from the Potsdam (2.4×10^{-3} ft/d) (sample 73NY34, table 4).

AIDS, Inc. (1968), however, determined from temperature logging that most of the flow occurred in four zones that contained principally fracture porosity rather than intergranular porosity. The zones, totaling 42 ft, were as follows:

Interval (ft)	Thickness (ft)	Formation	Rock type
3,795–3,807	12	Theresa	dolomite.
3,820–3,833	13	Theresa	dolomite.
4,066–4,074	8	Theresa	dolomite.
4,113–4,122	9	Potsdam	sandstone.

Thus, an "effective" permeability, based on only 42 ft of rock, is 110 mD or 320×10^{-3} ft/d.

The use of a K value based on a selected "effective" zone rather than on the entire exposed section is necessary in analysis of the hydraulic-conductivity changes that occur when the injected fluid differs from that of the receiving formation. As stated earlier, an injectant will displace the formation fluid and cause a change in the apparent permeability because of differing fluid-viscosity values (chemical effects are discussed later) and thus will affect the pressure head developed in the disposal well. The extent of the injectant movement depends on the "effective" zone—the thinner the zone, the farther a given quantity of injectant moves and the greater the extent of K change will be.

Of concern in evaluating K of the disposal unit are the occurrence and the degree of hydraulic fracturing caused by high injection pressures. Hydraulic fracturing increases the K in the immediate vicinity of the borehole, or, in hydraulic terms, increases the effective diameter of the well, which affects the pressure in the injection well. Regional pressure effects would not be affected by hydraulic fracturing. The theory of hydraulic fracturing and the probabilities of fracturing the formation in the Lackawanna well are discussed in the section "Hydraulic Fracturing."

Another vital aspect in predicting the hydraulic effects of waste disposal involves the chemical effects on formation permeability. Bethlehem Steel Corp. reported to the New York State Health Department (C. R. Symons, written commun., April 16, 1969) their appraisal of chemical effects:

Effect of Injected Waste Pickle Liquor on Disposal Formation

The disposal formation is composed principally of dolomite and sandstone. Sandstone will not react with hydrochloric acid. Dolomite will react to form soluble chlorides of calcium and magnesium and, at atmospheric pressure, carbon dioxide will be liberated. However, since the reservoir pressure at Lackawanna is known to be over 130 atmospheres, we expect that the carbon dioxide will remain in solution.

Tests were made in the laboratory in which core plugs of dolomite and of sandstone taken from the formation were immersed in synthetic hydrochloric acid waste pickle liquor at atmospheric pressure and at ambient temperature. Prior to immersion in WPL half of the samples were immersed in connate water from the well for 24 hours.

The sandstone samples did not react with the WPL. The dolomite samples reacted with the WPL as expected. The reaction with the dry sample (#1) was instantaneous; the reaction with the sample which had been immersed in connate water (#2) began two minutes after immersion in WPL.

After 95 minutes immersion in WPL, sample #1 had lost 7.23% of its original weight and #2 had lost 6.64%. Less than 4% of this weight loss was found as insoluble matter; the remaining 96% was either soluble in the WPL or was evolved as carbon dioxide gas.

Tests of this type do not simulate what actually will occur underground when WPL is being injected. For example, we have assumed that the zones of the formation which accept water during injection tests are saturated with connate water. Therefore, reaction between injected WPL and dolomite underground may be inhibited to some extent.

We interpret these results as evidence that there should be no adverse effects caused by injecting HCl-WPL into permeable dolomite formations. That is, we do not expect precipitates to form which will plug the well face and cause an increase in injection pressure.

Further evidence that injected HCl-WPL may improve formation permeability is found in the fact that oil and gas well service companies have used HCl to improve permeability of dolomite and limestone formations for many years.

In summary, we believe the results of these laboratory tests show that there should be no adverse effects on the disposal formation from the injection of HCl-WPL.

Because of the high total iron concentration (181,000 mg/L, sample 1, table 5) of the waste pickle liquor and its potential for precipitation within the pore spaces under field conditions, deep-well injection of the liquor was simulated in the laboratory. The U.S. Geological Survey designed an apparatus to simulate field conditions for use in laboratory experiments.

The U.S. Bureau of Mines (Bayazeed and Donaldson, 1973) conducted similar experiments, but without high pressures, with cores from the Mount Simon Sandstone (correlative with the Potsdam Sandstone) from Indiana. Bayazeed and Donaldson (1973, p. 30) concluded "that after a long period of storage [in the formation] most of the acid [HCl] in the WPL [waste pickle liquor] will be neutralized and the iron irreversibly adsorbed by the geologic formation." They also noted (p. 22), "A slight decline in permeability is observed, but for practical purposes it is negligible." Small loss of permeability noted in the Bethlehem Steel Corp. tests on sandstone cores seems substantiated, but reaction with dolomite cores under field conditions was still in doubt.

CHEMICAL EFFECTS BY LABORATORY EXPERIMENTS

As far as was known, the planned injection of highly acidic waste with an extremely high iron concentration (181,000 mg/L) into carbonate rocks at a depth of 4,000 ft and at pressures that approached or exceeded theoretical hydraulic fracturing pressures was to be the first of its kind. Several possible reactions between rock and injected fluid were considered. One possibility was that the reaction between acid waste and carbonate rock would dissolve enough rock to develop large chambers and

TABLE 3.—*Selected laboratory determinations on core samples from the Lackawanna well 101*

[Analyses by U.S. Geological Survey, Denver, Colo.]

Laboratory sample No.	Depth (ft)	Lithology	Mineralogy: X-ray analysis (weight percent) Quartz	Dolomite	Calcite	Potassium feldspar	Clay minerals	Total	Chemical analysis (weight percent) Dolomite equivalent [1]	Specific gravity of solids (g/cm³)	Porosity (percent) Total	Effective
73NY10	3,819.8	Microcrystalline dolomite.	2	[2] 98	--	--	--	100	92	2.77	7.1	2.9
11	3,821.2	Oolitic dolomite	8	78	0	0	--	86	85	2.82	1.4	.86
12	3,823.1	Dolomitic sandstone	--	--	--	--	--	--	78	2.79	2.4	1.3
13	3,827.1	Oolitic dolomite	1	[2] 99	0	0	--	100	94	2.83	8.1	7.0
14	3,830.3	Cryptocrystalline dolomite.	5	[2] 89	0	6	--	100	82	2.84	14	13
15	3,832.5	Dolomitic sandstone	--	--	--	--	--	--	57	2.77	4.4	3.7
16	3,928.3	Microcrystalline sandy dolomite.	6	71	0	9	--	86	75	2.78	4.0	3.9
17	3,930.8	Dolomitic sandstone	--	--	--	--	--	--	75	2.73	.9	.9
18	3,938.1	Massive dolomite	--	--	--	--	--	--	74	2.83	.93	.55
19	3,939.8	Sandy dolomite	--	--	--	--	--	--	86	2.83	6.0	4.2
20	3,942.2	Dolomitic sandstone	43	22	5	10	--	80	21	2.67	13	12
21	3,944.8	Gray sandstone	45	42	0	13	--	100	37	2.77	11	7.5
22	3,970.9	Orthoquartzite	--	--	--	--	--	--	0	2.65	13	11
23	3,975.1	Dense dolomite	--	--	--	--	--	--	76	2.84	1.9	1.6
24	3,978.4	Dolomitic sandstone	--	--	--	--	--	--	30	2.67	4.5	4.5
25	3,981.7	Sandy dolomite	12	74	0	5	--	91	73	2.85	6.0	2.6
26	4,089.8	Coarse calcareous sandstone.	52	36	0	5	--	93	29	--	--	--
27	4,093.3	Sandstone	--	--	--	--	--	--	3.7	2.65	13	12
28	4,096.0	Sandstone	--	--	--	--	--	--	5.7	2.63	7.1	7.0
29	4,102.4	Calcareous sandstone	45	26	0	17	--	88	22	2.71	13	8.8
30	4,103.4	Coarse dense sandstone.	43	42	0	7	--	92	30	2.67	7.4	6.8
31	4,130.1	Crossbedded sandstone.	55	0	0	36	--	91	.22	2.62	12	9.8
32	4,134.7	Light-gray sandstone	43	36	0	13	--	92	29	2.70	9.4	8.6
33	4,136.8	Sandy dolomite and dolomitic sandstone.	12	50	0	18	--	80	50	2.76	4.2	1.2
34	4,140.1	Quartzite	57	0	0	32	--	89	0	2.70	13	11
35	4,144.2	Gray sandstone	17	4 ?	0	36	<10	57	4.2	--	--	--
36	4,148.0	Light-gray sandstone	38	0	0	43	--	81	0	2.60	13	11
37	4,152.2	White sandstone	--	--	--	--	--	--	0	2.61	12	11
38	4,153.1	Light-gray sandstone	--	--	--	--	--	--	0	2.68	17	13
39	4,154.5	Limey sand	12	57	0	17	--	86	51	2.83	6.8	6.2

[1] Analyses on 40 mesh.
[2] Dolomite content by difference.

TABLE 4.—*Hydraulic conductivity of cores from the Potsdam Sandstone, Lackawanna well 101*

[Analyses by U.S. Geological Survey, Denver, Colo.]

Sample No.	Depth (ft)	Rock type [1] (table 3)	Confining pressure (lb/in ^{2})	Nominal pore pressure (lb/in ^{2})	Hydraulic gradient (cm/cm)	Hydraulic conductivity at 40°C (m/d): Simulated brine, Horizontal	Simulated brine, Vertical	Pickling liquor, Horizontal	Pickling liquor, Vertical
73NY10	3,819.8	dol	----	----	----	----	----	----	[2] 3.0×10^{-7}
			----	----	----	----	----	----	[3] 5.7×10^{-8}
13	3,827.1	ss	4,130	1,635	118	6.6×10^{-2}	1.0×10^{-3}	----	[2] 6.3×10^{-4}
						----	----	----	[3] 3.1×10^{-7}
14	3,830.3	dol	----	----	----	----	----	[2] 5.6×10^{-4}	----
			----	----	----	----	----	[3] 4.6×10^{-6}	----
16	3,928.3		----	----	----	3.4×10^{-6}	----	----	----
21	3,944.8	ss	----	----	----	3.9×10^{-5}	6.6×10^{-6}	----	----
30	4,103.4	ss	----	----	----	4.1×10^{-5}	5.6×10^{-6}	----	[2] 1.3×10^{-6}
			----	----	----		----	----	[3] 4.2×10^{-7}
31	4,130.1	ss	----	----	----	1.2×10^{-3}	----	----	----
34	4,140.1	qtzte	4,475	1,794	20.2	3.8×10^{-3}	----	----	[2] 1.2×10^{-2}
			4,425	1,785	[4] 555	----	----	[2] 2.4×10^{-3}	[3] 2.7×10^{-3}
								[3] 1.4×10^{-3}	
36	4,148.0	ss	----	----	----	1.3×10^{-5}	----	----	----

[1] dol, dolomite; ss, sandstone; qtzte, quartzite.
[2] At beginning of test.
[3] At end of test.
[4] For horizontal core with pickling liquor.

that the greatly increased porosity would accommodate the injected material. A second possibility was that, as the waste was neutralized by the carbonate rock, an iron hydroxide gel would be formed and the rock interstices would be completely plugged. Another possibility was that, during injection, early solution of the carbonate grains would be followed by deposition of an iron carbonate coating on the grains and crystals, which would reduce the rate of solution and would cause a large reduction in transmissivity. Reaction between hydrochloric acid and carbonate rock produces carbon dioxide. Thus, injection of the acid waste might start a reaction that would produce increasing pressures even if injection were terminated.

Because of the various theories on the probable effect of injection of acid waste into the carbonate rock, a series of laboratory experiments was undertaken to simulate conditions that would approach the physical environment at the injection zone 4,000 ft below land surface. The experiments were done at the U.S. Geological Survey laboratory at Denver, Colo., by Francis S. Riley. The experiments involved the development of equipment to permit duplication of down-the-hole pressures and temperatures. In addition to the problems of working with pressures of more than 2,000 lb/in^2, the highly acidic character of the pickling liquor was of concern.

The core of the injection section of the Bethlehem Steel Corp. well 101 was examined, and 30 samples of the core were prepared by William Rogers of the New York State Geological Survey for testing in the Denver laboratory. Testing of the core samples began in October 1972. Several physical and hydrologic characteristics were determined for each of the samples. Dolomite content was determined by CO_2 evolution; calcite content was determined by X-ray diffraction; specific gravity was measured; total porosity was determined; and effective porosity was measured by the mercury-injection process. The laboratory determinations are presented in table 3. Hydraulic-conductivity determinations of the cores are shown in table 4. Some of the graphs of hydraulic-conductivity changes of the cores with volume of fluid injection are included as figures 15–18.

Movement of native brine and pickling liquor through unfractured sections of the target strata was studied in the laboratory. Techniques and results of the laboratory injections under simulated field conditions are reported elsewhere (Ragone, Riley, and Dingman, 1978). Although the laboratory tests did not identify all phase transformations in the reaction of the pickling liquor with the target rock types, several pertinent facts were documented (figs. 15–18):

1. Passage of simulated native brine through target-rock cores did not plug pores.
2. Passage of pickling liquor into target-rock cores plugged dolomitic samples but had no obvious effect on noncarbonate sandstones.

TABLE 5.—*Chemical anlyses of samples of pickling liquor from Bethlehem Steel plant at Lackawanna, N.Y.*

[Analyses by U.S. Geological Survey, Albany, N.Y.; all values in milligrams per liter unless otherwise indicated]

Characteristic or constituent	Sample 1 (collected 7-8-70)	Sample 2 (collected 12-5-72)
Iron (Fe), unfiltered sample:		
Total	181,000	180,000
Ferrous	--	160,000
Iron (Fe), filtered through 0.45-micron filter:		
Total	--	170,000
Ferrous	--	150,000
Iron (Fe), centrifuged sample:		
Ferrous	--	180,000
Total	--	160,000
Manganese (Mn)	820	--
Silica (SiO_2)	90	--
Calcium (Ca)	7.0	--
Magnesium (Mg)	4.0	--
Sodium (Na)	1.7	--
Potassium (K)	.7	--
Bicarbonate (HCO_3)	0	0
Carbonate (CO_3)	0	0
Sulfate (SO_4)	792	--
Chloride (Cl)	224,000	--
Fluoride (F)	2.0	--
Normality	--	4.56
Acidity, as $CaCO_3$	--	228,000
Acidity, as H^+	1,080	4,600
Carbonate alkalinity, as $CaCO_3$	0	0
Bicarbonate alkalinity, as $CaCO_3$	0	0
Total alkalinity, as $CaCO_3$	0	--
Carbon dioxide	0	--
Color (platinum-cobalt)	800	--
Specific conductance (lab.)	123,000 μmho/cm at 25°C	--
Density (at 20°C)	1.33 g/mL	--
Specific gravity (at 25°C)	--	1.2182
Viscosity (at 105°F)	--	1.4023 centipoises
Dissolved solids (at 180°C)	261,000	--
Dissolved solids (sum)	407,000	--
Hardness (noncarbonate)	34	--
Hardness (total)	34	--
Methylene blue active substances (MBAS)		
Nitrite (NO_2)	7.5	--
pH (lab.)	15	--
Cadmium (Cd)	0	0
Chromium (Cr), dissolved	--	810 μg/L
Cobalt (Co)	--	81,000 μg/L
Copper (Cu)	--	220,000 μg/L
Lead (Pb)	--	14,000 μg/L
Lithium (Li)	--	2,600 μg/L
Nickel (Ni)	--	0
Oil-grease	--	250,000 μg/L
Silver (Ag)	--	3.0 μg/L
Strontium (Sr)	--	300 μg/L
Zinc (Zn)	--	3,600 μg/L

3. Passage of concentrated hydrochloric acid (simulated pickling liquor minus iron) did not plug dolomite.
4. Neutralization of the acidic pickling liquor by dolomite under simulated field temperature and pressure did not produce an observable gas phase.

To explain the observations in the laboratory tests, several calculations are presented to typify the probable reactions between the acidic waste and the target formations. Thermodynamically rigorous calculations are virtually impossible for solutions as concentrated as the pickling liquor used in the laboratory experiments. Chemical analysis of the extremely acid pickling liquor is presented in table 5. Because reliable activity-coefficient and ion-complexing data are lacking for this system, all calculations are based on the assumptions that (1) activity coefficients are equal to unity and (2) ion-complexing does not occur. These approximations negate any quantitative use of the calculations but still allow many useful qualitative predictions to be made.

CALCULATIONS

Initial reaction in the injection tests should be reaction of the hydrochloric acid with the dolomite component of the receiving rock. The reaction can be written:

$$[CaMg(CO_3)_2] + 4[H^+] + 4[Cl^-] = [Ca^{+2}] + [Mg^{+2}] + 4[Cl^-] + 2[H_2CO_3], \quad (1)$$

with the subsequent partitioning of the carbon dioxide between the aqueous and gaseous phases being approximated by

$$P_{CO_2} = 10^{1.5}[H_2CO_3]. \quad (2)$$

The brackets used above denote activity of the species (assumed equal to the molal concentration), and P_{CO_2} denotes atmospheres of the carbon dioxide produced in reaction 1.

The $\log_{10}$ of the equilibrium constant for reaction 1 is calculated to be 13.7 at 25°C and 1 atm of pressure on the basis of values from Garrels and Christ (1965) for the free energy of formation of the reactants and products of reaction 1. A useful simplification of reaction 1 is to consider the case where approximately 80 percent of the acid has been neutralized, and $[Ca^{+2}] = [Mg^{+2}] = [CaMg(CO_3)_2] = 1$. The pH of the solution would still be less than 1, and further neutralization would result in only minor changes in the concentration of the calcium and magnesium and no change in the activity of the dolomite. Under these conditions,

$$\log[H_2CO_3] = 6.8 - 2\text{pH}, \quad (3)$$

and the pressure of the carbon dioxide in equilibrium with the system is $10^{(1.5)} \times 10^{(6.8-2pH)}$. Thus, at a pH of 1, the pressure of the carbon dioxide necessary to maintain equilibrium would be $10^{(1.5)} \times 10^{(4.8)} = 10^{6.3}$ atm, which is more than 14,000 times greater than the observed hydrostatic head of 137 atm. For a hydrostatic pressure of 137 atm, the dolomite would be in equilibrium with reacted pickling liquor at a pH of approximately 3.1. At higher pH, the pressure of the carbon dioxide would be less than the hydrostatic head and, thus, would be incapable of causing a blowout of pickling liquor if pumping pressure were not maintained. Under natural conditions, any separate carbon dioxide phase would be a gas, but a comparatively dense one, with a density of approximately 0.027 lb/in^2.

Density differences could cause a separation of any carbon dioxide gas phase from the other reaction products, leading to the reaction shown by

$$[CaMg(CO_3)_2] + 2[H_2CO_3] = [Ca^{+2}] + [Mg^{+2}] + 4[HCO^{-3}]. \quad (4)$$

The hydrochloric acid analog of reaction 4 would also take place between the dolomite and pickling liquor after the pH of the pickling liquor had increased to a sufficiently high value.

Laboratory studies did not define any discrete mineral-phase reaction product, but plugging of the dolomitic cores was probably due to the formation of either ferrous carbonate or ferrous hydroxide; the corresponding ferric possibilities are not considered because of the dominance of the ferrous iron in the pickling liquor and the exclusion of oxidants from the laboratory and injection-well systems. The relative stabilities of the two minerals, siderite and crystalline $Fe(OH)_2$, can be evaluated from

$$[Fe(OH)_2] + [H_2CO_3] = [FeCO_3] + 2[H_2O]. \quad (5)$$

At 25°C and 1 atm of pressure, the $\log_{10}$ of the equilibrium constant for equation 5 is 7.24, which yields an equilibrium H_2CO_3 concentration of $10^{-7.24}$. At higher concentrations of H_2CO_3, the hydroxide phase disappears and more siderite forms. Equation 3 shows that equation 5 should be in favor of the siderite phase at pH's as much as 7.

An additional mineral stability relationship of importance to this study, the relation between dolomite and siderite, is shown by

$$[CaMg(CO_3)_2] + 2[Fe^{+2}] = 2[FeCO_3] + [Ca^{+2}] + [Mg^{+2}]. \quad (6)$$

The equilibrium constant for equation 6 at 25°C and 1 atm of pressure is 41, which indicates that in a system containing excess dolomite virtually all the dissolved iron will exchange with the dolomite to form siderite. Although siderite occupies only 91 percent of the space occupied by an equivalent amount of dolomite, the negative volume change on reaction does not control the available volume for the products because the system is not a closed system.

DISCUSSION

The probable effects of pickling-liquor injection into the dolomitic rock strata are of four main types: (1) physical alteration of the rock matrix, (2) chemical alteration of the pickling liquor, (3) displacement of the formation brine, and (4) possible leakage through the confining bed of partially reacted pickling liquor and reaction products.

Physical alteration of the rock matrix will depend on the lithology and the mineralogy of the rock, and on the hydraulic pressures attained during injection. The pickling liquor will penetrate the more permeable strata and any existing fractures in the less reactive nondolomitic strata and through fractures connecting with nondolomitic strata. Obstruction of pores by iron precipitates in dolomitic strata should limit the propagation of pickling-liquor fronts either to dolomite zones in contact with relatively nonreactive rocks such as quartzites or to fractures. Any creation of rock fractures, or propagation of existing fractures, resulting from excessive injection pressures would facilitate the transport of pickling liquor to fresh, reactive sites in the dolomitic rock. Pickling-liquor transport would become increasingly dependent on nonreactive strata and newly propagated fractures as injection continued and as the dolomitic walls of the original fractures became plugged.

Pores in the dolomitic rock are probably plugged by siderite $[Fe(CO_3)]$. Although the problem of detecting small differences between large numbers precludes the possibility of demonstrating a loss of iron in the laboratory system, injection of iron-free hydrochloric acid does not result in pore plugging. Additionally, filtration of the pickling liquor before injection into the test cores suggests that only precipitates formed by reaction products are responsible for pore plugging. A likely sequence of events in the formation of siderite is the reaction of hydrogen ions from the pickling liquor with the dolomite, reaction of the resultant carbon dioxide with dolomite until the pH has risen to some critical value, and then precipitation of siderite at the same rate that the dolomite neutralizes the resulting acidity. The acid promotes the substitution of siderite for dolomite by transporting carbon dioxide from the dolomite crystal to the interstitial solution. Without the acid as a catalyst in the reaction between dolomite and iron, the siderite would probably form a compact crystal armor on the dolomite surface by lattice substitution of ferrous ion for calcium and magnesium ions. In such a case, the negative volume change of the reaction would probably preclude a decrease in permeability of the rock. The rate of reaction is much faster with the acid intermediate than without it. This results in the formation of small crystallites, not the smooth amoring of lattice substitution. The crystallites could plug the rock by flocculating or otherwise jamming together, or by recrystallization to form larger interstitial crystals.

Equations 1, 4, and 6 describe the reactions most likely to explain the neutralization of the pickling liquor by the dolomitic rocks. The major changes in the neutralization involve: (1) replacement of dissolved iron and hydrogen ion (acidity) with calcium and magnesium from the dolomite, (2) precipitation of siderite in amounts equivalent to the dolomite dissolved by the acid, (3) eventual replacement of dolomite by any residual dissolved iron, and (4) generation of carbon dioxide, which may be used to precipitate dissolved iron and to regenerate hydrogen ions or may separate from the pickling-liquor zone and react with dolomite to form a calcium and magnesium bicarbonate solution.

Waste pickle liquor injected into the formation displaces the interstitial brine. Because the dolomite ahead of the pickling-liquor front is not plugged by reaction products, formation brine is freer to move through a wider variety of rock types than the pickling liquor. Fractures probably play an important role in brine transport and may serve as the origin for fracture propagation caused by excessive hydraulic pressure transmitted by the formation brine.

Perhaps the most perplexing and potentially dangerous problem in the proposed injection is the fate of carbon dioxide liberated by neutralization of the pickling liquor; in particular, the question of pressure (possibly up to 14,000 times hydrostatic) caused by generation of carbon dioxide. (See equations 1 and 2.) The pressure is determined by a variety of factors; for example, rate of reaction of hydrogen ion and dolomite, rate of reaction of ferrous ion and carbon dioxide, rate of reaction of carbon dioxide and dolomite, permeability of the rock, net volume changes with the reactions taking place, and the ability of the rock strata to relieve pressure differentials by expanding or fracturing. Thus, pressure calculations for this system depend on kinetics rather than equilibria. Equilibrium calculations of pressure for this system can yield only approximations of the maximum pressures theoretically attainable from reaction; that is, the pressures resulting if the system does not release the carbon dioxide. If the pickling liquor is injected slowly enough to allow the pH to stay above 3 (approximated earlier in this paper), then the pressure resulting from carbon dioxide evolution will not exceed the present hydrostatic head and, thus, will not add to pressures causing the migration of the pickling liquor or brine. Unfortunately, evaluation of the actual kinetic constraints necessary to maintain a pH above 3 cannot be reliably determined in the laboratory.

If partially reacted carbon dioxide-charged pickling liquor should experience a sudden drop in confining pressure, the liquid could effervesce. Fracturing of the overlying rock by increased hydraulic pressure could cause the effervescent liquid to migrate until the pressure was relieved by reaction, expansion, or venting.

SUMMARY

Laboratory and calculated data (table 4 and figs. 15–18) indicate that the waste pickle liquor can be neutralized by injection into dolomitic rock of the Theresa Formation but that several problems will result. Dissolved iron in the pickling liquor will precipitate, probably as microcrystalline siderite, within the dolomitic strata. Reaction of the dissolved iron and acidity of the pickling liquor will be highly dependent on fresh reaction surfaces in the dolomite. Because of plugging and the need for fresh reaction surfaces, most of the pickling liquor will probably move through nearly inert strata and (or) through fractures; reaction will be greatest at dolomitic boundaries.

Pressure caused by carbon dioxide evolution may be a major problem if rate of injection proceeds too rapidly; however, this problem can best be evaluated by an injection test.

Long-term effects of injecting waste pickle liquor into the Theresa Formation should be a mixed siderite-dolomite solid phase in contact with a dense calcium and magnesium chloride and bicarbonate brine. The net effect is that effective coupling of the borehole to the formation may be decreased. But the "effective" permeable zone (fractured dolomite and nondolomitic sandstone) would probably be only slightly affected by plugging. Therefore, plugging of the disposal unit by precipitated chemical reaction products would not be considered a major factor in pressure buildup at the well.

DIGITAL-MODEL ANALYSIS

Of interest are the required injection pressures at the wellhead and the changes in brine level that injection may cause throughout the formation. A digital model of the disposal formation was developed to determine this information.

MODEL CHARACTERISTICS AND BOUNDARIES

The modeling technique described by Prickett and Lonnquist (1971) was used to build the digital model. In this approach, finite-difference equations are used to approximate the differential equations of fluid flow through the porous system. Solution of these equations by a digital computer gives the buildup of brine head, as a function of time, at the injection well or elsewhere in the formation.

Normally, digital models of the type just described are used only if extensive data on transmissivity and storage coefficient throughout the problem area are available. In the present study, such data were not available. Determinations of permeability were available only at wells 101 and 104 (fig. 4). However, computations made with a model, even using assumed values for hydraulic factors, are generally superior to computations made using the same data in an analytical solution to the flow equation because a model can more satisfactorily account for the geometry of the system and boundaries than the analytical solution can. For this reason the model was used in computations even though the data were restricted. Verification of the model in any true sense was not possible, and results, accordingly, are open to question.

The model used in this study is a two-dimensional areal representation of the formation. A rectangular grid is superposed on a map of the formation (fig. 5); the grid intersections form a set of nodes, or discrete points, at which values of head are to be calculated. The formation may be regarded as being subdivided into rectangular blocks surrounding each node. A value of transmissivity (estimated hydraulic conductivity multiplied by formation thickness) is specified for each boundary between adjacent blocks; a value of storage coefficient is specified for the area within each block. A series of discrete steps represents time change. The object of the analysis is to calculate an average head within each block for each time step. A system of algebraic equations that approximates Darcy's law expresses the flow between adjacent blocks in terms of the head differences between those blocks. Accumulation of water in storage within a given block is expressed in terms of the head change between time steps within that block by an approximate form of the storage equation. Simultaneous numerical solution of this system of equations yields the required value of head for each block in each time step.

Boundaries of the model are along the outer edges of the grid in figure 5. All boundaries were treated as impermeable barriers—that is, lines along which no flow could enter or leave the formation. The northern boundary coincides with the edge of the formation as it pinches out to the north. The other boundaries have no counterpart in the real system; however, the mesh spacing is extended progressively in the other three directions. These artificial boundaries are distant from the proposed disposal site, and their effect on the calculations is minimal.

The model is based on the assumption that flow is horizontal, whereas the dip of the formation implies that flow will generally involve some vertical movement if it is confined within the unit. However, the generally small vertical components generated by the formation dip would probably not cause significant error. The model is also based on the assumption that the formation is saturated with a fluid of uniform density and viscosity—that is, the entire formation is saturated with brine identical to that in the vicinity of well 101, and the injected waste is identical in viscosity to this brine. The model results were corrected for the viscosity differences between formation brine and injected waste; no corrections were made for the effects of density variation on the flow pattern. Head values calculated by the model represent elevations, above datum, to which brine equivalent to that at well 101 would rise in piezometers or observation wells tapping the formation at each node.

Each head calculated by the model represents an average value for the block of formation surrounding the node. The node spacing in the center of the mesh is approximately 19,000 ft; thus, the head computed by the model for the node representing a well is an average for an area of nearly 13 mi^2. Computations for the center node, injection well 101, therefore do not represent the head within the injection well. A method of correction suggested by Prickett and Lonnquist (1971, p. 61) was used to calculate head within the injection well on the basis of the average head determined for the node block. This correction is discussed in more detail in the section, "Correction of Field-Test Data and Comparison with Model Results."

TRANSMISSIVITY AND STORAGE COEFFICIENTS

As noted in the section "Geologic Conditions of Disposal Unit," flow capacity testing of well 101 by AIDS, Inc., in 1968 indicated an intrinsic permeability of 110 mD through 42 ft of the formation. From figure 5, 42 ft represents roughly 10 percent of the thickness of the Cambrian disposal unit in the vicinity of well 101. Two of the assumptions used in designing the digital model were that (1) the permeable zones within the disposal unit constitute 10 percent of the thickness of the unit everywhere throughout the modeled area, and (2) the average intrinsic permeability of these zones is 110 mD throughout the area. This intrinsic permeability can be converted to a hydraulic conductivity of 0.32 ft/d for brine of the density and viscosity of that at well 101. This hydraulic conductivity was likewise considered constant throughout the area in designing the model—no attempt was made to adjust for brine variation. The transmissivity to brine at each node in the model was obtained by multiplying 10 percent of the thickness of the disposal unit at each location (fig. 5) by the hydraulic conductivity, 0.32 ft/d. Thus, the transmissivity at the well site was 13.44 ft^2/d.

Testing by AIDS, Inc. (1968), involved analysis of "pressure fall-off data following the injection tests at 400 gpm * * * ." The injection test in question was done in stages (see fig. 12) of 25, 50, 100, 300, and 400 gal/min. As will be explained in the section "Hydraulic Fracturing," the formation was probably hydraulically fractured by the pressure developed during the 100- to 400-gal/min injection rates. Therefore, one might expect that the permeability value derived from the AIDS test would be high and would indicate artificial fracturing close to the well. To check this possibility, the first stage of the injection test was simulated. Rate of injection was 25 gal/min, and, presumably, hydraulic fracturing did not occur or was minimal. This simulation and its comparison with the injection-test results are discussed in greater detail in the section "Correction of Field-Test Data and Comparison with Model Results." The results indicated that the permeability reported by AIDS, Inc., was low. Two possible reasons for the differing permeabilities are that (a) errors were involved in the original permeability determination, and (b) the hydraulic fractures were held open by the injection pressure and closed almost immediately when that pressure was released. Although the permeability seemed low, adjustment of model permeabilities to obtain better agreement with the test results was not attempted. Increasing the permeability did not seem warranted because the only other available field-test result, at well 104, was lower than the figure used in the model, as were all the core-permeability determinations for well 101. In addition, use of a low value in the model to insure conservative results seemed appropriate.

No field determinations of storage coefficient were made for the disposal unit. Jacob (1950, p. 334) gives an analysis of storage coefficient in terms of porosity, thickness, and compressibility of the formation, and the weight, density, and compressibility of the formation fluid. Jacob's expression for storage coefficient,

$$S = \theta b \delta_0 \ \beta (1 + \frac{\alpha}{\theta\beta}),$$

where θ is formation porosity, b is formation thickness, δ_0 is fluid density, β is fluid compressibility, and α is formation compressibility. Specific storage (S_s), or storage coefficient, per foot of formation thickness therefore would be

$$S_s = \frac{S}{b} = \delta_0 (\theta\beta + \alpha).$$

Use of conservative values of storage coefficient, which would give maximum resultant head increases, was considered desirable for the simulation test. For this reason, only 10 percent of the formation, corresponding to the 42 ft of permeable interval at well 101, was considered porous enough to contribute to the storage coefficient; and the formation was considered incompressiblc—that is, α was assumed to be zero. With these modifications, the formula for specific storage of the formation becomes

$$S_s \frac{S}{b} = 0.10 \delta_0 \theta \beta.$$

Assuming θ is 8 percent, β is 2.2×10^{-8} ft^2/lb, and δ_0 is 75 lb/ft^3,

$$S_s \simeq 1.3 \times 10^{-8}/ft.$$

The storage coefficient for each node of the model was calculated by multiplying thickness of the disposal unit in each node block times specific storage of the formation. The resulting values, which generally range from 10^{-6} to 10^{-5}, are low when compared with storage coefficients in typical freshwater aquifers. However, low values should be expected at the great depths and overburden pressures considered.

The purpose of the simulation was to estimate the injection pressures that might be required at the disposal well, as well as the increases in brine head throughout the formation, which could cause abandoned oil wells to flow or to leak brine upward into freshwater aquifers. For both purposes, maximum head buildup is of interest, so that a conservative value of storage is appropriate.

Variations in formation thickness are considered in the preceding methods of estimating transmissivity and storage coefficient, but variations in all other parameters are ignored. Moreover, simulating the variation in thickness may itself be unwarranted, as porosity and permeability are to a large extent secondary and can be expected to cut across formation boundaries. For these reasons, the model must be considered no more than a first approximation to conditions in the formation, and model results must similarly be considered approximate.

CORRECTION OF FIELD-TEST DATA AND COMPARISON WITH MODEL RESULTS

The question of whether the permeability reported by AIDS, Inc., for well 101 in 1968 represented true formation conditions or hydraulic fracturing was investigated by simulating the first phase of the AIDS test. Discharge during this phase was 25 gal/min, and, presumably, hydraulic fracturing did not occur at this rate. The model can simulate only the injection of fluid having a viscosity identical with that of of the formation fluid. Freshwater of viscosity substantially different from that of the formation brine was injected in the AIDS test. The model calculates results as head, in feet, of brine above the static brine level, whereas data in the test were recorded as pressure, in pounds per square inch, at the wellhead. Therefore, test data were converted to feet of brine above static brine level before any other adjustments or corrections were made.

Viscosity effect is illustrated in figure 6. Viscosity of the injected freshwater is lower than that of the formation brine, and, hence, the hydraulic conductivity of the formation to the injected water will be higher than its conductivity to the brine. If the injected water is assumed to move outward on a radial pattern without dispersion and to remain within the 42-ft permeable section, a continuously expanding cylindrical zone of freshwater is established around the well. Radial head gradients within this zone are less than those that would be observed if the zone were saturated with formation brine (fig. 6); therefore, head buildup in the injection well will be less than that shown in figure 6. A single continuous interval of flow is shown in figure 6, whereas the permeable zones at well 101 seem to fall into several separate zones; however, if the rates of movement are roughly equal in the various horizons and the head gradients are similar, the effect will be virtually the same as if a single zone were present.

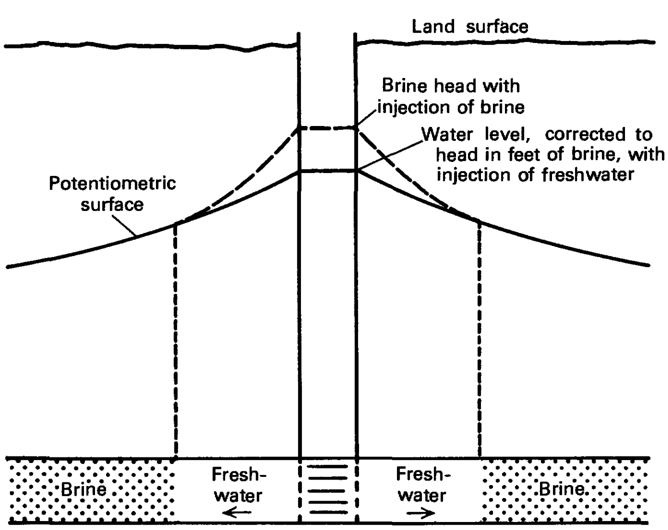

FIGURE 6.—Schematic diagram of the viscosity effect during injection of freshwater.

An approximate method of correction suggested by G. D. Bennett (written commun., 1974) was used to adjust heads for the viscosity effect. In this method, the radius of the cylindrical interface between freshwater and brine for a series of selected times is calculated using volume injected up to each given time, thickness of the injection zone, and porosity. The Thiem equation for steady-state radial flow is used to determine the hydraulic conductivity between the well radius and the interface radius, for each selected time, using both the hydraulic conductivity to brine and that to freshwater. Thus, two head changes between the interface and the well radius are calculated for each selected time; one corrsponds to injection of brine, and one to injection of freshwater. The difference between these two head changes constitutes the correction for head buildup. This correction was tabulated as a function of time and was added to the head buildup recorded during the 25-gal/min injection test to obtain the head buildups that would have been recorded if formation brine had been injected.

Validity of the viscosity correction is questionable because the freshwater was undoubtedly warmed as it was piped downward to, and as it flowed outward through, the formation. The freshwater was assumed to have a temperature of 20°C at land surface. At this temperature, the freshwater viscosity is 1.01 centistokes. The formation temperature at well 101 is reported to be 40°C (AIDS, Inc., 1968), and the viscosity of the formation brine at this temperature is 1.15 centistokes. If the injected freshwater were completely warmed to 40°C, its viscosity would be 0.66 centistoke. The hydraulic conductivity to the cooler freshwater is substantially lower than that to the warmer freshwater. Thus, if the injected water is assumed to be completely warmed as it is piped downward so that it enters the formation at a temperature of 40°C, a viscosity correction should be made. On the other hand, if the injected water is assumed to maintain its original temperature throughout the operation, its viscosity is close to that of the formation brine, and the viscosity correction would not be as great as that for the warmer water. Because the degree of warming of the injected water was unknown, viscosity corrections were calculated for the two extreme cases—no warming so that the injected water remained at 20°C, and complete warming so that the injected water entered the formation at 40°C. On the basis of the flow rate in the 7-in well casing at 25 gal/min, the time of first entry of freshwater into the formation was estimated to be 430 min after the start of injection.

The equivalent brine-head buildup in well 101 for the two temperature extremes was calculated using data from the freshwater-injection test by AIDS, Inc. An equivalent brine-head buildup of 408 ft is calculated if the freshwater is assumed to have been a constant 20°C at all points within the interface throughout the first phase of the test. A brine-head buildup of 484 ft is calculated if the temperature of the freshwater is assumed to have increased to 40°C before the water entered the formation. The actual brine-head increase after 1,200 min would presumably lie between these two values and is probably close to 484 ft because there was ample opportunity for warming of the injected water during the operation.

The model simulates input or withdrawal of formation brine at formation temperature. Thus, the model results, after application of the correction for discharging-well effects (Prickett and Lonnquist, 1971) may be compared with the corrected head-buildup curves derived from the AIDS test. The method of correction accounts for differences between the loss of head generated in radial flow to a well and that generated in flow through the sides of a rectangular block surrounding a model node. It does not account for differences between the model and the formation in the pattern in which water is accumulated in storage around the injection well. If the node spacing represents a few hundred feet, the pattern of storage accumulation in the model is similar to that in the formation, even at early times in the injection history. If the node spacing is very large, however, storage accumulation in the model early in the simulation will be concentrated in the single node representing the location of the injection well. This accumulation of storage is evenly distributed over the entire node block rather than in the spreading radial pattern observed around the injection well. Because the correction proposed by Prickett and Lonnquist does not account for this difference, discrepancies between the corrected model results and the field results can be expected early in the test. As the simulation continues, the area of storage accumulation in the model spreads to surrounding nodes and assumes a radial character that more closely approximates conditions in the formation. Thus, the corrected model heads and the field results tend to approach each other with time.

The head buildup indicated by the model after 1,200 min of brine injection at 25 gal/min and 40°C is 535 ft. This is somewhat higher than either of the adjusted field test values given previously and suggests that the hydraulic conductivity of the model is too low and should be increased by 10 to 30 percent. However, the pattern of head increase with time for the node representing the site of well 101 suggests that the variation in head buildup relates to differences in the pattern of storage accumulation between the model and the formation and affects the results of the model. The adjusted test data and the model results approach each other near the end of the 25-gal/min phase. Closer agreement would probably have been achieved if this phase had lasted longer than 1,200 min. Because of this possibility as well as the uncertainties associated with viscosity corrections and the lower permeability determined at well 104, the authors decided not to increase model hydraulic conductivity.

Data for the higher rates of injection were not processed for comparison with model results. The uncertainties in the adjustments become progressively greater at the higher rates and, together with the uncertainties associated with hydraulic fracturing, would cause the adjusted data to be too questionable for use.

PREDICTION OF EFFECTS OF INJECTION

Effects of injection were predicted in a simulated continuous injection at an average rate of 50 gal/min over a period of several years. The planned disposal operation was to involve injection of waste pickle liquor at 150 gal/min for 8 to 10 h/d (W. E. Loveridge, New York State Dept. Environmental Conserv., oral commun., 1973). Continuous injection at the average daily rate was used in the simulation to avoid computing difficulties. The waste pickle liquor was assumed to enter and move outward within a section 42 ft in thickness.

Results of the predictive run are summarized in figures 7–10. Figure 7 shows the head increase in the disposal well as a function of time. Two scales are shown: one indicating head of brine as feet above static level, and the other showing waste pickle

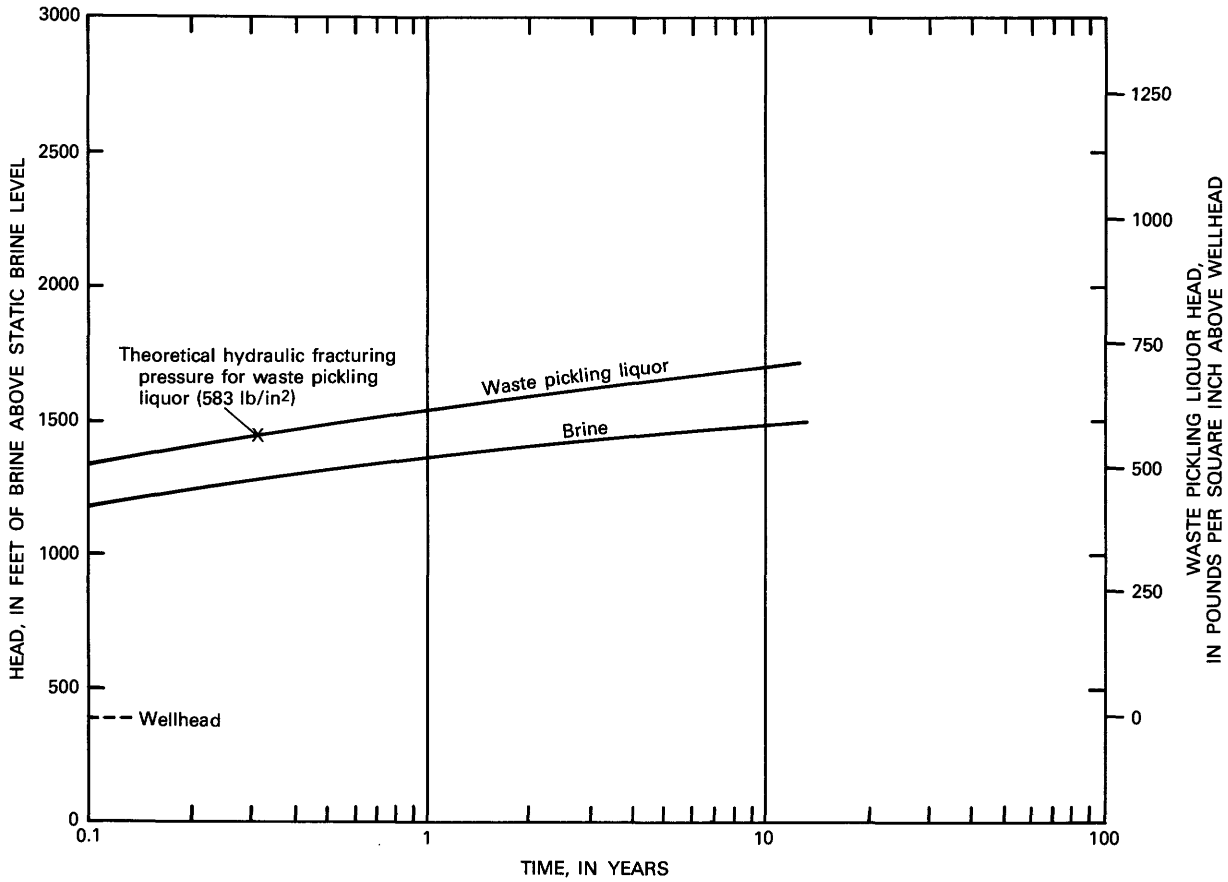

FIGURE 7.—Predicted head buildup in the Lackawanna well (101) at 72,000 gal/d injection rate.

liquor pressure at the wellhead, in pounds per square inch. The lower curve shows the head buildup corresponding to the injection of formation brine. This curve was obtained by adding the discharging well correction of Prickett and Lonnquist (1971, p. 61) to the brine head buildup indicated by the model for the node containing well 101. The upper curve represents the head buildup corresponding to the injection of waste pickle liquor. This curve was obtained by adding a viscosity correction to the data of the lower curve. The authors assumed that the waste pickle liquor would be injected at 20°C and would retain this temperature as it moved outward through the formation. The viscosity of the injected fluid was thus assumed to be 2.22 centistokes and to remain at this value throughout the period of injection. The viscosity correction was made in the same way as was described previously for the adjustment of test data, except that here the viscosity of the injected fluid is higher than that of the formation brine. Thus, the resultant heads exceed those that would be recorded for the injection of brine. The equivalent wellhead pressure, for waste pickle liquor only, is shown on the right scale of figure 7.

The viscosity correction of figure 7 may be slightly excessive because the waste pickle liquor would tend to warm toward formation temperature as it moves outward and its viscosity would decrease accordingly. However, the decrease would probably be small because most of the excess head buildup due to the viscosity difference is very close to the injection well, where, after a long period of disposal, the temperature should approach that of the incoming waste.

The theoretical hydraulic fracturing pressure at the wellhead for waste pickle liquor (583 lb/in^2) for the disposal unit is indicated in figure 7. During waste pickle liquor injection at a uniform rate of 50 gal/min, this pressure would be reached after approximately 100 days of operation. However, if the liquor were injected intermittently at 150 gal/min, the hydraulic fracture pressure would be attained during each daily cycle of operation and, on the basis of results of freshwater injection at rates

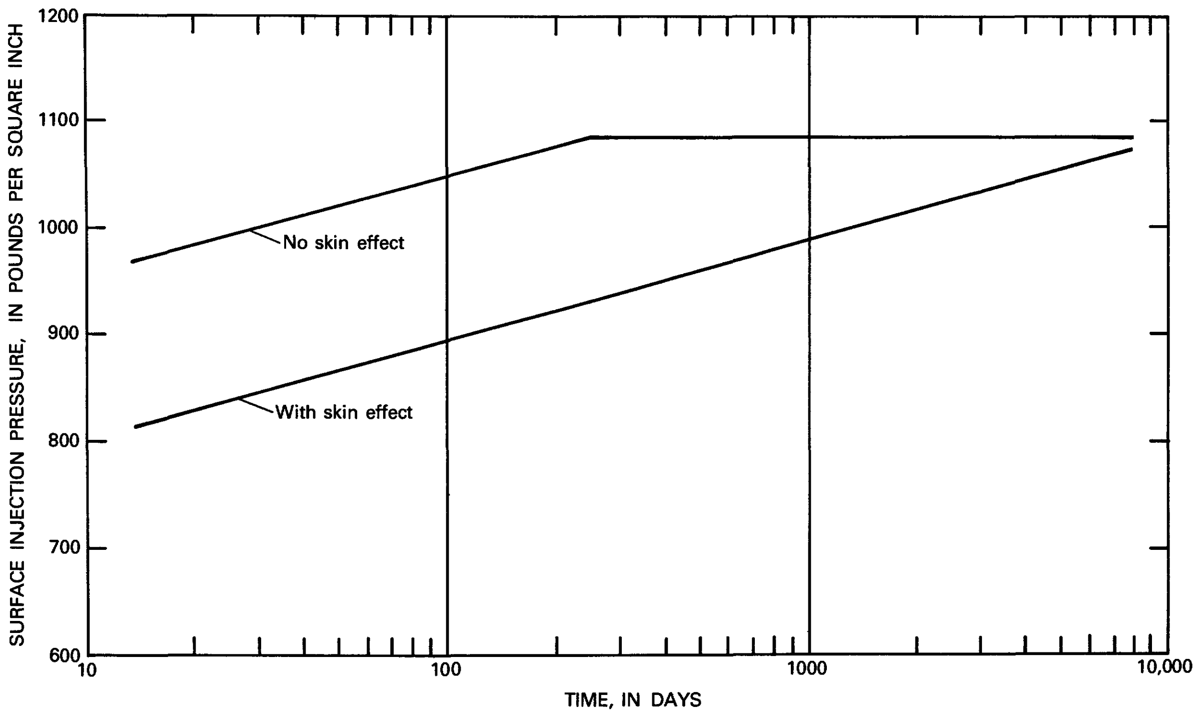

FIGURE 8.—Predicted head buildup in the Lackawanna well (101) at 93,600 gal/d injection rate (modified from AIDS, Inc., 1968, fig. 2).

higher than 150 gal/min, hydraulic fracturing would occur. (See section, "Hydraulic Fracturing.") The head increase in the well during injection under conditions of repeated hydraulic fracturing is difficult to predict; however, the average head during any 24-hour period, including both injection and recovery, might still approximately follow the trend indicated in figure 7.

AIDS, Inc. (1968), predicted the injection pressures shown in figure 8. The pressure increases that they predicted for brine are considerably higher than those predicted in the model analysis, even when allowance was made for the higher injection rate (65 gal/min), which they assumed would be used. Figure 8 is discussed further in the next section.

Figures 9–11 show head buildup for varying periods of time. The head indicated for the injection well on each map includes the correction for the higher viscosity of waste pickle liquor but no adjustment for the effects of hydraulic fracturing. The head contours within the formation in figures 9–11 would not be affected by hydraulic fracturing. The contours shown in figures 9–11 are of interest in that they indicate the potential for upward leakage of formation brine through abandoned oil and gas wells. In figure 11, which represents 10.8 years of injection, the head buildup is sufficient to cause brine heads in such abandoned wells to reach land surface within a radius of about 4 mi of the injection well and, perhaps, to contaminate freshwater aquifers and surface-water bodies within this radius. Freshwater aquifers beyond the 4-mi radius might also be contaminated wherever the increased brine head is sufficient to cause upward flow into them through the abandoned wells.

The results indicated in figures 9–11 depend on the values of hydraulic conductivity and storage coefficient used in the model. Because of the uncertainty of these values, the results must be treated as approximate. The model predicts head increases in the disposal unit but does not have the resolution to predict directions and rates of movement of waste pickle liquor. In the modeling analysis, a simple radial pattern of movement away from the well was assumed for the liquor. This should be approximately true close to the well. Ultimately, however, the flow pattern would be influenced by distribution of the permeability and by regional movement of the brine, if such movement exists. Kazmann (1974) notes that an injectant of higher density than that of the receiving fluid should move to the base of the formation and will generally move downdip.

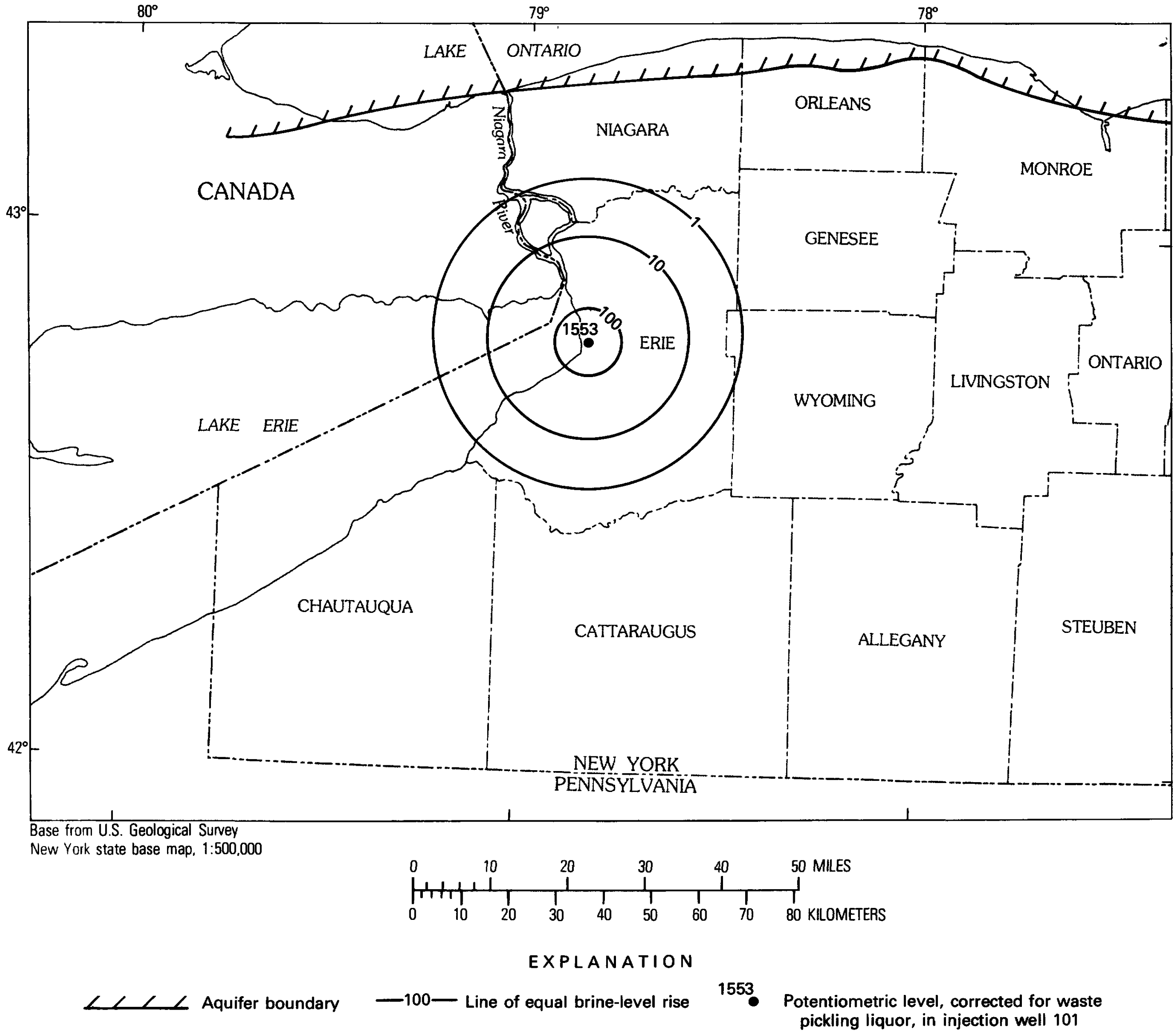

FIGURE 9.—Predicted areal head buildup, in feet of brine above static brine level, after 396 days injection at 72,000 gal/d.

HYDRAULIC FRACTURING

The mechanics of hydraulic fracturing were discussed by Hubbert and Willis (1972) in a revised version of their 1957 publication on the orientation of induced fractures. Hydraulic fracturing in rocks penetrated by a wellbore can be induced by injection pressures. The injection pressure required to induce fracturing depends on the character of the rock and the state of the stress underground. Hubbert and Willis concluded (1972, p. 257) that

1. The state of stress underground * * * depends upon tectonic conditions * * * . 2. Hydraulically induced fractures should be formed approximately perpendicular to the least principal stress * * * . 3. Ruptured or breakdown pressures are affected by * * * preexisting regional stresses, by the hole geometry including any preexisting fissures, and by the penetrating quality of the fluid. 4. Minimum injection pressures depend solely upon the magnitude of the least principal regional stress and are not affected by the hole geometry or the penetrating quality of the fluid. In tectonically relaxed areas, the fractures should be vertical and should be formed with injection pressures less than the total overburden pressure. In tectonically compressed areas, provided the deformation is not too great, the fractures should be horizontal and should require injection pressures equal to, or greater than, the total overburden pressures.

The freshwater injection test involved a maximum wellhead pressure of 1,180 lb/in^2 during the 400-gal/min rate of injection. In the analysis of the injection test AIDS, Inc. (1968), stated:

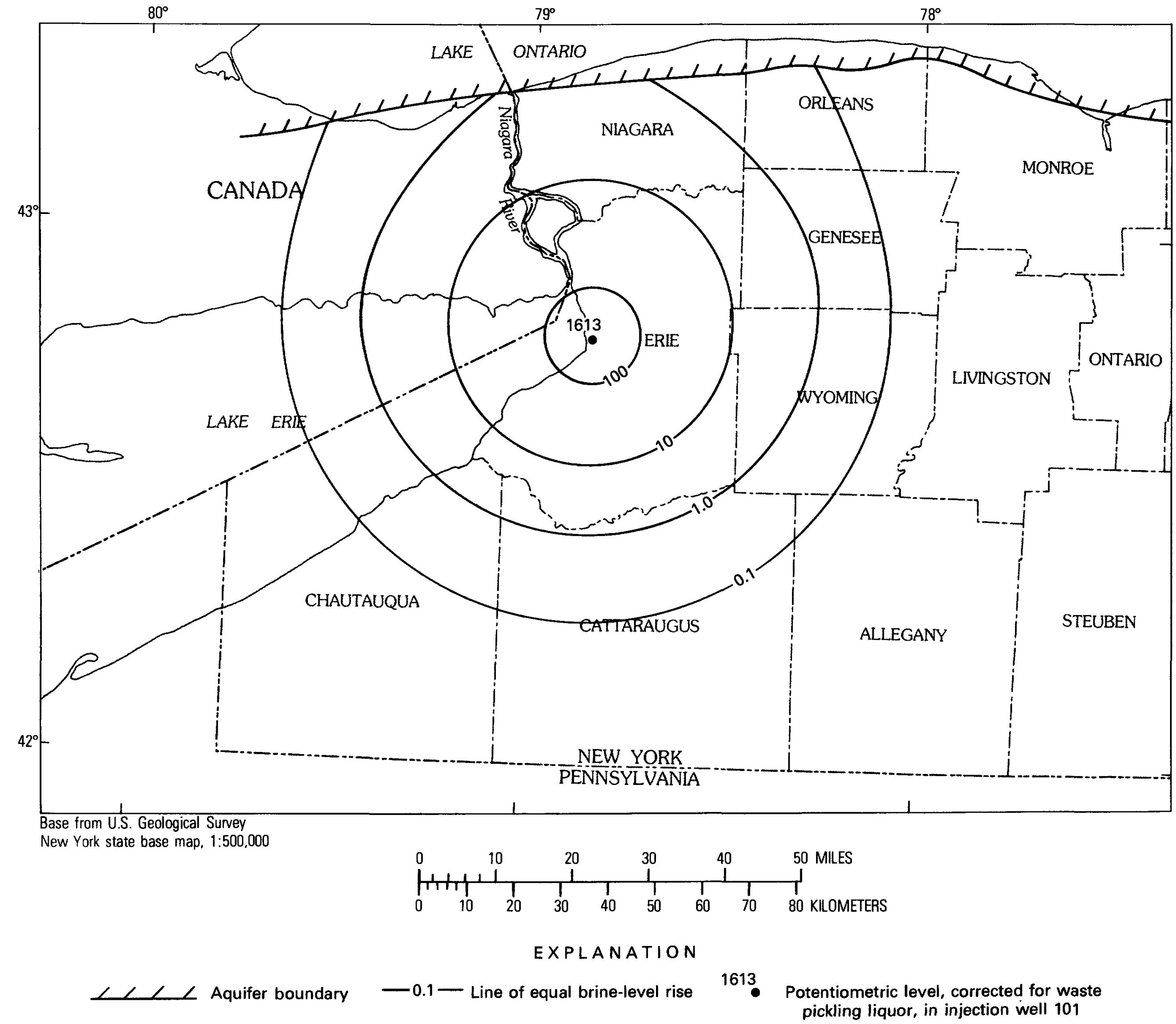

FIGURE 10.—Predicted areal head buildup, in feet of brine above static brine level, after 2.4 years injection at 72,000 gal/d.

During the sequences of pumping tests, a slight hysteresis in the injection pressures occurred when the injection rates were decreased. The reason for the slightly lower injection pressures which resulted on the decreasing rate cycle is attributable to the presence of a negative skin effect around the well bore. This negative skin effect was caused by an improvement in permeability around the well bore resulting from the highest injection rate.

As noted earlier, the disposal unit was probably hydraulically fractured during the test. The "negative skin effect" probably is the fracturing effect. The probable fracturing creates a special problem in the verification and predictive capabilities of the mathematical model. The two critical questions are (1) at what wellhead pressure was the disposal unit fractured, and (2) does fracturing cause a localized permanent increase in permeability? For example, did the fractures remain open adjacent to the borehole after injection stopped? Oil-field-fracturing methods use propping agents (sand or other spherical particles) to keep the fractures propped open.

Because of the possibility of hydraulic fracturing while injecting freshwater at the injection well, the authors attempted to determine (1) at what injection pressure fracturing occurred, (2) the increase

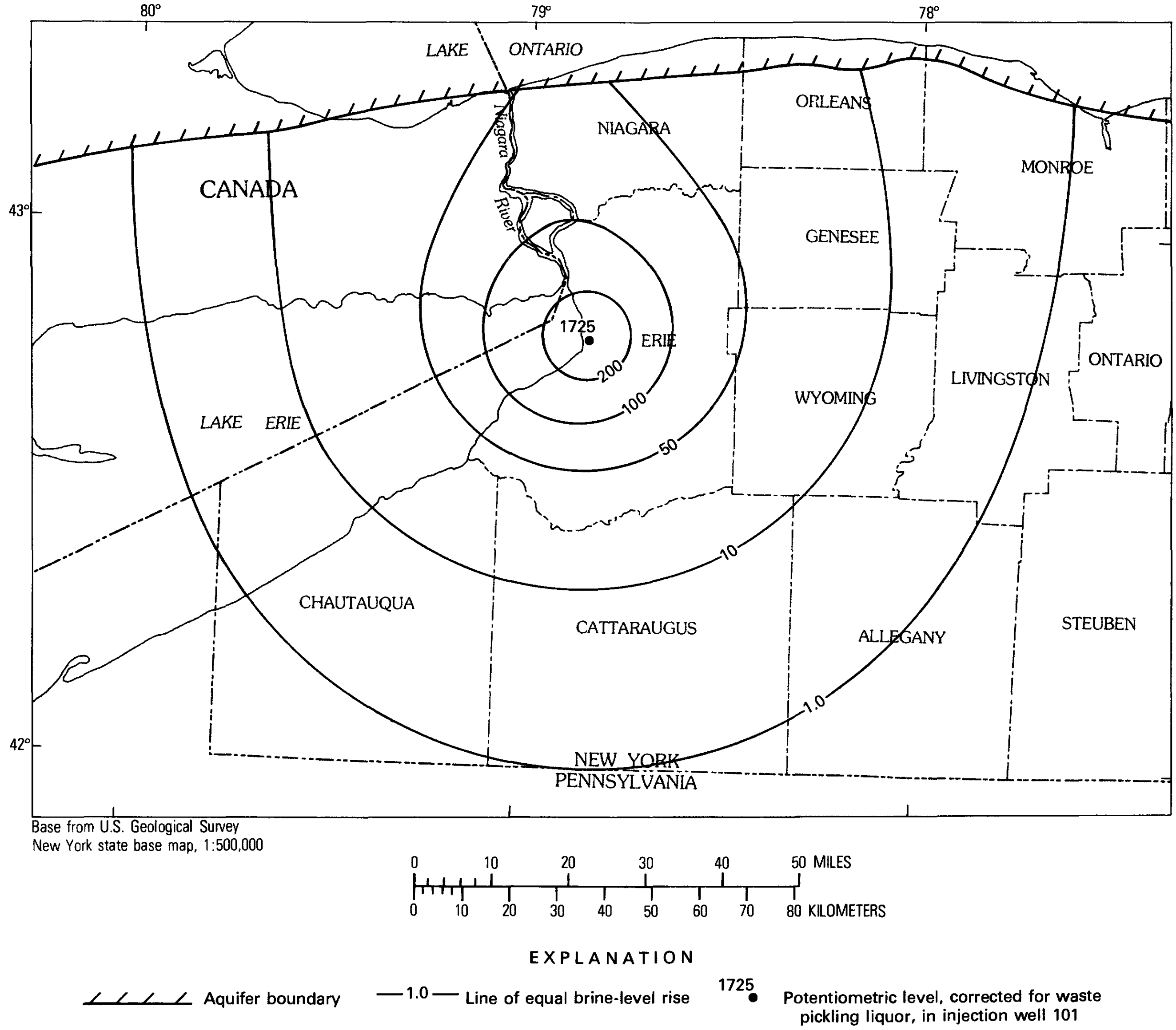

FIGURE 11.—Predicted areal head buildup, in feet of brine above static brine level, after 10.8 years injection at 72,000 gal/d.

in permeability or effective well diameter that resulted, and (3) whether the increase in effective well diameter persisted. AIDS, Inc. (1968), claimed an increased permeability when injection pressure at the wellhead reached about 1,090 lb/in^2. AIDS attributed the increase to a "negative skin effect," which is an alteration in permeability of the borehole wall caused by drilling and completion operations. Whether or not this effect is caused by hydraulic fracturing is not clear.

To evaluate the freshwater injection-test data, wellhead pressures reported by AIDS, Inc. (1968), were plotted against time for the first five injection stages (fig. 12). The injection stages were run with brief shutdowns (of 1 to 4 h) between stages. The fourth injection stage (300 gal/min) could not be maintained because of pump inadequacies, so its curve is useless for any further analysis. The fifth stage was run with a higher capacity pump than the other stages. No explanation is given for the steady pressure-rate curve after about 200 min.

From the same data, bottom-hole pressures, corrected for the injection of freshwater into the disposal unit, were calculated and plotted against time on a semilog graph (fig. 13). After about 230 min of the first stage, the brine in the casing had been displaced by the freshwater. It is assumed that the borehole remained full of freshwater during subse-

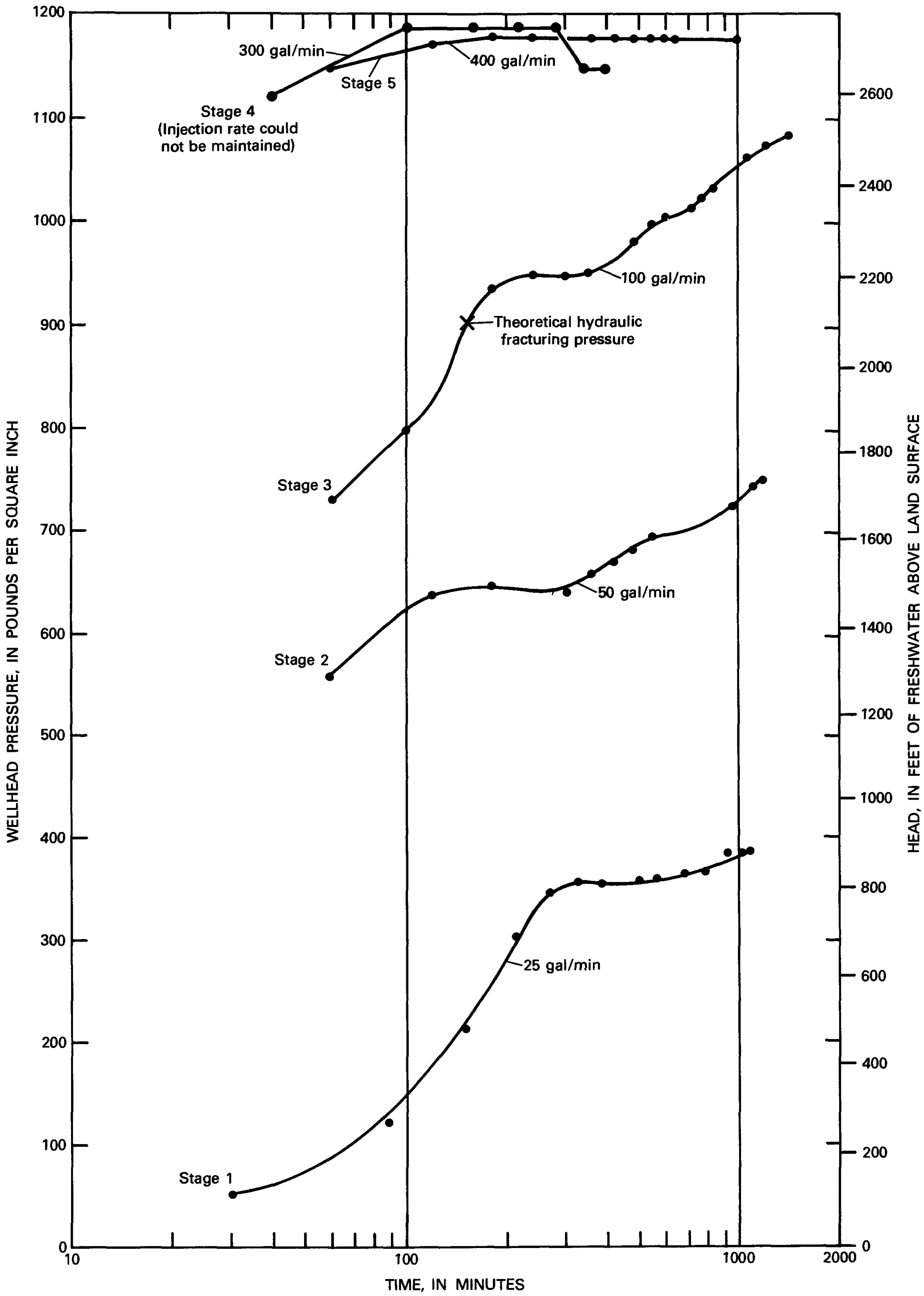

FIGURE 12.—Relation of wellhead pressure to time in various stages of well 101 injection test.

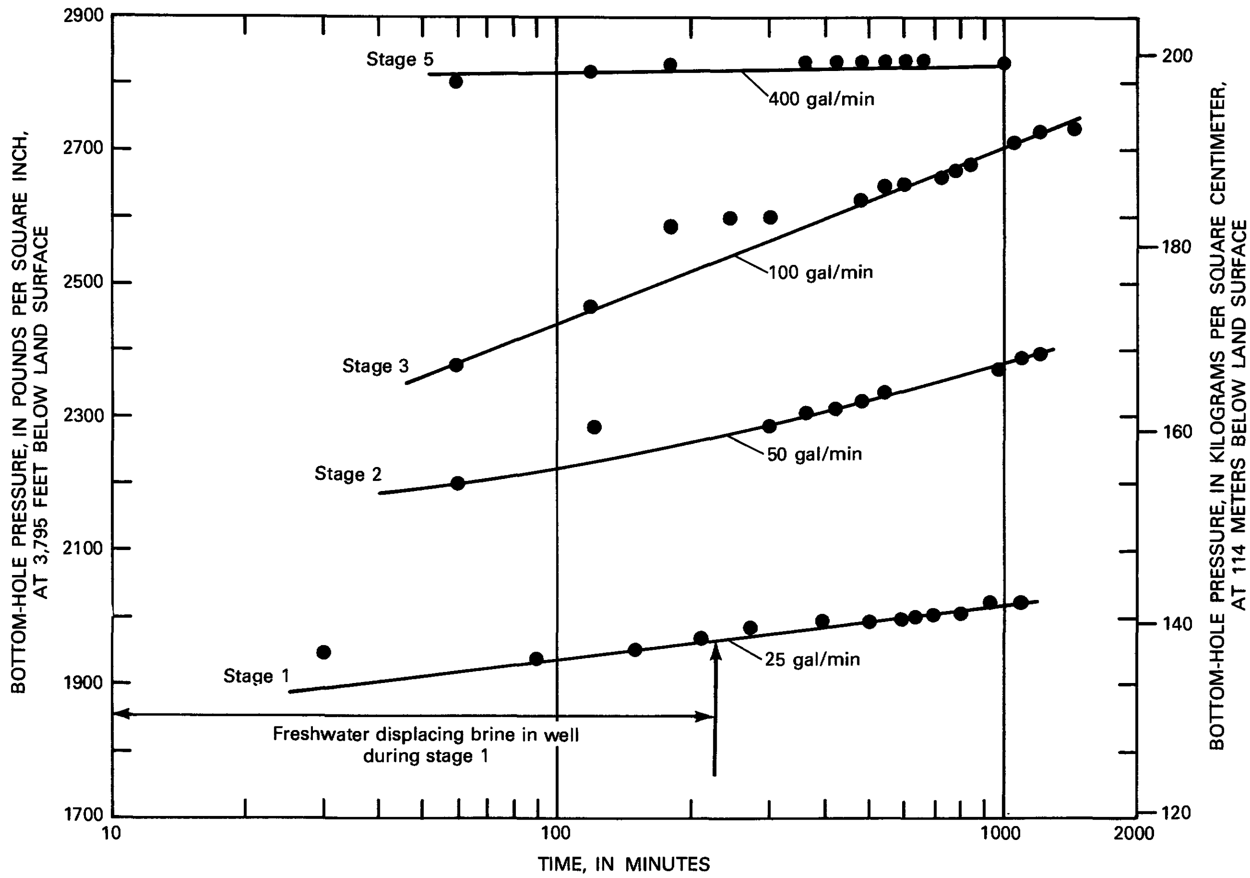

FIGURE 13.—Relation of bottom-hole pressure to time in various stages of well 101 injection test.

quent noninjection periods. The semilog plots should be straight-line curves for a "normal" hydraulic response. In figure 13, all the plots are fairly straight. The plot of the first stage (25 gal/min) resulted in a smooth curve in figure 13, as compared with the first-stage plot of wellhead pressure in figure 12. The 100-gal/min plot shows a prominent "break" in the slope at about the 2,600-lb/in^2 bottom-hole pressure level. The observed wellhead pressure was about 950 lb/in^2 at this time (fig. 12).

One method of estimating whether hydraulic fracturing has occurred during injection is to plot injection pressure against injection rate, as has been done in figure 14. Injection pressure is bottom-hole pressure minus formation-brine pressure at 3,795 ft, the first intake zone. Intersection of the curves shows that fracturing probably occurred in the 950- to 1,000-lb/in^2 range of wellhead pressure, or during the third injection stage (100 gal/min), or later. No breakdown pressure is obvious during stage 3 (fig. 12), which suggests that existing fractures were opened rather than new fractures formed.

The most likely instantaneous shut-in pressure (lower horizontal curve projected back to zero injection rate in fig. 14) is estimated to be 920 lb/in^2. This pressure is the sum of the effective earth stress normal to the fracture plane and the cohesive forces at the fracture tip (Sun and Mongan, 1974). If the cohesive forces can be neglected and vertical joints are assumed to be opened, then 920 lb/in^2 is equivalent to the effective earth stress in the horizontal direction.

Hubbert and Willis (1972) present a means of estimating the minimum bottom-hole fracture pressure of rocks in a tectonically relaxed geologic environment. The Lackawanna area is considered herein to be in such an environment, on the basis of the injection-test data, even though the Clarendon-Linden thrust fault indicates a tectonically compressed area. Hubbert and Willis state (1972, p. 251) that "under conditions of incipient normal faulting, the least principal stress, σ_A, will be horizontal and will have a value of approximately one-third the effective overburden pressure, σ_Z"; therefore,

$$\sigma_A = (S_Z - P)/3,$$

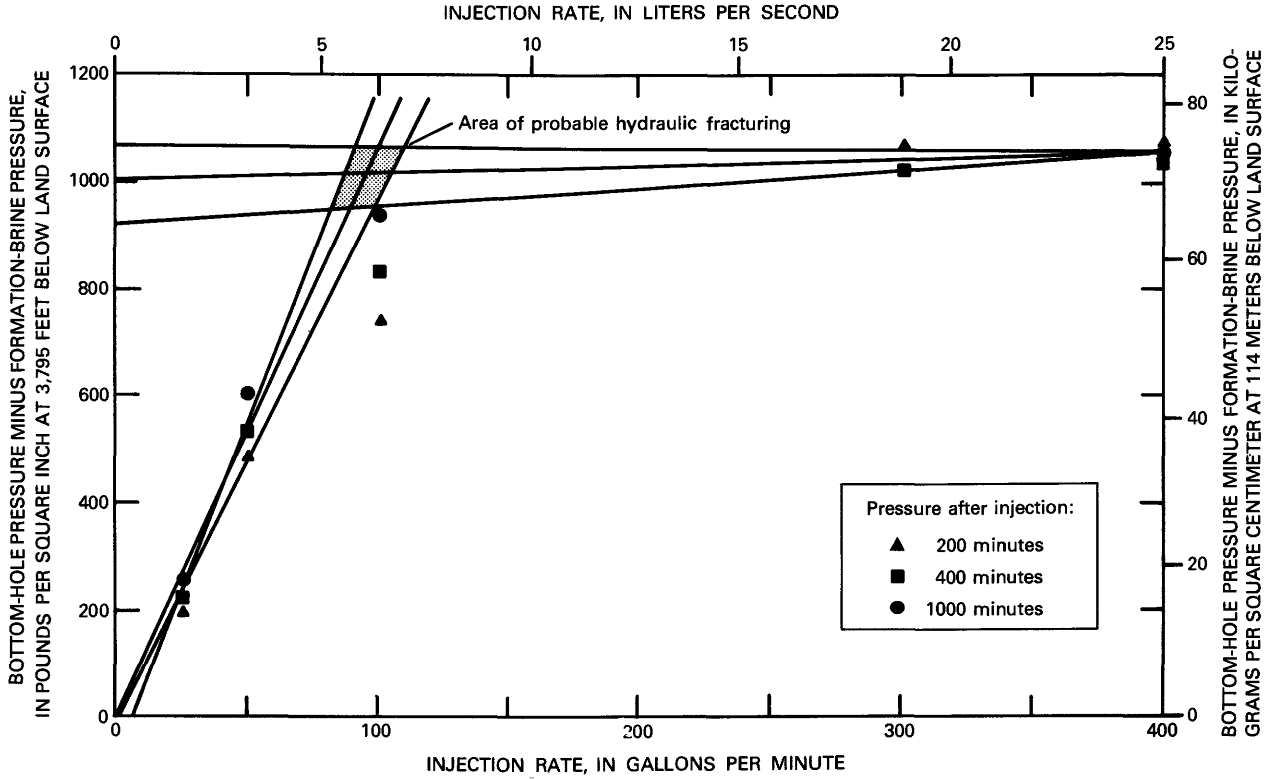

Figure 14.—Bottom-hole pressure versus injection rate in well 101.

where S_Z is the total vertical stress, and P is the fluid pressure in the formation.

On the basis of a 0.0976-lb/in³ density of the rocks, the overburden pressure gradient at the Lackawanna site is estimated to be 1.17 (lb/in²)/ft. Therefore, at the depth of the first permeable zone (3,795 ft), the overburden pressure, S_Z, = 3,795 × 1.17 = 4,440 lb/in². The formation fluid (density 0.0432 lb/in³) pressure under static-level conditions (380 ft) is $P = (3{,}795 - 380) \times [1.1969 \times 0.4331 \text{ (ft/in}^2\text{)/ft]}$ or 1,769 lb/in². Thus, the effective horizontal earth stress is

$$\sigma_A \simeq (4{,}440 - 1{,}769)/3 \text{ or } \sigma_A = 890 \text{ lb/in}^2,$$

which is close to the estimated instantaneous shut-in pressure of 920 lb/in² obtained from figure 14.

The minimum hydraulic fracturing pressure, P_i, at 3,795 ft in the injection well, equal to the effective horizontal earth stress, σ_A, plus the formation fluid pressure, P, is

$$P_i = 890 + 1{,}769 = 2{,}659 \text{ lb/in}^2.$$

If the injectant is freshwater, then the wellhead pressure (Whp) that will cause hydraulic fracturing, exclusive of pressure loss due to friction in the casing, is

$$\text{Whp} + [3{,}795 \text{ ft} \times 0.4331 \text{ (lb/in}^2\text{)/ft}] = 2{,}659 \text{ lb/in}^2$$

or

$$\text{Whp} = 1{,}015 \text{ lb/in}^2,$$

which is close to the estimated wellhead hydraulic fracturing pressure noted in figure 14. Heavier waste pickle liquor at 0.547 (lb/in²)/ft would have a wellhead fracturing pressure of 583 lb/in². Brine at 0.514 (lb/in²)/ft would cause fracturing at 693 lb/in² wellhead pressure.

In summary, the disposal unit apparently was hydraulically fractured during the test, probably by about 950 lb/in² injection pressure, but almost assuredly by 1,000 lb/in² pressure, and, according to Hubbert and Willis (1972, p. 239), vertical fractures would occur under these pressure conditions. If the area is under tectonic compression, fracturing would have occurred only with injection pressures exceeding the overburden pressure, S_Z, of 4,400 lb/in².

EFFECTS ON INJECTION OPERATIONS

Hydraulic fracturing is possibly of more importance in the operations of the injection well than in predictive effects. In rocks of low permeability, such as those in the Cambrian, hydraulic fracturing may be the only feasible means of injecting fluids. On the negative side, the fracturing may cause leaks out of the disposal zone. In particular, fracturing may occur at undetermined places, and the ensuing movement of injectant is indeterminate. Months or years may go by without detection of the leak. Ultimately, the wastes may show up at the surface or in freshwater aquifers.

Existing joints or fractures may be extended by hydraulic fracturing. Hubbert and Willis (1972, p. 249) state that under the proper applied pressure, a fracture once started can be extended provided the pressure "can be transmitted to the leading edge" of the fracture. They also state, "* * * in general, two types of possible down-the-hole pressure behavior need [occur] during fracturing treatment * * *. In one case, the breakdown pressure might be substantially higher than the injection pressure * * *. In the second case, there is no distinct pressure breakdown during the treatment, indicating that the pressure required to start the fracture is less than, or equal to, the injection pressure."

LEAKY CONFINING BED

In addition to the possibility of hydraulic fracturing while freshwater was injected, there also was, and is, the possibility of leakage through confining beds. Formations having extremely low permeability, either primary or secondary, can transmit fluids under induced pressure. A common occurrence in ground-water development is the transmittal of substantial quantities of water from one aquifer to another through semipermeable beds when either aquifer's pressure is reduced by pumping. Conversely, under injection conditions, ground water can move in the opposite direction through the semipermeable beds. The net effect on pressure levels is to reduce the rate of head decline or drawdown in the cone of influence during pumping and to reduce the rate of head buildup during recharge or injection.

In long-term operations, a leaky confining bed may be of more significance than hydraulic fracturing. It may be that both vertical and horizontal fracturing occur only in the receiving formation and that, relative to vertical fracturing, horizontal fracturing extends only a short distance. Thus, hydraulic fracturing generally may affect only the local movement of the injectant. A confining bed, however, may "leak" as far away as suitable pressure gradients occur.

Interpretation of test data for leaky confining beds requires data obtained in observation wells in either the receiving or confining formation. In the former case, the water-pressure level would indicate whether the formation is responding to the expected conditions; for example, water levels less than the predicted increase imply water loss through leaky confining beds or fractures.

In addition to leaky confining beds, which commonly occur to some degree, lateral "boundary" conditions eventually control the injection rate and (or) head buildup. An aquifer system may pinch out laterally or change facies to less permeable rock or cemented faults, and thus reduce the limits of fluid movement. Conversely, an aquifer may thicken laterally or increase in permeability, such as in a highly permeable fault zone, and thus increase its capacity to transmit fluid.

EFFECTS OF POTENTIAL INJECTION AT OTHER SITES

GEOLOGIC LIMITS

Injection of wastes into the Cambrian unit in western New York would be controlled by the geologic characteristics. The unit varies in thickness, lithology, structure, and depth below land surface.

Figure 4 shows areal variations in thickness of the disposal unit. The unit thins to the north and is absent near the Lake Ontario shoreline. To the south, it thickens considerably and occurs at an increasingly deeper level (fig. 3).

Although the Potsdam Sandstone is primarily sandstone and the Theresa Formation is primarily dolomite, both formations contain sandstone and dolomite throughout much of the region. In some wells, in fact, the contact between the two units is difficult to determine from the lithology, which is gradational between the units. Fundamentally, the Potsdam is a basal arkosic sandstone that grades upward into alternating beds of dolomite and sandstone in the thickest parts of the unit. Where the dolomite beds dominate, transition to the Theresa is assumed. Sandstone beds of the Theresa are extensive in some localities, and an upper sand bed is fairly consistent in the region. The Theresa grades upward into the Little Falls Dolomite. In the northern part of the region, the upper beds of the Theresa, the Little Falls Dolomite, and the Beekmantown Group have been removed by erosion (fig. 3). The Little Falls and the overlying Beekmantown Group are primarily dolomite. Both units occur only in the southern part of the region.

Evidence of faulting within the Cambrian unit is known for only one area—the Clarendon-Linden fault zone (fig. 2). Minor faulting may occur elsewhere in the region in association with gentle folds.

Movement along the Clarendon-Linden fault may have taken place in 1971 during nearby well-injection operations in north-central Wyoming County (Sykes and others, 1972). A maximum 1.5-magnitude (Richter scale) earthquake occurred among a "swarm" of seismic events recorded from a recently emplaced seismograph (one of eight in the Attica area) after initiation and development of fracturing in a new solution-mining operation well 0.9 mi from the nearest seismograph. The seismic events occurred at 700 to 1,700 lb/in^2 injection pressures in the 3,200-ft well (J. B. Fletcher and others, written commun., 1977). The possibility of injection-induced earthquakes makes it very important to consider the relation of faulting to the environment of a proposed well-injection system.

The Cambrian disposal unit is everywhere overlain by carbonates of the Black River and Trenton Groups. The carbonates are considered to be dense and massive, which restricts vertical movement of fluids. However, carbonates are readily dissolved by acid. The Knox unconformity occurs below the confining layer (fig. 3), and the underlying zone is known in some areas to be quite porous and permeable. Hence, lateral migration at the contact of the confining layer is a likelihood and accounts for part of the permeability of the disposal unit.

MODEL SIMULATION

The model and method of analysis used herein can be used to simulate other proposed injection wells in western New York. A site selected at a nodal point (fig. 4) to represent the immediate surrounding area would simulate the proposed well. A nodal point at or close to a model boundary would not be usable, however. The injection rate and well characteristics would be simulated by the computer program, and the relation of pressure heads to length of injection time both at the well and in the surrounding area could be predicted. If the proposed well is near an existing or another proposed injection well, the effects of combined injection can also be simulated.

The assumed model values of permeability, transmissivity, and storage coefficient can readily be changed anywhere on the model. Where new data become available, or when observations of hydraulic effects become known, proper value adjustments can be made. As more data become available, the factor most likely to be changed in the model is permeability. Reliable data on permeability may be obtained from drill-stem or pumping tests on new test holes.

MONITORING DISPOSAL OPERATIONS

PURPOSE

As a result of a few experiences with well failures, leakage of waste, and rupture of rock, most States now require monitoring of disposal-well systems. Such monitoring generally includes effects within the well system and sometimes effects within the aquifer system. Effects within the well system are the easiest to monitor and provide the earliest indication of possible problems. Safe disposal of waste in injection wells depends largely on proper well design and construction based on adequate geologic and hydrologic information and upon proper operation and monitoring of the injection-well system.

COMPARISON OF ACTUAL WITH PREDICTED HYDRAULIC EFFECTS

Monitoring of a disposal-well system by pressure gages on the disposal well and observation well(s) open to the disposal formation is useful to determine whether predictions concerning pressure buildup in the aquifer system and the well itself are correct. Variations from predictions indicate (1) plugging of the face of the borehole, (2) a need for revising the estimated aquifer values, or (3) unexpected effects on the well system, which may forewarn of the potential hazards that may develop. For example, if pressure buildup in the well approaches a preset safety limit, the system can be shut down before mechanical failure occurs. Or, if the built-up pressure is much greater than predicted, the operation of a well or proposed additional wells in the area of influence may have to be curtailed to prevent fracturing in the confining layer.

MOVEMENT OF WASTES

Movement of wastes away from the disposal well is of great concern. Monitoring this movement is desirable, but the only way to determine movement is by use of observation wells. Such wells are potential avenues of waste or formation-fluid escape. Generally, more than one well is needed to determine the direction or movement because the disposal formation is rarely homogeneous and has a hydraulic gradient.

Monitoring for waste movement out of the disposal formation is uncommon. However, overlying freshwater aquifers may be monitored for quality changes that may be related to leakage around the casing or through the confining layer.

LEAKAGE OF SYSTEM

Liquid waste may leak from the well, from the disposal formation, or from both. Leakage from the disposal unit is usually less easily detected than leakage from the well.

WELL

Tubing, casing, packer, or cement may fail, and have failed, in disposal-well systems. These failures are easily detected by monitoring the pressure in the well except when the leak is small and becomes progressively larger coincident with formation-pressure buildup. Leakage results in a decrease in the pressure needed to inject a given quantity of waste. Carefully maintained recording gages can alert the operator to leaks from the well and thereby prevent escape of appreciable quantities of injectant. However, leakage in the well system is difficult to determine if the injection rate is uneven. Storage facilities to permit steady injection rates would be desirable to monitor variations in injection pressure. Sealing the bottom of the injection tubing periodically with a packer and pressure-testing the system will reveal leaks in the tubing. Continuous monitoring of the fluid pressure in the annular space between the tubing and the casing will also reveal leaks in the tubing. Leakage around or through the cement seal between the casing and the formation may require an observation well above the confining layer and very close to the injection well unless the leak is large. Cement bond logs may indicate failure of the casing cement.

FORMATION

Leakage from the disposal unit is difficult to detect in overlying formations by observation wells that are sampled periodically. Leakage and flow may occur in a concentrated zone and never intersect an observation well unless the observation well is pumped enough to establish a gradient toward it. A network of passive observation wells to detect all possible leakage directions would not be economically feasible. Detection of leakage in an observation well may occur weeks, months, or even years later unless the well is in the direct flow of the waste. However, one or a few observation wells in overlying freshwater aquifers are sometimes required.

PERMEABILITY CHANGES

A well-designed monitoring system may be useful in determining changes in borehole coupling to the injection zone. The formation adjacent to the borehole may be affected by hydraulic fracturing or by chemical reaction between the injectant and the formation or with the aquifer fluid. The change may be either an increase or a decrease in effective well diameter by changes very close to the borehole. The change in formation permeability is very local and would not affect long-term pressure buildup. If permitted, fracturing of the receiving formation would result in short-term decreases in injection pressure for a constant rate of injection. If bottom hole pressure exceeds the critical pressure, records should indicate the level(s) at which fracturing may have taken place. Theoretically, such fractures close with reduced injection pressure and reopen when pressure is increased to the critical level.

Permanent decreases in pressure may be due either to fractures remaining open or to part of the rock dissolving. A steadily decreasing rate of pressure may indicate a constant rock-dissolving process, which increases effective well diameter. It also may be an indication of a leak in the casing or around the casing that is steadily increasing in size.

Direction of leakage is the prime purpose of monitoring. Accurate pressure-monitoring records and careful appraisal of them may alert the observer to changes that may indicate potential problems involving leakage or movement of wastes or formation fluid to places that will contaminate freshwater.

MODIFICATION OF MODEL

The model can be modified by changing the values originally estimated for the formation characteristics. Monitoring the pressure levels in an injection well and, ideally, in nearby observation wells being affected can aid materially in modifying the formation values used in the model. An increase in effective well diameter resulting from hydraulic fracturing or solution channels can be incorporated into the model to modify predictions. Likewise, if permeability data in confining beds are obtained, modifications to the model can be attempted by simulating a "leaky" confining-bed.

SUMMARY OF DISPOSAL-WELL TEST PROCEDURES

Injection wells require an initial test to determine aquifer characteristics and whether the formation is capable of receiving injectants at a desired rate and chemical content. Formation characteristices can be evaluated by either a pumping test or an injection test. Fluid characteristics are determined by analysis of samples. Both types of tests offer certain advantages and are necessary for data needs.

After drilling and well completion, a pumping test can furnish formation and fluid characteristics that may not be obtainable once injection has been done. For example, injection may involve hydraulic fracturing and a fluid foreign to the formation fluid. The pumping test will provide data on the geologic and hydrologic characteristics of the formation for use in comparison with borehole-log analysis and in subsequent injection tests or injection operations. Where fracturing occurs with injection and changes the effective well diameter, the prefracturing permeability data obtained from a pumping test are invaluable. Pumping tests run after an injection test may not provide natural-formation data because injection of foreign fluid may alter conditions, change the character of the formation fluid for any subsequent withdrawal testing, and may cause irreversible formation changes.

Injection tests are seldom conducted with formation fluid or the proposed waste fluid. Hence, injection-test data are corrected to compensate for differences in fluid characteristics. Variations in temperature, viscosity, and density are critical physical characteristics affecting rate of injection. An ideal testing program would involve extraction of formation fluid for desired rates and periods, confined storage of the fluid, then reinjection of the fluid for desired rates and periods. Temperature differences may be the only variable to correct, although chemical changes in the formation fluid resulting from pressure and temperature changes may occur. Flowmeter surveys during either extraction or injection are valuable to determine permeable zones.

Injection tests involving fluids that differ in chemistry or temperature from the formation fluid will invariably result in chemical reactions in the fluid and possibly with the rock matrix. Laboratory tests simulating field temperatures and pressure conditions can be used to predict ultimate field reactions. Adverse chemical reactions are usually inhibited by injection of a neutral or immiscible fluid to create a buffer zone between the injectant and formation fluids or by pretreatment of the waste.

Chemical reactions that reduce entrance losses by increasing the permeability around the well bore are generally desirable. In some instances, attempts are made to reduce entrance losses by chemical reaction. All man-induced increases are local and generally confined to the immediate well-bore area. The reduced entrance loss lowers the rate of pressure-head buildup in the injection well, but its effect decreases with distance from the well.

A monitoring system is desirable for deep-well disposal of most industrial wastes. Most industries design a monitoring system for disposal wells that will provide warning of excessive pressures, well failure, or malfunction. Such warning may prevent losing a disposal system. Ideally, a monitoring system is needed for public protection to detect contamination of freshwater supplies and other undesired migration of wastes or formation fluid. However, the feasibility and cost of an ideal system are major obstacles.

A monitoring system for public protection would involve a series of observation wells to monitor water quality in freshwater aquifers. In addition, at least one observation well penetrating the disposal formation would be constructed far enough away from the injection well to be beyond the expected radius of the injectant front. Such an observation well could provide data on head buildup in the system without creating an escape route for waste. Data on the head buildup in the system are needed to confirm predicted hydraulic effects.

Observations of pressure head in the disposal well and nearby observation wells after injection is discontinued are valuable, especially where a substantial pressure head was developed during injection. A capped disposal well under a wellhead pressure of several hundred pounds per square inch may require an appreciable length of time to return to preinjection pressure levels.

A reliable estimate of regional hydraulic interference between two or more injection wells is not possible with the available data. The low permeability and low porosity of the disposal formation can cause overlapping of head buildup between the wells. Injection rates on the order of tens of gallons per minute for several years may involve head buildups several miles distant. Thus, great distances between injection wells would seem to be necessary; two or more wells operating on one industrial site may be too close to one another.

CONCLUSIONS

An appraisal of the data for the Lackawanna deep-well disposal site (Bethlehem Steel Corp.) indicates that deep-well disposal of waste pickle liquor into sandstone or fractured dolomite is hydraulically feasible at low rates of injection. Injection rates of 72,000 gal/d (50 gal/min) or less are required in order to prevent excessive head buildup in the well. At this rate, well-head pressure will probably exceed 600 lb/in^2 within 1 year. Hydraulic fracturing will probably occur at less than 600 lb/in^2 in about 100 days. It is estimated that regional head buildup within a 4-mi radius would probably exceed the land surface after 10 years.

Chemical studies (figs. 15–18) indicate that the waste pickle liquor will react with the dolomite and

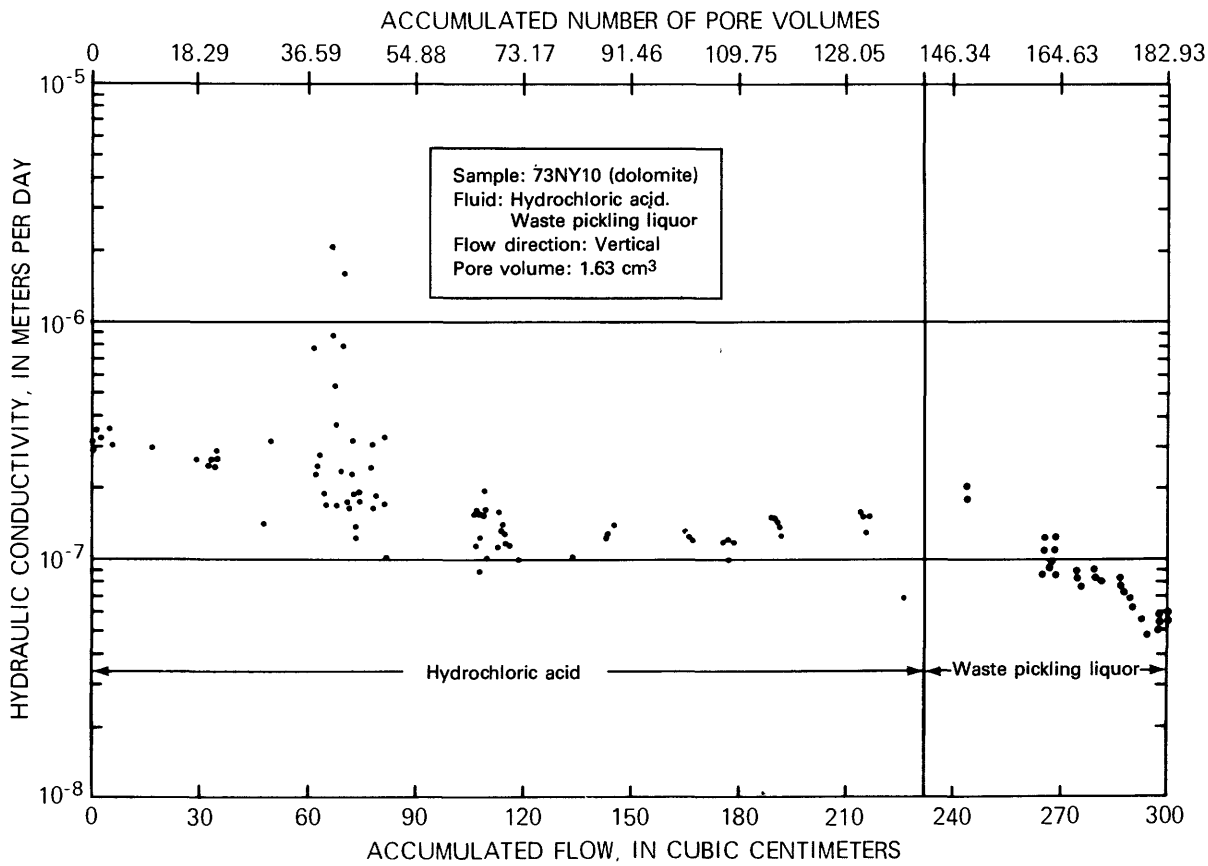

FIGURE 15.—Hydraulic conductivity versus acumulated flow: sample 73NY10 (dolomite).

rapidly reduce its permeability. Fracture and intergranular permeability of the sandstone would transmit the bulk of the waste with little impedance from chemical effects. The extent of generation of carbon dioxide could not be determined. The formation of carbon dioxide in situ would result in formation pressures exceeding those based on hydraulic factors and would be a significant factor. The potential for reduction in the overall formation permeability is indeterminate.

A short-term injection test with brine or waste pickle liquor under operating conditions appears mandatory in order to compare measured field pressures and calculated pressures; also, data on pressure buildup and chemical reaction should be obtained for predictive purposes.

Although little is known of the characteristics of the Potsdam Sandstone and Theresa Formation elsewhere in western New York, deep-well disposal under present field conditions may be physically feasible at very low injection rates in widely separated wells in much of the region. The regional head buildup may limit such wells to a useful life of less than 10 years. The least desirable areas would be along the northern boundary of the formations (fig. 4), where the formations and confining layer are thinner than they are near Lackawanna (fig. 3). To the south, the formations are thicker and deeper. Test drilling would be needed to delineate the characteristics of the formations for any new disposal site.

The model constructed for this regional study can be used to evaluate potential injection well sites. Initially, the proposed injection rate can be used to obtain an estimate of hydraulic effects. After test drilling and aquifer testing have produced the necessary formation data, revised values can be applied to the model to predict hydraulic effects. However, development of more sophisticated models incorporating fluid changes, hydrodynamic dispersion, and energy transport will be available and will make predictions more reliable.

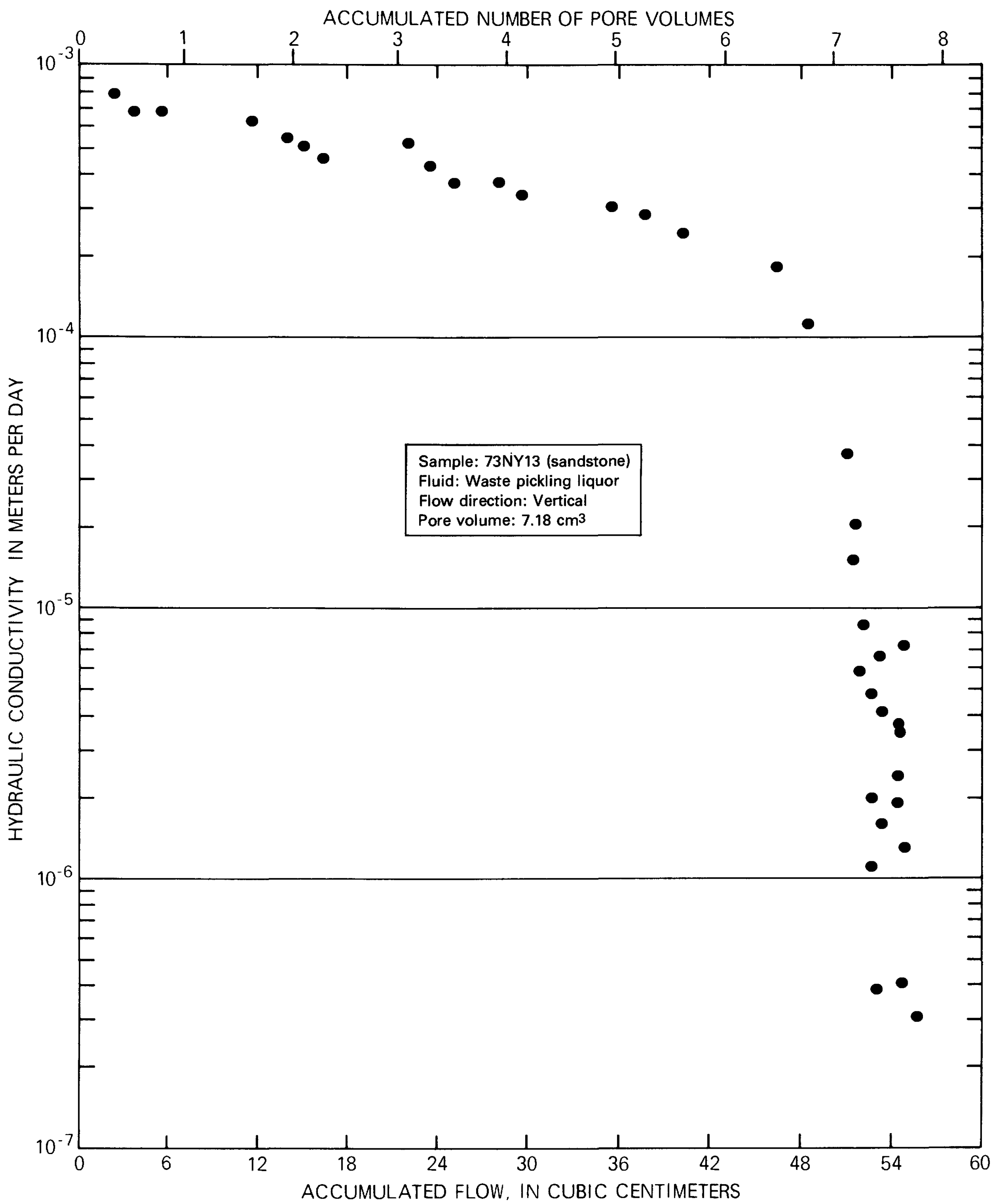

FIGURE 16.—Hydraulic conductivity versus accumulated flow: sample 73NY13 (sandstone).

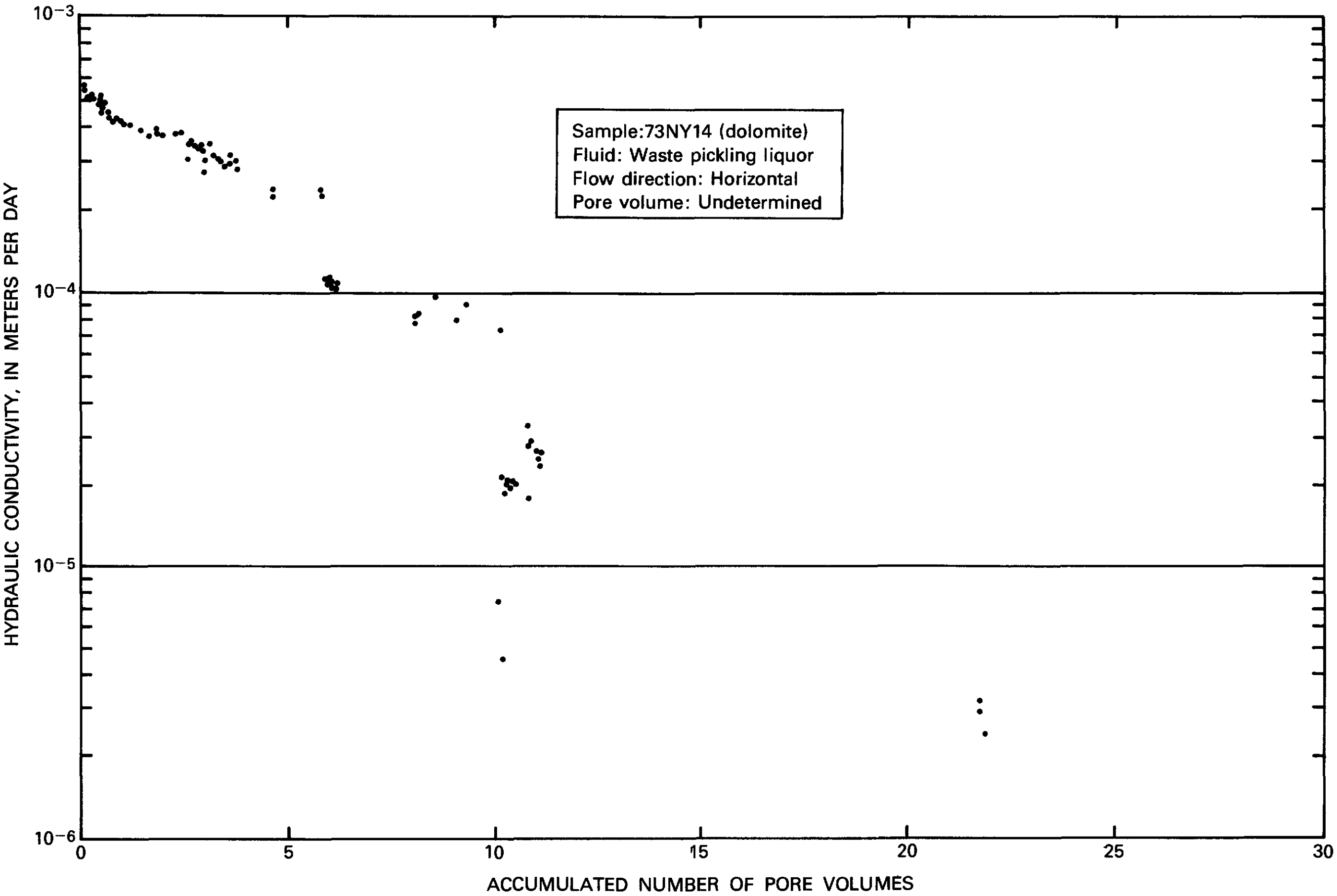

FIGURE 17.—Hydraulic conductivity versus accumulated flow: sample 73NY14 (dolomite).

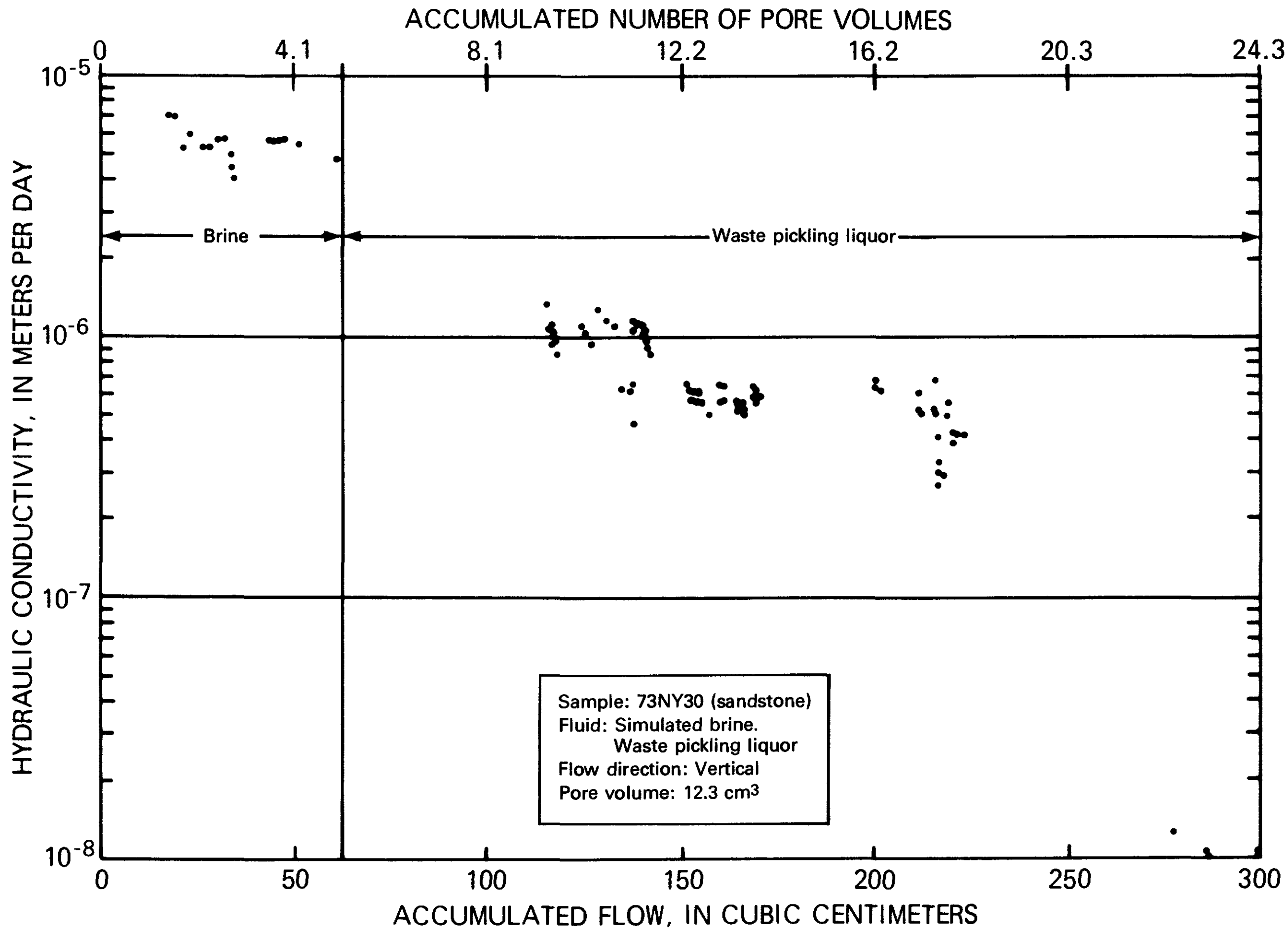

FIGURE 18.—Hydraulic conductivity versus accumulated flow: sample 73NY30 (sandstone).

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