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A REVIEW OF THREE DECADES OF DEEP-WELL INJECTION AND THE PRESENT STATE OF THE ART

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ABSTRACT

Approximately 325 deep-wells are operating throughout the world, about 85 percent of which are in the United States. Over thirty years of observed operation has shown that deep-well systems are feasible and safe for receiving and containing large volumes of toxic and hazardous waste without any deleterious effect upon the quality of usable groundwater reserves and the environment when geologic reservoir parameters are observed and individual well completions are by design rather than random choice. Exceptions to the generally favorable operating history of the systems are several rather spectacular and well publicized failures which have created questions as to the advisability of using the method for waste management. However, in almost all of these cases of failure the outcome was predictable from available reservoir and completion data.

Data show that the chemical and allied industries constitute approximately 50 percent and petroleum refining approximately 20 percent of the users of deep-well systems. Sandstone reservoirs receive about 62 percent of the injected effluent and carbonate reservoirs approximately 34 percent. Rocks of Tertiary age contain about 40 percent of the reservoirs while nearly 53 percent are distributed throughout Paleozoic strata. Depths of injection range from under 300 m to greater than 2440 m, 79 percent of which lie between 300 m and 1830 m. Approximately 21 percent of the wells have been drilled to a depth range of 300 m to 600 m.

Improvement of material, equipment, and well design have permitted the handling of corrosive, toxic and hazardous liquids with relative ease and safety. Equipment monitoring has become highly sophisticated and dependable, but reservoir monitoring still needs to be refined.

Despite stringent regulations by governmental agencies and local public opposition to well construction, deep-well systems remain the most economical method for handling large volumes of hard to treat liquid waste. Construction and operating regulations are becoming more strict and legal aspects of deep-well injection are still in the developmental stage.

INTRODUCTION

The prolific worldwide expansion of industrial complexes during the past thirty years has brought into acute focus the chronic dilemma that has plagued industry since the beginning of the industrial revolution -- the disposal of its generated waste. The time is here when industry and the general population must exist symbiotically and each must recognize the problems and the needs of the other.

One system which has been used effectively under favorable geologic conditions is deep-well injection. This is a modification of the system of disposing of oil field brine by injection into subsurface reservoirs which has been used successfully for over 60 years. This unique method for managing hard to treat and unwanted industrial plant liquid effluent probably was first used successfully over an extended period of time by the Sohio Petroleum Co. refinery at Latonia in the State of Kentucky beginning in 1941 (refs. 1-2). Since that time, because of economic considerations and the basic simplicity of operation the number of operating wells worldwide now is estimated to be about 325. The review is based principally upon the North American experience which, it is believed, may relate to any similar geologic condition wherever it may exist. This is intended to be as comprehensive as the format will permit and to show the strength and weakness of deep-well injection as an effective system for hazardous waste management.

It must be emphasized that deep-well injection systems do not offer the ultimate solution to the problems of industrial waste management in all situations, but when used in areas where they are feasible and when operated within the limits established by the host reservoirs these systems are powerful tools to be used by industry.

GEOLOGIC SUITABILITY

As a background data review, because they are too often ignored during feasibility studies and construction, an outline of the basic geologic requirements for an area feasible for injection and the optimum conditions desired for a host reservoir are shown.

The area must have a sedimentary section; at least part of which is a salaquifer and it must be one of low seismic risk. More specifically, the host reservoir and as large an area as possible surrounding the proposed well site (ref. 3) should have the following characteristics:

1) Uniformity
2) Large areal extent
3) Substantial thickness
4) High porosity and permeability
5) Low pressure
6) Salaquifer
7) Separated from fresh water horizons

8) Adequate overlying and underlying aquicludes
9) No inadequately plugged wells or escape routes near the injection wells
10) Compatibility between reservoir and injected wastes

These conditions are relative, and definitive figures may be established only when specific volumes and injection rates have been determined for a given system at a given location. However, each of these reservoir conditions must be met by any injection system or that system will not be successful either for the controlled injection of waste or for the protection of potable groundwater in the area of injection.

With the available operating histories of numerous deep-well systems, it is time to examine the past performance of these operating systems to observe the present status and to determine what the future role of these systems in the scheme of industrial waste management is to be.

OPERATING SYSTEMS

Industrial and/or municipal deep-well systems have been operating in Canada, France, the Federal Republic of Germany, the German Democratic Republic, Japan, Mexico, Taiwan, the U.S.A., and the U.S.S.R. with varying degrees of success for many years.

This injection of industrial waste is being made into rocks of all types of lithologies, all geologic ages, and at a wide range of depths. Tables 1, 2 and 3 (ref. 4) show these divisions determined from wells operating in the United States.

TABLE 1
Percentage of lithologic types of host reservoirs from 269 wells

Lithology	Reservoir Percentage
Sand and sandstone	62.1
Limestone and dolomites	33.8
Evaporites	3.0
Shale	0.7
Schist and gneiss	0.4

TABLE 2
Percentage of host reservoirs by geologic age from 269 wells

System	Reservoir Percentage
Tertiary (undifferentiated)	39.4
Cretaceous	7.0
Jurassic	0.0
Triassic	0.4
Permian	10.4
Pennsylvanian (Upper Carboniferous)	2.6

TABLE 2 (CONTD)
Percentage of host reservoirs by geologic age from 269 wells

System	Reservoir Percentage
Mississippian (Lower Carboniferous)	1.9
Devonian	11.9
Silurian	2.9
Ordovician	8.2
Cambrian	14.9
Precambrian	0.4

TABLE 3
Percentage of wells injecting at various depths from 262 wells

Depth (m)	Well Percentage
0 - 305	8
305 - 610	21
610 - 915	13
915 - 1220	13
1220 - 1525	15
1525 - 1830	17
1830 - 2135	7
2135 - 2440	5
2440+	1

It is estimated from the well data reviewed which was related to wells outside the United States that these percentages will not change appreciably when all the operating and planned wells worldwide are considered statistically.

TABLE 4
Percentage of distribution of injection wells related to the industry using the system from 268 wells (ref. 4)

SIC* and Industry	Percentage Well Use
Mining (9.3%)	
10 Metal mining	0.7
12 Coal	0.4
13 Oil and gas extraction	6.4
14 Non-metallic mining	1.9
Manufacturing (80.6%)	
20 Food	2.2
26 Paper	1.1
28 Chemical and allied products	48.9
29 Petroleum refining	19.0
32 Stone and concrete	0.4
33 Primary metals	5.9
34 Fabricated metals	1.1
35 Machinery - except electronics	0.4
36 Electronics	0.4
38 Photographics	1.1

TABLE 4 (CONTD)

Percentage of distribution of injection wells related to the industry using the system from 268 wells (ref. 4)

SIC* and Industry	Percentage Well Use
Transportation, Gas and Sanitary Services (9.8%)	
47 Transportation service	0.4
49 Sanitary service	8.6
50 Wholesale trade - durable	0.4
55 Auto dealers and service	0.4
Other (0.4%)	
72 Personal service	0.4

* - Standard Industrial Classification

As a group, the performance of these systems has been exceptionally good. In 1972, these systems accounted for 0.08% of the total waste discharge of U. S. industry which represented an injection volume of 114 000 m^3 per day or approximately 42 million m^3 per year (ref. 5). Once these systems are operating the user, because of the extremely favorable economics may often inject fluids which could easily be treated on the surface and returned to the hydrologic cycle by discharge into surface streams.

OPERATING SYSTEM FAILURES

Despite the overall favorable performance of deep-well systems, there have been a few rather spectacular failures. Thus far no permanent environmental damage has been identified.

The cause of failures in the systems are of three basic types: 1) An inadequate feasibility study prior to drilling or ignoring unfavorable aspects of an adequate report, which includes the 10 basic reservoir criteria outlined in the introduction, 2) Poor completion and/or operating techniques, and 3) Incompatibility of injected fluids with formation fluids. The first two causes for failure are of the greatest concern and usually remain as a source of problems throughout the life of the system. The third cause, although often serious, may usually be remedied by preinjection treatment and eliminated as a serious problem source. Cursory reviews of some of the more notable problem wells in the U. S. follow:

Rocky Mountain Arsenal, Colorado

Injection was made into 21 m of open hole in highly fractured Precambrian gneiss at a depth of 3671 m. Between March 1962 and February 1966, a volume of 625 593 m^3 was injected at an average rate of 13 dm^3/s and 3.4 MPa. After 7 weeks of injection, an earthquake of magnitude 1.5 was recorded. From April 24, 1962 through

August 1967, 1514 earthquakes were recorded, all correlating closely with injection schedules. The use of the well was discontinued and seismic conditions approached those prior to injection (ref. 6). This situation may have been predictable by in-depth feasibility studies, but this cannot be certain.

Erie, Pennsylvania

Injection was into the Bass Island Dolomite and the Mount Simon sandstone in a system composed of 3 wells. During the life of the system 4.3/hm^3 were injected. On April 14, 1968, the casing and tubing were lifted out of the well bore because of failure of the underground equipment. Sulphite liquors backflowed to the surface at the rate of 8.7 dm^3/s and flowed directly into Lake Erie. After correcting the problem, the system was never returned to full use and was abandoned during the latter part of 1972. The backflow of sulphite liquors had a temporary degrading effect upon the environment (ref. 6). This situation could have been prevented by different completion methods and an effective monitoring system.

Marshall, Illinois

Injection was into Devonian Dolomite at a depth of approximately 732 m, at a rate of 3.0 dm^3/s and a pressure of 558 kPa; overall a very successful operation until Secureloy sections in the casing were dissolved by caustic waste, resulting in the loss of the well. The loss of this well can be attributed directly to the completion method used. Secureloy sections should never have been used in the casing especially where exposed to an acid or caustic environment. This may have been prevented by setting the injection tubing on a packer and filling the annulus between the casing and tubing with an inhibiting fluid. The loss of the well did not contribute to any degredation of potable groundwater aquifers or other aspects of the environment.

Wilmington, North Carolina

Injection began in early 1968 into a salaquifer of sand, silt, clay and limestone with head pressure of 262 kPa at a depth of 259 m to 312 m and at a rate of 13 dm^3/s. The permissible injection pressure was 103.4 kPa. Surface sands to a depth of 23 m represented the only fresh water aquifers. Within 14 months the head pressure in the salaquifer was 1.3 MPa and permission was granted by the North Carolina Department of Natural Resources for two of the monitor wells to be used as emergency injection wells. Pressure monitoring during this time indicated upward leakage into shallow aquifers. Leakage also had been noted earlier in shallower monitor wells. An attempt was made to salvage the system in January 1977 by drilling a new injection well; however, it was concluded that deep-well injection was not feasible in that location and the system was abandoned in November 1972 in favor of a conventional waste treatment facility (ref. 7).

The outcome of this system probably could have been accurately predicted with an adequate feasibility study and should never have been constructed.

The four examples are illustrative of the types of problems which have been encountered with deep-well systems. There are others which may be cited, but they involve the same basic problems. On balance, when designed and used properly, the systems are safe and have an important role in the waste management scheme. In a report entitled Hazardous Waste Disposal Methods: Major Problems With Their Use by the Comptroller General of the United States (ref. 8) and dated November 19, 1980, it was recommended that the Administrator, EPA:

"Identify additional areas of the county suitable for deep-well disposal of hazardous wastes (EPA - designated Class I wells) and, when appropriate, encourage industry to use deep-well disposal as a hazardous waste disposal alternative."

COMPLETION AND OPERATING TECHNIQUES

Material

During the past thirty years cementing material and completion hardware has improved considerably. Many corrosive resistant alloys have been developed and many types of plastics suitable for injection tubing or tubing lining are available which allow highly corrosive, toxic and hazardous liquids to be handled with relative ease and safety. Logging and testing equipment are more sophisticated and more dependable thus aiding in more smoothly operating systems.

Design

Industrial waste injection well design has evolved from the status of wells designed and completed as "oil wells" and converted to the injection of liquid industrial waste to unique systems designed to handle specific waste types to be injected at a range of specific rates and pressures.

MONITORING

The monitoring of some aspects of deep-well injection is well developed and highly sophisticated. This is especially true when applied to the surface treatment installation and the injection well of a deep-well system. Continuous monitoring can be maintained to determine equipment malfunction with monitor equipment programed for automatic shutdown, remote alarm, automatic switching to standby equipment or whatever additional action is required.

Reservoir monitoring has not reached the point of sophistication developed with equipment monitoring (ref. 9). A reservoir monitor well may detect waste passage within a given aquifer, but often a single monitor well cannot confirm the escape of waste or vertical fluid movement by direct observation, but must rely upon interpretation of collected data. However, a systematically planned monitor well network can often help detect adverse fluid movement in sufficient time to limit any damage to a minimum. In conjunction with a monitor well system, it is often advantageous to use radioactive tracers to establish the existence of suspected breaches in the integrity of the reservoir. There is need for research in the area of reservoir monitoring. This is a field in which there has been very little advancement since the beginning.

OPERATIONAL ECONOMICS

Investigations by Wright (ref. 10) in 1969, showed the economic advantages of deep-well systems over other methods of industrial waste disposal. Tables 5 and 6 show costs for the year 1969 in the Great Lakes (GL), Mid-Continent (MC), and Gulf Coast (GC) areas. Although the exact dollar figures are no longer valid, the relationship between items has remained at a relatively consistent ratio. With the application of an acceptable average yearly inflation factor, the figures presented in Tables 5 and 6 should closely approximate present costs.

TABLE 5

Economic comparison of deep-well systems and surface treatment (U.S. - $)

Plant & Area	Capital: Well System	Capital: Surface Treatment	Operating Cost/Year: Well System	Operating Cost/Year: Surface Treatment	Yearly Savings Well System
A-MC	225 000	500 000	20 000	100 000	80 000
B-GC	300 000	140 000	52 000	178 000	126 000
C-GL	468 000	1 250 000	62 000	395 000	333 000
D-GL	270 000	1 500 000*	100 000	600 000	500 000

* - Incineration, system cost estimated

TABLE 6

Deep-well facility average operating cost

Area	Wells*	Cumulative Injection/Well (million m^3)	Injection/Well/Year (million m^3)	Yearly Cost (U.S. - $/$m^3$
GL	10	1.95	.236	0.111
MC	5	.77	.258	0.042
GC	14	1.07	.261	0.309

* - Available data

OPERATING REGULATIONS

The Safe Drinking Water Act (SDWA) of 1974 is the primary law protecting the surface and groundwater in the United States (ref. 11). Under the SWDA, the Congress of the U. S. recognizes the primary responsibility of the States to regulate injection wells for the protection of actual or potential potable groundwater sources. The Act requires the Environmental Protection Agency (EPA) to list those States that need Underground Injection Control (UIC) programs and to set minimum national requirements for effective State programs. EPA can grant funds to individual States for the development of such programs and must approve the adequacy of the programs proposed by the States. Some States are already carrying out effective injection control programs, and the law stipulates that EPA requirements should not unnecessarily disrupt State programs already being effectively enforced. Where a State fails to carry out a UIC program; however, EPA must carry out such a program itself.

EPA's requirements for State UIC programs were issued during 1980. The regulations would set different requirements for five different types of wells: deep waste disposal wells (or those below usable aquifers), wells related to oil and gas production, wells for special processes such as solution mining and geothermal energy, shallow wells (or those injecting into usable aquifers) for hazardous waste disposal, and all others.

The regulatory requirements for hazardous waste disposal wells injecting into a drinking water source are in abeyance at this time until the Hazardous Waste Management Regulations are promulgated in final form. Other high-risk types of wells will have to be authorized by permits before they may be operated. Lower-risk wells may be operated without individual permits under general rules. The Congress specifically instructed EPA to develop regulations that would not interfere with oil and gas production unless necessary to protect underground sources of drinking water.

Where needed, UIC permits will impose both technological and administrative requirements on disposal well operators. These requirements will cover construction, operation, monitoring, reporting, special corrective actions, well abandonment, government access to operator records and facilities, and provisions for permit review, modification, and termination.

Many States in the U. S. were ahead of the EPA in formulating regulations controlling the construction and operation of underground injection systems. Others exercised their perrogatives and developed regulations before having their jurisdictional rights usurped by a federal agency. Many good sets of State regulations have been developed, varying widely in their requirements; but all are designed to permit controlled underground injection with adequate protection for groundwater aquifers.

LEGAL ASPECTS OF INJECTION

The detail involved with this subject is far too greatly involved to attempt a discussion of the potential legal problems confronting an operator of a waste injection system. Trelease (ref. 12) defines 5 areas of responsibility in which an operator of an injection system might be subject to legal action:

1) Nuisance
2) Negligence
3) Liability without fault

4) Trespass

5) Conditional fault

Walker and Cox,(ref. 13) and Trelease (ref. 12) agree that the legal aspects of deep-well injection are in the developmental stage and that there is no general acceptance of these systems as an environmentally sound method of waste management. However, Trelease postulates that the courts will consider deep-well injection a desirable activity, not to be discouraged, not to be stopped; but requiring all industries using the method to bear all costs when there is a malfunction and damage or injury occurs.

CONCLUSIONS

Operating experience over three decades has shown that deep-well systems may be operated safely and successfully when the site for the well is properly chosen and the system designed for the waste stream to be injected.

The storage capacity of potential host salaquifers, although considerable in some areas, is finite and should be treated as a natural resource. The high success ratio in the use of deep-well systems does not preclude caution in the use of this method nor does it relieve the operators of the responsibility of close monitoring of injected fluid, the reservoir, and the meticulous maintenance of the well facilities.

Well design and construction is a multidiscipline effort and each discipline needed should be represented on the design team to ensure a successful venture.

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