49

Direc

INLAND WATERS BRANCH

DEPARTMENT OF THE ENVIRONMENT

Subsurface Disposal of Waste in Canada

R.O. VAN EVERDINGEN and R.A. FREEZE

TECHNICAL BULLETIN NO.49

CANADA

TECHNICAL BULLETIN NO.49

Subsurface Disposal of Waste in Canada

Injection of Liquid Industrial Waste in Deep Wells
A Preliminary Appraisal

R.O. VAN EVERDINGEN and R.A. FREEZE

INLAND WATERS BRANCH
DEPARTMENT OF THE ENVIRONMENT
OTTAWA, CANADA, 1971

Contents

Illustrations

Tables

Subsurface Disposal of Waste in Canada

R.O. VAN EVERDINGEN and R.A. FREEZE

CHAPTER 1

Introduction

The accelerating rate of production of industrial wastes, of ever-increasing complexity and toxicity, makes it imperative that methods of waste management are developed that are both safe and effective. As far as liquids and solids are concerned, the disposal of waste can take place either on the surface (e.g. sanitary landfill, sewage lagoons, discharge into rivers or lakes), or below the surface (injection into deep wells, placement in mined cavities, or injection in shales as a waste/grout mixture). In view of the growing concern about the existing industrial pollution of air, soil and surface waters, the subsurface disposal of industrial waste is rapidly becoming an alternative with considerable attraction for those in the waste-management field. In many cases it is not only technically feasible, but also economically attractive, especially when new standards for surface-water quality necessitate extensive capital lay-outs for new waste-treatment facilities.

What must not be overlooked, however, is that use of the method will result in irreversible pollution of a number of subsurface formations. In addition, the representation of the method as either final or permanent is unrealistic, in view of the fact that injected waste may be subject to dispersal by diffusion and convection in natural subsurface flow systems.

A.M. Piper (99)*, of the United States Geological Survey, had the following comments on the subject:

> "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."
>
> "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."

---

* Bracketed numbers refer to the bibliographic listing, Appendix B.

> "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."

The present report presents a general appraisal of the principal limitations of the potential of the method. Extensive use was made of an excellent survey of the waste-disposal literature prepared for the Inland Waters Branch by Dr. R.A. Freeze under the title "Deep-well Injection of Industrial Wastes in Canada". Appendix B presents the bibliography included in that earlier report.

An attempt was made to introduce all pertinent concepts, without undue elaboration. A discussion of the qualification of waste for subsurface disposal is followed by a review of the criteria to be applied for the proper selection of disposal regions, sites and geologic formations, and chapters on subsurface-disposal facilities and their potential failures. After a review of the status of the method in Canada, requirements in the field of legislation and regulation are outlined, followed by a discussion of those aspects of the method that are most in need of further research.

Early recognition of the hazards presented by the subsurface disposal method, and of its consequences, is imperative. Therefore it is necessary to gain a better understanding and more detailed knowledge of the behaviour of injected waste. Through subsequent legislation and regulation it should be possible to avoid the costly mistakes, serious accidents and often irreversible damage to the environment that can result from subsurface disposal operations that are hastily conceived, inadequately investigated, improperly equipped and insufficiently monitored.

Waste Classification

1. *Waste Sources and Categories*

Figure 1 identifies a number of sources of both solid and liquid waste, and it indicates some of the different disposal methods that are available for these wastes. As far as subsurface disposal is concerned, the industrial wastes that form the subject of this report belong to one or the other of two main categories: a) "natural" liquid wastes, or b) "foreign" liquid wastes.

This distinction is based on the gross composition of the waste. "Natural" liquid wastes are those that contain in solution only constituents that are found normally in solution in the subsurface. The concentrations of the various constituents, however, may differ from those usually associated with a particular disposal formation. All other waste liquids are to be characterized as "foreign".

2. *"Natural" Liquid Wastes*

Liquid wastes belonging to the following groups can be characterized as "natural", provided that no foreign constituents have been introduced during their production and treatment.

a. 1) Saline water and brines produced by the petroleum industry (144, 145, 148-151).
   2) Waste brines generated by the potash, soda and salt industry (46).
   3) Waste brines resulting from the conversion of saline into fresh water through desalination (83).
   4) Brines generated during solution of salt beds for the formation of cavities for underground gas storage. These liquid wastes are in many cases disposed of in the subsurface.

b. Acidic drainage from active or abandoned mines, and from mill-tailings. At present these liquid wastes are usually disposed of in rivers and lakes. Various other disposal methods have been proposed for this group of liquid wastes, among others subsurface disposal (117-119).

The problems presented by the subsurface injection of "natural" liquid wastes are mainly confined to the fields of (1) hydrodynamics, (2) stress mechanics, and (3) fluid compatibility. In the field of hydrodynamics, subsurface disposal may lead to saline or acidic contamination of fresh-water aquifers, and to accelerated discharge of saline water or brine in discharge areas. In the field of stress mechanics, the relatively high injection pressures needed to inject the usually large volumes of these wastes may lead to *hydraulic fracturing* of the disposal formation (which may be

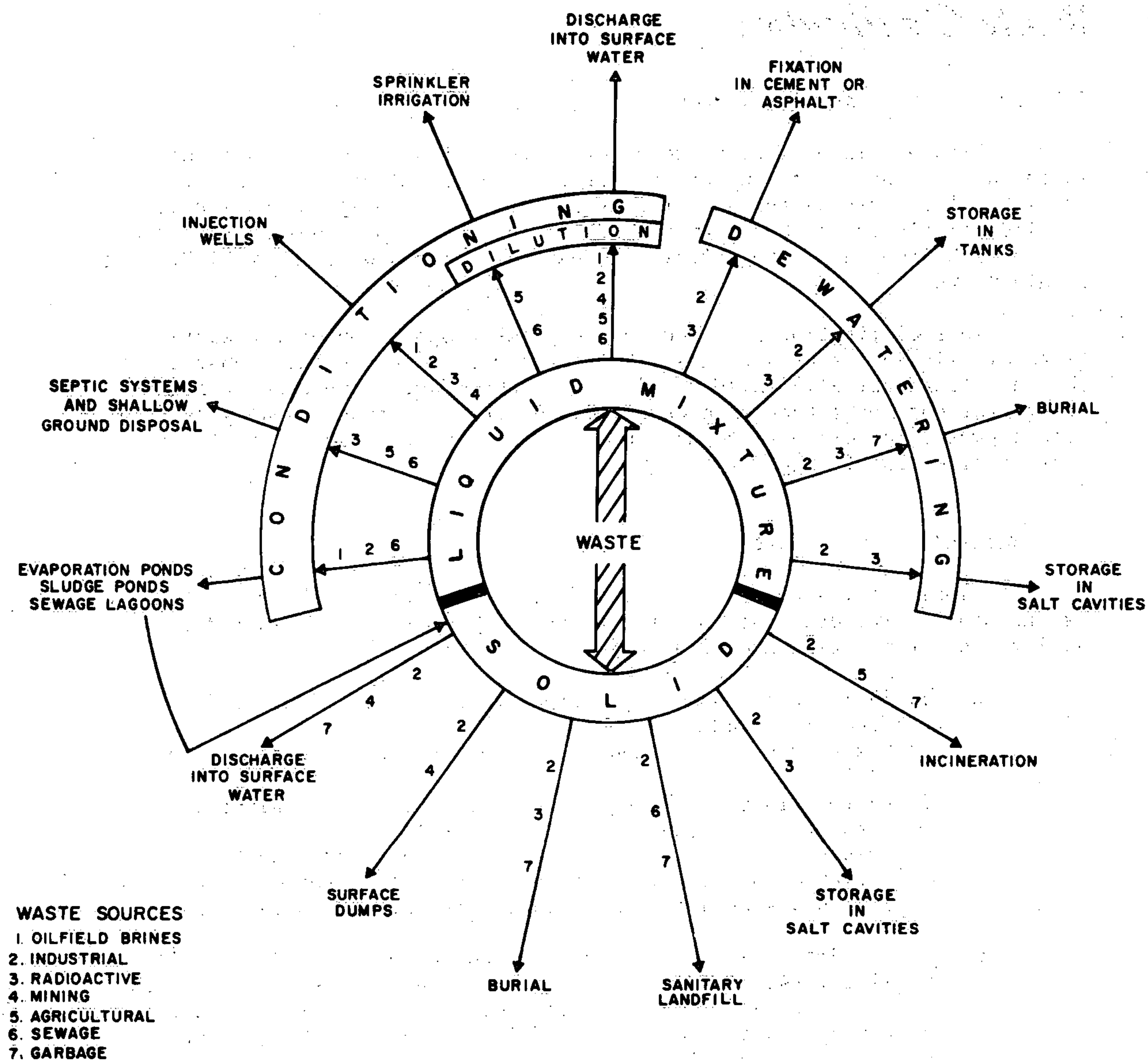

Figure 1. Waste sources and disposal alternatives for solid and liquid wastes.

beneficial), and of the confining beds above the disposal formation, which must be regarded as undesirable. Proper selection of disposal sites and formations (Chapter V), and careful monitoring of the disposal operation (Chapter VI) should prevent the occurrence of such adverse effects.

Chemical incompatibility between injected "natural" waste liquids and formation liquids and rocks may lead to plugging of the disposal formation, necessitating additional pre-injection treatment. Only rarely will it force abandonment of a disposal operation.

Some "natural" *non-waste* fluids also qualify for subsurface injection.

1) Fresh or saline water used by the petroleum industry for secondary recovery of hydrocarbons through waterflooding.

2) Fresh water for artificial recharge of aquifers.

3) Natural gas, for temporary underground storage.

4) Natural gas, for secondary recovery of petroleum by artificial gas drive.

Use of the subsurface for these purposes will be referred to further in the next chapter (III).

3. *"Foreign" Liquid Wastes*

Liquid wastes that can be characterized as "foreign" belong mainly to two groups, radioactive wastes and other industrial wastes.

a. Liquid radioactive wastes from uranium - mill tailings, nuclear-fuel processing plants, nuclear power plants and nuclear research institutions. They are commonly classified as low-, intermediate- and high-level radioactive; usually they contain high concentrations of nitric acid, aluminum nitrate and fission products. Increasingly large volumes of radioactive waste are being produced in Canada. It is expected that 5,400 megawatts will be generated by nuclear power plants in Ontario by 1979. If the waste:megawatt ratio remains similar to that for operations in the U.S., then a total of 400,000 gallons/year of high-level waste will be generated, as well as much larger volumes of low- and intermediate-level waste. High-level radioactive waste is generally stored on the surface, in special containers inside concrete bunkers; subsurface disposal is, however, being considered for some low- and intermediate-level radioactive wastes in the United States.

b. Other liquid industrial wastes are generated by petroleum refineries, and by the petrochemical, chemical, pharmaceutical, steel, pulp and paper, and food-processing industries. They include, among others, hydrochloric and sulfuric acid (37, 88, 91); hydrogen sulfide (91); sodium-chloride brine (56, 101); steel-mill pickling liquors (55); pulp-mill liquors (4, 24);

detergents (37); sulfides, sulfates, phosphates, nitrates, chlorides, cyanides and chromates (5, 37, 142); spent "caustics" (37, 88, 101); chlorinated and non-chlorinated hydrocarbons (37, 88, 97); organic acids, alcohols, ketones and esters (5, 34); phenols (5, 37, 88, 101); and heterocyclic steroids (97). Few figures are available; however, in Toronto alone 15 million gallons of liquid industrial wastes were removed by private disposal companies during 1969.

In addition, saline water, brine and acidic mine and mill-tailing drainage containing noticeable "foreign" constituent should also be characterized as "foreign" liquids.

The problems presented by the subsurface disposal of these "foreign" liquid wastes are not confined to the fields of hydrodynamics, stress mechanics and fluid compatibility. Essentially, nothing is known about the behaviour of many of these wastes when they come into contact with natural formation fluids and rocks, under the conditions of elevated temperature and pressure that prevail in the subsurface. Toxicity of some constituents may either decrease or increase through degradation; chemical reactions between relatively harmless compounds may produce more toxic compounds.

The hazards created by accidents involving "foreign" wastes are potentially of a more serious nature than those that would result if "natural" wastes were involved: a definite threat to health will result, rather than a more or less serious nuisance, when they "backfire" during a well blowout, contaminate fresh-water aquifers, or discharge to the surface at unexpected places and times. Therefore more detailed knowledge should be available, and more stringent controls applied in cases where it is proposed that "foreign" fluids be injected into the subsurface.

4. *Classification of Liquid Waste for Subsurface Disposal*

An improved classification of radioactive waste, based mainly on concentration and persistence of critical radionuclide components, proposed by the American Institute of Chemical Engineers, contains five classes (A-E). This classification can form the basis for deciding on the suitability of subsurface disposal for a particular radioactive waste. A similar classification for liquid industrial wastes, proposed by Piper (99), would enable rational evaluation of the suitability of subsurface disposal for these wastes.

Class A - *radioactive waste:* radionuclide concentration is low enough to justify dispersal without restriction. Disposed into surface waters.

Class A - *industrial waste:* "natural" and "foreign" liquids that are produced in large quantities, but do not contain "foreign" components in concentrations that would conceivably be harmful to life when introduced indiscriminately into the biosphere. Conforming to accepted public-health standards, these wastes could be disposed of into surface waters, but not in the subsurface because of the large volumes involved.

Class B - *radioactive waste:* radionuclide concentrations not more than 10 times those for Class A wastes. This class would have force only in areas where exposure and intake can be controlled and where safety precautions are strictly enforced.

Class B - *industrial waste:* contains "foreign" constituents in concentrations that exceed the limits for Class A, or that may be of a more noxious character than those allowed for Class A. This class should have force only in areas where dispersal can be so controlled, as to both time and space, or the wastes so diluted, that exposure of life to the waste would essentially satisfy the Class A standards (e.g. isolated installations). Class B wastes would be disposed of into surface water, not in the subsurface. This classification may be only transient and apply only in a few areas.

Class C - *radioactive waste:* radionuclide concentrations not more than 10^5 times those in Class A waste. Treatment of Class C waste would enable conversion of a major fraction into Class A wastes, to be disposed of as above, while a minor fraction would be converted into Class D (or E) waste.

Class C - *industrial waste:* containing "foreign" constituents to a degree unacceptable by public-health standards, while it is being produced in quantities that exceed practical subsurface injection limits. Such waste might be (1) diluted for conversion to Class A waste; (2) concentrated for conversion to Class D (or E) waste; (3) suitable in some cases for injection in relatively shallow formations with relatively rapid circulation in which residence time would still be sufficiently long to permit degradation and attenuation of noxious constituents.

Class D - *radioactive waste:* radionuclide concentrations not more than 10^9 times for those for Class A waste. To be stored indefinitely in suitable containers on the land surface, incorporated in a bituminous or concrete matrix, or reduced to a solid residue. Solid forms of the converted waste to be held on the land surface. Class D wastes could conceivably qualify for subsurface disposal by injection of a waste/cement slurry (grout) into thick shale formations (77, 139).

Class D - *industrial waste:* contains high concentrations of foreign constituents and is produced in relatively small volumes. The foreign constituents are relatively stable and of such a nature that they would produce a persistent but non-lethal nuisance on the surface. Class D wastes would usually qualify for subsurface disposal in the deep subsurface, where movement under natural hydrodynamic gradients is extremely slow, assuring a residence time of many decades or even centuries.

Class E - *radioactive waste:* radionuclide concentrations exceed the limits for Class A by a factor of more than 10^9. To be stored indefinitely in suitable containers on the land surface unless it can be converted to, or incorporated in, a radiation-stable solid. Class E wastes do not qualify for subsurface disposal in liquid form.

Class E - *industrial waste:* liquid wastes of such persistent noxiousness and concentration that they must be excluded from the biosphere essentially forever, necessitating unequivocal and detailed knowledge of their disposition at all times (e.g. chemical/biological warfare agents). Absolute immobility in the subsurface cannot be assured; detailed monitoring of subsurface movement is virtually impossible. Class E industrial wastes are therefore not qualified for subsurface disposal.

In summary, the following liquid wastes could potentially qualify for disposal by subsurface injection in liquid form:

1. "Natural" liquid wastes, without foreign components, including saline water, brine and acidic mine drainage.

2. "Foreign" liquid wastes belonging to the following classes:

   (a) some Class C industrial wastes,

   (b) Class D industrial wastes.

Disposal by injection of a waste/cement mixture into shales might be used to dispose of:

(a) some Class C radioactive wastes,

(b) Class D radioactive wastes.

Figure 2 presents a summary of the decisions involved in the evaluation of waste for subsurface disposal. The main requirement before any classification system like this can be applied is the establishment of rational and realistic limits for the various classes.

5. *Recycling of Waste and Recovery of Useful Constituents*

It is apparent from Figure 1 that subsurface disposal should only be regarded as one of a number of alternatives available for the disposal of liquid wastes. There is, however, a potential solution for some waste problems that is not represented in Figure 1. This is the treatment of waste to enable its re-use, or the recovery of some or all of the mineral and/or organic constituents for further use.

Such re-use and recovery processes are already technically possible and economically feasible for some industrial wastes that are at present being discharged into streams or injected into the subsurface through deep wells (6, 20). Phenols and acetic acid can be recovered from waste brines generated by some organic-chemical plants, enabling the recycling of purified brine for the production of chlorine and caustic soda [Env. Sci. and Techn. 4 (3), 183]. Hydrochloric acid and ferric oxide, or hydrochloric acid and ferrous-sulphate heptahydrate can be recovered from spent steel-mill pickling liquors (6).

Research into such re-use and recovery processes should be encouraged as much as possible. Wide application of such processes would serve the dual purposes of waste-volume reduction and resource conservation. Subsurface disposal of any particular waste should of course be prohibited as soon as the regulatory agency determines that such waste has become amenable to an alternate disposal method or a re-use or recovery process.

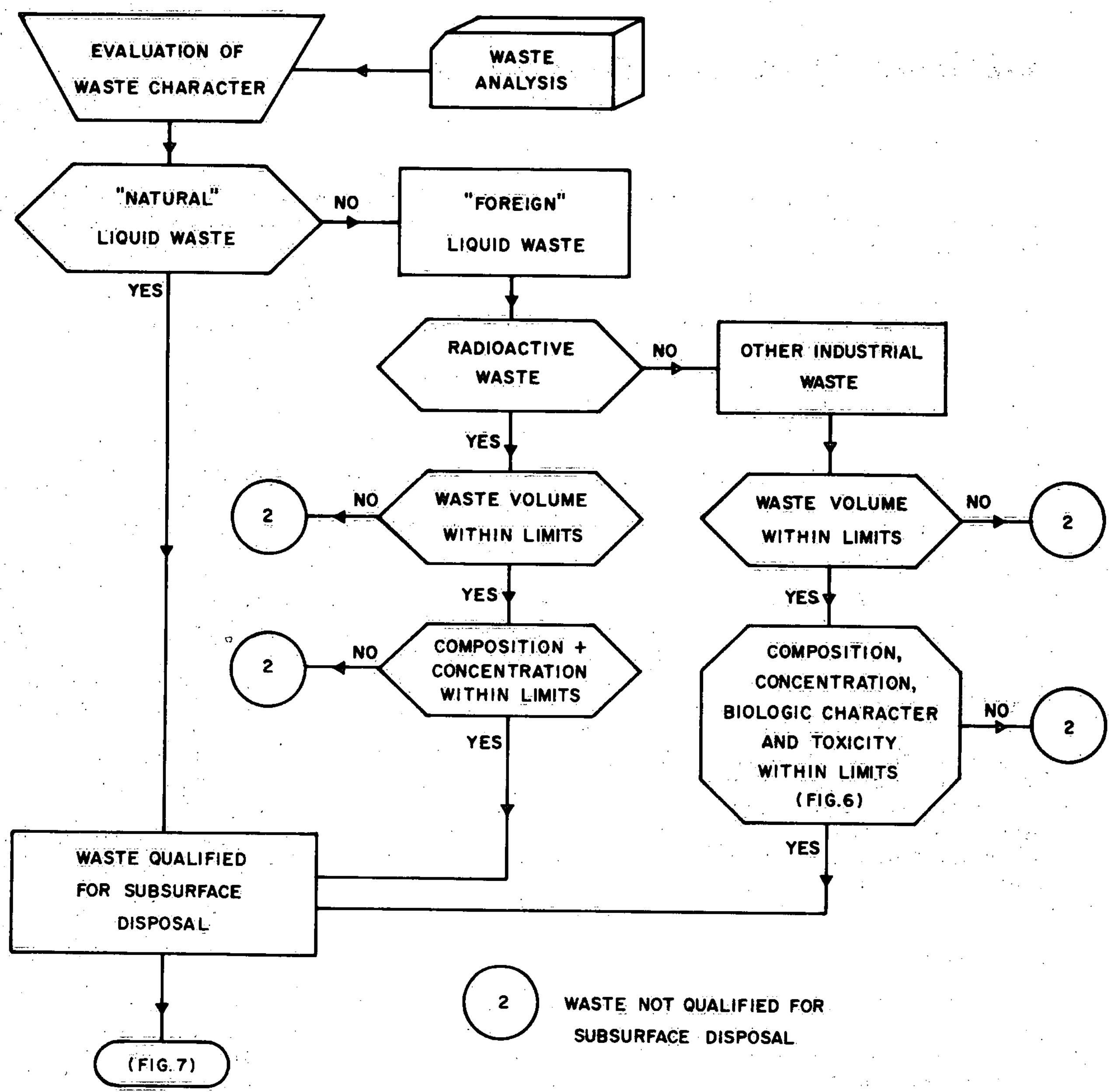

Figure 2. Qualification of liquid industrial waste for subsurface disposal.

Subsurface Space as a Natural Resource

1. *Positive and Negative Use of Subsurface Space*

Use of the space available in subsurface formations which produces an economic return, is a *positive use*. At least three positive uses of the subsurface can be identified.

a. Injection of fresh water, saline water, brine or natural gas for pressure maintenance in secondary recovery operations by the petroleum industry (143, 146, 147).

b. Artificial recharge of fresh-water (or saline) aquifers with fresh water for future use (152-162).

c. Injection of natural gas for temporary storage (163-167).

In principle the same subsurface space can be used repeatedly, over a long period of time for the above productive uses.

The use of space available in the subsurface for the disposal of wastes is a *negative use*, that may prevent other uses for an indefinite period of time. The liquid industrial wastes that could qualify for subsurface injection were discussed in the foregoing chapter. Of these, saline water and brines, produced by the petroleum, salt and potash industries, and by desalination plants, form a special case because they are "natural" wastes, produced in large quantities that can only be disposed of at present in the subsurface. For the remaining groups alternative disposal methods are often available. Their injection into the subsurface, which will prevent other uses of the available space, may also prevent the future potential use of saline formation water and brines for desalination and/or recovery of economic minerals.

2. *Management of the Subsurface*

The usable space available in the subsurface of a sedimentary basin is limited. Both positive and negative users may at times defend claims to the use of the same portion of this limited natural resource. In many cases the potential benefits to be derived from positive uses can be expressed relatively easily in terms of dollars and cents. Expression, in terms of dollars and cents, of the expected benefits (e.g. elimination of surface-water pollution) to be derived from a negative use of the subsurface, will often be extremely difficult. Proper evaluation of such benefits will necessitate advanced knowledge of other waste-management methods, and their respective advantages and disadvantages.

For the proper management of the subsurface, priorities should be established for the use of available underground storage space and fluids.

Subsurface injection of waste will then have to be considered in competition with underground gas storage, underground fresh-water storage, use of saline water and brines for desalination, recovery of minerals, etc. (71).

Legislation and regulations (see Chapter IX) will have to reflect the position that the subsurface storage capacity is a limited natural resource that should be conserved for maximum beneficial use.

Selection of Regions Suitable for Subsurface Disposal

1. *Criteria for Selection of Disposal Regions*

If a particular waste is qualified for subsurface disposal on the basis of its classification (Chapter II), safe underground disposal may still be impossible because of regional or local conditions in the subsurface. In order to enable the safe disposal of liquid waste by means of deep-well injection, the subsurface conditions have to be suitable for the introduction of the waste with a minimum of problems, confining the waste within the disposal formation, preferably within a short distance from the disposal well. Eventual movement of the waste away from the disposal point should not lead to the contamination of useful resources; the behaviour of the waste under subsurface conditions will thus have to be predicted with a high degree of accuracy.

To satisfy these requirements, a potential *disposal region,* and the eventual disposal site and formation will have to meet a number of geological and hydrological criteria. Gross criteria, determining the potential suitability of large regions, are discussed below. The more detailed criteria to be applied at the level of site and formation selection are discussed in Chapter V.

Regions that hold potential for the safe subsurface disposal of liquid waste should satisfy the criteria listed below.

a. *Extensive, thick sedimentary sequence.* Areas with outcropping igneous and metamorphic rocks are unfavourable, because of the generally restricted amount of space available in these rocks, even at shallow depths.

b. *Region free from major faulting.* Faults may provide pathways for leakage of waste to other formations or to the surface.

c. *Region free from seismic activity.* Seismic activity may result in damage to confining strata; on the other hand, the injection of liquid waste may trigger minor earthquakes (42).

d. *Low hydrodynamic gradients prevailing* over a large part of the region.

Regions with various degrees of potential with respect to the safe subsurface disposal of liquid waste should be designated, e.g. as "potential", "limited" and "closed". The designation "potential" would imply extensive potential for subsurface disposal of liquid waste; the designation "limited" would indicate limited potential in some smaller portions of the overall region; all subsurface disposal would be prohibited in a "closed" region. Figure 3 presents a summary of the proposed regional evaluation procedure.

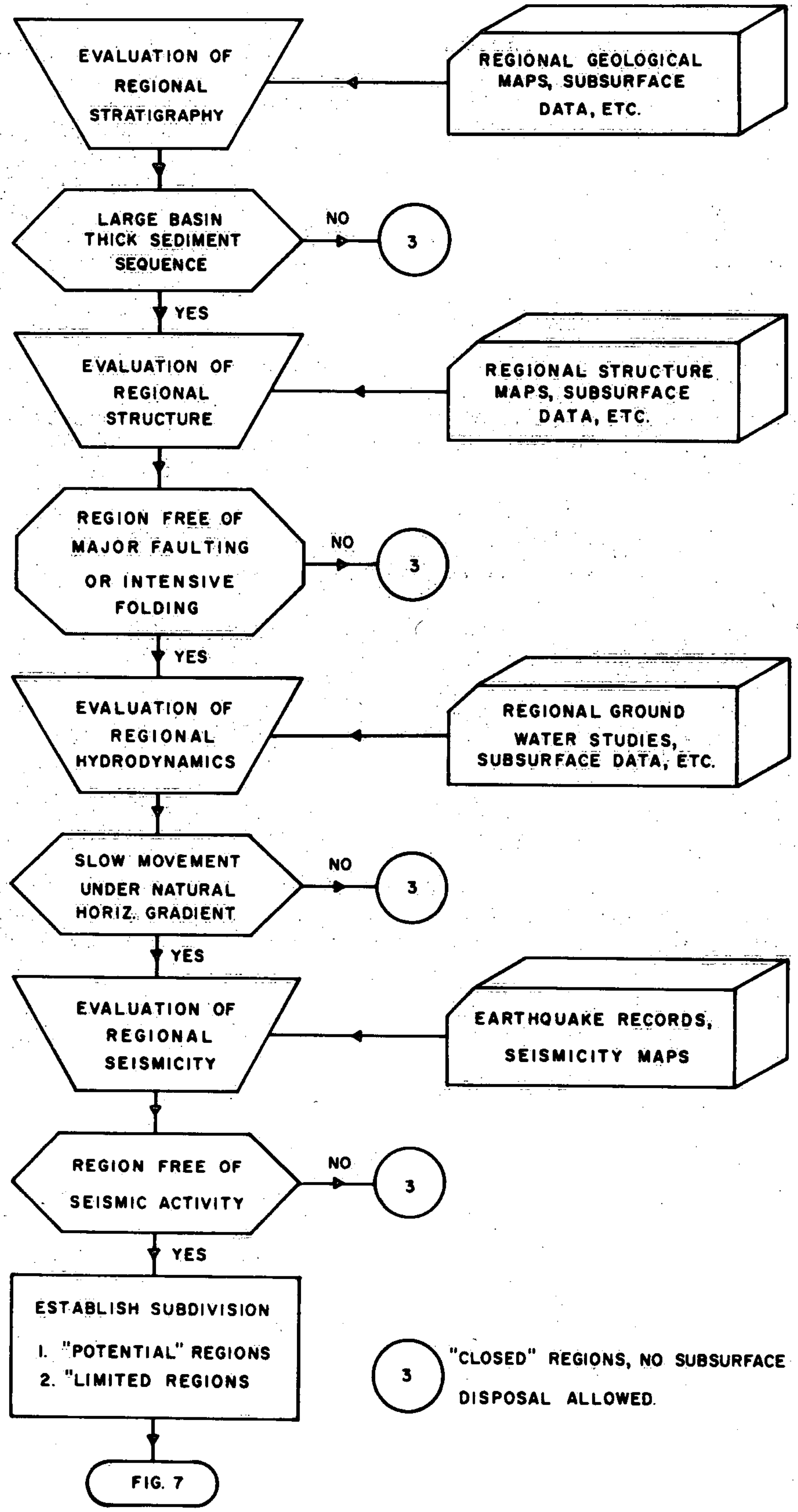

Figure 3. Selection of regions for subsurface disposal of industrial waste.

Some portions of a region, while unsuitable for one type of subsurface waste disposal, might still be suitable for another. For example, in large portions of the Western Canada Sedimentary Basin the solution of salt from the Prairie Evaporite Formation has resulted in the collapse of the overlying strata, leading to extensive faulting and brecciation, which renders these overlying formations unsuitable for the disposal of liquid waste (criterion b). Some of the thick marine shales in the upper portion of the stratigraphic section in the affected areas could, however, still be suitable for the injection of waste-and-cement slurries by hydraulic fracturing (77, 139).

2. *Background Data for Selection of Disposal Regions*

Much of the background information required for the evaluation of most of Canada in terms of gross potential with regard to subsurface disposal of liquid waste is available in one form or another.

a. Existing geological, stratigraphic and structural information from regional studies; to be re-interpreted in terms of potential for subsurface disposal (criteria a and b).

b. Existing seismicity maps will indicate areas that should be excluded on the basis of seismicity (criterion c).

c. Regional groundwater flow systems should be subdivided where possible into zones of rapid, delayed, slow and stagnant flow (criterion d).

As the criteria are strictly descriptive at present, efforts should be directed as soon as possible to their rational quantification.

The region-by-region evaluation of all of Canada in terms of disposal potential would be simplified if it is approached on the basis of established physiographic/geologic subdivisions rather than on a province-by-province basis.

Selection of Disposal Formations and Disposal Sites

1. *Criteria for Selection of Disposal Formations and Prospective Disposal Sites.*

A potential disposal formation and site should satisfy the following criteria to enable safe subsurface disposal of liquid waste in the context of this report.

a. *Disposal formation sufficiently thick, with adequate porosity and permeability* to accept waste at the proposed injection rate without necessitating excessive injection pressures.

b. *Disposal formation of large areal extent,* so that disposal site can be removed far enough from existing or potential discharge areas to prevent "breakthrough" of waste.

c. *Disposal formation "homogeneous"* (without high-permeability lenses or streaks), to prevent extensive fingering or the waste-*vs*-formation water contact, which would make adequate modelling and monitoring of waste movement extremely difficult or impossible.

d. *Overlying and underlying strata* (confining beds) *sufficiently thick and impermeable,* to confine waste to the disposal formation.

e. *Injection zones adequately separated from potable water zones,* both horizontally and vertically.

f. *Waste injection not to endanger present or future use of mineral resources* (coal, oil, gas, brine, others).

g. *Waste injection not to affect existing or potential gas-storage or freshwater-storage projects.*

h. *Formation water* in the disposal formation of *no apparent economic value,* i.e. not potable, unfit for industrial or agricultural use, and not containing minerals in economically recoverable quantities.

i. *Waste fluids compatible with both rocks and natural fluids of the disposal formation;* incompatibility could lead to permeability reduction, heat generation or undesirably rapid solution (see Chapter VII - Well failures).

j. *No unplugged or improperly abandoned wells* penetrating the disposal formation in the vicinity of the disposal site, which could lead to contamination of other resources.

k. *Formation-fluid pressures low*, enabling a higher effective injection pressure for the same actual well-head pressure; minimizes the chance of backflow in case of pump or well failures.

l. *Vertical hydrodynamic gradient directed downward or negligible*, to prevent upward movement of waste. Disposal sites should thus preferably be located in "recharge" areas or the lateral-flow portion of a subsurface flow system, never near or in a discharge area.

m. *Slow lateral movement under natural conditions*, to prevent rapid movement of waste to a natural discharge area.

The above criteria a, b and c should be stated somewhat differently for cases where solid-waste storage in mined cavities in evaporite deposits is contemplated, or where waste-grout injection in hydraulically fractured shales is being planned. Prime requirements would then be (1) adequate thickness and *low permeability* of the disposal formation, to provide protection against waste movement; and (2) adequate depth to minimize the chances of occurrence of vertical fracturing in the case of grout injection.

The criteria e, f, g and h are prime considerations in the management of subsurface resources, as outlined in Chapter III.

It could be argued that in principle the deepest favourable formation present should be selected for waste injection. At greater depth, higher injection pressures would be allowable, while both geological and hydrological safety factors are higher. Such a "maximum-depth" requirement would, however, lead to excessive drilling and well-completion costs for the deeper portions of large sedimentary basins. A realistic balance between the safety-through-depth concept and increasing costs may have to be found in such cases.

In view of the above criteria, new industries that are expected to produce liquid waste qualified for subsurface disposal would have reason to look for a favourable location in a potential disposal region. In highly industrialized areas with a restricted potential for subsurface disposal, the establishment of central waste-disposal facilities would have both economic and safety advantages, by enabling use of only the best available disposal sites.

In each potential disposal region, an inventory of potential disposal formations should be made on the basis of the above criteria. Each potential disposal formation could be subdivided in "zones" according to permeability and porosity distribution, proximity to other resources etc., as has been done in Ontario (88). Zones could be identified as "favourable", "restricted" and "closed". Requirements regarding pre-testing, design, monitoring and safeguards, would to some extent vary with the designation of the zone. Figure 4 presents a summary of the disposal-formation-and-site selection process.

2. *Methods Employed in Evaluation of Prospective Disposal Sites*

After a regional study of stratigraphy, structure and groundwater hydrology has indicated the potential of a particular region for subsurface disposal of waste, detailed information should be obtained on the subsurface

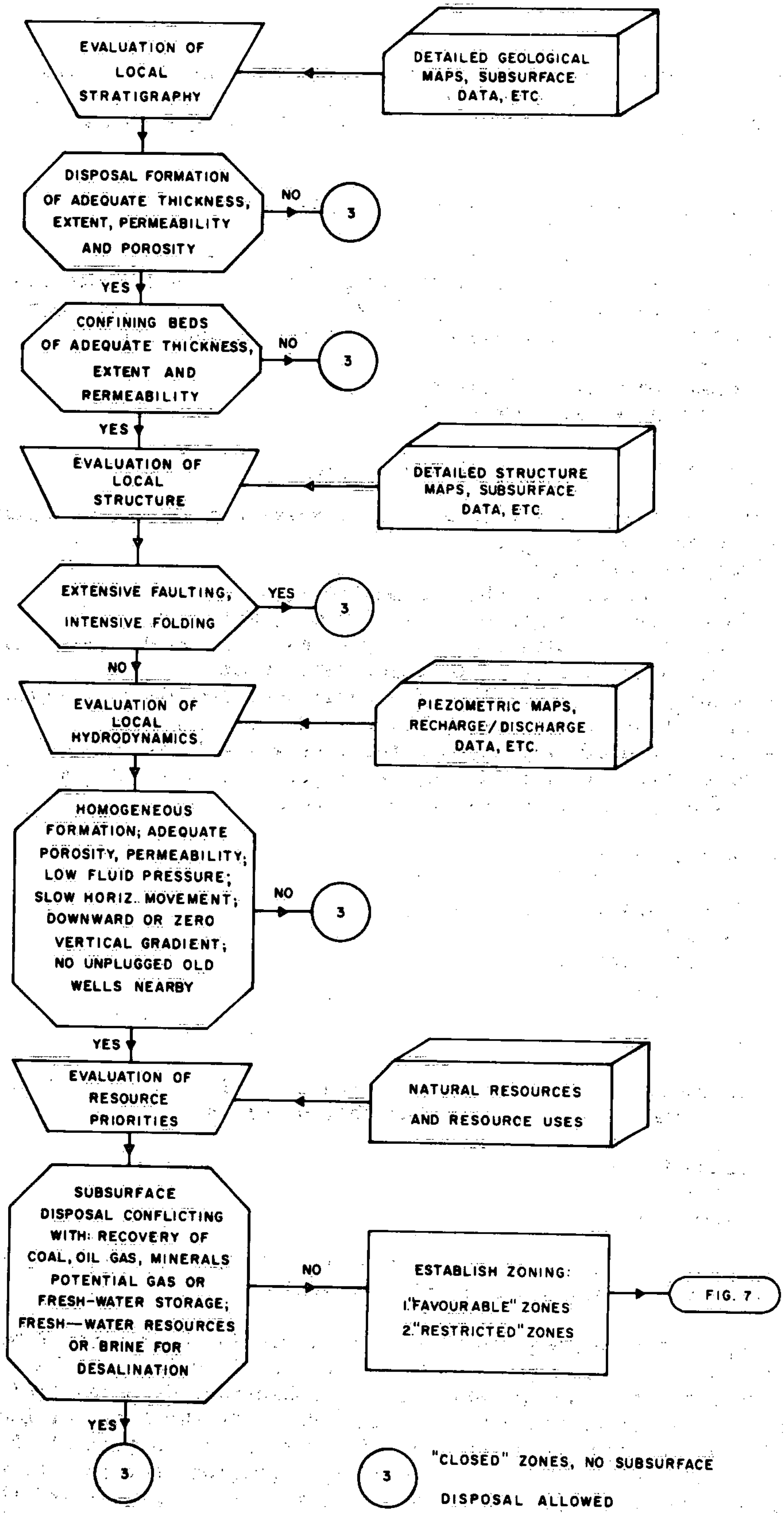

Figure 4. Selection of formations and areas for subsurface disposal of industrial waste.

conditions at the prospective site of a planned disposal facility. Problems would be minimized if the site were planned in a "favourable" zone within the region. The following methods should supply the information that is needed to evaluate the site.

a. *Drilling, coring, geophysical logging:*

- Stratigraphy at the site.
- Thickness and lithology of prospective disposal formations.
- Thickness and lithology of underlying and overlying confining strata.
- Location and thickness of potential freshwater aquifers.
- Porosities.
- Formation-water salinities.
- Formation temperatures.

b. *Drill-stem tests, pumping tests, injection tests;*

- Permeabilities of prospective disposal formation and confining beds.
- Storage coefficients.
- Compressibilities.
- Fluid pressures in the various formations.
- Character of formation fluids (water, oil, gas).
- Presence of faults or other hydrogeologic boundaries of either recharge, discharge or impermeable type.
- Magnitude and direction of natural hydrodynamic gradients.
- Prediction of pressure-distance-time relationships.
- Prediction of dispersion directions and velocities.
- Prediction of limiting injection pressure at which hydraulic fracturing can be expected to occur.

c. *Core analyses:*

- Water-saturation percentages.
- Porosities.
- Permeabilities.
- Lithology.

d. *Fluid analyses:*

- Character of formation fluids (water, oil, gas).
- Type and concentration of dissolved solids.
- pH
- Conductivity
- Density
- Viscosity

In areas of extensive exploration for oil and gas, much of the above information may be readily accessible for study.

Pump-test technology is highly developed in the fields of both groundwater hydrology and petroleum reservoir engineering. It has, however, not been used to its full potential in the subsurface disposal field, although reviews are provided by (43) and (88). On the basis of pump-test theory, it can be shown that the injection rate is a function of the permeability and thickness of the receiving formation, the injection pressure, the reservoir pressure, the viscosity of the fluids and the radius of the well (43). The volumes that can be injected at various injection pressures can be calculated. The increase in pressure with time at any distance from the well can also be predicted with reasonable confidence.

Nevertheless, the mechanics of injection of fluids into porous media is widely misunderstood. Many of the case histories in the bibliography use erroneous concepts of the fluid displacement processes. An excellent review of the misconceptions is provided by Piper (99). Perhaps the most prevalent misconception is that the ultimately available storage is equal to the total pore space. As stated by Piper:

> "The volume of waste that can be injected practically is at least 100-fold less than the aggregate pore space within the injection zone. The volume of waste that can be injected is limited to that achieved by compression of native and injected fluid, compression of reservoir rock, and by dilation (upward elongation) of the zone of influence, all under an acceptable injection pressure".

Detailed information should also be available on a number of waste characteristics, to enable evaluation of the compatibility of the waste with the geologic and hydrologic conditions at the prospective site.

e. *Waste characteristics:*

- Type and concentration (ranges) of all constituents, including dissolved, colloidal and suspended solids.
- Stability under subsurface conditions of temperature and pressure.
- Reactivity with formation rocks and fluids.
- Predicted heat generation (radioactive waste).
- Biological character
- Temperature
- Density
- Viscosity
- pH
- Gas content (type and concentration).
- Toxicity
- Predicted rate of production and anticipated total volume.

Next to nothing is known at present about chemical attenuation or modification of contaminants in the subsurface, whether by ion exchange, adsorption, fixation, chemical or biological degradation, or complexing. It should be assumed *a priori* that no attenuation is going to take place, and that potentially more toxic compounds could be formed through some of the above mentioned processes. Safety factors to be included in regulations should take this possibility into account.

Subsurface Waste-Disposal Facilities

1. *Drilling and Completion of Injection Well*

Standardization of procedures and materials to be used for drilling and completion of waste-disposal wells is not practicable, because well depth, waste type, waste volume, injection pressure, type of disposal formation and confining beds all have a bearing on the drilling and completion program. References (9), (88), (91) and (130) describe drilling methods, casing diameters and other details regarding installation of subsurface-disposal systems. Certain basic requirements should, however, be pointed out here.

Surface casing should in all cases be set through all potable water supplies and unconsolidated sediments; it should be cemented over its full length. Scrapers and casing centralizers should be employed. Once completed, the cementing job should be verified by temperature and cement bond logs, and pressure-tested.

Intermediate casing should be used where mineral extraction or other storage projects are making use of intermediate formations in the vicinity of the disposal site.

The type of completion to be used (perforated casing or open hole) depends to a large extent on the character of the disposal formation. In carbonate rocks with varying permeability, selective perforation followed by acidizing might have advantages. In this case the *long casing string* should be set below the disposal formation. If the disposal formation is uniform and of consistent permeability, open-hole completion might be favoured. Here the long casing string should be set in the overlying confining beds. In both cases the long casing should be cemented from the top of the disposal formation to the surface; the cementing job should again be verified by temperature and bond logs.

Injection tubing, set on a packer inside the long casing string, should be used for the waste injection. This way, the annular space between casing and tubing, closed off at the top with an appropriate flange, and filled with a non-corrosive liquid, can be used to monitor for leaks of either casing or tubing (annulus pressure monitor, Fig. 5). This is particularly important when the injected wastes and/or the natural brines in the formations overlying the disposal formation are very corrosive. Such corrosiveness should also be taken into account in the selection of casing and tubing grades, and of cement additives.

Stimulation techniques can be employed to improve the intake capacity of an injection well, or to prolong its useful life. Methods commonly used are acidizing, nitro-shooting, jetting, back-washing and hydraulic fracturing. The last of these methods should preferably not be used for waste-disposal wells, until more is known about its influence on the performance of confining strata (see next section and Chapter VII, 4).

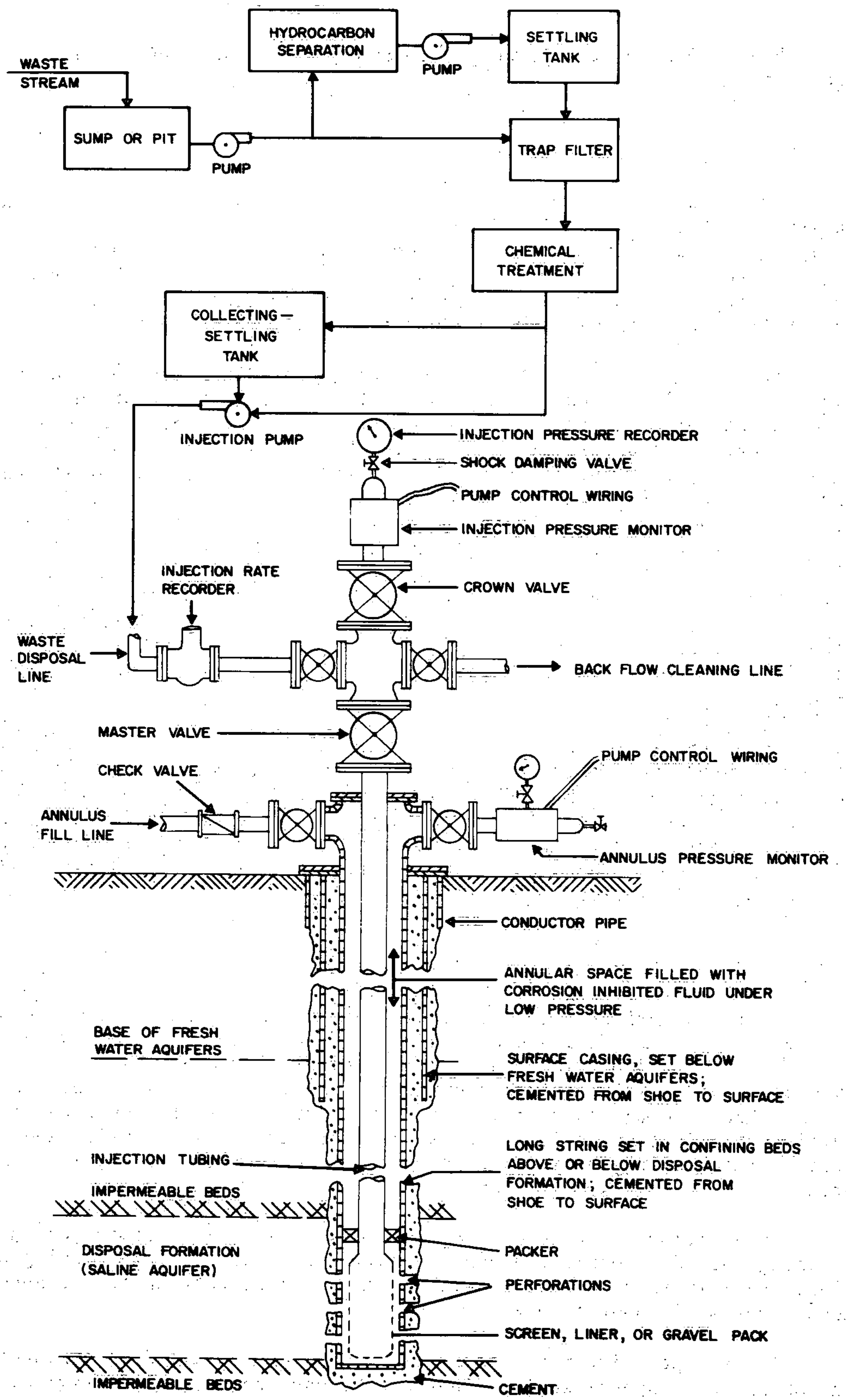

Figure 5. Schematic diagram of pre-injection treatment system and injection well.

Figure 5 shows the principal components of a subsurface waste disposal facility.

2. *Testing of Injection Well and Disposal Formation*

Once a disposal well has been completed and developed, the intake capacity of the system (well + disposal formation) must be determined. Usually this is done by means of a "stepped" water-injection test, in which injection pressures are increased stepwise. During the test, both the injection pressures and the injection rates are recorded. In general, a straight-line relation will be obtained for these two parameters.

If an injection test is carried to a high-enough pressure, a point of inflection will eventually be found on the pressure-*vs.*-input curve, indicating an abrupt increase in the injection rate per unit pressure. This point of inflection occurs at the "critical" input pressure, which is generally regarded as the pressure at which rupture or lifting of strata (hydraulic fracturing) occurs. The American Petroleum Institute (2) has stated that "subsequent reduction in (injection) pressure will *usually* result in closing of the (hydraulically opened) fractures". Where this is true, it is unlikely that any permanent damage was done to the confining beds. The test could thus be used to determine the maximum safe injection pressure for a newly-completed waste-disposal well. The uncertainty revealed by the word "usually" in the A.P.I. statement, however, indicates that indiscriminate use of this test may occasionally result in damage to the confining beds.

After the water-injection test, further tests should be run with the waste liquid, to determine whether a behaviour different from that during water injection can be expected during normal waste-disposal operations. *Input pressures should not approach the critical input pressure during these tests.* It should be borne in mind, that the same well-head pressure will lead to higher input pressures at the formation face when the density of the injected liquid is increased.

3. *Monitoring of Disposal Operations*

Every subsurface waste-disposal project should provide for *monitoring of injection pressure* (well-head pressure), *injection rate, waste density, injected volume,* and possibly *waste composition.* For the first three parameters. *continuous recording* should be mandatory, preferably coupled with an *alarm system* in the case of injection pressures. Regular spacing of intermittent injection periods and stabilization of waste density and injection rate would simplify analysis of the performance of the disposal system.

In addition, *fluid pressures in the annular space* between casing and tubing should be monitored continuously for leaks in either tubing or casing. Facilities should be available for pressure-testing of the annular space in cases of doubt (see Fig. 5).

It is imperative that *observation wells* be installed in conjunction with subsurface disposal wells. They can be used to determine original hydrodynamic gradients, and changes in gradient resulting from waste injection; they are necessary for proper interpretation of pump- and injection-test results; and they should subsequently be used to monitor formation pressures during waste injection. The magnitude and direction of waste movement could be calculated from the observed pressure changes with the aid of diffusion and dispersion theory. The waste itself may not reach the observation well (130), but this is not necessary for a prediction of the position of the waste "front".

The extent of the observation-well network needed would be determined by the geologic and hydrologic conditions near the disposal site, and by the character (toxicity) of the waste. Provisions should be made for *periodic sampling and analysis of fresh-water horizons near the disposal well* and around nearby abandoned bore holes, to enable early detection of contamination problems.

It should be stressed that the criteria and requirements for observation wells can only be quantified after sufficient knowledge has been accumulated. Initially, extensive monitoring by observation wells will be required to gain knowledge and experience that eventually may enable reduction of the requirements for future installations on a rational basis.

4. *Operational Safeguards*

Operational safeguards should be provided to ensure that no environmental damage results from shutdown or failure of a subsurface-disposal facility. Already mentioned was an alarm system coupled to the injection-pressure monitor. The few additional examples given below are intended only as an illustration; many more possible contingencies undoubtedly will have to be provided for.

A waste-injection well should be shut in automatically to prevent back-flow of waste when injection pressure drops suddenly as a result of pump failure or a break in a surface line.

Similarly, injection pumps should be turned off automatically when a sudden pressure-drop in the injection well indicates a possible tubing and/or casing failure.

Emergency storage on the surface should be available for waste produced during periods of shut-down of the disposal system, and to cope with the results of an accidental blow-out of the disposal well.

Stand-by pumping capacity would reduce the down time in cases of pump failure or shut-down for pump maintenance.

Alternate disposal should be available in case a waste-injection facility becomes disabled for an extended period of time, if the waste-producing process can not be discontinued.

Surface installations must in all cases be located and arranged in such a manner that failure of any part of the system can not lead to contamination of surface-water or ground-water resources.

5. *Abandonment of Injection Wells*

The object of proper abandonment of a waste-disposal well is to insure that waste is confined inside the disposal formation and that surface and subsurface resources will not be contaminated through the well. The recommended abandoning method includes removal of the injection tubing, followed by pressure cementing of the casing all the way from bottom to top with a neat-cement slurry. Other methods may give satisfactory results in some cases, but surface casing should always be left in the hole and abandoned with it. The site of an abandoned waste-disposal well should be permanently marked.

6. *Economics*

The total cost of a subsurface-disposal system depends on a number of factors (5, 37, 88, 142). Costs of drilling, testing, casing and development of the injection well depend on well depth, waste type, and anticipated injection pressure and injection rate. The cost of pumping equipment depends on waste type, and desired injection pressure and injection rate. Costs of waste-conditioning facilities depend on waste volume and type. Operating costs vary with extent of pre-injection treatment and waste volume.

Figures for capital cost ranging from $30,000 to about $4,000,000 have been quoted in the literature. The average cost reported for 1964 (37) was $200,000: $50,000 for the injection well, $125,000 for waste-conditioning facilities, and $25,000 for miscellaneous. Operating costs may vary from 2.5 to 35 cents per 1000 gallons of waste.

The amortization period of capital investment depends mainly on the expected useful well-life, taken to be about 20 years in reference (83). The well life is in turn largely determined by the factors listed below.

a. Deterioration of installation materials.

b. Ultimate storage capacity of the disposal formation.

c. Rate of increase in pressure with time needed to maintain the desired injection rate.

d. Degree of permeability reduction in the reservoir resulting from waste injection.

As pointed out earlier, the useful life of a disposal well could be extended by the use of stimulation techniques, if deterioration in performance is caused by the latter two of the above factors.

Reference (105) includes a list of economic criteria for the selection and use of a deep aquifer for waste injection. References (37), (69), (70), (138) and (142) contain extensive economic analyses, and many case histories include information on costs. An economic comparison of subsurface disposal systems with the alternate surface disposal systems is presented in (142). The analysis shows that capital investment at installation is comparable for the two methods, and that operating costs for subsurface disposal are an average of 5 times less than those for surface treatment. Two conclusions can be drawn:

1. Where injection is feasible, the economic advantages will soon be recognized by a wide range of industries, especially those under pressure to reduce surface-water pollution.

2. The economic advantages are so pronounced under present conditions, that the more restrictive approach encouraged in this report to insure environmental protection, will *not* put the method out of economic reach of industry.

CHAPTER 7

Failure of Subsurface Disposal Systems

1. *Types of Failures*

A general description of ways in which subsurface disposal systems can fail may be found in references (30), (37), (64), (105), (111) and (130). Failures can be grouped according to their principal causes as: *mechanical failures, failures due to waste properties,* and (regional) *geological failures.*

2. *Mechanical Failures*

A mechanical failure occurs when mechanical (construction or operation) problems prevent the completion of the well, or the operational delivery of design injection rates. Such failures often are of direct concern only to the industry involved; the public interest may be affected if pollution results from such failures. A number of different kinds of mechanical failure, their possible causes, and potential preventive measures are listed below.

a. Inability to complete the well, due to sanding back, unsuccessful packing or cementing, etc.

b. Leakage from the well, due to poorly set and sealed surface casing, leaks in casing, rupture in injection tubing, inadequate cementing job, insufficient corrosion resistance of construction materials.

c. Damage to pumps, lines, tubing and/or cement seals as a result of excessive pressure.

d. Damage to any part of the system resulting from an earthquake. (This could equally well be regarded as a geological failure).

Failures of the first two kinds should be preventable by proper drilling and installation methods; failures of the third kind must be prevented through the use of adequate materials, and the use of continuous pressure monitoring. The chances of failure through earthquake damage can only be minimized by avoiding areas with any appreciable seismicity.

3. *Failures due to Waste Properties*

Three kinds of waste properties, i.e., physical, biological and chemical, can lead to failure of a subsurface waste-disposal project.

a. *Physical properties of the waste.*

1. Reduction in formation permeability as a result of plugging by suspended solids, or by dissolved and entrained oxygen or other gases.

2. Unspecified damage resulting from heat generation by radioactive waste [relatively unimportant (103)].

b. *Biological properties of the waste.*

1. Reduction in formation permeability as a result of plugging of the formation through the actions of bacteria, algae, fungi or other microorganisms.

c. *Chemical properties of the waste.*

1. Reduction in formation permeability resulting from reactions between waste and natural formation fluid that produce precipitates and/or gases.

2. Reduction in formation permeability resulting from reactions between waste and formation rocks that produce precipitates and/or gases.

3. Reduction in formation permeability resulting from reactions in the waste itself (under formation pressure and temperature), that produce a precipitate and/or gas.

All of these failures should be predictable if proper *analyses* of waste, formation fluids and formation rocks are made *on representative samples*, and if *compatibility tests* are carried out in the laboratory *under conditions of temperature and pressure* closely *approximating those prevailing inside the disposal formation*. Results of such tests carried out at room temperature and under atmospheric pressure should be regarded as irrelevant. Adequate pre-injection treatment of the waste, based on the results of proper compatibility tests, should prevent the occurrence of waste-related failures. Figure 6 shows the various factors involved in a complete compatibility evaluation. A summary of undesirable waste properties and the procedures suggested for their treatment are listed in Table I.

4. *Geological Failures*

A geological failure occurs when the waste-injection process leads to unexpected contamination of other resources, or to physical damage to the geologic environment. A few different kinds of regional failure are listed below with their possible causes.

a. *Contamination of other resources by upward and/or downward migration of wastes* through:

1. permeable confining beds,

2. faults or joint systems,

3. unplugged abandoned wells penetrating the disposal formation,

4. damaged confining beds resulting from application of excessive injection pressures.

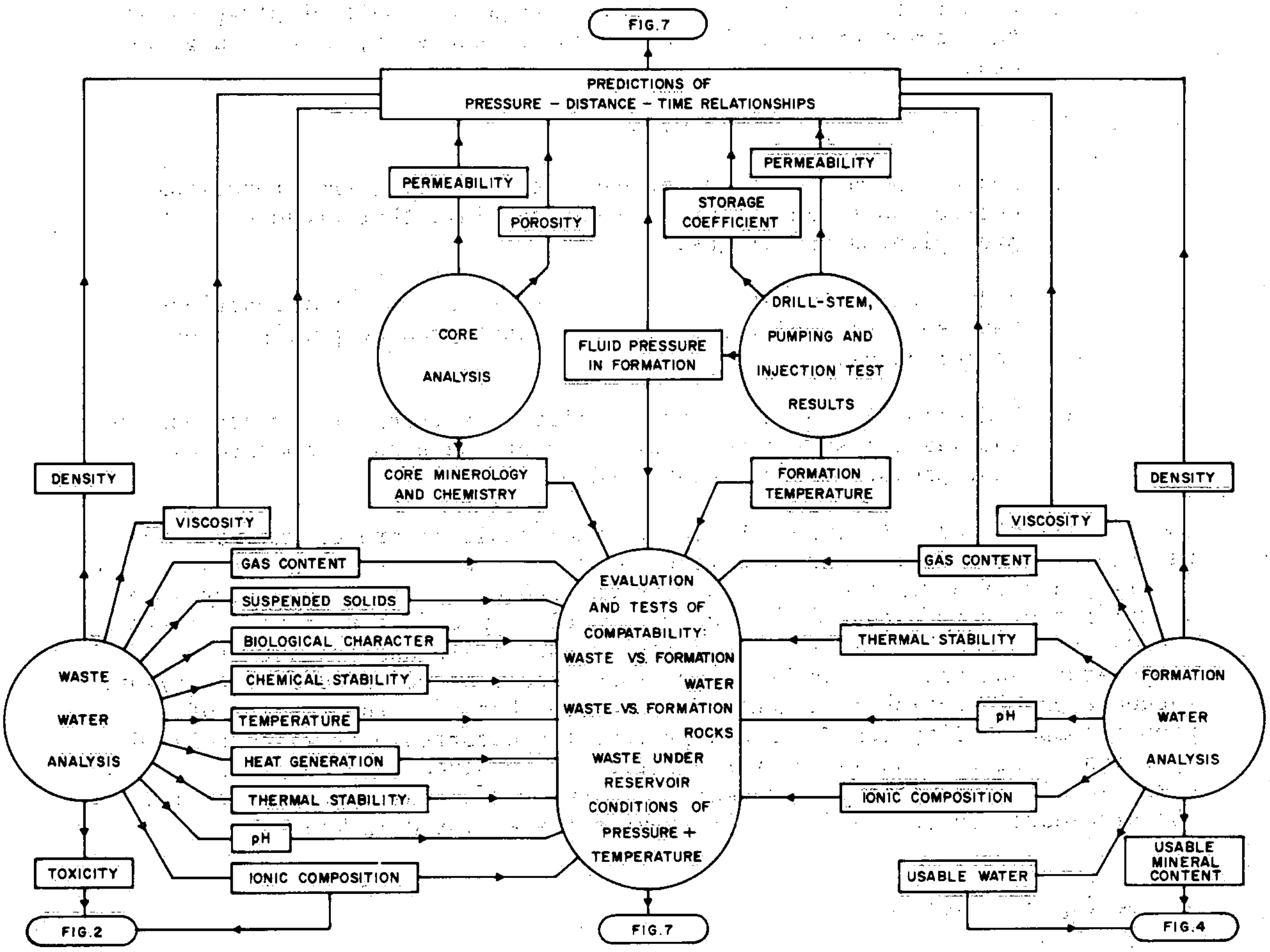

Figure 6. Use of analytical and test results in evaluation of planned subsurface disposal projects.

TABLE I

Summary of Undesirable Waste Constituents

Constituent	Suggested Treatment Procedure
Suspended Solids	Coagulation, sedimentation, filtration; max. suggested limit 1 ppm.
Organic Polymers or Resins	Effect complete removal by process control.
Dissolved Oxygen	Vacuum deaeration, steam stripping; max. suggested limit 0.05 ppm.
Bacteria	Sterilization by chlorine, heat or bactericides.
Alkaline Earth Ions (Ca, Mg, Sr; producing precipitates)	Treatment by aeration, settling, addition of lime, filtration, acidification. Removal of free CO_2 by stripping. Treatment should include recirculation with sludge to remove any super-saturation.
Heavy Metal Ions (Fe, Mn, Zn, Cu, Cd; producing precipitates)	Aeration to oxidize iron and manganese, followed by treatment with lime, settling, and filtration. Exclude air after iron removal.
Components leading to oxidation-reduction precipitates	Treat by oxidation or reduction to precipitate offending materials. Reduce chromates, oxidize sulfides and sulfites. Finished waste should not be oxidizing or strongly reducing.

b. *Contamination of other resources by unexpectedly rapid lateral movement of waste* caused by:

1. incorrect assessment of formation permeability and permeability distribution,

2. increased hydrodynamic gradients,

3. accelerated dispersion.

c. *Damage to geological environment through:*

1. earthquakes induced by waste injection.

Most, if not all, of the failures listed under a and b could be prevented by proper site and formation investigations. Failures of type c-1 could possibly also be avoided by proper site selection. Establishment of criteria for site and formation selection is thus urgently needed.

Failures resulting from a-4 should be prevented by a pressure-monitoring and alarm system. No reliable method has yet been established for the prediction of the "safe injection pressure". A rule of thumb states that hydraulic fracturing occurs at pressures at the formation face in the well ranging from 0.5 to 1.5 psi for each foot of well depth (88). A fairly extensive body of literature exists that deals with hydraulic fracturing (see Appendix B, Subject Index). The available theoretical development (60) has so far not been applied to the subsurface disposal problem; controlled hydraulic fracturing is, however, widely used as a stimulation technique in the oil industry. A study is underway in the United States to investigate the feasibility of injection of a mixture of radioactive waste and cement slurry into hydraulically-fractured impermeable shale beds (77, 139).

5. *Case Histories of Failures*

By far the best documented case of deep-well failure is that of the Rocky Mountain Arsenal well near Denver, Colorado. The subject index lists 9 references dealing with this particular case history; reference (42) provides a good summary. At the Rocky Mountain Arsenal, a direct correlation was made between volume and pressure of injected waste and seismic activity. Injection rates of 2 - 9 x 10^6 gal/month at injection pressures ranging from 0 - 1050 psi caused 710 earthquakes measuring up to 4.3 on the Richter scale over a period of 4 years.

Other case histories report lesser failures resulting from major drilling problems (40), and a corrosion failure leading to an explosive blowout (30) [this at a well that was described in two earlier case histories (4, 24)]. Regional leakage leading to contamination of surface and near-surface water has been mentioned, but not emphasized, in two papers (46, 81). Piper (99) noted that brine disposal into the Permian Basin in Texas and Oklahoma has increased salt-water seepage into streams.

Leakage through abandoned unplugged wells may be the sleeping monster. As yet there have been no documented cases, but as waste fronts advance, the likelihood of such leakage becomes greater. There may be as many as 30,000 unplugged wells in southwestern Ontario in the vicinity of the waste-disposal wells near Sarnia.

Trouble may even develop before injected waste reaches an unplugged abandoned well. An article in the Wall Street Journal (May 21, 1970, p. 29, col. 5) stated that two crude-oil seeps and one natural-gas seep have recently started from three abandoned wells in Port Huron, Michigan (under the post-office parking lot, under a private home, and beside a hospital, respectively). According to the report, the Michigan Department of Natural Resources claims that build-up of pressure resulting from subsurface disposal of chemical wastes in the Sarnia, Ontario area is responsible for the occurrence. No conclusive evidence to back up or refute this claim exists as yet. The urgent need for both research and the development of monitoring methods is well demonstrated by the variety of failures reported in the case histories.

Subsurface Disposal of Liquid Industrial Waste in Canada

1. *Waste Disposal Wells*

The number of waste-disposal wells in Canada is not very large as yet. There are 31 registered disposal wells, distributed as follows: 16 in Ontario, 10 in Alberta, 4 in Saskatchewan and 1 in Manitoba. Details about these wells are given in Table II. Disposal depths in Ontario are disturbingly shallow, generally less than 1000 ft. In the Western Canada Sedimentary Basin depths range from 1373 to 5087 ft. (top of disposal interval). This difference reflects the difference in available sediment thickness in the two areas.

For comparison purposes, some information concerning waste-disposal wells in the United States may be useful. As of January 1st, 1970, there were 124 recorded waste disposal wells in the United States (64, 99, and 132), with a distribution by industry as follows (5):

Chemical, petro-chemical, pharmaceutical	55%
Refineries, natural-gas plants	20%
Metal products (e.g., steel plants)	7%
Others	18%

A comparison of the distribution of well depths in the U.S. (5) with those in Canada (Table II) looks unfavourable as far as Canada is concerned, mainly as a result of the relative shallow depths of most of the waste disposal wells in Ontario.

Depth	U.S.	Canada
0 - 1,000 ft.	5%	42%
1,000 - 2,000 ft.	32%	19%
2,000 - 4,000 ft.	27%	32%
4,000 - 6,000 ft.	28%	7%
6,000 - 12,000 ft.	6%	0%
>12,000 ft.	2%	0%

TABLE II

Industrial Waste-Disposal Wells in Canada

Province	Well No.	Area	Formation	Disposal Depth (ft.)	Inj. Rate (gpm)	Inj. Press (psi)	Waste
Ontario	1	Sarnia	Detroit River	900	36	420	Spent refinery caustic
	2-6	Sarnia	Detroit River	700	10-30	300-350	Spent refinery caustic
	7	Sarnia	Detroit River	800	50	225	Spent refinery caustic
	8-9	Sarnia	Detroit River	800	80	180	Phenols
	10-12	Sarnia	Salina Salt	1900	-	Gravity	Waste oils
	13-14	Sarnia	Detroit River	800	90	380	Steam condensate water, with ammonia & CO_2
	15	Sarnia	Detroit River	800	30	Gravity	Hydrocarbon Chlorides & ethers, phenols
	16	Sarnia	Detroit River	850	4	275	Spent caustics and sulfuric acid
Alberta	17	Edmonton	Nisku	1373-1515	21	-	Alkaline brine, chlorinated phenols
	18	Edmonton	Nisku	2020-2190	63	-	Undefined plant residue
	19	Edmonton	Nisku	2007-2088	-	-	Undefined refinery wastes
	20	Edmonton	Nisku	1939-2159	23	-	Undefined refinery wastes
	21	Edmonton	Nisku	1974-2133	32	-	Refinery process water and spent lye
	22	Red Deer	Viking	5087-5128	-	50	Sulfuric acid from alkylation of butane and butylenes
	23	Edmonton	Nisku	1897-2002	291	-	Undefined refinery wastes
	24-26	Lloydminster	Sparky	2100-2800	19	-	Undefined refinery wastes
Saskatchewan	27	Regina	Nisku	3800	35	-	Spent caustic
	28	Regina	Blairmore	3565	50	-	Waste water
	29	Saskatoon	Blairmore	2000	29	-	Phenolic, non-phenolic and organic wastes
	30	Esterhazy	Interlake	3850-4037	600	900	Waste potash brine NaCl (+$MgCl_2$, $MgSO_4$)
			Winnipeg	4593-4673	50		
Manitoba	31	Virden	Lodgepole	2080-2142	<1	<1000 psi	Undefined refinery waste

Sources of Data: Ontario: (81); Alberta, Saskatchewan, Manitoba: Provincial Agencies (See Appendix A).

2. *Provincial Legislation and Regulations*

Information supplied by the Provincial agencies listed in Appendix A indicated that only one province, Ontario, has legislation specifically dealing with subsurface disposal of industrial waste. Like the legislation of Ohio (5) and Missouri, it is based largely on the pioneering legislation in this field by the State of Texas (45). Other provinces control subsurface disposal of industrial waste through legislation and regulations set up for related activities, such as control of disposal of oil-field waters or control of surface-water pollution. Although the latter approach may be less satisfactory than the use of specific legislation, it should be noted that in no case can subsurface disposal be carried out legally without the permission of some governmental regulatory agency.

Table III shows the legislative situation in Canada early in 1970. Only two provinces, Ontario and Quebec, have significant references to deep-well disposal of industrial waste in their statutes. Two others, Prince Edward Island and Nova Scotia have a single-line statement disallowing pollution through wells.

As far as regulation and control are concerned, only Ontario has invested authority in a regulatory agency. Quebec is in the process of writing regulations and presumably these will be in operation soon. Alberta, Saskatchewan and Manitoba do not have specific legislation for subsurface disposal of industrial wastes, but they do have legislation and supporting regulatory machinery for the control of subsurface disposal of salt water from oil-field operations. Manitoba has included "refinery wastes" in this legislation. New Brunswick, Nova Scotia, Prince Edward Island and Newfoundland do not have any established regulatory machinery for this purpose, but neither do they have any waste disposal wells in their territories.

3. *The Canada Water Act*

The Canada Water Act (Bill C-144) provides "for the management of the *water resources of Canada* including research and the planning and implementation of programs relating to the conservation, development and utilization of water resources."

Groundwater provides about 10 per cent of the municipal water supplies that serve communities with a population of 1000 or more, as well as a similar or larger proportion for smaller communities. In addition, large unrecorded industrial and agricultural water supplies are obtained from groundwater resources. Groundwater thus forms a significant part of the *water resources* of Canada, and as such its *conservation* is provided for under the Canada Water Act.

Subsurface disposal of liquid waste constitutes a potential threat to both surface and underground water resources. Subsurface disposal of liquid waste could thus be subject to control under the terms of the Canada Water Act. Regulations made under the Canada Water Act in the field of subsurface disposal of waste would apply to all territories under federal jurisdiction; to cases with international implications; and to cases involving more than one province. The Canada Water Act could, moreover, be used as a basis for a Federal-Provincial cooperative effort toward the formulation of country-wide, uniform regulations to deal with subsurface waste disposal.

TABLE III

Subsurface Waste-Disposal Legislation and Regulation in Canada

Province or Territory	B.C.	Alta.	Sask.	Man.	Ont.	Que.	N.B.	N.S.	P.E.I.	Nfld.	Yukon and Northwest Territories
Specific legislation for deep-well injection	No	No	No	No*	Yes	Yes	No	No	No	No	No
Established regulations and regulatory agency	No	No	No	No*	Yes	Yes (Proposed)	No	No	No	No	No
Regulation carried out under salt water disposal regulations	Yes	Yes	Yes	Yes	No	No	No	No	No	No	Yes
Legislation under which authority resides (or is assumed to reside)	Pollution Control Act	Oil & Gas Conservation Regulations	Oil & Gas Conservation Act	Clean Environment Act	Energy Act	Mining Act	Mining Act & Water Act	Water Act & Well Drilling Act	Well Drillers Act Regulations	Water Resources & Pollution Control Act	Canada Oil & Gas Drilling & Production Regulations
Research capability in subsurface disposal field	No	No	Yes	No	No	No	No	No	No	No	No
Number of industrial waste disposal systems	0	10	4	1	16	0	0	0	0	0	0

* Except 'refinery wastes' which are covered under salt-water disposal legislation and regulations

Regulation and Control of Subsurface Disposal

1. *Enabling Legislation*

The major purpose of enabling legislation covering the underground disposal of industrial waste would be to set up and/or to invest authority in a regulatory agency, and to define the nature of its regulatory program. As far as a possible Federal regulatory program is concerned, the Canada Water Act would serve as enabling legislation, as indicated in the foregoing chapter. Water management agencies to be set up under the Act have a purely local focus but have the virtue of being implementable in the immediate future.

Wherever specific legislation covering underground disposal of industrial waste does not exist, the necessary regulations could, of course, be made under existing Acts, such as those listed in Table III; special legislation, however, might be more suited to enable proper regulation and control of this potential environmental hazard. Country-wide uniformity in basic regulations, (as advocated in Chapter VIII), although generally not easily attainable utilizing existing provincial or federal legislation would simplify the solution of problems that involve more than one province. It would also prevent the emergence of subsurface disposal "havens", that might penalize those provinces that have established adequate, and thus restrictive regulations.

Provision could be made for the establishment of central or cooperative waste-disposal facilities which charge fees for underground disposal of wastes.

2. *Regulatory Program*

A number of requirements for the regulation and control of subsurface disposal of industrial waste can be outlined on the basis of the technical and scientific aspects discussed in the foregoing chapters. A summary is presented in Figure 7.

The first task of a regulatory agency would be to designate "potential", "limited", and "closed" disposal regions. As pointed out in Chapter IV-1, this first task could best be approached on a country-wide basis. Subsequently, potential disposal formations in regions of the first two types would have to be subdivided into "favourable", "restricted", or "closed" zones, as discussed in Chapter V-1.

For each proposed waste-disposal project, the following steps would in general have to be taken.

Step 1. *Feasibility study.*

a. Waste to be injected should be shown to qualify for subsurface disposal, according to guidelines like those given in Chapter II-4.

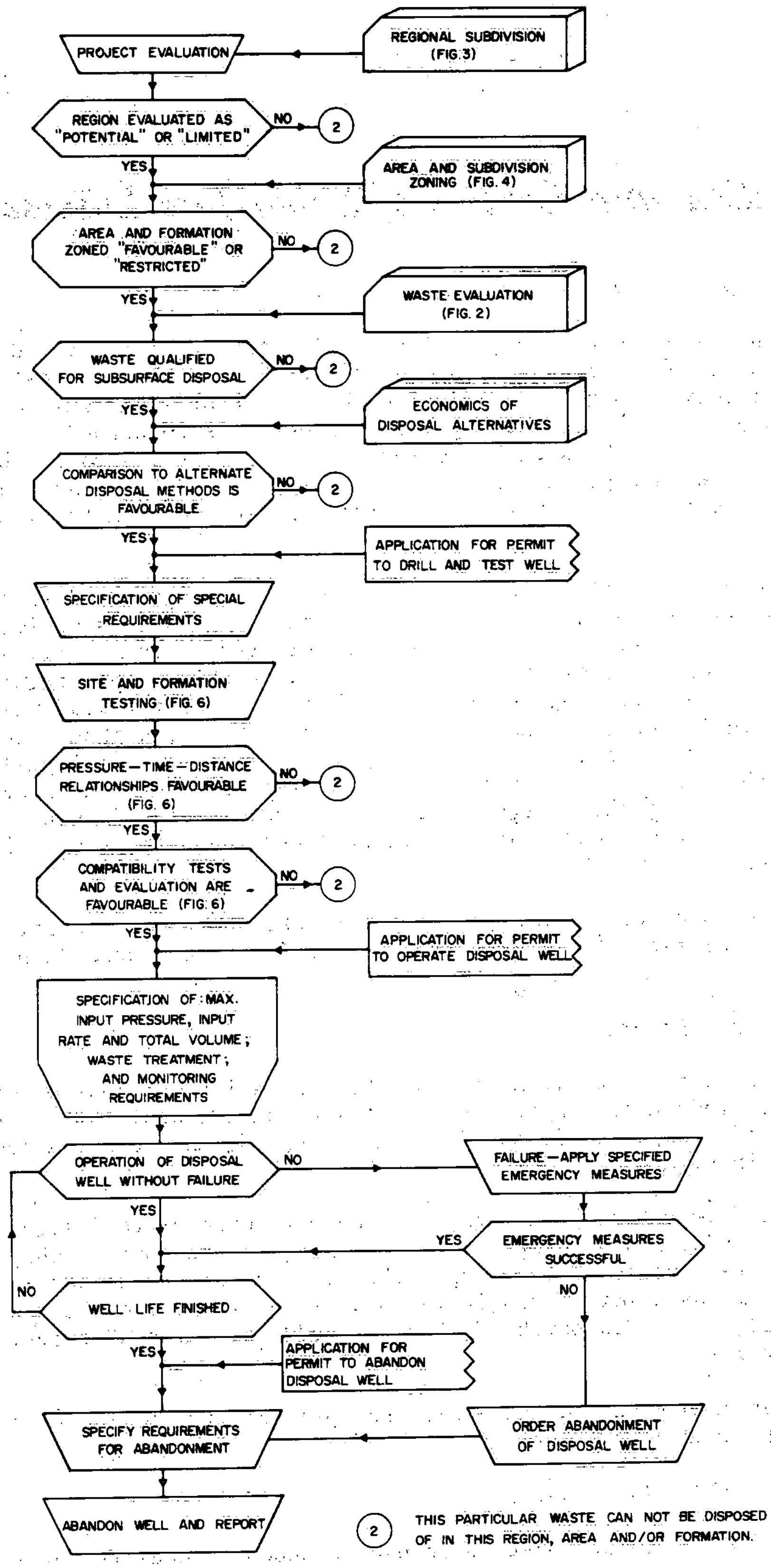

Figure 7. Evaluation and regulation of subsurface disposal of liquid industrial waste.

b. The applicant's feasibility study should show that the proposed disposal site falls within a "favourable" or "restricted" zone of one of the pre-established "potential" or "limited" regions.

Step 2. *Application for permit to drill and test a well.*

a. The applicant should supply the regulatory agency with plans and a description of the proposed drilling and testing program.

b. The regulatory agency could specify special conditions regarding drilling procedures and required testing, including installation of observation wells, in accordance with the "zoning" of the proposed site.

Step 3. *Drilling and testing.*

a. The applicant should comply with the above mentioned special conditions, and carry out all required testing necessary for proper evaluation of the site and disposal formation(s).

b. Interpretation of results of pumping or injection tests should be based on the most recent transient-flow analyses.

c. The applicant should be required to prepare a realistic prediction model of expected pressure fields, resultant lateral and vertical waste movement, and dispersion effects.

Step 4. *Application for permit to operate a disposal well.*

a. The applicant should furnish the regulatory agency with *all* test results.

b. The applicant should supply the agency with detailed plans and a description of the proposed disposal facility.

c. Permits should be issued only where a favourable combination of waste class, disposal region, disposal formation and disposal zone exists, and if plans for the proposed facility comply with minimum safety requirements.

d. The agency should specify maximum allowable injection pressure and injection rate, and may have to establish time or total-volume limits on the permit, in view of resource-management requirements (see Chapter III-2).

e. The agency should specify requirements regarding monitoring of:

1. Injection pressures and injection rates at the well head (continuous).

2. Waste properties (especially density) at the well head (preferably continuous).

3. Pressure in annular space between tubing and casing (continuous).

4. Pressure build-up and chemical analyses in observation wells (daily or weekly).

5. Chemical analyses of fresh-water supplies in the vicinity of the disposal well (weekly or monthly).

<u>NOTE</u> - A specific-injection-capacity test at regular intervals should not be required if the first four of these monitoring requirements are fulfilled properly.

f. The agency should reserve the right to suspend or revoke the permit in cases of:

1. Violation of any law, regulation or condition of permit.

2. Development of unforeseen hazards (Chapter VII).

3. Technical inadequacy of the installation (Chapters VI, VII).

g. Contingency procedures should be specified to handle accidents or unforeseen developments (see Chapter VI-4).

Step 5. *Operation of a disposal facility.*

a. The operator should comply with all requirements specified by the agency and should supply the agency regularly with reports on the operation, including monitoring results.

b. The agency should be empowered to inspect facilities for subsurface disposal whenever such is deemed desirable.

Step 6. *Application for abandonment of a disposal well.*

a. Applicant should state his reasons for wanting to abandon the disposal well, and describe the procedure to be used.

b. The regulatory agency should specify requirements for the proper abandonment of the disposal well (Chapter VI-5), in accordance with the "zoning" of the disposal site.

Step 7. *Abandonment*

a. The operator should comply with the agency's requirements as specified, and submit a report on the abandonment operation upon its completion.

b. The agency should maintain on file all records pertaining to waste injection wells within its jurisdiction.

c. Immediate abandonment could be contemplated in cases specified under Step 4-f; abandonment with a time limit for compliance could be requested whenever a superior alternative treatment (e.g., recycling, or re-use of waste constituents) becomes available for a particular waste that is currently being injected into the subsurface.

3. *Staffing Requirements*

A regulatory program can only be effective if a qualified staff is available to administer it. It should be stressed here that the staff of a regulatory agency in the field of subsurface waste disposal would be concerned not only with the purely administrative aspects, but also, at least as important, with all aspects relating to the evaluation of feasibility studies, test results, waste classification etc., as well as with control and enforcement of the regulations in the field. In addition they would be expected to give advice to the policymakers. The professional staff of the regulatory agency should thus cover a wide range of capabilities. Close liaison should be maintained with agencies in the field of water resources management, water pollution control, public health, fossil-fuel and mineral resources development, and geological surveys.

4. *Legal Liabilities and Constraints*

Discussions of legal ramifications that might arise from subsurface disposal projects are included in references (30) and (128). Two areas of potential litigation are related to contamination of groundwater supplies, and to interference with recovery of valuable mineral resources. Proceedings for the adjudication of such litigation have been based on the doctrines of *trespass*, *negligence*, *nuisance*, or *strict liability*. In the case of trespass, invasion of property rights of another person is implied, and damage has to be demonstrated; negligence is constituted by the failure to exercise reasonable care; nuisance implies only that a certain degree of interference occurred, regardless of the amount of care exercised; the doctrine of strict liability contends that fault is not a prerequisite, and its applicability to deep-well disposal depends on the determination of whether such an undertaking is inherently dangerous.

A further means for legal action in cases of subsurface pollution from underground waste disposal operations would be available when violation of a specific statute or regulation can be demonstrated.

From the foregoing sections it is again evident that much more extensive knowledge about the possible consequences of underground waste disposal, and about the behaviour of injected waste is urgently needed.

Research Needs

1. Basis Data and Present Knowledge

Future regulations covering the subsurface disposal of industrial waste can only be adequate, rational and equitable, when they are based on a firm understanding of the processes involved. Only then can a regulatory and control program be fully effective, and only then can the law courts be expected to solve ensuing legal conflicts in a just and enlightened manner. To accomplish these goals, extensive research will undoubtedly be needed, but full use should also be made of experience gained to date in related fields, and of available basic data.

Extensive experience has been accumulated by the petroleum industry in the fields of salt-water disposal and water injection for the secondary recovery of petroleum (5, 49). Unfortunately the experience gained from such projects may not be directly applicable to the waste-disposal field, because of some important differences.

a. "Natural" instead of "foreign" liquids are involved.

b. Brines are sometimes returned to the formation from which they were produced, thus tending to restore prior pressure conditions (99).

c. Injection is often under gravity flow, not under positive pressure (88).

d. In pressure-maintenance projects, other fluids are simultaneously withdrawn from the formation elsewhere, so that pressures tend to remain stable (88).

e. Detailed subsurface data are generally available for the disposal area, from prior exploration for oil and gas (133).

f. Required safety precautions are not nearly as stringent and subsurface movement is often not as critical, as in the case of noxious industrial waste (133).

g. Pre-injection treatment is usually relatively simple compared to that required for many industrial wastes (133, 150).

h. "Break-through" of injected water to a producing well is a disadvantage rather than a potential hazard.

Nevertheless, at least part of the experience gained from such operations will be of use in the evaluation and operation of waste-disposal schemes.

Much of the technology of subsurface exploration, well construction, testing and operation, developed by or for the petroleum industry, is of immediate use in the waste-disposal field. In addition, the exploration for petroleum as well as for other natural resources has produced a vast amount of subsurface data that could provide the basis for the initial appraisal of regional disposal potential. In some areas the available subsurface data may also significantly reduce the extent of exploratory work needed for future subsurface-disposal projects.

A continuing source of experience is of course provided by the approximately 160 industrial disposal wells now in operation in North America, as well as by a number of disposal projects in various parts of Europe [e.g., (46)]. This experience, as well as current research efforts by industrial and government agencies in the waste-disposal field, both in Europe and North America, should be taken into account whenever a research program is to be formulated.

In the following sections a number of subjects in need of research are identified under the major headings of physics, chemistry, technology, and waste management. It should be noted here, that research into subsurface disposal of waste is a wide-open field. Of the 142 references in the general bibliography, only four (96, 105, 113 and 131) can be classified as research studies directly related to injection of liquid waste into the subsurface.

2. *Physics*

a. Injection-well hydraulics.

1. Validity of pumping-test equations for injection tests.
2. Pressure-distance-time relationships under non-ideal geologic conditions.
3. Injection-well hydraulics in fractured media.
4. Validity of groundwater equations in low-permeability confining layers.
5. Optimization of observation-and-monitor-well design.

b. Stress mechanics.

1. Prediction of maximum safe injection pressure.
2. Physical nature of hydraulic fracturing and its relation to natural stress fields.
3. Effect of hydraulic fracturing on confining beds.
4. Possibility of positive use of hydraulic fracturing in subsurface disposal of waste.

c. Hydrodynamics.

1. Proper location of waste-disposal wells in relation to local and regional groundwater-flow systems.

2. Methods for prediction of both natural and induced hydrodynamic gradients.

3. Relative importance of geochemical osmosis as a fluid-driving force (98).

d. Dispersion.

1. Application of hydrodynamic-dispersion theory to injection of waste into the subsurface.

2. Nature of interface between waste and formation fluids; dispersion, fingering; gravitational segregation resulting from density differences.

3. Use of buffer zones.

e. Prediction models.

1. Numerical mathematical models with digital-computer solutions for the prediction of pressure fields, hydrodynamic gradients, and nature and shape of interfaces in complex, non-homogeneous and anistropic formations.

2. Methods for collection of data on waste movement and behaviour, to enable checking of model predictions.

f. Heat dissipation.

1. Heat from radioactivity of waste.

2. Heat produced by chemical reactions.

3. *Chemistry*

a. Waste classification.

1. Detailed quantitative criteria for classification of liquid industrial waste.

b. Compatibility problems.

1. Methods and equipment for sampling and testing of formation fluids under subsurface conditions of temperature and pressure.

2. Chemical interactions of various wastes with various types of formation fluids and formation rocks under subsurface conditions.

3. Chemical interactions between incompatible wastes in intersecting zones of influence of closely-spaced wells.

4. Changes in permeability resulting from various chemical reactions.

5. Waste conditioning to prevent incompatibility reactions.

c. Chemical modification of contaminants.

   1. Attenuation through ion exchange, adsorption, fixation, chemical (or biological) degradation.

   2. Formation of, or increase in, noxious properties through chemical degradation or formation of new compounds.

4. *Technology*

   a. Well design and construction methods.

   b. Long-term corrosion resistance of construction materials.

   c. Waste-conditioning installations.

   d. Monitoring installations.

      1. Pressure and chemistry transducers for installation in observation wells.

      2. Alarm and automatic shut-off systems.

5. *Waste Management and Economics*

   a. Reduction of waste volumes through modification of production processes.

   b. Processes for waste treatment that enable recycling, or re-use of waste constituents.

   c. Techniques for economic optimization of waste management (alternatives including subsurface disposal):

      1. on a plant basis,

      2. on an industry-wide basis,

      3. on a society-wide basis.

   d. Techniques for including environmental damage, resulting from pollution, into economic-optimization models.

   e. Waste management as part of the management of natural resources.

Conclusions

1. The storage capacity of geological formations is a limited natural resource, re-usable when used for gas or fresh-water storage, but not re-usable after use for the disposal of wastes.

2. Subsurface disposal of waste does not constitute *permanent* disposal in the strictest sense of the word. Rather, it detains waste in transitory storage; it may lead to irreversible pollution of a portion of the subsurface environment; injected waste may also reappear at the surface.

3. The volume of waste that can be injected under safe injection pressures is limited to that which can be provided by compression and displacement of original formation fluids and by compression of the formation rock; this represents only a fraction of the aggregate pore space.

4. Subsurface disposal should only be allowed for "natural" fluids and some classes of "foreign" fluids (as defined in Chapter II); a waste-classification system should be established on the basis of quantitative criteria, to enable a rational evaluation of individual cases.

5. Subsurface disposal of any waste should be discontinued as soon as an economical alternative treatment and/or disposal method, or a re-use or recovery process becomes available for such waste.

6. Proper management of subsurface space and the establishment of priorities for its use should preferably be approached on a regional basis.

7. A regional subdivision of the country, e.g., into "potential", "limited" and "closed" disposal regions, should be established; for this purpose some quantification of the qualitative criteria given in Chapter IV may be necessary.

8. Prospective disposal formations within "potential" and "limited" disposal regions should be zoned, e.g., as "favourable", "restricted" and "closed", for the purpose of subsurface disposal. Such zoning, as well as formation and site selection for particular disposal projects, should be based on quantitative criteria similar in nature to the qualitative criteria given in Chapter V.

9. All phases of a subsurface disposal project, from conception to abandonment, should be subject to regulation and control, to prevent failures and the creation of unnecessary environmental hazards.

10. Where injection is feasible, the economic advantages will soon be recognized by a wide range of industries, especially those under pressure to reduce surface-water pollution.

11. Economic advantages of the method are so pronounced under present regulations, that the more restrictive approach encouraged in this report, to ensure environmental protection, will not put the method out of the economic reach of industry. Justification of deep-well injection on a strictly financial basis should not be allowed.

12. The role of government in the field of subsurface waste disposal must be underlain by an environment-oriented philosophy, which can tolerate the method only if full protection of the public interest in the environment can be assured.

13. As of January 1970 there were 31 industrial-waste disposal wells in Canada; an increase in this number in the future is to be expected.

14. Only two provinces in Canada have legislation specifically covering deep-well injection of industrial wastes. Only Ontario has invested authority in a functioning regulatory agency; Quebec is in the process of establishing such an agency. The prairie provinces carry out a regulatory program under the authority of oilfield water-disposal statutes. The very real differences between saline-water and industrial-waste injection should be taken into account in future legislation, and in the design of scientific research programs.

15. Future legislation and regulations will have to reflect the position that subsurface storage capacity is a limited resource that should be conserved for maximum beneficial use.

16. Country-wide uniformity in basic regulations for the waste-disposal field would simplify enforcement and control by the limited professional manpower available.

17. The feasibility of centralized or co-operative injection facilities will have to be investigated; industries that produce wastes qualified for subsurface disposal could be encouraged to locate near "favourabled" zones in "potential" disposal regions.

18. Research is urgently required on a number of waste-disposal problems identified in Chapter X of this report.

APPENDIX A

1. *Provincial Agencies*

Alberta:

Development Department,
Oil and Gas Conservation Board,
603 - 6th Avenue S.W.,
Calgary 1, Alberta.

British Columbia:

Water Resources Service,
Department of Lands, Forests and Water Resources,
Parliament Buildings,
Victoria, B.C.

Manitoba:

Oil and Gas Conservation Board,
Mines Branch,
Department of Mines and Natural Resources,
901 Norquay Building,
Winnipeg 1, Manitoba.

New Brunswick:

Mines Division,
Department of Natural Resources,
P.O. Box 1270,
Fredericton, N.B.

Newfoundland:

Newfoundland and Labrador Water Authority,
St. Johns, Newfoundland.

Nova Scotia:

Nova Scotia Water Resources Commission,
Halifax, Nova Scotia.

Ontario:

Petroleum Resources Section,
Department of Energy and Resources Management,
880 Bay Street,
Toronto 181, Ontario.

Prince Edward Island:

P.E.I. Water Authority,
P.O. Box 2000,
Charlottetown, P.E.I.

Quebec:

Petroleum and Natural Gas Division,
Quebec Department of Natural Resources,
Quebec City, P.Q.

Saskatchewan:

Petroleum and Natural Gas Branch,
Department of Mineral Resources,
Government Administration Building,
Regina, Saskatchewan.

2. *Federal Agencies*

Department of the Environment

Hydrologic Sciences Division
- scientific research in hydrogeologic, hydrochemical and hydrodynamic aspects of deep-well injection.

Water Quality Division
- scientific research in industrial wastewater treatment.

Policy Research and Coordination Branch
- policy coordination
- economic analyses

Public Health Engineering Division
- Research and Development Section.

Department of Indian Affairs and Northern Development

Resource and Economic Development Group
Resource Management Division
- Mining Administrator
- Oil and Gas Administrator

3. *National Committees*

There are also three federally-sponsored committees in whose sphere the deep-well injection problem lies:

N.R.C. Associate Committee on Water Pollution Research.

N.R.C. Associate Committee on Geodesy and Geophysics, Subcommittee on Hydrology.

Mines Ministers Conference, Salt Water Disposal Committee.

APPENDIX B

1. *Bibliographic Listing*

Note: Capitalized references are either important contributions or major review articles.
References with numbers in parentheses were added during final review of the report; they are not referred to in the text, nor listed in the "Subject Index".

1. Adinoff, J. 1955. Disposal of organic chemical wastes to underground formations. 9th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 87: 32-38.

2. American Petroleum Institute. 1958. Problems in the disposal of radioactive waste in deep wells. Am. Petroleum Inst., Production Div., Dallas, Texas.

3. American Water Works Association. 1952-1960. Underground Waste Disposal Task Group Reports. Am. Water Works Assoc. Jour., v. 44: 685-689 (1952); v. 45: 1295-1297 (1953); v. 49: 1334-1342 (1957); v. 52: 1211-1219 (1960).

4. Anonymous. 1965. Operation deep-well. Water Well Jour., v. 19(5): 28-29.

5. Anonymous. 1968. Deep well injection is effective for waste disposal. Environ. Sci. and Technol., v. 2: 406-410.

6. Anonymous. 1970. Water pollutant or reusable resource? Environ. Sci. and Technol., v. 4: 380-382.

7. ARLIN, Z.E. 1962. DEEP-WELL DISPOSAL OF URANIUM TAILING WATER. PROC. 2ND CONF. GROUND DISPOSAL RADIOACT. WASTES, U.S. AT. ENERGY COMM. TID - 7628: 356-360.

8. Bardwell, G.E. 1966. Some statistical features of the relationship between Rocky Mountain Arsenal waste disposal and frequency of earthquakes. Mountain Geologist, v. 3(1): 37-42.

9. Barker, W.M. 1963. Waste disposal well completion and maintenance. Indus. Water and Wastes, v. 8(6): 43-47.

10. Barraclough, J.T. 1966. Waste injection into a deep limestone in northwestern Florida. Ground Water, v. 4(1): 22-24.

11. Batz, M.E. 1964. Deep well disposal of nylon waste water. Chem. Eng. Prog., v. 60(10): 85-88.

12. Beikman, H.M. 1962. Geology of the Powder River Basin, Wyoming and Montana with reference to subsurface disposal of radioactive wastes. U.S. Geol. Survey TEI - 823.

13. Bergstrom, R.E. 1968. Disposal of wastes: scientific and administrative considerations. Ill. State Geol. Survey Environ. Geology Note 20.

14. Bergstrom, R.E. 1968. Feasibility of subsurface disposal of industrial wastes in Illinois. Ill. State Geol. Survey Circ. 426.

15. BERGSTROM, R.E. 1968. FEASIBILITY CRITERIA FOR SUBSURFACE WASTE DISPOSAL IN ILLINOIS. GROUND WATER, v. 6(5): 5-9.

16. Bernard, G.B. 1955. Effect of reactions between interstitial and injected waters on permeability of rocks. Producers Monthly, v. 20(2): 26-32.

17. Billings, N.F. 1955. Some geological factors in underground waste disposal. 9th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 87: 132-137.

18. Birch, F. 1958. Thermal considerations in deep disposal of radioactive waste. Natl. Acad. Sci., Natl. Res. Counc. Publ. 588.

19. Bird, J.M., and H.M. Bullard. 1962. Use of subsurface flowmeter and fluid density analyzer for studying fluid flow in producing and injection wells. Producers Monthly, v. 26(2): 2-6.

20. Bovet, E.D. 1970. Industrial waste desalting for byproduct recovery. Am. Water Works Assoc. Jour., v. 62: 539-542.

21. BREDEHOEFT, J.F., C.R. BLYTH, W.A. WHITE, AND G.B. MAXEY. 1963. POSSIBLE MECHANISM FOR CONCENTRATION OF BRINES IN SUBSURFACE FORMATIONS. AM. ASSOC. PETROLEUM GEOLOGISTS BULL., v. 47: 257-269.

22. Briggs, L.I., Jr. 1968. Geology of subsurface waste disposal in Michigan Basin. In Subsurface Disposal in Geologic Basins, Am. Assoc. Petroleum Geologists Mem. 10: 128-153.

23. Brown, R.E., H.M. Parker, and J.M. Smith. 1955. Disposal of liquid wastes to the ground. Internat. Conf. Peaceful Uses of At. Energy Proc., Geneva, v. 9: 669-675.

24. Brown, R.W., and C.W. Spalding. 1966. Deep well disposal of spent hardwood pulping liquors. Water Pollution Control Federation Jour., v. 38: 1916-1924.

25. Caswell, C.A. 1970. Underground waste disposal: concepts and misconceptions. Environ. Sci. and Technol., v. 4: 642-647.

26. Cecil, L.K. 1950. Underground disposal of process waste water. Indus. Eng. Chemistry, v. 42: 594-599.

27. Cecil, L.K. 1950. Injection water treating problems. World Oil, v. 131(3): 176-180.

28. Cerini, W.F., W.R. Battles, and P.H. Jones. 1946. Some factors influencing the plugging characteristics of an oil well injection water. Am. Inst. Mining Metall. Engrs., Trans. Petroleum Div., v. 165: 52-63.

29. Clebsch, A., Jr., and E.H. Baltz. 1967. Progress in the U.S.A. towards deep-well disposal of liquid and gaseous radioactive wastes. In Disposal of Radioactive Wastes into the Ground, Internat. At. Energy Agency, Vienna: 591-605.

30. CLEARY, E.J., AND D.L. WARNER. 1969. PERSPECTIVE ON THE REGULATION OF UNDERGROUND INJECTION OF WASTEWATERS. OHIO RIVER VALLEY WATER SANITATION COMMISSION. (Abbreviated version in Am. Water Works Assoc. Jour., v. 62: 489-498, 1970).

31. Cleary, J.M. 1958, 1959. Hydraulic fracture theory. Ill. State Geol. Survey Circs. 251, 252 (1958) and 281 (1959).

32. Colton, C.W. 1961. Geological summary of the Appalachian Basin, with reference to the subsurface disposal of radioactive waste solutions. U.S. Geol. Survey TEI - 791.

33. Crawford, P.B. 1962. How to locate casing leaks and theft zones in water injection wells. Producers Monthly, v. 76(9): 6-7.

34. DEAN, B.T. 1965. THE DESIGN AND OPERATION OF A DEEP-WELL DISPOSAL SYSTEM. WATER POLLUTION CONTROL FEDERATION JOUR., v. 37: 245-254.

35. De Ropp, H.W. 1951. Chemical waste disposal at Victoria, Texas, plant of the DuPont Co. Sewage and Indus. Wastes, v. 23(2): 194.

36. De Witt, W., Jr. 1960. Geology of the Michigan Basin with reference to the subsurface disposal of radioactive wastes. U.S. Geol. Survey TEI - 771.

37. DONALDSON, E.C. 1964. SUBSURFACE DISPOSAL OF INDUSTRIAL WASTES IN THE UNITED STATES. U.S. BUR. MINES INFO. CIRC. 8212.

38. DRESCHER, W.J. 1965. HYDROLOGY OF DEEP-WELL DISPOSAL OF RADIOACTIVE LIQUID WASTE. AM. ASSOC. PETROLEUM GEOLOGISTS MEM. 4: 399-406.

39. Edmund, R.W., and E.D. Goebel. 1968. Subsurface waste-disposal potential in Salina basin of Kansas. In Subsurface Disposal in Geologic Basins, Am. Assoc. Petroleum Geologists Mem. 10: 154-164.

40. Elliot, A.M. 1967. Subsurface waste disposal problems. 7th Indus. Water and Waste Conf. Proc., Univ. Texas, pt. III: 37-47.

41. Evans, D.M. 1966. The Denver earthquakes and the Rocky Mountain Arsenal disposal well. Mountain Geologist, v. 3(1): 23-36.

42. EVANS, D.M. 1966. MAN-MADE EARTHQUAKES IN DENVER. GEOTIMES, MAY/JUNE: 11-18.

43. EVERDINGEN, A.F. VAN. 1968. FLUID MECHANICS OF DEEP-WELL DISPOSALS. IN SUBSURFACE DISPOSAL IN GEOLOGIC BASINS, AM. ASSOC. PETROLEUM GEOLOGISTS MEM. 10: 32-42.

44. Ewing, R.C. 1968. Refinery waste products pose pollution problem. Oil and Gas Jour., v. 66(50): 77-82.

45. FINK, B.E. 1967. STATE REGULATION OF SUBSURFACE WASTE DISPOSAL IN TEXAS. 7TH INDUS. WATER AND WASTE CONF. PROC., UNIV. TEXAS, PT. III: 58-63.

46. Finkenwirth, A. 1967. Deep well disposal of waste brine in the Werra potash region. Internat. Assoc. Hydrogeologists Mem. VII: 123-129.

47. Finkenwirth, A. 1968. Injection d'eaux résiduaires industrielles en profondeur dans le sous-sol. Tribune du CEBEDEAU, 299: 1-9.

48. Galley, J.E. 1962. Geologic basin studies as related to deep well disposal. In Proc. 2nd Conf. on Ground Disposal of Radioactive Wastes, Chalk River, Canada.

49. GALLEY, J.E. 1968. ECONOMIC AND INDUSTRIAL POTENTIAL OF GEOLOGIC BASINS AND RESERVOIR STRATA. IN SUBSURFACE DISPOSAL IN GEOLOGIC BASINS, AM. ASSOC. PETROLEUM GEOLOGISTS MEM. 10: 1-10.

50. Garbarini, G.S., and H.K. Veal. 1968. Potential of Denver basin for disposal of liquid wastes. In Subsurface Disposal in Geologic Basins, Am. Assoc. Petroleum Geologists Mem. 10: 165-185.

51. Garcia-Bengochea, J.I., and R.O. Vernon. 1970. Deepwell disposal of waste waters in saline aquifers of South Florida. Water Resources Res., v. 6: 1454-1470.

(51a) Goolsby, D.A. 1971. Hydrochemical effects of injecting waste into a limestone aquifer near Pensacola, Florida. Ground Water, v. 9(1): 13-19.

52. Hardaway, J.E. 1968. Possibilities for subsurface waste disposal in a structural syncline in Pennsylvania. In Subsurface Disposal in Geologic Basins, Am. Assoc. Petroleum Geologists Mem. 10: 93-127.

53. Harlow, I.F. 1939. Waste problem of a chemical company. Indus. Eng. Chemistry, v. 31: 1345-1349.

54. Harrison, E., W.F. Kieschnick, Jr., and W.J. McGuire. 1954. The mechanics of fracture induction and extension. Am. Inst. Mining Metall. Engrs., Trans. Petroleum Div., v. 201: 252-263, 317-321.

55. Hartman, C.D. 1968. Deep-well disposal of steel-mill wastes. Water Pollution Control Federation Jour., v. 40: 95-100.

56. HENKEL, H.O. 1968. DEEP-WELL DISPOSAL OF CHEMICAL WASTE WATER. POWER, v. 112(3): 82-85.

57. Hess, H.H. *et al.* 1957. The disposal of radioactive waste on land. Natl. Acad. Sci., Natl. Res. Counc. Publ. 519.

58. Holland, H.R., and F.R. Clark. 1965. A disposal well for spent sulfuric acid from alkylating isobutane and butylenes. 19th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 117, pt 1: 195-199.

59. Hoover, D.B., and J.A. Dietrich. 1969. Seismic activity during the 1968 test pumping at the Rocky Mountain Arsenal disposal well. U.S. Geol. Survey Circ. 613.

(59a) Hoppe, W. 1962. Grundlagen, Auswirkungen und Aussichten der Kaliabwasserversenkung im Werra-Kaligebiet. Geologie, v. 11, Hft. 9: 1059-1086.

60. HUBBERT, M.K., AND D.G. WILLIS. 1957. MECHANICS OF HYDRAULIC FRACTURING. AM. INST. MINING METALL. ENGRS., JOUR. PETROLEUM TECHNOL., v. 210: 153-168.

61. Hundley, C.L., and J.T. Matulis. 1962. Deep-well disposal. 17th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 112: 175-180.

62. Hundley, C.L., and J.T. Matulis. 1963. Deep-well disposal. Ground Water, v. 1(2): 15-17.

63. Inoue, Y., and W.K. Kaufman. 1962. Deep well injection of radioactive wastes. Health Physics Soc. An. Mtg.

64. INTERSTATE OIL COMPACT COMMISSION. 1968. SUBSURFACE DISPOSAL OF INDUSTRIAL WASTES. A STUDY CONDUCTED BY RESEARCH COMM., OKLA. CITY, OKLA.

65. Jukkola, W.H. 1967. Deep-well disposal of liquid wastes. 39th Ann. Conf. Water Pollution Control Assoc. Penn., Penn.State Univ.

66. Kaufman, W.J., *et al.* 1961. Disposal of radioactive wastes into deep geologic formations. Water Pollution Control Federation Jour., v. 33(1): 73-84.

67. Kehle, R.O. 1964. The determination of tectonic stresses through analysis of hydraulic well fracturing. Jour. Geophys. Res., v. 69: 259-273.

68. Klotzman, M., and B. Vier. 1966. Celanese Chemical pumps waste into disposal wells. Oil and Gas Jour., v. 64(15): 84-87.

69. Koenig, L. 1958. Disposal of saline water conversion brines - an orientation study. U.S. Dept. Int., Office of Saline Water Res. and Devel. Prog. Rept. 20.

70. KOENIG, L. 1964. ULTIMATE DISPOSAL OF ADVANCED WASTES. U.S. PUBL. HEALTH SERV. AWTR - 8, 999-WP-10, Pt. 1.

71. Kohout, F.A. 1970. Reorientation of our saline water resources thinking. Water Resources Res., v. 6: 1442-1448.

(71a) Korotchansky, A.N. 1969. Injection des effluents industriels dans les couches profondes du sous-sol. Annales des Mines, May: 43-63.

72. Lacey, W.J. 1961. Laboratory work on certain aspects of the deep well disposal problem. Health Physics, v. 4: 228-231.

73. Laguna, W. de, and J.O. Blomke. 1957. The disposal of power reactor waste into deep wells. U.S. At. Energy Comm. CF-57-6-23, Wash., D.C.

74. Laguna, W. de. 1959. What is safe waste disposal? At. Sci. Bull., v. 15: 34-43.

75. Laguna, W. de, and B.L. Houser. 1960. Disposal of radioactive waste by hydraulic fracturing. U.S. At. Energy Comm. ORNL 2994: 128-136.

76. Laguna, W. de. 1962. Engineering geology of radioactive waste disposal. Geol Soc. America Eng. Geology Rev., v. 1: 129-160.

77. LAGUNA, W. DE. 1966. DISPOSAL OF RADIOACTIVE WASTES BY HYDRAULIC FRACTURING. NUCL. ENG. AND DESIGN, v. 3: 338-352; v. 3: 432-438.

(78a) Laguna, W. de. 1970. Radioactive waste disposal by hydraulic fracturing. Indus. Water Eng., v. 7, Oct: 32-37.

79. Laird, R.W., and A.F. Cogbill. 1958. Incompatible waters can plug oil sand. World Oil, v. 146(6): 188-190.

80. Lansing, A.C., and P.S. Hewett. 1955. Disposal of phenolic waste to underground formations. 9th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 87: 184-194.

81. Lee, J.A. 1950. Throw your wastes down a well. Chem. Eng., v. 57(9): 137-138.

82. LeGrand, H.E. 1962. Geology and groundwater hydrology of the Atlantic and Gulf Coastal Plain as related to disposal of radioactive wastes. U.S. Geol. Survey TEI - 805.

83. LeGros, P.G., C.E. Gustafson, G.L. Nevill, E.C. Majeske, R.D. Mathews, J.S. Talbot, and W.F. McIlhenny. 1969. A study of deep-well disposal of desalination brine waste. U.S. Dept. Interior, Office Of Saline Water Res. and Devel. Prog. Rept. 456.

84. Lockett, D.E. 1967. Subsurface disposal of industrial wastewater. 7th Indus. Water and Waste Conf. Proc., Univ. Texas, pt. III: 48-57.

85. Love, J.D., and L. Hoover. 1961. A summary of the geology of sedimentary basins of the United States, with reference to the disposal of radioactive wastes. U.S. Geol. Survey TEI - 768.

(85a) Lum, Daniel. 1969. Preliminary report on geohydrologic exploration for deep well disposal of effluent, Waimanalo sewage treatment plant, Oahu. Hawaii Dept. Land Natl. Resources, Div. Water Land Managem. Circ. C54.

86. Lynn, R.D., and Z.E. Arlin. 1962. Anaconda successfully disposes uranium mill waste water by deep well injection. Mining Eng., v. 14(7): 49-52.

87. MacLachlan, M.E. 1964. The Anadarko Basin (of parts of Oklahoma, Kansas, Texas and Colorado). U.S. Geol. Survey TEI - 831.

88. McLEAN, D.D. 1968. SUBSURFACE DISPOSAL OF LIQUID WASTES IN ONTARIO. ONTARIO DEPT. OF ENERGY AND RESOURCES MANAGEMENT PAPER 68 - 2.

89. McLean, D.D. 1969. Subsurface disposal: precautionary measures. Indus. Water Eng., v. 6(8): 20-22.

90. MacLeod, I.C. 1961. Disposal of spent caustic and phenolic water in deep wells. 8th Ontario Indus. Waste Conf. Proc.: 49-60.

91. MARSH, J.H. 1968. DESIGN OF WASTE DISPOSAL WELLS. GROUND WATER, v. 6(2): 4-8.

92. McCann, T.P., N.C. Privrasky, F.L. Stead, and J.E. Wilson. 1968. Possibilities for disposal of industrial wastes in subsurface rocks on North Flank of Appalachian Basin in New York. In Subsurface Disposal in Geologic Basins, Am. Assoc. Petroleum Geologists Mem. 10: 43-92.

93. Mechem, O.E., and J.H. Garrett. 1963. Deep injection disposal well for liquid toxic waste. Am. Soc. Civil Engrs. Proc., v. 89(CO2): 111-121.

(93a) Moyen, D., and P. Rognon. 1970. Rejet dans les couches géologiques profondes d'eaux résiduaires industrielles. Techn. et Sci. Municip.-l'Eau, v. 65: 215-219.

94. Nace, R.L. 1960. Contributions of geology to the problems of radioactive waste disposal. In Disposal of Radioactive Wastes, Internat. At. Energy Agency, Vienna, v. 2: 457-480.

95. Nace, R.L. 1961. Underground storage of radioactive wastes. Interstate Oil Compact Comm. Bull., v. 3(1).

(95a) Obermann, P. 1967. Die hydrogeologischen Möglichkeiten für die Versenkung von Solen und Oberflächenwasser im Bereich des Ruhrgebietes. Mitt. Westfälischen Berggewerkschafts Kasse, Bochum, Hft. 27.

96. Orcutt, R.G., M.N.E. Rifai, B. Klein, and W.J. Kaufman. 1957. Underground movement of radioactive wastes. Sewage and Indus. Wastes, v. 29: 791-804.

97. Paradisio, S.J. 1956. Disposal of fine chemical wastes. 10th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 89: 49-60.

(97a) Payne, R.W. 1970. Waste disposal well performance. Water and Wastes Eng., July: D14-D18.

98. Pickett, G.R. 1968. Properties of Rocky Mountain Arsenal disposal reservoir and their relation to Derby earthquakes. Colo. School Mines Quart., v. 63(1): 73-100.

99. PIPER, A. 1970. DISPOSAL OF LIQUID WASTES BY INJECTION UNDERGROUND - NEITHER MYTH NOR MILLENNIUM. U.S. GEOL. SURVEY CIRC. 631.

100. Polumbus, E.A., Jr., and Associates. 1961. Drilling of pressure injection disposal well, Rocky Mountain Arsenal, Denver, Colorado, v. I.

(100a) Poschke, K. 1965. Praktische Erfahrungen beim Betrieb der Laugenversenkanlagen im Kalikombinat "Werra". Freib. Forschungshefte, Leipzig, A 354, Aufbereitung: 7-21.

101. Querio, C.W., and T.J. Powers. 1962. Deep-well disposal of industrial wastewater. Water Pollution Control Federation Jour., v. 34(2): 36-144.

102. Repenning, C.A. 1959. Geologic summary of the San Juan Basin, New Mexico, with reference to disposal of liquid radioactive waste. U.S. Geol. Survey TEI - 603.

103. Repenning, C.A. 1961. Geologic summary of the Central Valley of California with reference to disposal of liquid radioactive waste. U.S. Geol. Survey TEI - 769.

104. Roedder, E. 1957. Atomic waste disposal by injection into aquifers. In Advances in Nuclear Engineering, J.R. Dunning and B.R. Prentice (Ed.), v. 1, pt. 1: 359-371. Pergamon Press.

105. ROEDDER, E. 1959. PROBLEMS IN THE DISPOSAL OF ACID ALUMINUM NITRATE HIGH-LEVEL RADIOACTIVE WASTE SOLUTIONS BY INJECTION INTO DEEP-LYING PERMEABLE FORMATIONS. U.S. GEOL. SURVEY BULL. 1088.

106. Sadow, R.D. 1963. How Monsanto handles its petrochemical wastes. Wastes Eng., Dec.: 640-644.

107. Sadow, R.D. 1966. Waste treatment at a large petrochemical plant. Water Pollution Control Federation Jour., v. 38: 428-441.

108. Sandberg, C.A. 1962. Geology of the Williston Basin, Montana, North Dakota and South Dakota, with reference to subsurface disposal of radioactive wastes. U.S. Geol. Survey TEI - 809.

109. Scopel, L.J. 1964. Pressure injection disposal well, Rocky Mountain Arsenal, Denver, Colorado. Mountain Geologist, v. 1(1): 35-42.

110. Selme, R.F., and B.T. Hulse. 1959. Deep-well disposal of industrial wastes. 14th Indus. Waste Conf. Proc., Purdue Univ. Eng. Ext. Ser. 104: 566-586.

111. SELME, R.F., AND B.T. HULSE. 1960. DEEP WELL DISPOSAL OF INDUSTRIAL WASTES. CHEM. ENG. PROG., v. 56(5): 138-144.

112. SHELDRICK, M.G. 1969. DEEP-WELL DISPOSAL: ARE SAFEGUARDS BEING IGNORED? CHEM. ENG., APR. 7: 74-78.

113. SKIBITZKE, H.E. 1961. TEMPERATURE RISE WITHIN RADIOACTIVE LIQUID WASTES INJECTED INTO DEEP FORMATIONS. U.S. GEOL. SURVEY PROF. PAPER 386-A.

114. Snow, D.T. 1968. Hydraulic characteristics of fractured metamorphic rocks of front Range and implications to the Rocky Mountain Arsenal well. Colo. School Mines Quart., v. 63(1): 167-199.

115. Spalding, C.W., D.L. Hakalo, and H.S. Carpenter, Jr. 1965. Deep-well disposal of spent pulping liquors. Tech. Assoc. Pulp and Paper Industries, v. 48(5): 68A-71A.

116. Stahl, C.D. 1962. Compatibility of interstitial and injection waters. Producers Monthly, Nov.: 14-15.

117. Stefanko, R., K. Vonder Linden, and V.G. Tilton. 1965. Subsurface disposal of acid mine water by injection wells. Penn. State Univ. Spec. Res. Rept. SR-52.

118. Stefanko, R., K. Vonder Linden, and V.G. Tilton. 1967. Development and testing of an injection well for the subsurface disposal of acid mine water. Penn. State Univ. Spec. Res. Rept. SR-60.

119. Stefanko, R., K. Vonder Linden, and V.G. Tilton. 1967. Potential injection well strata for acid mine water disposal in Pennsylvania. Penn. State Univ. Spec. Res. Rept. SR-66.

120. Stewart, R.S. 1968. Techniques of deep-well disposal--a safe and efficient method of pollution control. 15th Ontario Indus. Waste Conf. Proc.

121. Stiff, H.A., Jr., and L.E. Davis. 1952. A method for predicting the tendency of oil field waters to deposit calcium sulfate. Am. Inst. Mining Metall. Engrs., Trans. Petroleum Div., v. 195: 25-28.

122. Stiff, H.A., Jr., and L.E. Davis. 1952. A method for predicting the tendency of oil field waters to deposit calcium carbonate. Am. Inst. Mining Metall. Engrs., Trans. Petroleum Div., v. 195: 213-216.

123. Talbot, J.S. 1967. Some basic factors in the consideration and installation of deep well disposal systems. 7th Indus. Water and Waste Conf. Proc., Univ. Texas, pt. III: 1-24.

124. Talbot, J.S., and P. Beardon. 1964. The deep well method of industrial waste disposal. Chem. Eng. Prog., v. 60(1): 49-52.

125. Theis, C.V. 1955. Geologic and hydrologic factors in ground disposal of waste. Sanit. Eng. Conf. Baltimore, U.S. At. Energy Comm. WASH - 275: 261-283.

(125a) Theis, C.V. 1956. Problems of ground disposal of nuclear wastes. Internat. Conf. Peaceful Uses At. Energy Proc., Geneva, 1955, v. 9: 679-683.

126. U.S. Dept. HEW. 1961. Symposium on groundwater contamination. Robt. A. Taft Sanit. Eng. Center Tech. Rept. W 61 - 5.

127. Veir, B.D. 1967. Celanese deep-well disposal practices. 7th Indus. Water and Waste Conf. Proc., Univ. Texas, pt. III: 25-36.

128. Walker, W.R., and R.C. Stewart. 1968. Deep-well disposal of wastes. Am. Soc. Civil Engrs. Proc., v. 94(SA5): 945-966.

129. Warner, D.L. 1965. Deep-well disposal of industrial wastes. Chem. Eng., Jan. 4.

130. WARNER, D.L. 1965. DEEP-WELL INJECTION OF LIQUID WASTE: A REVIEW OF EXISTING KNOWLEDGE AND AN EVALUATION OF RESEARCH NEEDS. U.S. PUBLIC HEALTH SERVICE, ENVIRONMENTAL HEALTH SERIES PUBL. 999 - WP - 21.

131. WARNER, D.L. 1966. DEEP-WELL WASTE INJECTION - REACTION WITH AQUIFER WATER. AM. SOC. CIVIL ENGRS. PROC., v. 92(SA4): 45-69.

132. Warner, D.L. 1967. Deep wells for industrial waste injection in the U.S. - summary of data. U.S. Fed. Water Pollution Control Admin., Water Pollution Control Res. Ser. Pub. WP-20-10.

133. WARNER, D.L. 1968. SUBSURFACE DISPOSAL OF LIQUID INDUSTRIAL WASTES BY DEEP-WELL INJECTION. IN SUBSURFACE DISPOSAL IN GEOLOGIC BASINS, AM. ASSOC. PETROLEUM GEOLOGISTS MEM. 10: 11-20.

134. Warner, D.L. 1970. Regulatory aspects of liquid waste injection into saline aquifers. In Saline Water Symposium, Water Resources Res. v. 6: 1458-1463.

135. Wasson, J.A. 1963. The application of hydraulic fracturing in the recovery of oil by waterflooding: A summary. U.S. Bur. Mines Info. Circ. 8175.

136. WATKINS, J.W. 1955. DESIGN AND OPERATION OF PLANTS FOR THE PREPARATION OF WATER FOR INJECTION INTO OIL RESERVOIRS. JOUR. PETROLEUM TECHNOL. v. 7(4): 17-23.

137. Watkins, J.W. 1958. New trends in treating waters for injection. World Oil, v. 146(1): 143.

138. Watkins, J.W., F.R. Armstrong, and R.J. Heemstra. 1960. Feasibility of radioactive waste disposal in shallow sedimentary formations. Nucl. Sci. and Eng., no. 7: 133-143.

139. Weeren, H.O. 1966. Disposal of radioactive wastes by hydraulic fracturing. Pt. 3--Design of ORNL's shale-fracturing plant. Nucl. Eng. and Design, v. 4: 108-117.

140. Winar, R.M. 1967. Underground disposal of waste water. Indus. Water Eng., v. 4(3): 21-24.

141. Woodley, R.A., and S.L. Moore. 1966. Deep-well disposal of industrial wastes in Indiana. Jour. Milk and Food Technol., v. 29: 211-213.

142. Wright, J.L. 1969. Underground waste disposal. Indus. Water Eng., v. 6(5): 24-27.

(142a) Yudin, F.R., M.K. Pimenov, A.I. Nazarov, S.I. Zakharova, S.V. Metal'nikov, and V.M. Sedov. 1968. Experimental storage of liquid radioactive wastes in deep geologic formations. Soviet At. Energy, transl. from Atomnaya Energiya, v. 25(2): 128-133.

2. *Selected References from Related Fields*

Saltwater Disposal and Secondary Recovery of Oil by Water Flooding

143. American Petroleum Institute. 1950. Secondary recovery of oil in the United States, 2nd ed., New York.

144. American Petroleum Institute. 1960. Subsurface salt-water disposal. Book 3, Vocational Training Ser., Production Div., Am. Petroleum Inst., Dallas, Texas.

145. Bell, A.H. 1957. Brine disposal in Illinois oil fields. Ill. State Geol. Survey Circ. 244.

146. Byars, H.G., and J.P. McDonald. 1968. How to plan, design and operate economic water injection systems. World Oil, April.

(146a) Farley, J.T., and D.G. Redline. 1968. Evaluation of floodwater quality in the West Montalvo Field. Jour. Petroleum Technol., July: 683-687.

(146b) Gates, G.L.,;and W.H. Caraway. 1970. Water for waterflooding San Joaquin, Calif., petroleum reservoirs. U.S. Bur. Mines Rept. Inv. 7401.

147. Grandone, P., and J.B. Holleyman. 1949. Injection rates and pressures for water flooding Mid-Continent oil sands. U.S. Bur. Mines Rept. Inv. 4600.

148. Jessen, F.W. 1949. Subsurface disposal of oil field brines. Chem. Eng. Prog., v. 45(1): 11-16.

149. Morris, W.S. 1960. Subsurface disposal of salt water from oil wells. Water Pollution Control Federation Jour., v. 32: 41-51.

150. Ostroff, A.G. 1965. Introduction to Oilfield Water Technology. Prentice-Hall Inc., Englewood Cliffs, N.Y.

151. Schmidt, L., and C.J. Wilhelm. 1939. Theory and practice in the underground disposal of oil field brines. Southwest Water Works, v. 21(1): 17-19.

Artifical Groundwater Recharge Through Wells

152. Baffa, J.J. 1970. Injection well experience at Riverhead, N.Y. Am. Water Works Assoc. Jour., v. 62: 41-46.

153. Baumann, P. 1955. Groundwater phenomena related to basin recharge. Am. Soc. Civil Engrs. Proc., v. 81, sep. 806.

154. Esmail, O.J., and O.K. Kimbler. 1967. Investigation of the technical feasibility of storing fresh water in saline aquifers. Water Resources Res., v. 3: 683-695.

155. Johnson, A.H. 1948. Ground-water recharge on Long Island. Am. Water Works Assoc. Jour., v. 40: 1159-1166.

156. Kimbler, O.K. 1970. Fluid model studies of the storage of freshwater in saline aquifers. Water Resources Res., v. 6: 1522-1527.

(156a) Kumar, A., and O.K. Kimbler. 1970. Effect of dispersion, gravitational segregation, and formation stratification on the recovery of freshwater stored in saline aquifers. Water Resources Res., v. 6: 1689-1700.

157. Moulder, E.A. 1970. Freshwater bubbles: a possibility for using saline aquifers to store water. Water Resources Res., v. 6: 1528-1531.

158. Rebhun, M., and J. Schwarz. 1968. Clogging and contamination processes in recharge wells. Water Resources Res., v. 4: 1207-1217.

159. Steinbrugge, G.W., L.R. Heiple, N. Rogers, and R.T. Sniegocki. 1954. Groundwater recharge by means of wells. Agric. Expt. Sta., Univ. Arkansas.

160. Taylor, S. 1964. The problem of groundwater recharge with special reference to the London basin. Inst. Water Engrs. Jour., v. 18: 247-254.

161. Todd, D.K. 1959. Annotated bibliography on artificial recharge of groundwater through 1954. U.S. Geol. Survey Water Supply Paper 1477.

162. Unklesbay, A.G., and H.H. Cooper, Jr. 1946. Artificial recharge of artesian limestone at Orlando, Florida. Econ. Geology, v. 41: 293-307.

Underground Gas Storage

163. Bays, C.A. 1964. Groundwater and underground gas storage. Ground Water, v. 2(4): 25-32.

(163a) Diekmann, E., and R. Wager. 1967. Gasspeicherung als geohydrologisches Problem. Internat. Assoc. Hydrogeologists Mem. VII: 130-136.

164. Gardner, G.H.F., J. Downie, and M.R.J. Wylie. 1962. Problems in the recovery of gas from aquifers used for gas storage. Inst. Petroleum Jour., v. 48: 457.

165. Hallden, O.S. 1961. Underground natural gas storage (Herscher dome). In Groundwater Contamination, Robt. A. Taft Sanit. Eng. Center Tech. Rept. W 61 - 5: 110-115.

166. Katz, D.L., and M.R. Tek. 1970. Storage of natural gas in saline aquifers. Water Resources Res., v. 6: 1515-1521

(166a) Wissmann, W. 1967. Über die Bedeutung von Kapillar druck und relativer Permeabilität beim Einpressen von Gas in ein Aquifer und über Möglichkeiten zur Berechnung der entstehenden Gasblase. Internat. Assoc. Hydrogeologists Mem. VII: 143-150.

167. Witherspoon, P.A., I. Javandel, S.P. Neuman, and R.A. Freeze. 1967. Interpretation of aquifer gas storage conditions from water pumping tests. Am. Gas Assoc. Monogr.

Hydrodynamic Dispersion

168. Bachmat, Y. 1969. Hydrodynamic dispersion in a saturated homogeneous porous medium at low Peclet numbers and nonhomogeneous solution. Water Resources Res., v. 5: 139-143.

169. Bear, J. 1961. On the tensor form of dispersion in porous media. Jour. Geophys. Res., v. 66: 1185-1198.

170. Bear, J. 1969. Hydrodynamic dispersion. In Flow Through Porous Media, R.J.M. de Wiest ed., Academic Press, N.Y.

171. Bear, J., and Y. Bachmat. 1967. A generalized theory on hydrodynamic dispersion in porous media. Internat. Assoc. Sci. Hydrology Publ. 72: 7-16.

172. Bear, J., D. Zaslavsky, and S. Irmay. 1968. Physical principles of water percolation and seepage. UNESCO Arid Zone Res. XXIX: 307-349.

173. Brigham, W.E., P.W. Reed, and J.N. Dew. 1961. Experiments on mixing during miscible displacement in porous media. Soc. Petroleum Engrs. Jour., Mar.: 1-8.

174. Day, P.R. 1956. Dispersion of a moving salt-water boundary through saturated sand. Am. Geophys. Union Trans., v. 37: 595-601.

175. Harleman, D.R.F., P.F. Mehlhorn, and R.R. Rumer. 1963. Dispersion - permeability correlation in porous media. Am. Soc. Civil Engrs. Proc., v. 89(HY2).

176. Harleman, D.R.F., and R.R. Rumer. 1963. Longitudinal and lateral dispersion in an isotropic porous medium. Jour. Fluid Mechanics, v. 16, pt. 3: 385-394.

177. Nielsen, D.R., and J.W. Biggar. 1961/1962. Miscible displacement. Soil Sci. Soc. Am. Proc., v. 25: 1-5 (1961); v. 26: 125-128 (1962); v. 26: 216-221 (1962).

178. Ogata, A., and R.B. Banks. 1961. A solution of the differential equation of longitudinal dispersion in porous media. U.S. Geol. Survey Prof. Paper 411-A.

179. Perkins, T.K., and O.C. Johnston. 1963. A review of diffusion and dispersion in porous media. Soc. Petroleum Engrs. Jour., March: 70-84.

180. Porch, M. 1965. The dispersivity tensor in isotropic and axisymmetric mediums. Jour. Geophys. Res., v. 70(16): 3909-3914.

181. Rumer, R.R. 1962. Longitudinal dispersion in steady and unsteady flow. Am. Soc. Civil Engrs. Proc., v. 88(HY4).

182. Saffman, P.G. 1960. Dispersion due to molecular diffusion and macroscopic mixing in flow through a network of capillaries. Jour. Fluid Mechanics, v. 7: 194-208.

183. Scheidegger, A.E. 1960. Underground dispersion of miscible liquids. Internat. Assoc. Sci. Hydrology Publ. 52: 462-469.

184. Scheidegger, A.E. 1961. General theory of dispersion in porous media. Jour. Geophys. Res., v. 66: 3273-3278.

185. Shamir, U.Y., and D.R.F. Harleman. 1967. Numerical solutions for dispersion in porous media. Water Resources Res., v. 3: 557-582.

186. Simpson, E.S. 1962. Transverse dispersion in liquid flow through porous media. U.S. Geol. Survey Prof. Paper 411-C.

187. Simpson, E.S. 1969. Velocity and the longitudinal dispersion coefficient in flow through porous media. In Flow through Porous Media, R.J.M. de Wiest ed., Academic Press, N.Y.

188. Skibitzke, H.E., and G.M. Robinson. 1963. Dispersion in groundwater flowing through heterogeneous materials. U.S. Geol. Survey Prof. Paper 386-B: B1-B3.

3. *Subject Index*

Notes: 1. Numbers refer to bibliographic listings.
2. Underlined numbers are important contributions or major review articles.

Major Review Articles

15	49	130
30	64	133
37	88	
38	99	

Short Review Articles (usually with emphasis on hydrogeology)

2	25	65	94	123
3	29	66	95	124
5	46	73	96	125
13	47	74	101	126
17	48	76	104	129
20	57	78	117	132
23	63	89	120	138

Hydrogeology of Specific Areas (with regard to injection)

12	39	82	88	103
22	50	85	92	108
32	51	87	102	109
36	52			

Case Histories

1	40	64**	97
4,24*	51	68,127	106,107
7,86	53	80	115
10,11,34	55	81	140
26	58	84	141
35,56	61	90	RMA***
37**	62		

* Where more than one number appears the references treat the same case history.

** Includes many short case histories.

*** A single injection well at the Rocky Mountain Arsenal near Denver has evoked nine discussions:

8	59	100
41	93	109
42	98	114

Hydrochemistry

16	72	90	111	121
18	79	105	113	122
21	88	110	116	131

Hydrodynamics - Subsurface Flow

21	43	96	126
38	88	105	168-188

Hydrodynamics - Hydraulic Fracturing and Seismic Effects

31	60	75	135	RMA***
54	67	77	139	

*** See Rocky Mountain Arsenal list under Case Histories.

Well Construction and Operation

9	29	88	136
19	33	91	137
27	83	130	

Legal and Regulatory

14	44	88	130
15	45	112	134
30	64	128	

Economics

69	83	130	142
70	88	138	

Type of Fluid Injected

Radioactive waste:	2	66	94
	18	73	95
	23	74	96
	29	75	104
	38	76	105
	57	77	113
	63	78	138
			139
Acid mine drainage:	117	118	119

Concentrated brine:	16	46	121
	19	69	122
	28	79	135
	33	116	143-151
Liquid natural gas:	163-167		
Industrial wastes:	All others		