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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, espe-