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THE DISPOSAL OF POWER REACTOR WASTE INTO DEEP WELLS

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THE DISPOSAL OF POWER REACTOR WASTE INTO DEEP WELLS

Wallace de Laguna and J. O. Blomeke

For various reasons it is not possible to leave the uranium or other nuclear fuel in a power reactor until all of it has been "burned up" by fission. In the case of liquid fuel (homogeneous) reactors a small part is continuously bled out, purified and returned. In the case of solid fuel reactors, fuel elements are periodically removed, reprocessed and the "unburned" fuel put back into service. In both cases the purification produces wastes which contain radioactive fission products and transuranic elements, and it is with the disposal of these wastes that we are concerned. For technical reasons we will limit our consideration to the wastes from the processing of solid fuel elements, and from the processing of the very similar solid "blanket" elements in which fissionable fuel is made from non-fissionable isotopes of uranium and thorium by interaction with neutrons in the outer regions of the nuclear reactor.

Although they constitute the hazard, the fission products, their stable end products, and the transuranic elements make only a negligible contribution to the gross chemical composition of the wastes. This chemical composition is determined by the nature of the fuel elements, which must contain far more than just the uranium or other fissionable fuel, and by the particular method of chemical separation that is used to process the fuel elements after they have been removed from the reactor.

For the purposes of this brief summary, the many possible types of fuel elements will first be divided into those containing essentially the natural proportion of U^{235} and U^{238} , and those in which the proportion of U^{235} has been very substantially increased.

The natural uranium fuel slugs are for the most part cylinders an inch or so in diameter and anywhere from several inches to several feet in length. The uranium is very carefully clad with an aluminum jacket, not only to retain the fission products, which would otherwise contaminate the water or air used for cooling, but also to prevent the coolant from reacting chemically with the hot uranium metal and to provide mechanical strength. After the fuel element is removed from the reactor, the first processing step is to remove the aluminum jacket. This may be done either by stripping it off mechanically or by dissolving it chemically. The aluminum metal or the sodium aluminate solution contains a small amount of fission products, which diffused into the jacket from the fuel. The mechanically removed jackets, not being particularly soluble, could be disposed of into pits or trenches, later filled and then covered with a thin impermeable blanket membrane to deflect the rain. If caustic is used, the sodium aluminate solution is generally added to the main waste streams; but for disposal into deep wells, this may not be desirable.

Many processes are under consideration; but in the one important to us, after dejacketing, the uranium core is dissolved in nitric acid and this solution passed counter-currently through a stream of organic solvent, which removes the uranium and the newly created fissionable plutonium, while leaving the fission products behind in the aqueous phase. Two similar but distinct processes are used.

"Redox", the older of the two processes, uses hexone as the organic solvent. In order to drive the fuel into the solvent while keeping the fission products back, it is necessary to salt the aqueous phase with large quantities of aluminum nitrate. The waste is therefore dominantly acid aluminum nitrate. The fresh waste, containing many short-lived rapidly decaying fission products, is intensely radioactive and to facilitate the final disposal, it is stored in tanks to age. To reduce the corrosiveness of the waste, and so prolong the life of the tanks, the waste is neutralized with sodium hydroxide. This reacts with the aluminum nitrate to form sodium aluminate, which decomposes on standing, forming precipitates and sludges that settle to the bottom of the tank. Sodium nitrate is also formed; this largely remains in solution. To prepare waste such as this for disposal into a deep well it would have to be aged, centrifuged, and filtered to remove the aluminum and other insoluble hydrates and hydroxides, and diluted to reduce the viscosity, to prevent precipitation of sodium nitrate, and to reduce the problems of overheating after disposal. In these respects, the treatment would be much the same as for any of the wastes, but it would be made somewhat more difficult, because of the need to remove substantial amounts of aluminum hydroxide, which is hard to handle. On the other hand, this precipitate would entrain a substantial part of the fission products which, now in solid form, could be stored safely at the surface, thus reducing the thermal problems of disposing of the liquid phase into the ground.

The "Redox" method of separation was so named because reduction and oxidation are used to separate the plutonium and uranium. It has now largely given way to "Purex", a name which stands for "plutonium-uranium extraction". The de jacketing and primary solution in nitric acid are much the same for both methods; the difference comes in the choice of organic solvent. Purex uses tributyl phosphate, referred to as TBP. This solvent acts differently from hexone; it must be diluted with a hydrocarbon such as kerosene, and nitric acid is used as the salting agent to force the separation (not aluminum nitrate). The waste is, therefore, very largely a solution of the fission products in nitric acid together with a little iron and other material picked up by corrosion. Because it is relatively low in dissolved solids, it can be greatly reduced in volume by evaporation. There is, however, a catch. Very small amounts of TBP are left in the aqueous waste stream and when heated in the evaporator may react with the nitric acid and explode. In some cases, this unpleasant eventuality is eliminated by carefully stripping all the TBP, in others by neutralizing the waste with sodium hydroxide before evaporation.

As these wastes are aged, a precipitate (predominately sodium nitrate) is formed, occupying about 10% of the waste volumes. This granular precipitate is much easier to handle than the flocculent precipitate formed by aluminum hydroxide, and it would not be difficult to pump both supernatant and precipitate out of the tank, separate them by centrifuging and filtration, and return the solids to the tanks. The clear liquid could, after dilution, be disposed of into deep wells. It would carry with it a larger proportion of the fission products than would be the case with the liquid resulting from "Redox" separation, for the Purex sludge carries with it a smaller proportion of fission products than does Redox sludge.

The natural uranium fueled reactors are poorly adapted to breeding or to the economical production of commercial power. The enriched fuel reactors, with U^{238} or thorium blankets for breeding, will probably be the major power sources of the future. Three general types of fuel elements are being considered for these reactors, differing in the choice of metal used to alloy with or clad the fissionable material. The first type is the aluminum-alloy, aluminum-clad element. This differs from the natural uranium element described above in its shape and fabrication and in that the core of the element is an alloy of uranium and aluminum, not pure uranium metal, and which preclude mechanical dejacketing. The whole element must therefore be dissolved giving a solution rich in aluminum nitrate. In the "25" process, this is treated with hexone as in the Redox process, and the waste is similar to the Redox waste. Salting with aluminum nitrate is not necessary for the fuel elements contain over 90% aluminum. The uranium-aluminum alloy fuel elements are not at present regarded as potentially the most useful for power reactors; stainless steel and zirconium elements appear to hold greater promise.

For the stainless steel elements, a process called Darex -- for dilute aqua regia extraction -- is under development. The fuel would be dissolved in a mixture of hydrochloric and nitric acids, an obvious problem being the manufacture of the vessels in which this dissolution could take place. The resulting solution would then be stripped of the hydrogen chloride, for this is what makes the solution so very corrosive, although it is unlikely that all traces can be removed. The unburned fuel is then separated from the nitric acid solution with TBP, giving a waste somewhat similar to that from the "Purex" process. There will be, however, much iron, chromium, and nickel present, although far less than the Redox waste. These can be separated without serious trouble, and will carry many of the fission products with them, although not the cesium-137. If traces

of chloride do remain in the waste, it may be more corrosive and harder to store than that from the true "Purex" process, and consequently, it may be desirable to dispose of it without decay storage.

There are two processes under consideration for treating the uranium-zirconium fuel elements. The first, called FAN--for fluoride and aluminum nitrate, begins with dissolution of the fuel elements in a mixture of hydrofluoric acid, nitric acid, and aluminum nitrate. The amount of fluoride needed depends upon the proportion of zirconium in the fuel, which differs considerably from one type of fuel element to another. The amount of aluminum nitrate is appreciably less than is used in the "Redox" process. The solution is treated with TBP to remove the unburned fuel. The waste is in a sense intermediate between Redox and Purex in that it has an intermediate amount of aluminum nitrate. It differs from these however in that the fluoride makes it very corrosive and difficult to store, more difficult in general than the Darex wastes. It is hard to predict what effect the presence of the zirconium will have. In neutral solutions, it tends to complex with the fluoride, in which form it stays in solution, and might not interfere with disposal into deep wells. The complexes break down, however, at the high pH at which these solutions are stored, and also break down as the result of radiation damage, and the resulting zirconium hydroxide precipitate is hard to separate. The FAN wastes might turn out to be the most difficult to dispose of into deep wells.

Another process under development for handling zirconium alloy fuel elements is called "Zircex". The fuel elements may be prepared for this process by mechanically chopping them into small pieces to increase surface area. These small solid pieces are treated then with hydrogen chloride gas to form zirconium chloride which is volatile and can be driven off by heating. Once freed of the zirconium, the remaining uranium is dissolved in nitric acid and then separated

from the fission products with TBP. This produces a typical Purex-type waste, which may contain traces of chloride making it harder to store.

The blankets from the breeder reactors, that is, the fertile uranium-238 and thorium-232, which is being converted into fissionable fuel, will have to be reprocessed in much the same fashion as the spent fuel elements. Two general types of breeder reactors are being considered--thermal and fast--depending on the average speed of the neutrons used to produce fission. For the fast breeders, uranium-238 forms the best blanket material and will presumably be used in elements much like the fuel elements themselves. These can be processed by one of the methods described above. The wastes will, therefore, be chemically similar to the corresponding fuel processing wastes, but the level of activity will be lower.

For thermal breeders, thorium forms the better blanket material. Thorium-232 is not transformed directly into fuel, but is transmuted by neutron capture into thorium-233, which decays to protactinium-233, which in turn decays with a half-life of 27.4 days to uranium-233, the desired product. When the thorium blanket is processed, it is necessary to save both the U^{233} and the Pa^{233} . For this, the Thorex process is used. The thorium is dissolved in nitric acid with catalysis by fluoride ion. The thorium, U^{233} and Pa^{233} are extracted and separated from fission products by use of a TBP solvent extraction process. It is necessary to salt the aqueous phase with aluminum nitrate. The waste is therefore much like Redox waste, except that the fission product activity level is lower.

The Sulfex process (for sulfuric acid, extraction) is one of a number of processes which are in as yet a preliminary stage of development. These processes propose to dissolve stainless steel-clad fuels or zirconium-clad fuels or alloys in sulfuric acid. The effluent waste streams will undoubtedly contain significant

amounts of sulfate, and possibly dissolved stainless steel or zirconium.

Separation and recovery of uranium and plutonium will be effected by extraction with TBP.

The following generalizations may be made, if the reader will remember that the actual operations are far more complex than we can cover here.

Present wastes are all nitrate solutions, and may contain appreciable sodium nitrate resulting from the neutralization of nitric acid with sodium hydroxide. They also contain (if neutralized) either aluminum hydroxide, zirconium hydroxide, or a mixture of iron, nickel and chromium hydroxides, depending on the type of fuel element. The amount of these hydroxides varies greatly between the various waste types. It appears probable that all of the wastes will be aged in tanks before ultimate disposal, to permit the decay of the shorter-lived fission products. This aging may have to be cut short for those wastes which are particularly corrosive because of the chloride or fluoride which they contain.

If the aged wastes are to be disposed of into a deep well, they will have to be centrifuged and filtered to remove precipitates and suspended solids. There is equipment which will do this. These solids will carry with them a part of the activity, and, in the case of some of the wastes, a large part. This solid material will have to be disposed of at the surface. This is not necessarily a disadvantage, for if untreated waste could be put directly down a well, formidable problems would result from the subsequent generation of heat. Indeed, it may be desirable to treat some of the more concentrated types of waste, like Purex, to remove a part of the activity.

The question might then be asked, if a large part of the activity must be removed from the waste solutions and stored in some fashion at the surface, why not continue the treatment--remove all of the fission products and transmutation

Process	Fuel Type	Chemical Composition of Concentrated Unneutralized Hi-level Wastes	Volume gal/ton U	Chemical Composition of Concentrated, Neutralized Wastes	Volume gal/ton U
Purex	Normal or slightly Enriched U	7 M HNO_3 Traces: Fe, Ni, Cr, U, Hg	120 120	0.41 M NaAlO_2 0.37 M NaOH 1.44 M NaNO_3 0.31 M NaNO_2 0.023 M $\text{Fe}(\text{OH})_3$ Traces: Na_2SiO_3 , Hg $\text{Na}_2\text{U}_2\text{O}_7$, Na_2SO_4	765
Redox	Normal U, Aluminum-clad	65.4 wt% ANN ($\text{Al}(\text{NO}_3)_3 \cdot 9\text{H}_2\text{O}$) 4.9 wt% NaNO_3 ~1.2 M HNO_3 Traces: Fe, Ni, Cr, U, Si, Hg	1200	7.4 wt% NaAlO_2 4.4 wt% NaOH 25.7 wt% NaNO_3 Traces: Fe, Ni, Cr, U, Si, Hg	2600
Thorex	Thorium- U^{233}	0.55 M Al^{+3} ~0.11 M HNO_3 ~0.03 M F^- Traces: Fe, Ni, Cr, Hg, Po_4 , SO_4 , Si	1400	~0.4 M HNO_3 2.0 M Al^{+3} ~0.1 M F^- Traces: Fe, Ni, Cr, Si, Po_4 , SO_4 , Hg	400
Darex	Stainless Steel Clad slightly enriched U metal or oxide	2.3 M HNO_3 20-80 g/liter dissolved 34 STAINLESS STEEL Traces: (Fe, Ni, Cr), 41 TRACES CL	1200	Not neutralized	-
FAN	Zirconium clad, Zr-U alloy	3.5-7 M HNO_3 0.2-1.6 M Al^{+3} 0.2-1.1 M F^- 0.03-0.2 M Zr^{+4} 4-11 M HNO_3	3000	Not neutralized	
Gulfex	Stainless Steel or Zr Clad	7 M HNO_3 2.5 M H_2SO_4 10-40 g stainless steel Traces: Fe, Ni, Cr, etc.	2300	Not neutralized	

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products from the waste, and discharge a harmless liquid to the nearest stream? The answer is the very high decontamination factor that would be required to make the waste harmless. Satisfactory treatment would require the removal, not of 99 per cent, or 99.99 per cent, but of all but one part in many billions or hundreds or thousands of billions, for the long-lived fission products are poisons quite in a class by themselves.

Even after nuclear power has grown to an important place in our economy, it is anticipated that there will be only a very few--possibly only three--fuel-and-blanket element processing plants to which spent elements will be sent from many widely scattered reactors. This is because the processing plants must be heavily shielded and the equipment operated, repaired, and replaced by remote control, which is expensive. A single plant, with all its accessory equipment, may well cost the better part of a billion dollars and would be designed to use not only one, but several of the processing methods described above.

The solid fuel elements can be shipped with relative safety, but to ship liquid radioactive wastes would create such a hazard, in case of an accident, that waste disposal had better be at the plant site. This means a site suitable for the disposal of many kinds of wastes: solid, liquid, and gaseous. Two types of disposal--and therefore two types of sites--are being seriously considered: salt and deep wells.

Disposal into Salt Formations

The successful storage of petroleum products in cavities dissolved out of salt shows that such cavities can be made cheaply and to the dimensions specified, that they do not leak, and that they are strong. They would make excellent storage vessels for the radioactive wastes were it not for the heat generated by the wastes. Artificial cooling would be difficult, because the combination of nitrate and chloride ions is so very corrosive. Natural cooling by conduction through the

salt would limit disposal to cavities with a large surface-to-volume ratio or to relatively low-level waste, requirements which would add materially to the cost. The storage of solid waste in mined out cavities and the location of the processing plant also in rooms mined out of salt (the processing plants are not large, only expensive) have more obvious merit. Indeed, disposal into salt is at present regarded by many as the most promising method. It is not our purpose, however, to discuss the method here.

Disposal into Deep Wells

For some years the petroleum industry has been disposing of oil-field brines by pumping them back into the ground, in some cases deriving added benefit by returning them to the oil producing formation to help maintain reservoir pressure. The volume of brine so disposed of annually is in the hundreds of millions of gallons. The method works, and, as far as anyone can tell, none of the brine has ever come back up to contaminate fresh water at the surface. The method is also cheap, costing in the East Texas field about 1-1/2 cents a barrel, or about 0.03 cents a gallon. It will be the purpose of the balance of this paper to examine the possibility of disposing similarly of the radioactive wastes from power reactor fuel reprocessing. There is certainly no categorical answer of yes or no to either the feasibility or to the desirability of this particular method of disposal. The problem is rather to determine the favorable and unfavorable aspects of the method, to determine if possible the type of environment best suited, and to make comparisons with other alternative or supplementary methods.

The anticipated annual rate of liquid waste production for the entire country is about 50 million gallons by 1980 and 200 million gallons by the year 2000. This is not a firm figure, for the volume of certain waste types (for example, Purex) can be substantially reduced by evaporation to cut storage costs, and there will also be large volumes of low-level waste. The volumes produced, however, will be

small compared to the volumes handled by the petroleum industry and do not appear to be in themselves a limiting factor in deep well disposal. There is a possibility, therefore, that increasing these volumes by dilution might be desirable if this served to alleviate some of the more critical problems. What these critical problems may be is perhaps best explained by considering step by step our present concept of the actual disposal operation.

The Hydraulics of Wells

The heart of the operation is the disposal well. This will probably resemble more closely a deep water well tapping an artesian aquifer* than an oil well, so let us examine briefly the properties of an artesian water well.

Obviously, the first point of interest is the rate at which such a well can produce water. Within fairly wide limits this rate, for any particular well, is directly proportional to the drawdown, that is to the negative head developed by pumping. The ratio of drawdown, measured in feet, to flow, measured in gallons per minute, is known as the specific capacity; and for artesian wells, this ratio commonly lies between one-half and fifty. These are not the limits, and wells with higher

* The term "aquifer" should mean a stratigraphic or hydrologic unit capable of transporting or conveying water. The ability of the unit to store water is also always involved, and the measurement of both of these properties is one of the principal goals of most groundwater investigations. As the same values will be the goal of the hydrologic work on waste disposal, the term "aquifer" is used, although the emphasis will be on the storage of waste--not the movement of water.

An artesian aquifer is one that is confined by overlying relatively impermeable layers. The head within such an aquifer may be either greater or less than the distance up to the water table or the surface. If the head is great enough a well drilled into it may flow, but it is equally possible for the water in such a well to stand far below the land surface.

and lower capacities exist. The very high specific capacities are, however, largely confined to wells in limestones or basalt flows, which contain large through-going, but generally erratically distributed passageways. Such aquifers have certain grave disadvantages for waste disposal. A low specific capacity suggests that the well taps an aquifer of low permeability which may plug easily. A water well with a specific capacity of one will produce 100 gallons of water a minute with a drawdown of 100 feet. A well with a specific capacity of 50 would yield 2,000 gallons a minute with a drawdown of 40 feet. This does not mean that with a drawdown of 400 feet, the well would produce 20,000 gallons a minute; the concept of specific gravity is valid at best only over a limited range and only under the conditions for which it was determined.

If the flow is reversed, the specific capacity is also a measure of the rate at which the well will take water at any given head. If a well will yield a hundred gallons a minute with a hundred foot drawdown, it will take a hundred gallons a minute when the head applied is a hundred feet--about 40 pounds per square inch. If the natural water level in the well were 100 feet below land surface, it would only be necessary to keep the well filled; no additional pressure would be required.

A recharge of 100 gpm (gallons per minute) is not a large flow, and it could easily be attained with a well which was poor by water-supply standards, and yet in a year it amounts to 50,000,000 gallons--the estimated rate of production of waste production in 1980. This is not to suggest that one small-capacity well could handle all the waste production anticipated for that year, for the waste is not water by any means, but it does serve to illustrate that volume is not a problem.

The specific capacity of the injection well is hardly the full measure of the hydrologic aspects of the problem of deep well disposal. A somewhat more

complete picture can be obtained from the characteristics of the aquifer in which the well is screened, for it is the properties of the aquifer that will determine the buildup in head at the well with continued injection, and the distribution of increase in head out from the well.

The two important properties of an artesian aquifer are its coefficients of transmissibility and storage. The transmissibility of an aquifer is that quality which lets water move through it, and is the product of the permeability of the material composing the aquifer and the aquifer thickness. The coefficient of transmissibility is commonly expressed as the amount of water, in gallons per day, that flows through a one-foot wide section of the full thickness of the aquifer, at unit gradient. In artesian aquifers used for water supplies the coefficient of transmissibility usually lies between 1000 (wells in such an aquifer are likely to have specific capacities of .5 to 1) and 100,000 (in which aquifer wells have a specific capacity of about 30 to 50). A few aquifers, such as cavernous limestones or highly porous lava flows, have transmissibilities measured in millions, although it is doubtful that such large open passageways are to be found in deeply buried formations. At the other extreme, there are many materials, such as clay and granite, which if pure and uniform may have virtually no permeability.

The coefficient of storage is the volume of water, measured in cubic feet, released from storage in each column of the aquifer having a base one foot square and a height equal to the thickness of the aquifer when the water table or other piezometric surface is lowered one foot. It is also the volume of water which, if introduced into this prism of the aquifer, would raise the head one foot. For most artesian aquifers, the coefficient of storage lies between 10^{-5} and 10^{-3} . The water which moves into or out of an artesian aquifer does not do so by filling or emptying voids, as is the case under water table conditions; the volume changes

are due rather to the expansion and compression of the water, of the aquifer, and in some cases, to the raising or lowering of the land surface far above. Pressure changes, not the flow of water in the usually accepted sense, are the important considerations.

Water is not normally regarded as a compressible fluid as its bulk modulus is 3×10^5 pounds per square inch. However, a hypothetical one-foot thick layer of pure water, if buried in the earth, would have a "storage coefficient" of 1.42×10^{-6} , and an aquifer 100 feet thick, with a porosity of 10 per cent, would have a storage coefficient due to the compressibility of the water alone of about 1.42×10^{-5} . A square mile of such an aquifer would take up or yield about 3000 gallons of water for every foot change in head in the aquifer, due to the expansion or contraction of the two billion odd gallons of water it contained. The bulk modulus of the matrix of the aquifer is generally somewhat larger than that of the contained water, although the ratio will depend on the porosity, the composition, and the structure. In the hypothetical aquifer above for example, the matrix, which makes up 90% of the volume, might be six times as compressible as the water. In this case the total storage coefficient for the aquifer would be 10^{-4} .

A thickness of a hundred feet, a porosity of 10 per cent, and a storage coefficient of 10^{-4} are values which are typical of many artesian aquifers used for water supply and which might be used for the disposal of waste. Let us see what the effects would be of pumping water into such an aquifer for various lengths of time.

Let us consider only a pumping rate of 100 gpm, for virtually all the volume and pressure changes that might be observed are in simple direct proportion to the pumping rate, so that corrections for some other rate can be made easily.

At the end of one year of pumping at this rate, a deep well would have put over 50 million gallons of water into our hypothetical aquifer. If we assume

that the water moved out equally in all directions from the well as a center, it would extend out a distance of less than 500 feet; that is, it would fill the voids of a cylinder 100 feet thick and a little less than 1000 feet in diameter. After ten years, the diameter of the cylinder would be only a little over 3000 feet. The assumption that the water would move out equally in all directions and at all levels is not in accord with the experience gained from the secondary recovery of petroleum, and we will need to return to this point, but as a preliminary simplification, it is satisfactory. From purely hydrological considerations, the suggestion that all the waste to be produced between 1980 and 1990 could be put into one square mile or less of a mediocre aquifer, is quantitatively sound.

For an artesian aquifer we have seen that the addition or withdrawal of liquid is made possible by changes in head within the aquifer. In order to study the changes in head that would be produced in our aquifer by pumping water into it, it will be necessary to make some assumptions about the transmissibility of the aquifer. This can vary between wide limits, but, as we have seen for deep water-supply aquifers, it commonly lies between 1000 and 100,000 gallons per foot per day.

Let us suppose that we pump into a deep well at a rate of 100 gpm and calculate what would happen at the well itself. During this discussion, we will assume that well and aquifer do not plug up, and that the uniform aquifer extends for a large distance in all directions. We must also make some assumptions about the actual construction of the well. After a water well has been drilled, it is commonly treated by a combination of bailing, pumping and surging, sometimes involving acids, detergents and other agents, to improve the permeability of the formation in the immediate vicinity of the well. This work, called "developing", in effect increases the diameter of the well, and we shall assume that our well

has an effective radius of 3.16 ft. This figure is a little large, particularly for a well drilled in somewhat indurated material, but if we assume that the well development has been carried out energetically, in order to guard against later plugging of the well, the figure is not unrealistic.

Table II shows the head in feet of water that would be required to pump water at a rate of 100 gpm into our hypothetical well if it were finished in a formation of the indicated transmissibility.

Note the small increase in head after the first day, even if the discharge is continued for 350 years. In no case does the head much more than double. However, this depends on the validity of the assumption that the aquifer extends without discontinuity for an indefinite distance in all directions. How great this distance would have to be for these figures to apply will appear below. The calculations for Table II also assume that there is no loss in head at the well itself, as would be the case with a poorly screened well, so that in practice these figures would have to be increased slightly, depending on the construction of the well.

Table II

Increase in Head in Feet in Recharge Well Receiving Water at 100 GPM and Finished In Aquifer of Indicated Transmissibility. Effective Well Diameter 3.16 Ft.

<u>Transmissibility</u>	<u>1 Day</u>	<u>10 Days</u>	<u>1 Year</u>	<u>350 Years</u>
100,000	1.97	2.25	2.65	3.35
10,000	17.1	19.7	23.8	31.0
1,000	144	171	212	280
100	1,180	1,440	1,855	2,550

Note: These values are valid only for water; corrections must be made in the case of liquids with different density or viscosity.

Note also the marked dependence of the necessary head on the transmissibility of the aquifer. This is not because the injected water itself moves very far out from the well, for as we have seen, even after ten years of pumping, it will not have traveled outward much over half a mile. The importance of the transmissibility rests on the fact that if the pressure changes in the aquifer can reach out quickly over long distances, then the necessary volume changes will require only a small change in head. Where the transmissibility of the aquifer is low, the pressure changes are confined to the vicinity of the well, and for the same volume of discharge or recharge, the pressure changes must be larger.

Figures 1 and 2, also calculated from the Theis non-equilibrium formula, illustrate what might be expected in an ideal aquifer. The assumptions are that a central well is pumped or recharged at a rate of 100 gpm and that the aquifer has a storage coefficient of 10^{-4} . The curves indicate the change in head in feet that would be observed in an observation well screened in the aquifer at the indicated distance from the active well.

If the rate of pumping were different, all of the changes in head would be increased or decreased in exact proportion to the new rate. If the storage coefficient were different, say ten times as great, the change in head would be the same as though the time were one-tenth as long.

The figures suggest that after 10 days pumping into an aquifer with a transmissibility of 100,000 gallons per day per foot, there will already be a small change in pressure at a distance of 50,000 feet, or nearly ten miles. The head at the well will be only 2.25 feet and only 0.55 feet about a mile from the well. After a year the head at the well and for a distance outward of about a mile will have increased somewhat, but will not have doubled. However, at 50,000 feet, about 10 miles, the head would now be nearly half a foot and at 100,000 feet, nearly 20

FIG 1

FIG 2

miles, the change in head would be about a quarter of a foot. The theory indicates that some pressure change would be felt 500,000 feet away, or nearly 100 miles.

These values all apply to water. If the waste as injected has a higher viscosity than water, the result will be much as though there had been a decrease in the transmissibility of the aquifer near the well in the area occupied by the waste. The pressure gradients farther out would still be much the same. If the waste has a different density than the water in the aquifer, the distribution of pressure gradient will be little affected, but the distribution of the waste itself may be quite different. If more dense, it will move out along the bottom of the aquifer, or if the aquifer is dipping, it will tend to move down dip. If less dense, it will tend to move up dip in the upper part of the aquifer.

A transmissibility of 100,000 gallons per day per foot and a porosity of 10% appear to be quite suitable for an aquifer which is to be used for the disposal of radioactive wastes, although other factors must be considered. Certainly the indicated small buildup in head in and near the well is desirable. However, if we look at the predicted values for pressure distribution at the end of one year, it is apparent that there has been a significant increase in head out at least as far as twenty miles and some slight change nearly 100 miles away. Although these changes in head are small, only one-quarter of a foot or less out beyond twenty miles, they are applied to such large areas that they contribute significantly to the capacity of the aquifer. In fact, it would require an average increase in head of a little over two feet, out to a radial distance of 100,000 feet from the well, assuming that there was no pressure change beyond this distance for the aquifer to take in the 52.5 million gallons pumped in one year. None of these figures apply to the movement of the waste itself. As we have seen, if the aquifer were 100 feet thick and had a porosity of 10%, the waste would fill, in

theory, a cylinder with a radius of less than 500 feet.

It may be well to interrupt here the apparent suggestion that a very high transmissibility is desirable, and introduce some of the arguments against it. In most deep aquifers the natural rate of movement of the ground water is very slow, and only in exceptional cases does it exceed a value of a foot a day; commonly, it is much less. At a foot a day, it will require 14.5 years to move one mile, and in 300 years (10 half-lives for Sr^{90}) it will move only some 20 miles. This slow movement is one of the most important factors of safety in deep well disposal. But it is precisely in the aquifers of very high transmissibility that exceptionally rapid movement of ground water is found; in some cases, the rate is hundreds of feet a day. This is particularly true of thin aquifers of high permeability, for the rate of movement varies directly with the transmissibility and gradient, and inversely with the thickness and porosity. Many factors, most of them peculiar to the particular locality, will determine whether the transmissibility of an aquifer is too low, too high, or well suited to the disposal of radioactive wastes.

A transmissibility of 100,000 gallons per day per foot is a very high value for an artesian aquifer, and to limit consideration to aquifers as good as this would restrict the choice of areas materially. If the transmissibility were 10,000 which is still a high value, the head on the well itself would be some 20 feet for the first year or so, and might build up to 30 feet after many years. After 10 days there would be a head increase of 2.85 feet at 5,000 feet from the disposal well; and after one year, 0.63 feet at a distance of 100,000 feet. These are very moderate increases in head, and it would be entirely possible to use such an aquifer. However, an increase in head, which after a year reaches seven feet at a distance of about a mile, raises the question of upward movement of the waste solutions through the confining cover. We have assumed that our hypothetical aquifer

was overlain with an impermeable cover, but no earth material is completely impermeable. To be sure, the presence of oil and gas in certain structures shows that they have contained these fluids under high pressure for geologically significant lengths of time. But there have been other similar structures, which when drilled were found to be empty, suggesting that they had leaked. Oil and gas in small quantities have been found above or near oil-containing structures suggesting that here also there had been some slow leakage, even from an essentially tight structure. It is difficult to see how it would be possible to determine in advance that a particular waste disposal aquifer would not leak at all. There probably are ways of preventing the movement of waste even out of a leaky aquifer, but, as a general statement, it is probably correct to say that the pressures in the disposal aquifer should be kept low.

The problem of upward leakage assumes important proportions if we consider the buildup in head in an aquifer with a transmissibility of 1000. After one year the increase in head in the recharge well is over 200 feet, and at a distance of about a mile, the increase is over 40 feet. Note, however, that at 10 miles the head increase is only 1.6 feet, slightly less than in the preceding case where the transmissibility was taken to be ten times as great.

These pressures do not represent a serious operating problem, for it would not be mechanically difficult to pump 100 gallons of liquid a minute against a head of about 200 feet. They would, however, present a serious threat of leakage upward and it is doubtful if it would be safe to operate a waste disposal system in such an aquifer, at least by the simple procedures which we have been considering so far. There can be no question but that it would be undesirable to use an aquifer with a transmissibility of only 100 gallons per day per foot, as this would entail, under the assumed conditions, a head of over a thousand feet at the well, and of several hundred feet for a mile out in all directions.

Before proceeding, we may summarize the tentative conclusions we have just reached. The important hydrologic parameters of an artesian aquifer are its coefficients of storage and transmissibility. Both are important, but where the aquifer is extensive, the transmissibility is very likely to be the more important of the two. If the boundaries of the aquifer are near enough to restrict materially the outward movement of pressure, then the storage coefficient will be of more importance. A very high transmissibility, of the order of 100,000 gallons per day per foot, certainly appears to be attractive in many ways. However, to realize in practice the very low pressures shown in Figs. 1 and 2, the extent of the aquifer would need to be very great. In practice it might be safer if there were boundaries distant a few tens of miles to limit the movement of contamination, even if this resulted in a somewhat higher head. A transmissibility of 10,000 gallons per day per foot also appears to be quite satisfactory. A transmissibility of 1000 raises some questions of pressure increase, and a transmissibility of 100 appears to be out of the question.

The values shown in Figs. 1 and 2 are based on the assumption that the storage coefficient is constant, and that all the water taken in or released by the aquifer is due to the rapid elastic response of the liquid and the aquifer matrix. This is generally true, but where large areas and long times are involved, other factors must be considered. As we have seen, when water is pumped out of a deep aquifer, the drop in head is transmitted over wide areas. If the aquifer is overlain by or contains clay in the process of compaction, this natural process will be slowly releasing water to the aquifer. The drop in head incident to the pumping provides an opportunity for speeding up the release and may yield appreciable volumes of water. Pumping waste into such an aquifer might not force water back into the clay, for this process is probably not easily reversible. The buildup of head

with injection into a deep aquifer may therefore be more rapid than the drop in head due to water removal.

Where large amounts of water or petroleum are removed from a deep sealed reservoir, it is well established that there is subsidence of the surface. Some of this is due to elastic response, some is due to unwatering of clay layers and their compaction, and some may be due to other forms of slow plastic deformation. The slow plastic changes would act to increase the long term value of the storage coefficient. To whatever extent they were reversible they might act similarly if the aquifer were recharged.

Another factor which can influence materially the storage capacity of an artesian reservoir is the slow migration of the liquid in it. For example, where a fresh-water artesian aquifer is open in depth to the sea, sea water will come in until a balance is reached with the fresh-water head. If fresh water is pumped from such an aquifer, the salt water will move in, driving the fresh water ahead of it until a new balance is reached. Somewhat similar movements of water are important factors in the exploitation of oil fields. It is quite possible for a basin-shaped aquifer to contain salt water in its deeper parts and fresh water near the surface. If waste were pumped into the bottom of such a basin the structure would at first act like a completely enclosed and water-tight aquifer. Yet with time, there would be a slow displacement of fresh water by the salt with results resembling a slow increase in the storage coefficient, and the predicted head changes would not be realized. How material the difference would be between the predicted and real values would depend on the particular case. However, where applied intelligently to aquifers whose geologic structure is known, the quantitative methods of hydrology have repeatedly proved that they give accurate predictions, even under relatively unfavorable circumstances. We should anticipate that predictions of the hydrologic problems of waste

disposal into deep aquifers will be more reliable than predictions of the geochemical and thermal problems.

So far we have tacitly assumed that waste disposal into a deep aquifer would consist of pumping the waste down into a single well, or into a number of wells acting independently of each other. This might be done, but we should anticipate the need for a somewhat more sophisticated arrangement in which a group of wells would operate together.

Let us consider a grouping of wells consisting of a central disposal well surrounded by a ring of wells at such a distance that the waste would reach them in a few years. This distance would depend on the thickness and porosity of the disposal aquifer and on the rate of pumping. The outer ring of wells would, in the first instance, be used for monitoring the movement of the waste. However, a static well is not entirely suited for monitoring, and in the case of an important installation, the outer wells would be pumped. If the water pumped out were discharged to the surface, the movement of the waste could be controlled somewhat by selective pumping of the outer wells.

There are a number of advantages to be gained from diluting the waste, and in some areas, water pumped from the outer wells could be used for this purpose. To save cost, the waste will probably be shipped in as concentrated a form as possible, and this will apply to the stable salts and compounds present as well as to the active fission products. Dilution, by reducing these concentrations, will tend to prevent precipitation, that is, if the water used for dilution is not itself is not a potential source of a precipitate. In oil fields, connate saline water, such as would probably come from wells pumping out of the disposal aquifer, has been found to cause plugging where it has been returned to the ground. The plugging is due to the escape of carbon dioxide under the reduction of pressure at the surface, which changes bicarbonates to carbonates and results in precipitation.

Treatment of these brines by such conventional methods as flocculation, settling and filtration, and by the addition of hexametaphosphate can greatly reduce or eliminate this plugging. In general, the treated brines will not react with the dominantly nitrate wastes to form precipitates. Of course, where fresh water is available for dilution, it may be preferable. As we have seen, the volume of waste in itself is not a problem, and could be materially increased without adding to the expense or complexity of the operation.

Wasting of water pumped from the outer ring of wells would reduce the pressures in the disposal aquifer, an important consideration if its transmissibility were low. The net result at any point would be the algebraic sum of the head changes due to each individual well. This is an argument against locating the ring of wells too far out. In any case, their effect would probably be small on the buildup in head in the injection well itself. Their effect over the aquifer as a whole might reduce materially the danger of upward leakage, and the reduction in pressure would be particularly important in an artesian aquifer of limited areal extent where boundary conditions were responsible for pressure increases greater than those indicated in Figs. 1 and 2.

Where the petroleum industry has injected water into deep formations in order to push oil over to producing wells, the wells have been located in a number of simple geometric patterns. The petroleum industry's problem is somewhat different from ours, however, in that they are concerned with flushing out as much of the oil as possible, whereas it will be a matter of secondary interest in the case of deep-well disposal, whether or not all of the original water in the disposal aquifer has been displaced by waste. However, if the well-head installations are expensive, it may be desirable to keep the operations from covering too large an area, a possible incentive for using some such well grouping as the "five spot" pattern of the oil industry. Such a pattern may give the maximum safety and

control of the disposal procedure at the cost of a minimum number of wells.

Thermal Considerations. The heat released by the waste after it has reached the disposal aquifer is small in amount, but rocks are such poor conductors that with time high temperatures may be reached. As long as the well is open and waste is being pumped down, there will be no marked rise in temperature at the well, for the waste coming from the surface will be cool and the thermal capacity of the water it contains is high. At the outer face of the waste-containing cylinder of rock, the temperatures will also be low, for here the waste is invading a relatively cool environment. The highest temperatures will be found at some intermediate distance. Electronic computers are capable of determining the temperature distribution in such a system, if assumptions are made about the geometry and thermal parameters of the environment, and the attempt may be made. In the meantime, a more simple approach may be made to the question of the temperatures that might be reached after injection had stopped. The only conclusions we shall attempt to draw is that dilution may be a practical factor in solving the thermal problem. How much dilution will be needed depends on many circumstances; but, for the aquifer we have been considering (that is, one with a thickness of 100 feet and a porosity of 10 per cent) dilution of roughly 30 fold will be a material help.

Any such conclusion depends on what temperature rise can be permitted. The critical temperature of water, about 700°F , is certainly above the limit of safe operation, and chemical reaction between the waste and the aquifer matrix may become a controlling factor at lower temperatures. A conservative viewpoint would be to take 212°F , the boiling point at the surface, as the limit, for this would rule out any danger of gysering. In the following calculations we shall use 100°F as the permissible rise in temperature. We will also assume

that all the active material remains in solution and is not concentrated by adsorption or precipitation.

A gallon of the type of waste we are concerned with (high-level power reactor waste six years old) will, in the next thirty years, give out about 200,000 Btu, or about 6,000 to 7,000 Btu per year. During the next 500 years it will give out an additional 500,000 Btu, or about 1,000 Btu per year; the heat generated after 500 years may be neglected. These figures assume that all the Sr^{90} and Cs^{137} remain in the liquid waste.

Apart from the inert solids, a gallon of waste weighs about 7.5 pounds, so that during the first 30-year period each pound of water would have generated in it some 26,700 Btu. If the waste were injected into an aquifer with a porosity of 10%, and if the material of the solid matrix had a density of 2.8 and a specific heat of 0.2, then the heat absorbing capacity of rock and waste, for each pound of waste, would be the equivalent of about six pounds of water. Neglecting heat losses, at the end of thirty years the waste would increase in temperature about 2,770°F. However, if the waste were diluted by 27 parts of water, the heat rise over the first 30 years would be limited to about 100°F, which we have assumed could be tolerated.

During the next 500 years, an additional 500,000 Btu of heat per gallon of original waste will be released, which would raise the temperature an additional 250°F, if we continue to neglect conduction. But over hundreds of years conduction of heat does become a material factor, and preliminary computations suggest that the temperature will not increase much further, except near the center of the 100-foot thick aquifer. Such computations, however, although based on a sound mathematical approach to the problem, cannot make proper allowance for such factors as convection, or slow lateral movement of the waste under the residual hydrothermal gradients that would remain even after injection had ceased. The long term

thermal history of the waste after injection is a very complex problem, and one which may have to be solved, not in general terms, but in terms of specific localities.

We may summarize our approximation of the thermal history as follows: During the initial thirty years the heat evolved by the diluted waste could be absorbed by the liquid and the rock of the aquifer with a heat rise of roughly 100°F, and this would be true regardless of the rate of heat production, for we are neglecting loss of heat by conduction. During the next 500 years the heat generated could be carried away by conduction through the overlying and underlying rock, rapidly at first, when the gradients are steep, and less rapidly as the gradients get flatter. This will help compensate for the fact that the rate of heat production by radioactive decay is more rapid at first and slows down with time.

We have tacitly assumed that the waste solution will move out uniformly into the aquifer. This will hardly be the case. For example, water injected into the Bradford sand for secondary recovery reaches producing wells in roughly one-tenth the calculated time because of unequal rates of advance in different parts of the formation. To the extent that the waste fingers out into the disposal aquifer, there will be additional heat absorbed within the formation, and additional loss of heat by conduction. Because of this, it might be desirable to choose a formation consisting of alternate beds of more permeable and less permeable material in preference to a thick uniform aquifer. Even under favorable conditions, however, there appears to be a probability that dilution of some such order of magnitude as we have discussed, that is roughly 30 fold, might well prove desirable. Hydrologically, this should be feasible. It does not appear that dilution of many hundred fold, which would raise hydrologic problems, will be required by thermal considerations.

Before leaving the questions raised by the heat generation of the waste, there is one other consideration that should be mentioned. We have already seen that it is probable that some treatment of the waste will be desirable to reduce plugging of the disposal well. It is possible, even probable, that this treatment, even if aimed at the removal of non-radioactive materials, for example--aluminum and zirconium, will take out also some of the radioactive components. If so, this would reduce, perhaps substantially, the thermal problems.

The true heart of the thermal problem, however, lies in the possible absorption of activity close in around the well. It is uncertain that this can be entirely prevented. If such deposition does take place, the local concentration of heat will raise problems far more difficult to evaluate and far more serious, than those we have considered.

The Ideal Aquifer. The qualifications for the ideal deep-well disposal aquifer are not clear, for some of the requirements are at least partially contradictory, and any actual location will represent a series of compromises. It is possible, however, to qualify in a general way what such an operation would require, and even to suggest several areas in this country which, in advance of specific investigation, appear promising. We will not, however, take into account several non-geological factors which, although they would be of importance to any actual operation, are outside the field of this report. Among these are transportation, laws, and public opinion.

Perhaps the most obvious question is what is the best depth. Depth in itself is not a safety factor, and it is not true that the greater the depth, the safer the operation. Depth is synonymous with the thickness of the cover, but earth materials vary so much in permeability that the nature of the cover is apt to be more important than thickness alone. Greater depth does imply

a greater confining pressure and therefor a greater possible temperature rise before boiling, and, conceivably, geysering might take place, but any temperature appreciably above the boiling point at atmospheric pressure represents an unstable condition and potential hazard. The critical pressure for water is the equivalent of a head of slightly over 6,000 feet, and much more will have to be known of the thermal and geochemical problems before it would be wise to attempt to operate at temperatures near the critical temperature of water. A very few thousands of feet would appear to provide all the hydrostatic confining pressure that is likely to be of practical advantage.

The cost of drilling any single injection or monitoring well will be very roughly proportional to its depth for the first few thousand feet, but with deeper wells, the cost per foot increases materially, as do also the costs of any logging and monitoring operations. Safety is likely to depend more on the ability to get abundant, reliable and detailed information, particularly in the early operations, than on any other factor, and there is no apparent need to start out by looking for a disposal aquifer at a depth of 10,000 or 15,000 feet when the expense of drilling to such a depth may inhibit exploration and study. For the initial work, depths of 2,000 to 4,000 feet would appear to have a material advantage. It is possible that with the knowledge and confidence that comes from experience, later operations may be able to employ a single well, the drilling of which even to a great depth would represent a small part of the total cost.

There are three general types of geological formation which might provide an aquifer of the necessary high transmissibility: unconsolidated sands or sandy sediments, porous limestones, and lava flows.

Formations composed predominantly of sand or of sand and gravel are likely to have the important advantage of uniformity; that is, they are the most likely

to be isotropic and homogeneous. This is an important qualification, for the ability to determine the hydrologic properties of an aquifer depend on the validity of the almost inescapable assumption that it is uniform. If quantitative determinations of porosity, permeability, transmissibility and storage coefficient are not possible, then the disposal operation must be carried out with such uncertainty that the hazards are materially increased. A high transmissibility assures small head changes only if the aquifer has a wide areal extent, and a wide areal extent is somewhat more probable in a formation composed of sand than it is in a porous limestone or a lava. However, a wide areal extent, although an advantage in this respect, may be even more of a hazard if it provides a pathway through which the waste may move to some distant point.

Reference has been made to a hypothetical aquifer with a porosity of 10 per cent and a thickness of a hundred feet. These are not necessarily the best values and were used only for purposes of illustration. Unconsolidated, well sorted sands commonly have porosities of the order of 25 to 35 per cent. Such a formation is in some ways desirable for the permeability would be high and the probability of plugging low, but by concentrating the waste into a smaller volume, the higher porosity would increase the thermal problems. This might necessitate a higher dilution and negate the possible gain. In practice sands at a depth of several thousand feet are more likely to have a porosity of ten than of thirty-five per cent, and to restrict consideration to aquifers of very high porosity would, as in the case of a very high transmissibility, limit the choice by placing undue emphasis on a single characteristic.

Other things being equal, a large grain and pore size would certainly appear to be desirable, not only because they suggest a high permeability, but also

because they are less likely to plug. Coarse sand and gravel formations are less likely to have the uniformity and areal extent of a formation of medium grain sand, and to insist on a coarse texture would again limit the possibilities and involve undesirable as well as desirable characteristics.

The importance of the mineral composition of the aquifer will depend on the success with which the waste has been treated to prevent absorption of the activity on the solid matrix. Quartz is the major constituent in most sands. It has very low powers of absorption and is not likely to react with the waste solutions to promote plugging, unless the temperature is high. The quartz grains of some formations are coated with iron oxide, and such material might be very absorptive because it has a large surface area. Clay in general and, in particular, certain of the clay minerals have important ion exchange properties and therefore even a small proportion of clay might be a complication. Glauconite also will be an important absorbent. Carbonates, commonly present in small amounts, are not a potential absorbent, but they would be significant in the case of an acid waste because of the pH changes and consequent precipitation which they might produce. However, pretreatment of the waste, which would almost certainly be desirable, if not essential, could probably prevent this becoming a major consideration. Sulfate minerals such as gypsum could also cause precipitation since certain of the fission products have insoluble sulfates, the formation of which is facilitated at moderate to high temperatures. Chlorides are not likely to be a problem. We may briefly summarize our picture of a desirable aquifer as follows:

1. The transmissibility should be high, preferably ten thousand gallons a day per foot or more, although limiting values cannot be specified.

2. The hydrologic properties should be sufficiently uniform so that quantitative values for the movement of liquid through the aquifer can be determined and applied with confidence.
3. The aquifer should have a considerable extent but not so extensive that it creates a potential hazard at distant points.
4. A depth of a very few thousand feet is probably sufficient, particularly if the cover is known to be highly impermeable. Great depth is likely to make drilling and monitoring expensive and so reduce the safety that may be attained with a given expenditure of funds.
5. High porosity and coarse texture are in general desirable; how desirable will depend on the tendency of the waste to plug fine-textured formations.
6. A simple mineral composition is desirable. Assuming a dominantly quartz sand, iron oxide, clay, and glauconite are likely to be annoying absorbents; sulfate and, to a lesser extent, carbonates may promote undesirable precipitation; chlorides are no problem. The so-called heavy minerals and fresh feldspar are not likely to cause trouble.
7. A series of individually thin permeable beds separated by less permeable material rather than a single thick aquifer may serve to reduce the problem of dissipation of heat.

Limestone aquifers owe their permeability either to the fact that they are composed of granular matter (i.e., coral or coquina, a rock made of shell fragments) or to the formation of secondary openings by solution. The first class is not commonly found at depth in inland areas, in part because such rocks are easily compacted and the pores filled or otherwise destroyed. At shallow depth

aquifers of detrital limestone are known to yield large quantities of water, for example, in parts of Florida and on many coral islands, but it would be somewhat unusual to find one deeply buried in a sequence of other rocks in such a way as to make possible the safe disposal into it of radioactive wastes. If such an aquifer existed, there would be no particular reason why it should have either special advantages or disadvantages.

Limestone aquifers, which owe their porosity to solution, are likely to suffer from the disadvantage that their hydrologic properties are very non-uniform. In such material the difficulty of determining average values of transmissibility, storage and porosity, or of predicting rates or direction of movement, would be serious. Not all limestone aquifers are cavernous or markedly anisotropic, since their homogeneity depends on the composition and structure of the formation and on the combination of circumstances under which the openings were formed. This uncertainty, although it leaves open the possibility that a homogeneous limestone aquifer may exist, makes it mandatory to explore and test any limestone in considerable detail, and the problems of such a study would add to the cost of the operation. If reliable information were already available, as it might be in an oil-producing area, then such an aquifer might be well suited to the disposal of radioactive wastes. In fact, there may be limestone aquifers with such large openings and such high porosities and transmissibilities as to make highly desirable disposal reservoirs.

The upper and less frequently the lower surfaces of basalt lava flows are sometimes very rough and fractured and when buried may make thin but highly permeable aquifers. Some of the world's largest springs issue from rock of this type. As these lava flows commonly occur in series, it is quite possible for a single deep well to penetrate a number of thin aquifers of fairly high transmissibility separated by rock of rather low permeability, a pattern which we have

seen is not without its advantages. A sequence of such flows may also be covered by compact fine-grained ash or other impermeable sediments. The structure of most lava-covered areas is relatively simple. This is particularly true of the wide areas covered by the so-called plateau basalts. In some places flows have moved out into basins bordered by hills or mountains made of compact impermeable rock, a configuration which makes it possible to place very definite limits to possible movement of the radioactive wastes in certain directions. Basalt is less absorbent than some of the clay minerals, but is somewhat more likely to absorb activity than pure quartz or limestone.

Although somewhat less erratic than in limestone, the hydrologic properties of basalt aquifers are less regular and less isotropic than those of most sediments. A more serious disadvantage may prove to be the high cost of drilling in basalt, which is a very hard tough rock.

In summary, we may say that the best aquifers and certainly the wisest choice will be found among the sandy formations, although locally excellent formations of limestone or basalt may be discovered.

Regional Hydrology of the Aquifer Area. The early attempts at deep well disposal of large quantities of power reactor waste should not be undertaken in an area where the ground water is an important source of water supply, for in case of upward leakage the superficial ground water may become contaminated. There are two ways of meeting the hazard of ground water contamination: to use an area in which there is a large supply of surface water, or an area in which the ground water is so heavily mineralized or lies at such a great depth as to be of no value. The first alternative, to use an area with an abundant surface water supply, may be satisfactory if the contamination of the ground water is small and if the surface water is able to dilute to safe concentrations the contamination which in turn reaches it. But to work in an area of abundant surface water is to run the

risk of a major disaster if the upward leakage is large. For example, it is true that disposal into deep aquifers in an area adjacent to the Great Lakes or the Mississippi would offer an opportunity for extensive dilution of a small leak and abundant surface water to replace any lost ground-water supplies, but a major failure which contaminated the lakes or the Mississippi would be a national calamity. There are no large bodies of fresh surface water which are not too valuable to subject to the risk of serious contamination.

There are areas, many of them areas of very low rainfall, in which the ground water contains so much dissolved solids as to be of little value; to contaminate an aquifer in such an area is no great loss. The use of an aquifer containing saline water or brine has other advantages. The presence of brines, whether connate or secondary, suggests strongly that there is little circulation of surface water through the aquifer. Further, if brine from the aquifer is used to dilute the waste the mixture will have a density greater than that of fresh water, a difference which will tend to prevent the waste from mixing with overlying fresh water.

The most important part of a study of the regional hydrology of the disposal area will be to map the water table, the piezometric surface in the disposal aquifer, and in any other artesian aquifers present. Water can only move toward regions of lower head and in isotropic media will move in the direction of the pressure gradient. If the transmissibilities of the several aquifers can be determined, and this is generally possible although perhaps expensive, estimates can be made of the amount of liquid moving through them. Determinations of the rate of movement are more difficult than those of volume and are more subject to error, for such information cannot be derived directly from the data of pumping tests because it depends in part on the porosity of the aquifer. The rate is also subject to variation in different parts of the aquifer, to longitudinal

mixing due to purely hydrologic factors, and to absorption of the contaminant on the aquifer matrix.

The suggestion to use abandoned oil wells, or wells drilled unsuccessfully in the search for oil, has been made repeatedly. However, presently inactive oil fields in most cases still contain much oil, and new methods to make possible the recovery of part of it will certainly be developed. As the easily available oil is exhausted, the reworking of old fields will become even more important than it is today. Moreover, the structures that contain oil are typically uparchings of beds (anticlines) which make fine traps for oil, which is lighter than the surrounding water, but such structures would make poor traps for a solution more dense than the liquid around it. For concentrated wastes, if such are injected, a basin-shaped structure is certainly to be preferred. Certainly many "wildcat" wells have been drilled into structural basins, and possibly such a well may be so located as to be of value to early exploration and experimentation. The idea, however, that numerous abandoned deep wells are available at little cost is not correct. Deep oil wells, producers and "dusters" alike, are of most value for the information they provide.

Potential Deep-Well Disposal Areas in the United States. It is not possible to review here the whole of the area of the United States, applying those principles and generalizations which we have discussed above, and delineate those provinces in which deep well disposal would be possible. Something can be done, however, to outline some areas in which deep well disposal probably will not work and to suggest what are likely to be the principal problems in certain places which now appear favorable. For this purpose reference will be made to the ground water provinces of the United States as defined by Meinzer.

It appears unlikely that suitable areas exist in the Northeastern Drift province, the Piedmont province, the Blue Ridge-Appalachian Valley province, or

GROUND-WATER PROVINCES

- A Atlantic Coastal Plain province
- B Northeastern Drift province
- C Piedmont province
- D Blue Ridge-Appalachian Valley province
- E South-Central Paleozoic province
- F North-Central Drift-Paleozoic province
- G Wisconsin Paleozoic province
- H Superior Drift-Crystalline province
- I Dakota Drift-Cretaceous province
- J Black Hills Cretaceous province
- K Great Plains Pliocene-Cretaceous province
- L Great Plains Pliocene-Paleozoic province
- M Trans-Pecos Paleozoic province
- N Northwestern Drift-Eocene-Cretaceous province
- O Montana Eocene-Cretaceous province
- P Southern Rocky Mountain province
- Q Montana-Arizona Plateau province
- R Northern Rocky Mountain province
- S Columbia Plateau lava province
- T Southwestern Bolson province
- U Pacific Mountain province

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the Superior Drift-Crystalline province since, except for thin deposits of glacial drift or recent alluvium, there are few aquifers of sufficient permeability to receive the waste. What deep aquifers there are have structures somewhat too complex for our purposes, and others, such as some of the limestones, owe much of their permeability to solution cavities and are not hydrologically sufficiently homogeneous. Much the same is true of the northern and southern Rocky Mountain provinces.

There are other areas, such as the Great Valley of California and the irrigated valleys of southern Arizona and New Mexico, which comprise the western and southern part of the southwestern Bolson province in which there is hardly enough ground water to supply the many needs, and its contamination would be particularly serious.

Other parts of the southwestern Bolson province, and in particular much of Nevada and western Utah, may be particularly favorable for disposal. In this area there are many intermountain basins which are hydrologically self-contained, as what little rain falls is lost as evaporation. No rivers flow out of them. Under these circumstances the only danger would be to the occupants of the basin itself. In some of these basins there is a possibility of finding areas in which there are deep permeable aquifers in which the water is too saline to be of value and in which the piezometric surface stands somewhat below the surface of the land. Injection of waste into such aquifers could be accomplished with a minimum of hazard and offers one of the best possibilities for deep-well disposal. Where crops are grown in these basins the water used largely comes from ditches which are fed by the more permanent of the streams where they leave the mountains. Some irrigation water comes from wells in the coarser-textured upper parts of the fans, where the water table, while deep, stands well above the basin floor. The danger of contaminating these water supplies is small. The probable

disadvantages are the limited extent of the deep aquifers in these basins, which are in general lenticular, and the relatively large amounts of clay and weathered rock in them which would promote absorption of activity near the wells. The chances of finding a clean, well-sorted sand deep under one of these basins must be very small indeed. Another hazard lies in the deep circulation of the ground water, which, although slow and small in volume, could bring to the playa surface a part of the waste disposed of in depth. This hazard does not appear serious.

The Columbia Plateau Lava ground water province of Meinzer also offers some possibilities. This area includes a large part of northern and eastern Oregon, parts of southeastern Washington, and parts of southern and western Idaho. Much of this country is a plateau cut by deep canyons such as those of the Snake and Columbia Rivers, and in these areas the ground water emerges as large springs in the cliffs near the major streams. Disposal of waste into deep wells under these circumstances would be very hazardous, for the rate of movement of the ground water may be very rapid and its pattern of movement very difficult to determine. This, for example, appears to be the case at the Reactor Testing Station at Idaho Falls. However, there are parts of the vast area covered by these same general lava flows in which it may be possible to find deep aquifers well below the main drainage of the area in which the ground water would be more nearly stagnant and into which wastes could be discharged with safety. The advantages to be expected would be the very high permeability of these aquifers and the probable low ion-exchange capacity of the host rock. The disadvantages would be that they are hydrologically anisotropic and very expensive to drill.

In parts of the Great Plains Pliocene-Paleozoic provinces, and locally in the south-central Paleozoic province (that is, in parts of Kansas, Nebraska, and Texas) the petroleum industry is at present discharging large volumes of oil-field brines

into deep wells. For example, in Kansas, large quantities of brine are put into the Arbuckle formation, a silicious limestone, at depths of over 4000 feet with no injection pressure needed above that of the natural head. Although the requirements for the safe disposal of radioactive wastes are much more stringent than for brines, the possibility of using these same aquifers is obvious. It may even be possible to add the radioactive wastes directly to the oil-field brines where these are not used for the secondary recovery of petroleum, profiting in this way from the experience of a well-established practice and the detailed knowledge of the local geology.

Over most of the south-central Paleozoic and north-central Drift-Paleozoic provinces, which include much or all of Iowa, Kansas, Oklahoma, Arkansas, Missouri, Illinois, Michigan, Indiana, Ohio, Kentucky, and Tennessee, there are aquifers near the base of the Paleozoic which may well be able to take the required volumes of waste. Among these aquifers are such formations as the St. Peter sandstone and the Jordan sandstone. In some areas, particularly where they are near the surface, these formations contain fresh water and are important sources of water supply. Over wide areas, however, where they are more deeply buried, they contain water which is too highly mineralized to be of economic value, and in these areas it is possible that they may safely be used for disposal. In general these aquifers have the advantage of simple uniform structure and hydrologic properties, and the amount of reliable information about them is relatively large. There is a public relations problem, however, in using an aquifer which in other areas is an important source of water supply, and in some cases a genuine hazard.

The Atlantic Coastal Plain province begins on the north at Cape Cod and Long Island and extends south across New Jersey, Delaware, and Maryland, and eastern Georgia and Alabama, and all of the states of Florida, Mississippi, and Louisiana; and its extension north along the Mississippi River embayment includes

parts of Tennessee and Arkansas. To the west, it includes eastern and southern Texas. The geologic structure and stratigraphy are much the same over this area. The underlying rock floor is an ancient peneplain of low relief which outcrops along the inner margin of the province and slopes gently south or east toward the sea. On this floor rest sediments, largely sand and clay, of Cretaceous and Tertiary age, which are thinner and coarser-grained near their inner margin and get thicker and finer-grained toward the sea and out under the sea. This structure gives the overlying younger beds a gentler dip than the deeper formations.

The depth to the basement at the strand line is as much as 2000 feet on Long Island, 5000 feet in New Jersey, and 10,000 feet at Cape Hatteras. Depths of 5000 to 10,000 feet or more prevail in Florida and the Gulf Coast.

The aquifers in this province are the coarser beds--sands, or in some cases, sand and gravel. Some of these are lenticular and pinch out down the dip; some change to silt and clay as they get deeper; and some retain all or much of their permeability down to and out under the shore line. Water enters the coarser beds along their higher inner margins and finds its way down dip toward the sea. As it approaches the shore its path is blocked either by a pinching out or change in texture of the aquifer, or because the lower part of the aquifer contains salt water which has moved in from the sea due to its greater density. Near the shore it is common for the fresh water in the buried aquifers to turn and move upward. Because the cover contains beds of low permeability this upward movement across the beds is difficult and in the case of some of the deeper aquifers virtually impossible. Where this is the case, and in particular where the aquifer contains essentially stagnant salt water, the formation may be used for the disposal of radioactive waste. This is not true, however, where overlying aquifers or the landward extension of the aquifer in question are used for or may in the future be used for the production of large volumes of water. As we

have seen, in artesian aquifers the changes in pressure due to pumping may be felt over long distances, and with time the waste could be drawn inland or upward into even distant wells. There probably are places, however, near the shore, or even out on the barrier beach islands, which can be used for waste disposal. The inner margins of the province, as at the Savannah River Plant, are not particularly favorable for disposal, the depth to the basement being small and the aquifers charged with fresh water of considerable economic value.

Cost of Disposal. The cost of disposal into deep wells will depend on a number of factors, some of which will vary so considerably from one site to another that no realistic cost estimate is possible until a particular location has been chosen and tested. It is probable, however, that the important elements of cost will be transportation to the site, the preliminary exploratory well drilling and hydrologic testing, the capital cost of the actual disposal facilities including injection and pumped monitoring wells and injection water-treatment plant, the cost of operations, which may well include monitoring a large area over a long period of time, and the insurance costs, for the hazard of an operation must be considered as a charge against it.

The cost of transportation is not a subject to be considered here, important as it would be in the actual choice of a site. The cost of the preliminary exploration may well be considerable and is perhaps the most valid argument for working near but not in an oil-producing area to take advantage of the detailed knowledge that may be available. The capital cost of the surface plant and wells will depend on transportation, on the depth of the wells, and on the number required. It is possible that a few wells in a remote desert basin, although individually expensive, might cost less than the more numerous wells that would be required in a more densely populated area. The desert basin would also require

less monitoring and the operation there would be less of a hazard. It is probable that the initial expense and operating outlay will be large, but as we have seen, the capacity of even a mediocre aquifer can be very large so that the cost per gallon may be low.