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EARTHQUAKES AND FLUID INJECTION

Earthquakes have been clearly linked to subsurface fluid injection in two places—near Denver at the Rocky Mountain Arsenal's waste-disposal well, and at the Rangely oil field in northwestern Colorado. The theory linking fluid pressure to earthquakes is based on the effective stress concept, *i.e.*, that increases of pore pressure reduce the effective normal stress across existing or potential fracture surfaces. In both cases, evidence exists for substantial tectonic shearing stressses in the reservoir rock prior to injection. Although the initial shear stress was below the critical value necessary to cause failure, fluid injection relieved a fraction of the frictional resistance to shear fracture, and earthquakes resulted.

There is presently no way to determine before drilling whether injection at a given site will produce earthquakes. At Denver and Rangely the earthquakes appear to be located entirely along pre-existing faults. At Rangely, the earthquakes have been drastically reduced in frequency by reducing pore pressures in the hypocentral region. In placing injection wells, existing faults should be avoided. Seismic surveillance during injection can provide early warning of inadvertently triggered earthquakes and palliative measures can be taken. The Rangely experience suggests that seismic activity due to waterflooding in oil fields may be controlled without seriously disrupting production of oil.

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PRETREATMENT OF INDUSTRIAL WASTEWATERS FOR SUBSURFACE INJECTION

To ensure success of a subsurface waste-disposal operation, surface pretreatment of the wastewater is generally required. Pretreatment can be expensive, but can make the difference between a successful operation and one subject to repeated difficulties and even failure.

Various problems can arise. Reduction of formation permeabilities and porosity, face plugging, and precipitation and polymerization reactions will all lead to diminished acceptance rates and excessive backpressure levels. Injection compatibility is of varying importance and is directly influenced by formation structure, interstitial water properties, and waste characteristics including solids particle size, pH, corrosiveness, viscosity, bacterial content, dissolved gases, temperature, and specific gravity.

Each disposal problem and its related solution must be evaluated separately. Basic pretreatment designs vary considerably and are usually tailored to the particular operation. Of basic importance is the minimizing of precipitate-producing reactions and the removal of suspended solids before injection into unconsolidated formations. This is less important in vugular or fractured hard rock areas.

Usually, a pretreatment operation will involve waste storage, separation of oil and/or suspended solids through flotation or gravity means, filtration through coarse sand or fine cartridge and diatomaceous earth, chemical fixation of pH, treatment to correct for corrosiveness or biological growths, followed by additional storage, and final pumping to the disposal well.

A thorough chemical and physical analysis of the wastewater and the receiving formation will result in an optimum design. Simplicity should be striven for. Although difficult, it may be possible to define and classify the various types of wastes which are deemed suitable for deep-well injection.

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MECHANICAL AND CHEMICAL EFFECTS OF PORE FLUIDS ON ROCK PROPERTIES

The disposal of wastes underground involves injection of fluids into a rock mass that through natural processes has probably attained a state of at least metastable equilibrium. Injected fluids tend to disrupt this equilibrium mechanically and chemically. The primary question concerns what effect this disruption will have on the rock body. Fracturing, faulting, or the reactivation of old faults could lead to earthquakes and to the creation of fractures that may provide permeability channels through which injected fluids could escape from the intended disposal beds. Accelerated compaction, brought about by chemically weakening the load-bearing framework of the rock or by reducing fluid pressures upon withdrawal, can cause surface subsidence.

At depths of 3–4 km most rocks are brittle, and fracture and rigid-body rotation are the dominant mechanisms of deformation. The most important physical parameter in this regime is the effective confining pressure P_e, defined as the difference between the confining pressure P_c and the pore-fluid pressure P_p. Both the breaking strength and the compaction of rocks are dependent upon the magnitude of P_e regardless of the absolute values of P_c and P_p. Increases in P_p produced by injection of fluids decrease the normal stresses but do not change shear stresses across potential failure surfaces. This could lead to fracturing, faulting, or the reactivation of pre-existing faults. Decreases in P_p produced by withdrawal of fluids from a reservoir can lead to compaction and surface subsidence as the P_e is increased.

The second important aspect of the problem is the role of the pore-fluid chemistry. Significant reductions in rock strength have been shown to result from the lowering of the surface energy of solids that occurs from adsorption of pore fluids and associated modification of bonding. Triaxial compression tests on sandstone show that the coefficient of internal friction is not altered by pore solutions of 0.002 to 2 ppm of $FeCl_3$. The lowering of the breaking strength is due rather to the reduction of the intragranular cohesive strength as a function of the concentration of the electrolyte solution.

The frictional characteristics of already broken rocks may be significantly altered by the introduction of surface-active fluids. In light of man-made earthquakes, such as those near Denver, Colorado, the influence of pore-fluid pressure and chemistry suggests that more sophisticated tests of rock properties should be made if problems caused by unexpected rock failure are to be eliminated.

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REQUIREMENTS FOR MONITORING OF INDUSTRIAL DEEP-WELL WASTE-DISPOSAL SYSTEMS

Increasing interest in the use of the deep subsurface for disposal of industrial waste requires that both the practitioner and the government regulatory body be assured injection is not harming the environment.

Webster defines the verb "monitor" in the subject context as, "To watch, observe or check upon, especially for some special purpose," and, "To keep track of, regulate or control." There are three principal areas of interest in monitoring subsurface injection systems: (1) the well, (2) the surface equipment, and (3) the subsurface. The importance of performing the function on active systems should be apparent, but the monitoring requirement for "abandoned" installations can, on occasion, be equally important.

The well structure is usually possessed of a string of cemented surface casing to protect the fresh groundwaters, a fully cemented string of casing to the disposal stratum, and an injection tube to conduct the waste stream to the formation. The minimum monitoring function for the well requires measurement of wellhead injection pressure, injection tube-casing annulus pressure, definition of corrosive effects of the waste on the well materials and, on occasion, bottom-hole monitoring of injection pressure and the location of a conductor-insulator interface. Several techniques are available that are useful to the injector.

The monitoring of the surface equipment should include records of the injection-pump discharge pressure, the rate and cumulative measurement of injected volume, injecta temperature and quality, and the corrosive-erosive effects of the injected stream upon the materials of construction.

As the real purpose of the monitoring process is to establish that the waste is going where it is intended to go—and remaining there—an examination of the subsurface takes on a special importance. The requirement will vary depending upon the geographic location, the properties of the waste, the subsurface geology, and the design and construction of the disposal well itself. An occasional monitoring requirement is the drilling of one or more wells to the disposal formation to obtain pressure data and, sometimes, to obtain fluid samples. Although there is some purpose for monitor wells of this type where relatively shallow formations are used, their employment for measurements in deep aquifers may not serve a purpose commensurate with the expense and possible hazards that may result.

Once the disposal-well system is no longer needed sound practice dictates that the hole be effectively plugged. Although this technique has been well developed for abandoned oil and gas wells, some additional care is required where industrial injection systems are concerned.

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SORPTION PHENOMENA SIGNIFICANT IN RADIOACTIVE WASTE DISPOSAL

Disposal of radioactive liquid wastes poses a particularly vexing problem, as these wastes contain various radionuclides and chemicals used in processing operations which are potentially dangerous, even in low radionuclide concentrations. Sorptive properties of minerals, particularly ion-exchange reactions, have been studied for potential direct application in waste treatment and for defining the fate of radionuclides when released to soils and geologic formations.

Because most waste streams normally contain stable ion concentrations far in excess of radioactive ions, sorption reactions of interest are those which exhibit high selectivity for the radionuclides. Structural and/or steric factors are generally of highest significance in selective reactions. Micaceous minerals selectively sorb radiocesium from high sodium, aluminum, or calcium solutions, primarily because of favorable structure. Zeolitic minerals show selectivity for certain ions by excluding other ions whose size exceed lattice parameters. Some sorbents show selective sorption reactions under particular pH conditions; thus alumina and related hydrous oxides selectively sorb radioactive cobalt and radiostrontium in alkaline sodium systems. In addition to the exchange reactions, sorbent properties, such as flocculation, swelling, and absorption of liquids and chemical properties of radionuclides, are important considerations in waste-disposal operations and management.

In practical applications of the sorptive phenomena in waste disposal, it is necessary to know the solution characteristics, sorbent properties, and formation characteristics, as well as the interactions of these factors. In the hydraulic fracturing technique employed at Oak Ridge, the waste-solution characteristics influence the choice of sorbents used to prepare waste-cement slurries. The high sodium salt concentration requires attapulgite instead of bentonite, and illite is added to fix radioactive cesium. To immobilize the mix after injection underground, cement is added which further complicates the reactions and behavior of the clay slurries. The behavior during injection and ultimate setting of the grout is further influenced by the characteristics of the formation.

Each underground disposal operation will require understanding of the environment into which the waste is placed. The final facility and technique should be tailored to meet the requirements of maintaining safe operation, as well as of insuring long-term safety for future generations.

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LIABILITY FOR HARM FROM UNDERGROUND WASTE DISPOSAL

The general principles of civil liability for conduct which harms a person are that such a person must show a legal injury to a right protected by law, caused by an act of the defendant which the law regards as a wrong. The four theories of tort law most likely to be applied in a case of harm from underground waste disposal are (1) trespass, an intentional invasion of the physical property of the plaintiff; (2) negligence, the causing of harm through failure to use reasonable care to avoid injury; (3) nuisance, the use of property so as to cause unreasonable interference with the use and enjoyment of another's property; and (4) strict liability, imposed without regard to fault upon those who engage in abnormally dangerous activities. The plaintiff's remedies are damages and injunction. The plaintiff will choose that rule and that remedy most suitable to his case, most likely to be sustained by the local court, and easiest to prove. The actor has few defenses other than to attack the theory of the plaintiff for lack of (or lack of proof of) an element of his case.

The new trend in the law is toward "conditional fault" (reflected in the difference between the American Law Institute's Restatement of Torts of 30 years ago and the new Restatement of Torts, Second), which permits desirable conduct although it carries possibilities of harm, but requires the actor to pay if harm occurs.

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EFFECT OF RESERVOIR HETEROGENEITY ON UNDERGROUND WASTE DISPOSAL

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