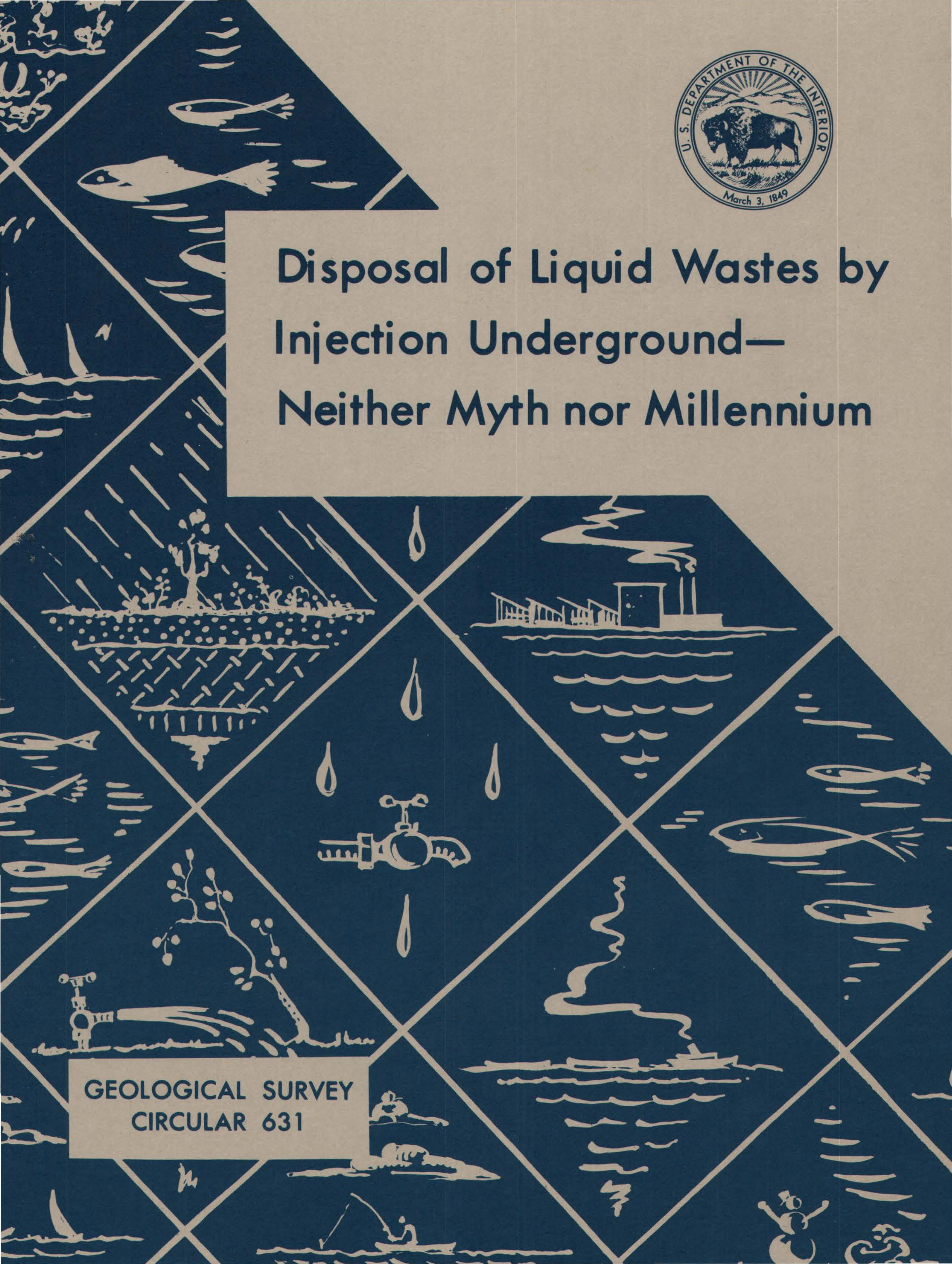

Disposal of Liquid Wastes by Injection Underground— Neither Myth nor Millennium

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By Arthur M. Piper

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By Arthur M. Piper[1]

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ABSTRACT

Injecting liquid wastes deep underground is an attractive but not necessarily practical means for disposing of them. For decades, impressive volumes of unwanted oil-field brine have been injected, currently about 10,000 acre-feet yearly. Recently, liquid industrial wastes are being injected in ever-increasing quantity. Dimensions of industrial injection wells range widely but the approximate medians are: depth, 2,660 feet; thickness of injection zone, 185 feet; injection rate, 135 gallons per minute; wellhead injection pressure, 185 pounds per square inch.

Effects of deep injection are complex and not all are understood clearly. In a responsible society, injection cannot be allowed to put wastes out of mind. Injection is no more than storage—for all time in the case of the most intractable wastes—in underground space of which little is attainable in some areas and which is exhaustible in most areas.

Liquid wastes range widely in character and concentration—some are incompatible one with another or with materials of the prospective injection zone; some which are reactive or chemically unstable would require pretreatment or could not be injected. Standards by which to categorize the wastes are urgently desirable.

To the end that injection may be planned effectively and administered in orderly fashion, there is proposed an immediate and comprehensive canvass of all the United States to outline injection provinces and zones according to their capacities to accept waste. Much of the information needed to this end is at hand. Such a canvass would consider (1) natural zones of groundwater circulation, from rapid to stagnant, (2) regional hydrodynamics, (3) safe injection pressures, and (4) geochemical aspects. In regard to safe pressure, definitive criteria would be sought by which to avoid recurrence of earthquake swarms such as seem to have been triggered by injection at the Rocky Mountain Arsenal well near Denver, Colo.

Three of the 50 States—Missouri, Ohio, and Texas—have statutes specifically to regulate injection of industrial wastes. Other States impose widely diverse constraints under unlike administrative authorities. Few, if any, State agencies currently have the staff skills, centralized authority, and financial resources to assure rights of the general public to be spared harm from, and to reap the benefit of accrued experience with, deep injection. Some new, fully competent institutional arrangement appears to be essential, under a unified policy. As required, such an institution might have en echelon components, respectively having nationwide, single State or major province, subprovince, or local jurisdiction.

GENERAL PERSPECTIVE

In perpetually increasing amount and ever more diverse kind, mankind produces wastes which, in and near areas of great population density, all but overwhelm the land-surface environment. Thus, it is increasingly urgent that wastes be managed effectively. In this situation, the possibility of injecting liquid wastes deep underground becomes attractive. This paper undertakes to assess the state of injection art, on the basis of published information.

Generally the earliest, and by far the most extensive, disposal of unwanted liquids deep beneath the land surface has been by the petroleum industry, to dispose of the brines that are incidental to the extraction of petroleum. The magnitude of such disposal is impressive—Texas alone has about 20,000 brine-injection wells (Department of Interior, unpub. data,

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1966) and Kansas had issued permits for about 3,000 such wells as of 1960 (Warner, 1965); the volume of brine injected into the ground each year is several billion gallons (in the order of 10,000 acre-feet). The technical experience with brine injection is covered by a voluminous literature, including that of Cleary (1958), Dickey and Andresen (1945), Grandone and Holleyman (1949), Horner (1951), Hubbert and Willis (1957), Joers and Smith (1954), Lynch (1962), Moran and Finklea (1962), and Yuster and Calhoun (1945).

Subsequently, noxious wastes from the chemical industry have been handled in the same manner. Very recently—in an effort fostered in part by clamor to diminish pollution in streams and lakes, and deriving from the experience of the petroleum industry—liquid industrial wastes are being injected deep beneath the land surface in ever-increasing quantity.

No exhaustive, nationwide canvass has been made of existing facilities for injecting industrial wastes underground. However, a considerable, and probably a representative, sample is afforded by the lists of Warner (1967) and the Interstate Oil Compact Commission (1968). The two lists cover 124 waste-injection wells (excluding brine-injection wells) in 18 States; two-thirds of the wells are in three States—Texas (34 wells), Louisiana (25 wells), and Michigan (21 wells). Only three of the listed wells had been recognized as failures, and 104 were in operation as of January 1968. Data on these representative wells summarize as follows:

	Maximum	*Minimum*	*Median*
Depth drilled, feet	12,750	295	2,660
Injection zone:			
Depth to top, feet	11,975	200	2,050
Thickness, feet	2,099	5	185
Injection rate:			
Gross, U.S. gallons per minute	[1]4,300	.15	135
Specific, U.S. gallons per minute per foot of zone thickness	22.6	.006	1.0
Injection pressure:			
Wellhead, pounds per square inch	4,000	[2]0	185
At top of injection zone:			
Pounds per square inch per foot depth[3]	2.1	[2].4	.5
Hydrostatic ratio[4]	4.8	[2]1.0	1.2

[1] In two wells, jointly.
[2] Pressure is "gravity." Values indicated are valid only so long as injection rate is sufficient that the well casing remains filled to the land surface; at a smaller injection rate, wellhead pressure is negative and top-of-zone pressure is less than indicated.
[3] Equal numerically to the so-called geostatic ratio—that is, the ratio of fluid pressure to overburden pressure. Ordinarily, overburden (lithostatic or geostatic) pressure is presumed to increase 1 pound per square inch per foot of depth—that is, the bulk density of the rock and any contained fluid is presumed to be 2.3, average.
[4] The ratio of fluid pressure to the pressure exerted by a column of fresh water extending to land surface.

In its predilection for grossly oversimplifying a problem, and seeking to resolve all variants by a single massive attack, the United States appears to verge on accepting deep injection of wastes as a certain cure for all the ills of water pollution. Uncritical acceptance would be ill advised. It is fostered by a technical and commercial literature which, to a distressing degree, describes capabilities of injection in terms so highly generalized as to be all but meaningless in relation to a specific waste in a particular environment. In part the assessments are projected from misleading or false premises. An instructive example of a misleading premise is quoted below from a commercial source; the same premise appears also in current technical literature.

"The amount of fluid that can be displaced into a disposal zone with broad areal distribution is staggering when standard reservoir formulas are applied. As an example, a disposal zone one hundred feet in thickness with a porosity of 20 percent will hold over 13,000,000,000 gallons of fluid within one mile of the borehole of a disposal well. Some disposal zones known to underlie several States constitute a veritable ocean of space available for waste disposal."

The preceding quotation would imply that total pore space of an injection zone is "available" to be filled by liquid waste. However, in the great majority of such potential injection zones, pore space is filled naturally with brine or another fluid which is, or at least is assumed to be, unusable. Extracting unusable native fluid in a volume equal to that of injectable waste clearly could do no more than relocate a disposal problem. In effect, therefore, within the so-called area of influence of an injection well the volume of waste that can be injected is limited to that achieved by compression of the native fluid and of the injected waste, by compression of the rock matrix of the injection zone, and by dilation (upward elongation) of that zone—all under a practicable and acceptable injection pressure.

So limited, volume of waste injectable is much less than gross pore space within the area of influence—commonly by at least two orders of magnitude—that is, at least 100-fold less.

Involved here is a seeming paradox. In most instances, the injected liquid waste would invade the zone very largely by displacing the native interstitial liquid, with relatively little dispersion of the one liquid into the other. (In regard to little dispersion, see Esmail and Kimbler, 1967.) Thus, the zonal volume invaded would be very nearly the waste volume divided by porosity of the zone, as implied in the preceding quotation. However, if the native interstitial fluid is wholly liquid, the displacement is possible only because of, and sensibly is compensated by, the elastic effects just identified. The same concept applies to multiple injection wells which may interfere one with another, but which have a composite area of influence within which the aggregate displacement compensates.

The area-of-influence concept just outlined is, at best, an approximation that applies only to early and close-in effects of injection. More comprehensively, injection modifies hydrodynamic gradient and accelerates movement of interstitial liquid away from the point, or points, of injection. In time, the accelerated movement may reach an outcrop. In principle, therefore, injection of waste ultimately may be compensated additionally by accelerated discharge of native interstitial fluid at some remote place on the land surface. Here, however, is a dilemma. On the one hand, if the discharged fluid is unusable, no advantage would have been gained and a necessity for disposal would merely have been relocated. On the other hand, if accelerated movement extends into a part of the aquifer system that contains fresh water or a usable fluid, then ultimately the injected waste must invade the fresh-water (or usable-fluid) source. Ordinarily, to abet such invasion would seem foolhardy.

Comprehensive explanation of the hydrodynamics of injection is not here practical. Neither would it nullify the point already made under the area-of-influence concept—namely, the volume of waste that can be injected practically is ordinarily much less than aggregate pore space within the injection zone.

A second common false premise is that strata deformed into a syncline, or downfold, afford an inviolable hydraulic trap—that waste placed in the bottom of a syncline would remain immobile for all time. Movement of interstitial fluid is, of course, determined not by geologic structure but by hydrodynamic gradient. Hydrodynamic gradient may be, and commonly is, virtually independent of geologic structure.

A third and final misleading premise is that experience in brine injection by the petroleum industry translates, in all aspects, to industrial-waste injection. Where the brine is returned to the same stratigraphic zone as that from which it had been extracted (along with petroleum and gas), such return tends commonly to restore, at least partially, the hydrodynamic gradient that had been disturbed by the antecedent extraction—in other words, at least partially to restore the natural equilibrium. Also, part of the native fluid being gas, which is very compressible, return of brine commonly induces relatively little change of hydrodynamic potential.

In certain petroleum-producing areas, however, brine is not returned to the same stratigraphic zone but is injected into another salt-water aquifer—commonly into the shallowest such aquifer, as in much of the Permian basin in Texas and Oklahoma (L. A. Wood, written commun., 1969). Such injection generally involves an all-liquid system rather than the liquid-gas system just summarized. The all-liquid system can accept by injection, over the long term, much the smaller volume under a particular increment of pressure. In this connection, injection of oil-field brine under high pressure, into shallow salt-water aquifers in the Brazos River basin, Texas, is reported to have accelerated the seepage of salt water into streams on the land surface (L. A. Wood, written commun., 1969).

THE ROCKY MOUNTAIN ARSENAL WELL

HYDROLOGIC FEATURES

Complexity and uncertainty of effects that can result from deep injection of liquid waste are shown forcefully by experience with the injection well at the Rocky Mountain Arsenal (Mechem and Garrett, 1963; Polumbus and Associates, 1961; Scopel, 1964). Among existing injection wells this one is unique in that a moderately comprehensive part of its performance record has been published. The well is located about 10 miles northeast of Denver, Colo., in the NW¼NE¼ sec. 26, T. 2 S., R. 67 W. Land surface is 5,187 feet above sea level.

The Arsenal well was drilled March 10 to September 11, 1961, to a depth of 12,045 feet. Casing, tubing, and a liner extend from land surface to 11,975 feet. These are cemented through the regional fresh-water aquifers, which occur from 1,250 to 1,426 feet below land surface. Potentiometric level of these aquifers is about 90 feet below land surface.

The injection zone is fractured gneiss from 11,975 to 12,045 feet below land surface. Natural potentiometric level (fluid level) of the zone was not determined adequately during drilling or before injection began. Subsequent observations are not definitive but suggest that level to be 2,500 to 3,000 feet below land surface (L. A. Wood, written commun., 1969). Thus, at the top of the injection zone, natural hydrostatic ratio would be about 0.80; geostatic ratio, about 0.33.

The injection zone is reported to have accepted "more than" 400 gpm (gallons per minute) under a wellhead pressure of "less than" 2,000 psi (pounds per square inch), when tested initially. From March 1962 to September 1963, and September 1964 to February 1966 waste liquid in an aggregate volume of about 165 million gallons (22 million cubic feet or 500 acre-feet) was injected. Maximum rate of injection was 514 gpm at a wellhead pressure of 1,100 psi; average rate, about 200 gpm at 500 psi. Thus during injection, maximum pressure at the top of the injection zone has been equivalent to a hydrostatic ratio of 1.2 and a geostatic ratio of 0.53; average pressure, equivalent to a hydrostatic ratio of 1.1 and a geostatic ratio of 0.48. The maximum geostatic ratio would be somewhat less than the minimum at which rock formations ordinarily would dilate by so-called hydraulic fracturing (American Petroleum Institute, 1958).

Average injection pressure has been equivalent to a head of about 1,250 feet potentially available to have driven waste into the fresh-water aquifers. That waste could have so escaped, through or around the cemented casings, seems most unlikely. Nonetheless, there is here at issue a general point: if deep injection at other places is to be demonstrably safe, standards for construction of the injection well and facilities may need to be uncommonly meticulous, and so verified by thoroughly documented tests. Also, the injection process will in general need to be monitored and documented rigorously at all stages.

In the Arsenal well, four saline-water aquifers are cased off in the 3,500-foot reach immediately above the injection zone (Scopel, 1964; and Hoeger, 1968). Available hydrodynamic information suggests that regionally these four aquifers, plus the underlying injection zone (which also is naturally saline), may constitute a zone of common hydraulic circulation. If so: (1) From the vicinity of the Arsenal well, in the eastern half of the Denver basin, fluid movement is generally northward, then northeastward or eastward, toward low outcrops of the Dakota Group in eastern Nebraska. (2) In this direction of movement, the composite zone increases notably in transmissibility and becomes a major source of fresh water. (3) Injection at the Arsenal well has placed noxious liquid waste in this same zone.

Assuming that, in the zone of common circulation just described, the 500 acre-feet of injected waste will move with the native liquids, in principle that waste ultimately could reach the areas of outcrop and of fresh-water withdrawal. To do so the waste would have moved a few hundred miles from the Arsenal well, in a time interval of probably several thousand years. Hopefully, over that space and during that time the waste will have been rendered harmless by sorption, dispersion, and degradation (L. A. Wood, written commun., 1969). Thus, an ultimate hazard is conjectural but one would be remiss not to note it (W. W. Rubey, oral commun., 1968). Data for assessing the hazard definitively are neither at hand nor readily obtainable. Here, the general point at issue is that for the most persistently noxious wastes, a responsible society cannot knowingly create even a remote hazard.

THE EARTHQUAKE SWARM

In the seventh week after injection began in the well at the Rocky Mountain Arsenal, a seismograph newly installed by the University of Colorado at its Bergen Park laboratory recorded an earthquake of magnitude 1.5. The date was April 24, 1962. Through August 1967, 1,514 earthquakes were recorded with magnitudes ranging from 0.5 to 5.3. All these were relatively shallow in origin, from a small area about midway between central Denver and the Arsenal well (Major and Simon, 1968). The following table summarizes the record.

In November 1965, near the end of the second period of injection at the Arsenal well, Evans (1966a, b) publicly expressed his view that the earthquake swarm

Denver (Derby) earthquakes, April 1962–August 1967

Period	Number recorded		Percent of total number at magnitude of—					
	Total	Average per month	0.5–0.9	1.0–1.9	2.0–2.9	3.0–3.8	4.0–4.3	5.0–5.3
April 1962–September 1963. Continual injection at Arsenal well.	447	25	15	67	16	2	0.4	0
October 1963–August 1964. No injection.	74	7	11	73	16	0	0	0
September 1964–February 1966. Continual injection.	614	34	0	82	16	18	0	0
March 1966–August 1967. No injection.	[1]380	21	.3	83	14	2	.3	.5

[1] Five additional earthquakes of undetermined magnitude.

just described had been caused by the injections. His conclusion was derived from the seemingly strong correlation between frequency of the earthquakes and volume of injection, month by month. Numerous other investigators have contributed to resolving the injection-earthquake relationships, which recently have been reviewed critically by Healy, Rubey, Griggs, and Raleigh (1968). Present consensus is that the earthquakes are products of a regional stress field of tectonic origin, triggered by the local incremental strain from injection into the Arsenal well. In several aspects, however, the stress-strain relationships in the vicinity of the Arsenal well seem not yet to have been resolved fully.

The injection-triggered earthquake swarm at Denver probably is not unique. Counterparts have been identified tentatively or contingently, but have not been studied intensively, in the Rangely oil field of western Colorado (Healy and others, 1968), also in Texas and Utah (L. C. Pakiser, oral commun., 1968). Criteria have yet to be developed by which such efforts of injection can be anticipated generally.

STATUS OF KNOWLEDGE AND STEPS TO BE TAKEN

Admittedly, injecting liquid wastes deep beneath the land surface is a potential means for alleviating pollution of rivers and lakes. But, by no stretch of the imagination is injection a panacea that can encompass all wastes and resolve all pollution, even if economic limitations should be waived. Limitations on the potentials for practical injection are stringent indeed—physical, chemical, geologic, hydrologic, economic, and institutional (including legal) limitations. A general appraisal of certain principal limitations, and of our state of knowledge concerning them, follows.

CATEGORIES OF WASTE

The very wide range in volume and in concentration and kind of noxious constituents in liquid wastes all but precludes meaningful generalization as to practicality of disposal by deep injection. Uniform and specific criteria are urgently desirable for categorizing wastes in this regard, principally according to type, quantity, and persistence of critical constituents. Such criteria have been proposed recently in one small part of the field of concern, wastes from the nuclear-energy industry (American Institute Chemical Engineers, 1967). Specifically, five categories or classes of radioactive waste would be defined with respect to "maximum permissible" concentration, exposure, and intake as established previously by the International Commission on Radiological Protection. The five classes, and their parallels for industry in general, can be summarized as follows:

> At one extreme, class A wastes would be those whose radionuclide concentration is so low as to justify dispersal without restriction. The parallel from general industry would be those liquid products to which an unnatural property has been imparted, but not to a degree that conceivably would be harmful to human beings, in the food chain, or indiscriminately in the biosphere. An appropriate general standard would be analogous to, and ordinarily close to, the maximum allowable concentrations that numerous public-health agencies have set for various chemical constituents in drinking water. Such limits of concentration are known in the main; they need only to be collated and promulgated through suitable channels. It is highly desirable that the general standard be equally comprehensive the nation over. For certain limits, however, some variation from one region to another would seem appropriate, according to the variable concentration of the particular constituents in local native waters. Vexatious questions would arise in regard to appropriate limits for the almost overwhelming array of new products from the chemical and pharmaceutical industries—for one common example, the very stable insecticide DDT which, along with other chlorinated hydrocarbons, is causing so much concern nowadays.
>
> Class B radioactive wastes would be those whose radionuclide concentration is greater than that of class A wastes, by a factor not greater than 10. The class would have force only in "controlled areas," where personnel would be exposed only during working hours and where suitable safety precautions could be enforced. In the general industrial parallel, an appropriate concentration factor between classes A and B probably would be neither 10, nor uniform among all waste constituents, nor uniform either regionwide or nationwide. Rather, the factor might relate to the acceptability of zoning under which dispersal of the waste would be so controlled as to time or place, or the waste would be so diluted, that the cumulative exposure of human beings to the waste was substantially as though the class A standard was satisfied. In this connection, dilution probably would be acceptable only transiently, until precluded by the ever-greater demand for water of highest purity.
>
> In regard to general industry, liquid products of classes A and B would of course not require disposal underground. However, specific definition of the two classes is desirable to discriminate wastes that, even in the distant future, need not preempt the limited space in which injection will be feasible.
>
> Nuclear-waste class C would be more concentrated than class B by a factor not greater than 10^4. In general it would be amenable to a treatment converting a major fraction to class B or class A, and a minor fraction to class D or class E. In the general parallel the concentration factor between analogs of waste classes B and C commonly would be much less than 10^4, and might relate more to chemical stability of the principal waste constituent than to its concentration. The general class C might comprise those wastes that are produced in volumes exceeding the underground space available for long-term storage but which might either (1) be reduced to a smaller volume or converted to a less concentrated class, or (2) be suitable for injection into the relatively

shallow zone of rapid circulation or the underlying zone of delayed circulation [zones to be described], in which residence time would suffice for disintegration of the noxious constituents. A common example of the first type would be spent pickling acid, which might be neutralized and filtered, and possibly otherwise treated, to yield an effluent of class B or class A. An example of the second type would be septic-tank effluent, that common product of rural and some suburban communities; or, certain unstable products and wastes from organic chemistry.

Nuclear class D wastes would be more concentrated than class C, again by a factor not exceeding 10^4. Alternatively, these would be either stored indefinitely in suitable containers on the land surface, incorporated into a bituminous matrix or into concrete, or reduced to a solid residue. The solid forms of converted waste would be held on the land surface. The general analog of class D might be those wastes which are produced in, or can be reduced to, relatively small volumes; which are relatively stable; and which are of such kind or concentration that on the land surface they would constitute a persistent, but ordinarily a nonlethal, nuisance. Examples among organic substances, would be certain oils and solvents; among inorganic substances, numerous highly soluble salts. Such are the wastes generally suitable for deep injection into the zone of lethargic circulation [to be described] where a residence time of many decades, or even centuries, could be assured and would suffice. Alternatively, analog class D wastes might be incorporated into concrete or otherwise converted to solid form, and retained on the land surface.

Nuclear class E waste is that whose concentration exceeds that of class D—that is, the class C concentration is exceeded by a factor greater than 10^4. It would be stored indefinitely in suitable containers on the land surface unless it can be converted to, or incorporated in, a radiation-stable solid. We must acknowledge, and face up to, the analog of class E in industry—that is, waste of such persistent intractability and concentration that (in the words of de Laguna, 1964) its "future disposition must be known unequivocally and in detail," and it must be excluded from the biosphere for virtually all time. Since absolute immobility cannot be assured underground, the analog class E waste would be unthinkable for injection. Included in the category would be stable substances so highly toxic as to be potentially lethal if dispersed in the biosphere, even at slight concentrations. Certain pesticides and chemical-biological warfare agents are potentially of this general sort.

The writer feels strongly that orderly mangement of liquid wastes by injection deep into the ground will prove elusive until general waste categories such as those just outlined have been defined, in terms of specific concentrations for each of numerous kinds or groups of waste constituents. Magnitude of the limiting concentrations seems less urgent than specific limits drawn so conservatively that the several categories might receive early and virtually universal acceptance. Adequate standards for the categories would be more comprehensive, but inherently no more complex, than those of the nuclear industry. As has been alluded to, drafting such standards would be largely a task of discriminately collating existing knowledge. Principal disciplines involved include chemistry, medicine, and public health.

CHEMICAL AND PHYSICAL ASPECTS

Background

Injection underground would of course put wastes out of sight but, in a responsible society, cannot be allowed to put them out of mind. Injection does not constitute permanent disposal. Rather it detains in storage and commits to such storage—for all time in the case of the most intractable wastes—underground space of which little is attainable in some areas, and which definitely is exhaustible in most areas. These precepts have been stated or implied repeatedly in diverse contexts, by numerous writers.

Wastes underground cannot be managed responsibly in the absence of comprehensive knowledge as to their character and expected history. The responsibility is in part, but only in part, separable into two phases: First, an agency creating wastes must know or determine, and fully disclose to a suitable public institution, the character and amount of wastes committed to underground storage. Second, and conversely, public institutions must know or determine, and maintain a suitable record of, where wastes are dispersed underground (in three dimensions, specifically), what their chemical characters are, and how those characters may change with time. Further, an agency creating and injecting a waste must constrain that waste within the land-surface boundaries of its real property, unless or until custody of the waste passes to a responsible agency, private or public, having wider jurisdiction. The restraints here outlined or implied are strict and in some respects novel. To relax them substantially, however, would disclaim reality.

Raw wastes

Physical and chemical character must be known for each raw waste that is a candidate for injection. Information should be specific as to: (1) Rate of production and anticipated aggregate volume; (2) temperature and thermal stability; (3) viscosity, pH, and density; and (4) concentration and stability of the several entrained, suspended, or dissolved constituents. If dissolved, suspended, or entrained constituents are nuclides, radiometric properties should be known in terms such as specific radioactivity; percentage distribution of the nuclides according to the kinds and energies of their radiations, or according to their half lives; and radioactivity due to key nuclides. (See Nace and others, 1962.) Any of or all these properties may determine whether a particular waste is suitable for injection. Thermal and chemical stability may be especially critical—for example, wastes from the nuclear industry commonly generate heat as they disintegrate or "decay," at rates greater than would dissipate through the rock matrix of an injection zone (Birch, 1958; Skibitzke, 1961). Chemical stability must be considered over not only the short term, but also the long term—possibly indefinitely long—of potential storage underground (injection). In this regard, the very feasibility of injection may hinge on the life of a noxious constituent in relation to predictable residence time of the waste in the particular injection zone. (More will be said concerning this.) Physical stability must be considered likewise—for example, the rate at which a suspension may convert to a gel.

Information such as just outlined is a product of the chemist, physicist, and laboratory technician. Commonly that information is known to the waste-creating agency, but may be considered by the agency to be of concern to it alone. If wastes are to be managed effectively, however, the writer considers such information to be everybody's concern, expressible through a public agency having appropriate responsibility and authority. The authority should include the prerogatives of requiring from the producing agency, and verifying, analytical data on all raw wastes.

Compatibility and interaction

Even though comprehensive, information as to chemical and physical character of a waste does not, of itself, determine suitability for injection. Additional information is required as to compatibility among (1) a particular waste as it might be injected, (2) other wastes with which it might make contact in the injection zone, (3) fluids native to the injection zone, and (4) both mineral and organic (perhaps including bacterial) constituents of the injection-zone matrix. The possibilities of interaction are many and complex. The environment in which interactions might occur is unlike that of the land surface, particularly in respect to temperature and pressure. The pH of waste and native fluid may differ little or much. All these environmental differences influence the kind and rate of potential interactions. Residence time of the waste in the injection zone may be indefinitely long, so that interactions that are slow in rate may be major factors in waste behavior.

The reactions of potential concern are diverse in kind—chemical reaction that results in a precipitate, diminishing pore space of the injection zone; separation of a gel with like effects; flocculation or deflocculation (dispersion) of clay minerals, with an influence on permeability; dissolution of mineral matter from the injection-zone matrix, with or without further reaction; base-exchange and sorption reactions between waste constituents and minerals of the zone matrix; buffer action inhibiting or modifying reaction between other constituents.

Exchange and sorption reactions may involve, not the dominant minerals of the injection-zone matrix, but only minerals which occur in minor quantity—for example, a clay-mineral fraction in a sandstone that is dominantly of quartz. Even so, these reactions may be of far-reaching effect, and even the principal factor in managing a waste.

Compatibility and potential interaction between waste and injection zone have for some years been studied intensively, but largely in general terms, by numerous persons. Much of this effort has been in regard to potential deep injection of radioactive wastes. Warner (1966b) summarizes current knowledge, and undertakes experimental and theoretical analysis.

There is an urgency to proceed soon from general to specific consideration of interactions between potential wastes and injection zones, collating dispersed experience and information now available with future experience that would be assessed systematically. First stages of this effort well might be in conjunction with the canvass of major injection provinces, which will be outlined. The primary disciplines involved would be those of geochemistry and geohydrology.

Pretreatment of wastes

Certain wastes, otherwise incompatible with a potential injection zone, can feasibly be pretreated. Possibly the most common step would be to adjust pH of the waste to the ends of chemical stability and minimum reaction in the injection zone. Conceivably a dilute waste might be concentrated to diminish its volume, where the available injection zone has only small capacity and where compatibility problems would not be worsened by the concentration.

Beyond these highly general considerations, pretreatment seems largely a matter of matching a specific waste to a specific injection zone. Such becomes a task of chemistry and geochemistry, in detail much too diversified for specific treatment here.

CANVASS OF INJECTION PROVINCES

To the end that injection as a means of waste management shall be planned effectively and administered in orderly fashion, there is here proposed a comprehensive canvass of all the United States to discriminate injection provinces according to their diverse potential capacities to accept wastes. Through identification and definition of such provinces, meaningful administration and regulation of injection would be facilitated, according to limitations peculiar to each province. Oversimplified, the alternative would seem to be spot-by-spot consideration under a dilemma of standards either impractically complex if all diversities of "injectability" were served, or generalized to the point of becoming ineffective.

First steps toward defining such injection provinces have been made, under sponsorship of the Atomic Energy Commission—specifically, in summary descriptions of salt deposits and major sedimentary basins over the United States (Griggs, 1958; Pierce and Rich, 1958; Repenning, 1959 and 1960; de Witt, 1960; Love and Hoover, 1960; Colton, 1961; Beikman, 1962; Le Grand, 1962; Sandberg, 1962; and MacLachlan, 1964). Most of these summaries considered only geologic aspects—stratigraphy and structure. In some respects more comprehensive, but in other respects more selective, than the summaries just listed is a review by the American Association of Petroleum Geologists (1964; also Galley, 1968).

A more comprehensive basis for discriminating injection provinces is necessary and, in preliminary scope, can be formulated from information at hand. More definitive classification by subprovinces could follow as data and experience accumulate. Both the preliminary and the ultimate canvass of provinces would involve numerous disciplines, chiefly those of geology (in an all-inclusive sense, including, in particular, geophysics and seismology), geochemistry, and hydrology (including hydrodynamics in particular). The preliminary canvass would assess the following aspects.

ZONES OF CIRCULATION

The manner of waste management underground may range widely indeed. A chemically stable, dilute waste may require only to be injected into, and dispersed thoroughly in, a body of rapidly circulating ground water that is recharged continually or copiously. Alternatively, a biochemically unstable effluent may require only a residence time, within the injection zone, of sufficient duration that disintergration proceeds to completion; dispersion into the native ground water may or may not be desirable and residence time of a few days or weeks may suffice. At another extreme, a persistently intractable or a very concentrated waste may require the longest possible residence time, with or without dispersion into the native water. Thus, freedom of native-water circulation is a primary criterion by which to scale "injectability." In this connection, Nace and others (1962) recognize a functional succession of ground-water zones, generally downward, in which circulation is respectively rapid, delayed, lethargic, and stagnant. The latter two are subzones of the so-called noncyclic zone, which includes a dry subzone also. Over much of the United States, information at hand should suffice for a general description of such zones and their potentials for injection of wastes—specifically, their depth and thickness, lithology, extent and continuity, and transmissibility (and other properties to be considered). The several zones are as follows (adapted from Nace and others, 1962).

Zone of rapid circulation

The zone of rapid circulation extends from land surface downward some tens, or a few hundreds, of feet; the aerated zone and the uppermost part of the saturated zone are included. Here, generally or commonly, the native soil water and ground water are unconfined, fresh, and largely or exclusively of meteoric origin; residence time is from a few hours to a few years; and the environment is oxidizing. Natural discharge from the zone of rapid circulation is the principal source of water sustaining the dry-season flow of streams; thus, injection of chemically stable wastes into it is precluded commonly although not universally, as will be outlined.

Injection of waste into the zone of rapid circulation could be feasible in a quantity so small, and at a site so placed, that the waste would be adequately diluted by dispersion, or stabilized by disintegration, before it could reach a point of discharge to a stream or of withdrawal for use. Feasibility of such injection, therefore, would depend on hydrodynamics of the area involved; hydrodynamic factors would need be established explicitly and monitored adequately.

Most common among wastes injected into the zone of rapid circulation probably is septic-tank effluent, to which reference has been made. Reference has been made also to successful management of certain wastes in this way on the Hanford reservation of the Atomic Energy Commission. Here dispersal of the waste within the zone has been monitored rather intensively, the path of waste travel within the reservation is some 20 miles, and adequate residence time appears to have been assured. Elsewhere, however, indiscriminate injection into the zone has led to the contamination of usable ground waters in numerous scattered areas, as described by Deutsch (1961, 1963, 1965) for Michigan.

Zone of delayed circulation

In the zone of delayed circulation, native ground water is also largely or exclusively of meteoric origin, is generally fresh, and may be unconfined and oxidizing at the shallower depths but commonly is confined and nonoxidizing at the greater depths. The water circulates continually and comparatively freely, but is retarded sufficiently that natural residence time within a given zone is a few to many decades, or even a few centuries. Depth to or through the zone may range from no more than a few hundred feet, in some geologic and geographic situations, to thousands of feet at other places.

The zone of delayed circulation being the principal source of water supplies drawn from the ground, injection of wastes into it is generally not advisable, as in the case of the overlying zone of rapid circulation. However, locally and under suitable monitoring, wastes have been injected successfully, as at the National Reactor Testing Station, Idaho (Jones, 1961a, b; Morris and others, 1965).

Subzone of lethargic flow

The subzone of lethargic flow is the common locus of so-called salaquifers—that is, in that subzone the native liquid is commonly saline. Much of, or even all, the water is of ultimate meteorologic origin, but its residence time in the subzone—in isolation from the normal hydrologic cycle—has been in the order of hundreds or even thousands of years. The very slow movement is considered generally to be hydrodynamic, but possibly in part is by geochemical osmosis. The environment commonly lacks free oxygen. Saline water and lethargic flow may occur within the upper few hundred feet of the earth's crust and are common at depths of a few thousand feet, but are generally at depths greater than 5,000 feet.

The subzone of lethargic flow is the chief potential locus for storing (disposing of) the more concentrated and moderately intractable wastes by injection (excepting wastes so intractable and noxious that absolute containment is required for virtually all time). Thus, delimiting and describing these subzones is largely tantamount to defining injection provinces. Description is needed, in terms as specific as is possible, for all principal factors that influence injectability. Fairly comprehensive and extensive data are at hand from oil fields, of which most are in the subzone here of concern. Aside from such fields, and a few commercial brine fields, the descriptive data at hand may not be definitive, but preliminary guides for injection may be inferable.

Stagnant subzones

In stagnant subzones the rocks are porous but the interstitial liquid (generally brine) appears to be hydrodynamically trapped and so essentially without Darcy-law flow. A very small movement may take place by geochemical osmosis or some other process that is not understood clearly. Pressure of the interstitial liquid ranges greatly: it may be considerably less than in overlying zones, but on the other hand may equal or even exceed the geostatic pressure for the depth of occurrence. With few exceptions, if any, stagnant subzones are at least several thousand feet below land surface.

Because by definition its native liquid is virtually motionless over a very long interval of time, a stagnant subzone would seem to afford the ideal locus of injection for intractable waste. However, the existence of such subzones is inferred commonly from sparse or weak evidence; proof of existence would be difficult and certainly costly. Injection, necessarily under pressure, would immediately change the stagnant state to one of local hydrodynamic movement; the reach of such an effect could be difficult to predict with certainty, from the data attainable by ordinary effort. Thus, the capability of a stagnant subzone to accept and retain an injected liquid should be assessed with extreme caution.

Dry subzones

Within depths that would be fully practicable for injection, dry subzones are in a sense anomalous. A common type would be a salt bed or plug (dome), in which free water is virtually nonexistent and which may be impermeable in a finite sense. Depth to such subzones ranges from a few tens to thousands of feet. Thickness and horizontal extent are likely to be conjectural except, for example, for salt domes that have been delimited in connection with extraction of petroleum or sulfur.

A waste injected into a dry subzone of the sort just described, by hydrofracturing or otherwise, would in principle be wholly isolated from the natural hydrodynamic circulation. However, injection would create a hydrodynamic potential, conceivably sufficient to induce movement of the injected fluid if the hydrofractures should extend to a boundary of the subzone. Thus, performance of a dry subzone under injection should be assessed cautiously; absolute containment of injected liquid cannot be assumed.

Dry (unsaturated) subzones do occur in permeable strata, but not commonly. Waste injected into such a subzone would move down dip until it reaches a saturated zone, then would come under local hydrodynamic forces. In detail, its behavior could be most difficult to foresee.

HYDRODYNAMICS; POTENTIOMETRIC LEVELS AND GRADIENTS

In general, virtually all movement of ground water and behavior of an injected liquid are hydrodynamic processes. Unfortunately, in a large fraction of the relevant current literature, effects of injection have been assessed only in terms of hydrostatics and of injection wells under hydraulic equilibrium. As a result, the assessment has not always been adequate.

It is contemplated that the canvass of injection provinces would seek to generalize, for each zone or subzone of circulation, the patterns of regional hydrodynamic circulation so far as these can be inferred. Two examples of regional circulation in the subzone of lethargic flow are described by McNeal (1965) and Hoeger (1968), respectively for the Permian basin and for the eastern half of the Denver basin. Data to delineate other analogous areas is expected to rest largely in the petroleum industry. Outside the oil fields, current information may not be definitive.

Potentiometric (fluid) levels and gradients should suggest relative rates of fluid movement. These must be assessed not only for the natural condition, but especially for the conditions of injection, when levels and gradients may change transiently or progressively, perhaps greatly, and commonly will fluctuate considerably. Under such conditions, only nonequilibrium concepts and formulas seem appropriate for analyzing and anticipating the fluid movements (Ferris and others, 1962). Prototypes for the conditions of waste injection doubtless rest in the experience with brine injection, in the petroleum industry.

A zone whose potentiometric level is substantially below those of overlying zones, or in which the potentiometric gradients are locally centripetal, seems, on casual consideration, especially favorable for injection. Such zones or areas should, however, be assessed cautiously for reasons that include these: First, fluid levels for deep zones are not easy to measure accurately, so that any isolated unverified level may be considerably in error. Second, centripetal gradients imply an anomalous hydrodynamic circulation that may have been misinterpreted. Third, the greater the depth of the potential level, the greater the degree to which injection pressure would diminish the friction across fracture planes in the injection-zone matrix (see Healy and others, 1968, p. 1306)—that is, other factors being the same, the greater the potential for injection-triggered earthquakes, such as have been mentioned.

HYDROFRACTURES; SAFE INJECTION PRESSURE

Experience of the petroleum industry with brine-injection wells indicates that as injection pressure increases, the rate of brine acceptance increases proportionally until, at a so-called critical pressure, the rate of brine acceptance quickens notably. At injection pressures greater than critical, the rock "hydrofractures" so that its permeability increases. At least approximately, however, if injection pressure then is diminished to less than critical, brine acceptance diminishes to its antecedent rate. Accordingly, it is reasoned that hydrofractures do not permanently modify the permeability of the rock matrix. (In this connection see American Petroleum Institute, 1958; Cleary, 1958; Dickey and Andresen, 1945; Grandone and Holleyman, 1949; Hubbert and Willis, 1957; and Yuster and Calhoun, 1945.)

Generally it has been assumed, expressly or tacitly, that the critical pressure determines the safe maximum injection pressure at a particular well. On this basis, safe pressure falls commonly between 0.6 and 1.0 psi per foot of depth (the higher of these limits is the common value of the so-called geostatic or lithostatic pressure—that is, the pressure exerted by overlying rock at 2.3 average density). Existing waste-injection wells operate at pressures as much as 2.1 geostatic—that is, at about twice the pressure necessary to "float" the rocks overlying the injection zone. Yet the brief reports available do not note excessive hydrofracturing at the maximum pressure cited.

Again, there is involved here a seeming paradox—specifically, a safe pressure less than critical pressure would, in general, foreclose hydrofractures and the greater injectivity they cause. Yet hydrofractures would, at some places and times, be both permissible and desirable. At Oak Ridge National Laboratory, for example, certain radioactive waste liquids are made into a slurry with cement, the slurry is injected into shale by hydrofracturing, and the radioactive constituents become sensibly immobile once the slurry hardens (de Laguna, 1962). Definitive criteria are lacking, by which to constrain hydrofractures appropriately.

In another context, a "safe" injection pressure would be less than that which could "trigger" an earthquake. The quakes originating near the Rocky Mountain Arsenal well were contemporaneous with injection pressures ordinarily not greater than about 0.53 psi per foot of depth—that is, somewhat less than that at which hydrofracturing is considered generally to start, and about half the ordinary upper limit of critical pressure which has been cited. Here, injection pressure is but one of numerous relevant factors. Involved are the stress in the injection zone due to overburden, that due to active tectonic forces, and that which is residual (D. J. Varnes, written commun., 1969); hydrodynamic and thermodynamic fluxes; geochemical processes; and mechanical properties of the injection-zone matrix. Injection of an extraneous liquid (waste) distorts the balance among the natural forces. Oversimplified, if the natural balance is delicate, a small distortion can trigger an earthquake; in detail, current theory and techniques of observation are little more than rudimentary (R. W. Stallman, written commun., 1969).

It seems necessary, therefore, to develop a fully comprehensive and wholly general concept of "injectivity" at a "safe" injection pressure, to serve as the ultimate basis for classifying potential injection provinces and their subzones. To that end it is proposed that the brine-injection experience of the petroleum industry, related theory, and the separate theory of injection-induced earthquakes all be reviewed critically and reexpressed as necessary in criteria generally applicable to waste injection. (See Healy and others, 1968; Kehle, 1964; and Scheidegger, 1960.) Here, there is particular need to discriminate clearly between wellhead pressure, the incremental pressure equivalent to weight of fluid between wellhead and natural water level, and total pressure on the zone. Further, it is emphasized that in some areas, brine injection has dealt with a fluid system in which one component (gas) is readily compressible, whereas generally all the fluids of a waste-injection system would be liquid—that is, none of the fluid components would be highly compressible. The comprehensive and general concept here outlined probably will not be realized easily.

GEOCHEMICAL ASPECTS

Allusion has been made to chemical compatibility among injected waste, materials of the injection-zone matrix, and native interstitial water of the zone. Possible combinations of the variables involved are numerous indeed, as are the relevant analytical data at hand—chemical analyses of brine, other native waters, rocks, and earth materials; temperature and pressure gradients; fluid densities; sparse but suggestive values of exchange capacities. In all the complexities and wealth of data it should be possible to isolate some criteria for classifying injection subzones according to broad types of chemical problems that could be anticipated with various categories of waste. A search for general criteria of this kind is suggested. The primary discipline involved would of course be geochemistry, with close support required by geohydrology.

Incidental allusion has been made to geochemical osmosis as a possible driving force acting between two aquifers that contain waters of unlike chemical concentrations at unlike pressures, and that are separated by a confining bed acting as a semipermeable membrane. That such a force acts at depth in the subzones of lethargic circulation and of stagnation has been suggested by several investigators, presumably from the spatial analogy of certain aquifer and confining-bed systems to the laboratory environment of unlike concentrations of fluid on either side of a semipermeable membrane. If strictly valid, the analogy to fluid transfer by osmosis, in the laboratory, anticipates the long-term history of certain deeply injected wastes. To the writer the analogy has not been, but if possible should be, demonstrated from rigorously screened field data, by theoretical analysis.

LEGISLATIVE AND INSTITUTIONAL CONSIDERATIONS

Three of the 50 States—Missouri, Ohio, and Texas—have enacted statutes specifically to regulate disposal of waste liquids by injection into the ground. Provisions of the statutes in the latter two States are generally alike; very greatly simplified, they may be summarized as follows: (1) A permit is required of any person who drills, modifies, or uses a well "for the injection of sewage or any liquid used in or resulting from any process of industry, manufacture, trade, business, or agriculture" [Ohio's language, disposition of oil-field brines is regulated by another statute in both Ohio and Texas], (2) application for such a permit is made to a named administrative agency, the application locating and describing the proposed injection facility and stating composition of the liquid intended to be injected, (3) an application may be denied only on a determination of "unreasonable risk [of] waste or contamination of oil or gas in the earth,*** unreasonable risk of loss or damage to valuable mineral resources, *** [or] pollution [of water]" [Ohio's language]; otherwise, a permit must be issued, (4) the permit may include conditions necessary to protect health, safety, conservation of resources, or purity of water supplies, (5) a permit may be suspended or revoked for infraction of the statute, of regulations promulgated under the statute, or of conditions attached to the permit, and (6) a permit may be suspended and, after a hearing, revoked if warranted by information disclosed after that permit was first issued [Ohio only].

The two statutes just summarized are concise, reasonably explicit as to intent, quite explicit as to placement of relevant responsibility and authority, and free from technical restrictions that would be tantamount to prejudgments of field conditions. In a "legalistic" sense they are perhaps ideally workable. To the writer, however, the two statutes share three substantial inadequacies: First, they require of the administering agency a binding judgment as to effectiveness of the proposal for injection whereas, in the present state of injection art, available information commonly does not suffice for a fully reasoned judgment. All uncertainty must be covered into conditions attached to the permit. This could lead to dilemma: futility for the administrator versus frustration for the injector. Second, the statutes admit only two parties to an injection—the individual who injects and the State agency that administers. Reasons will be advanced that this grossly oversimplifies and restricts the interests concerned. Third, the statutes neither establish, nor provide for promulgation of, "off-limit" zones or areas—the entire "subsurface" of each State is declared open for injection except where specific inimical effects are anticipated. Limitless injectability at any point seems to be implied. The art of injection being ill understood, and the effects of injection being irrevocable, a policy so openhanded verges on rashness.

The brief Missouri statute provides that (1) "any individual wishing to use underground wells or depositories for the injection of liquid waste" must apply for a permit, (2) a permit is granted provided the "health or property of others" will not be harmed, and (3) a "reasonable" bond may be required of the permittee to assure that the injection facility, if and when its use ends, is plugged or sealed.

Other States impose various degrees of constraint on injection of liquids underground, under as many as three regulatory agencies in a particular State (Warner, 1965, p. 23, 36–37). The diversity of these constraints is suggested by the following generalizations. Nearly all the States regulate the cementing of casings in wells drilled for petroleum or natural gas; only by implication and, so far as the writer is informed, in no instance by specific wording of statute would such regulation apply to injection wells. A few States prohibit all injection; several prohibit injection of liquids other than salt water or oil-field brine. Others require that oil-field brine be returned underground; among these, some require that the return be to the very stratigraphic zone from which the brine was extracted. California specifically prohibits disposal of waste into strata that are used, or are usable, as a source of domestic water supply. In respect to these diverse constraints, there are similarly diverse requirements as to application for a permit; preconstruction submittal of statement of location; postconstruction filing of a statement of location, plans, or log of a well; or filing of a record of facilities abandoned. All degrees of public involvement are represented.

The writer feels strongly that the current order in waste disposal by injection—in essence a private individual or corporation versus a State—is inherently and woefully insufficient. Principal reasons follow, in addition to others already implied.

Exploration to prove feasibility and absolute safety, together with adequate construction of a well and related facilities to accomplish deep injection, commonly would be exceedingly costly. For example, at one installation of the Atomic Energy Commission, somewhat more than a million dollars was expended on definitive exploration in an area of a few square miles, to depths of only about 800 feet, over a 3-year term. Construction of injection facilities and continuing monitoring have about equaled the exploration cost. Even so, some potentially critical questions remain unanswerable. Few private agencies have, or can command, the specialized technical skills and the financial resources necessary for demonstrably sound performance, when injection is to be at depths of thousands of feet. Should the skills and resources be at hand, full disclosure of findings by a pioneer injector could grant an unearned "free ride" to the competitors. The urge to shortcuts in exploration and construction, and to avoidance of disclosure, would seem all but irresistible. A joint injection facility, with cost of exploration and construction shared among several private agencies, would be advantageous to the participants but would aggravate the tendency to avoid disclosure.

At the opposite pole in the current order, the general public should have the inalienable rights to be spared harm from, and to reap the benefit of accrued experience with, deep injection. Few, if any, State agencies currently have the staff skills, centralized authority, and financial resources to assure these general-public rights. Some new, fully competent institutional arrangement appears to be essential. As suggestive means to that end:

1. An agency or commission of government or a public corporation, either designated from among existing institutions or created for the purpose, might be vested with exclusive authority and responsibility to (1) delineate provinces and stratigraphic zones suitable for injection, and (2) maintain a continuing record of waste storage in the several provinces and zones—both capacity occupied and capacity unused, both volumes and chemical character and concentration of wastes injected. As required, such institutions might exist in en echelon scope—nationwide, single State or major province, subprovince, and local zone. Staff capability and financial support, both commensurate with responsibility, would be presumed at each echelon. Each subprovince or local zone would constitute a hydrodynamic whole and would be administered as a whole; if any such unit had parts in more than one State, a single jurisdiction would be negotiated or otherwise arranged.
2. Each of the above governmental or public entities might (1) construct injection facilities and offer waste-storage service at a suitable fee or, alternatively (2) license a private agency or an association of such agencies to construct and operate an injection facility for its exclusive use. The fee charged for injection service might be scaled according to volume, concentration, and compatibility of the waste delivered to the public agency. Such a policy would create incentive for the waste producer to minimize his demand on the space available for waste storage. The license would require full disclosure of all information originating with the waste producer but required for orderly long-term managment of the injection province or zone. The license might also grant to the private agency or association the prerogative of exploring and delineating a suitable injection zone or zones.
3. Among its prerogatives, the public agency would be authorized to: (1) so regulate the construction and casing of injection wells that wastes are excluded, completely and permanently, from the zone between the land surface and the injection zone into which they are released, (2) promulgate and enforce "safe" injection pressures and rates of injection; these should be variable as hydrodynamic conditions might require, (3) prescribe an aggregate volume of waste permitted to be injected into a particular province, subprovince, or zone, (4) require any waste to be treated before injection, as may be necessary to render it chemically compatible or stable, (5) prohibit injection of chemically incompatible or excessively noxious wastes, (6) declare any province, subprovince, or zone to be "off limits" to injection, either permanently or temporarily, as may be necessary to achieve or maintain suitable hydrodynamic and geochemical balances, (7) as warranted, reserve any particular zone or subzone for a declared resource-management purpose—for example, as a source of some particular resource, as a source of fresh water by desalination, or for gas storage, (8) preserve the integrity of the confining layer above any designated waste-injection zone, by requiring that all wells or other openings drilled into that layer for any purpose be adequately cased, and plugged if abandoned, and (9) continually search for alternative and economically competitive methods of waste handling, to the ends of minimizing encroachment on the land-surface environment, while prolonging capacity for injection underground.

In the concept just suggested, the public agency having only a local jurisdiction would, in principle, act as an agency of one particular State, possibly in the form of a utility or conservancy district. To implement the concept fully would require legislation establishing the proper Federal role and approaching a uniform State role, both roles to encompass the full scope of technical and management problems discussed or implied.

Advisedly, the concept is concerned only with injecting wastes underground. Even in perfected form, it resolves only in part the necessity that mankind learn to manage the wastes it produces.

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