DISPOSAL OF RADIOACTIVE WASTES BY SLURRY FRACTURE INJECTION

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ABSTRACT

Slurry fracture injection is used in Saskatchewan and Alberta to dispose of inert, low-toxicity fine-grained oily quartzose sand and oily water. This waste disposal method can be extended to low-level, large-volume radioactive solid wastes with reasonable cost and low environmental risk; all technical factors seem favorable. Some of the geotechnical and monitoring issues related to large-volume emplacement of wastes are discussed in this article. Stress alterations and fracture orientation changes occur during solids injection. Injection processes are monitored using wells and the induced displacement field. Most sedimentary basins have favorable characteristics for implementation of slurry fracture injection; with proper site selection and slurry design, million-year security seems entirely reasonable.

1 INTRODUCTION

An ideal radioactive waste disposal approach should have the following characteristics:

a. The site must have a minuscule probability of interacting negatively with the biosphere for vast time periods (perhaps 10^5 - 10^6yr);
b. The disposal technology must be flexible in its capacity to handle the waste materials for which it was designed;
c. Any such approach for permanent disposal must be carefully monitored and must carry society's acceptance;
d. Transport and handling methods must be safe for workers and nearby communities;
e. Sites must be permanent with no long-term maintenance requirements, and land use should not be impaired.
f. The price of the disposal method must be reasonable, given the necessary constraints.

Permanent disposal of low-level, large-volume, solid radioactive waste involves surface or underground placement. Surface storage depends on excellent physical containment for indeterminate times. In landfill structures or ground-based concrete repositories used for long-term storage of radioactive waste, breaching is inevitable, and emissions or leachates will be generated. Given sufficient time, all shallow sites will leak, erode, slough, be breached, or otherwise return wastes to the biosphere, perhaps in diluted or altered form, perhaps in a relatively intact form as when a landfill is breached directly. Given the desired isolation time, security goals cannot be met by any surface storage technique (Arnould *et al.*, 1993).

Consider approaches used just 20-50 years ago. Solid wastes were buried in pits; toxicity was not appreciated, and environmental issues were less well understood than today. In some cases, these wastes have been excavated and placed in engineered landfills, or, exceptionally, in drums and stored in warehouses. Clearly, these are but temporary solutions: drums rust, landfills leak.

Indefinite maintenance is an option; landfills can be surrounded by purge wells, regularly redrilled or otherwise maintained; land use can be permanently restricted; repeated monitoring and sampling can be implemented. These seem undesirable burdens for our descendants, and risk assessment for long return periods show that problems will occur.

Thus, deep geological entombment is the only realistic option. We believe that, among geological entombment approaches (Dusseault et al., 1996), slurry fracture injection is the best and most economic option for low-level, large-volume, solid radioactive wastes.

2 SFI AND ENVIRONMENTAL SECURITY

Projects carried out in Alberta, Saskatchewan and Ontario over the last five years show that Slurry Fracture Injection (SFI) of a water/solids slurry into permeable, porous strata at depth using oil-field hydraulic fracturing technology is a safe, viable and permanent solid waste disposal method. After injection pressures dissipate, solid wastes are permanently entombed by large earth stresses. Good site selection and practice can lead to exceptional environmental security, achieved at relatively low cost.

Clarification of several terms is appropriate.

Large volumes means that a SFI well may accept $\approx 10^3$-$10^5 m^3$ of solid waste (volume *in situ*) over its life, depending on depth and waste type. SFI is advocated for inert granular wastes. **Inert** means no deleterious decomposition or gas generation after placement, and low reactivity with host strata or other wastes. **Granular** means that the waste is or can be prepared as a particulate medium to be slurried in a liquid stream for SFI.

Toxicity of a radioactive waste is an issue for regulatory agencies; classification affects SFI use, siting, and operations. Site constraints and depth can be modest if a waste is of very low toxicity (Davidson *et al.* 1994). Mildly toxic radioactive solids require more rigorous constraints, such as deep injection under stringent controls into most favorable sites.

Methods exist to reduce leachate generation rates or fluid mobility in situ to extremely low values. Wastes can be incinerated and vitrified or formed into stable pellets. The pelletized granular waste can be dispersed in a cement slurry to immobilize it. A mixture of fly ash, shale, and gypsum (or phosphogypsum or flue gas desulfurization sludge) could be used as the dominant solid phase (85-90%); toxic radionuclides would be immobilized by cementitious effects, creep processes, and cation exchange. Reducing flux will reduce leachate escape rates; injection of waste dispersed in a cementitious shale slurry will generate a low-permeability body in the high permeability stratum. After consolidation is complete, water will flow around, not through the wastes.

Clearly, SFI siting and operation depend on geological factors such as the lithostratigraphic and mechanical properties of the target stratum, structural features such as faults and dip, and hydrogeological factors such as the presence of barrier shales.

3 ANALOGUES TO SFI

Massive injection of "slurried solids" occurs in nature when planar magmatic bodies (dykes or sills, Figure 1) are formed by hydraulic fracture processes (Pollard, 1987). Planar extension develops normal to the minimum stress direction in the earth (i.e., $\perp$ to σ_3). Hydrothermalism is also a high-pressure injection process; planar veins form at 90° to σ_3. These natural examples show that large volumes can be emplaced permanently in the ground, provided injection as a slurry or viscous liquid can take place.

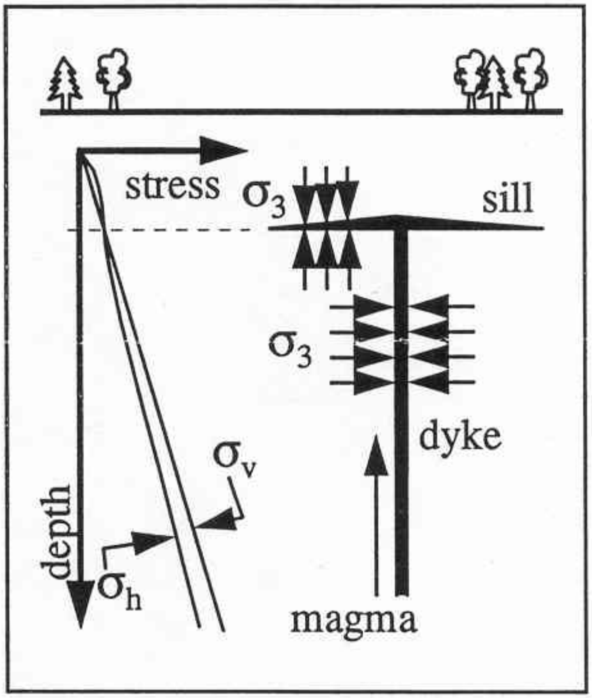


Figure 1: Dykes and Sills as Hydraulic Fractures

Since 1948, the oil industry has been using hydraulic fracturing to enhance well productivity or to introduce chemicals or thermal energy into porous reservoirs (Figure 2). Slurries or fluids are injected through perforated casings at depths varying from a few hundred to several thousand metres (Flak and Brown, 1988; Gidley *et al.*, 1989). Hydraulic fracturing also occurs during cement or clay slurry grouting when $p_{inj} > \sigma_3$. The deep penetration of fracturing is exploited to seal foundations and improve rock properties (Franklin and Dusseault, 1991) because slurries can seal joints and block pores. Drilling muds and wastes have been injected into shales at fracture pressures (Willson *et al.*, 1993); however, if injection is into low permeability rocks, elevated pore pressures can persist for long times. In the 1950's and 60's (and continuing into the 80's), nuclear waste disposal by grouting cementitious slurries into shallow impermeable rocks was tried in the United States (Stow *et al.*, 1985). Unfortunately, choosing impermeable and fractured host rocks led to control problems and poor predictability for grout sheet emplacement.

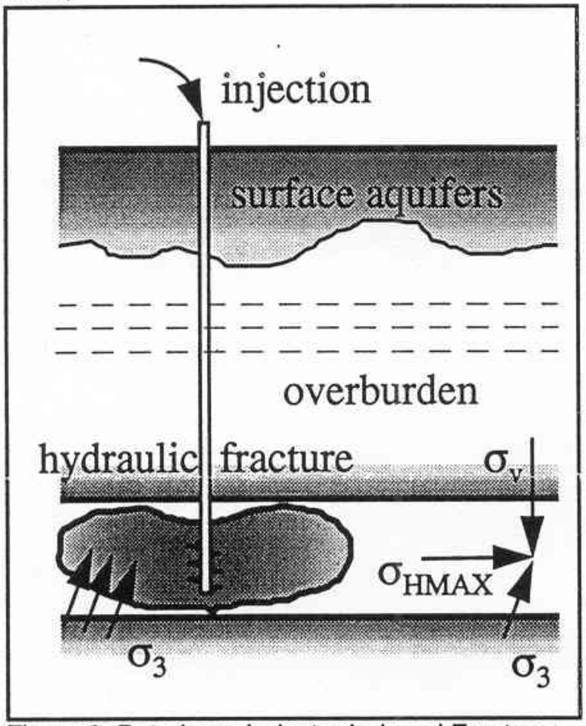


Figure 2: Petroleum Industry Induced Fractures

These cases imply that wastes can be successfully and economically disposed of by SFI. An important case history of experimental long-term waste sand injection took place recently near Lloydminster, Saskatchewan. Mobil Oil Canada Ltd. disposed of 9500 m^3 of oil-contaminated sand generated during heavy oil production from cohesionless sandstones (Dusseault, 1993). Sand was slurried with waste water and injected at pressures of 1.15-1.30$\cdot\sigma_v$ at -675 m into the Lower Cretaceous Dina Formation, a laterally extensive, 35 m thick, 30% porosity, 3-7 Darcy permeability quartzose sandstone. The formation sand was medium- to coarse-grained, the injected sand was 60-140 µm in grain size. *In situ*, emplaced sand permeability is likely about 2-4 Darcy at 33-35% porosity. Injection episodes were carried out regularly for 4-8 hours, daily or several times a week. The well operated for several years, and monitoring of formation pressures and well back-pressures indicated that the sand did not go far from the wellbore (50-100 m). The reservoir was never impaired with respect to its ability to accept sand, transmit fluids, and drain off excess pressures generated by the injection process. The pressure response indicated a waste body of a horizontal shape, as suggested in Figure 3.

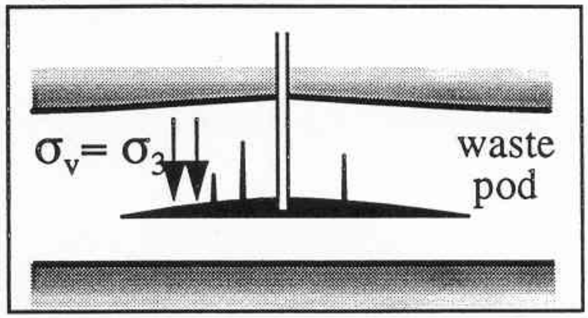


Figure 3: Horizontal Solid Waste Pod

Since that time, commercial SFI operations have been carried out in Alberta at sites varying in depth from 370 to 600 m, in single-well volumes ranging up to 17,000 m^3 of sand. In all cases, a porous, permeable stratum of great lateral extent was chosen. Sites also have protection from surface water by thick ductile shale barriers. In one case, a depleted heavy oil reservoir was used, with excellent success. In several operations, the injection well was inactive for several months between episodes, without impairing the ability of the well and the formation to accept the slurry.

4 GEOTECHNICAL ASPECTS OF SFI

Given a suitable site, what geotechnical issues are involved in SFI? Issues include stresses, stress changes, displacements, and fluid flow.

Natural earth stresses vary from site to site (Adams and Bell, 1991); stress conditions (σ_3 directions) dictate whether induced fractures are initially vertical or horizontal. However, we know that at shallow depths (< 1000 m, but perhaps also at greater depths), massive injection increases lateral stresses, but vertical stresses remain dominated by the overburden weight and the earth's free surface.. For SFI and steam injection cases we have been involved in, permanent stress re-orientation took place after large injection volumes, and induced fractures were dominated by horizontal components.

Figure 4 is a conceptual injection pressure-time record of stress direction change. After vertical fracture initiation, continued sand-water slurry injection results in sand deposition on the walls of the fractures because fluid rapidly escapes into the formation under high gradients. Clearly, this leads to an increase in σ_h with fracture evolution similar to the sketch in Figure 5. Laboratory tests show discrete segregation between the host and injected sand; there is no mixing or fingering of the injected material. This is because high pressure gradients during active injection generate true effective body forces on grains, "plastering" them in place (Figure 6), so that they are not free to move as long as $p_{frac} > \sigma_{cl}$, the closure pressure of the fracture. Seepage force on particles can be expressed as $\mathbf{F} = C \cdot A \cdot (\Delta \mathbf{p})$, where A is the area of the grain, Δp is the pressure drop across the grain, and C is a shape factor (1.0 for a tabular grain, less for other shapes). Viscosity does not enter into the seepage force, but a pressure gradient must exist, and induced forces are parallel to gradient.

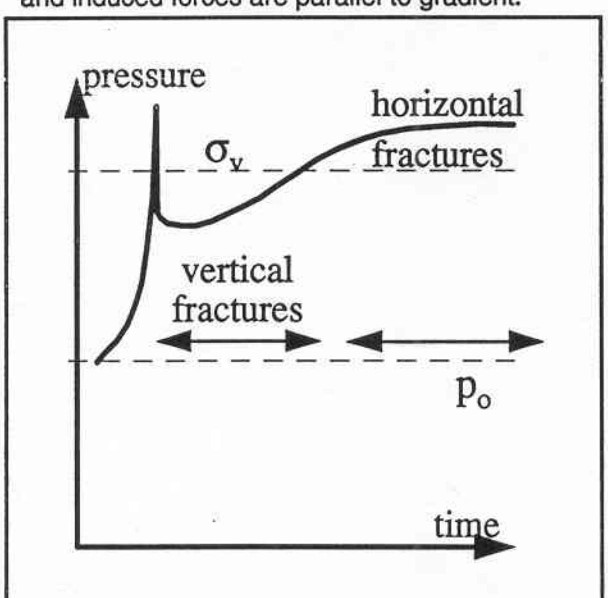


Figure 4: P-t Record of Orientation Changes

What proof do we have of change of fracture orientation to a dominantly horizontal geometry? We have some direct proof and some strong indirect arguments. For an injection depth of 500 m in the Lloydminster area of Alberta, the following conditions are reasonable: $\sigma_v = \sigma_2 = 11$ MPa, $\sigma_{hmin} = \sigma_3 \approx 10$ MPa, $\sigma_{HMAX} = \sigma_1 > 11$ MPa, and initial pore pressures of 4.2-4.5 MPa. Because p_{inj} must be large enough to overcome σ_{hmin} plus hydraulic losses, Δp driving flow away from the fluid-filled part of the fracture is at least 5-6 MPa. The high permeability of the formation and emplaced sand mean than a fracture cannot travel far before the free fluid escapes and the solids are left behind. The thickness and extent of the target stratum are large, and at some distance (~100 m), no observable pressure response can be detected, a fact confirmed by monitoring of adjacent wells in recent projects.

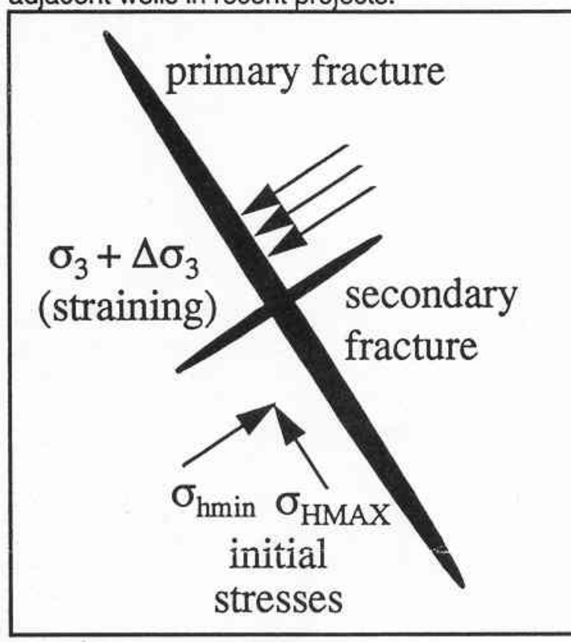
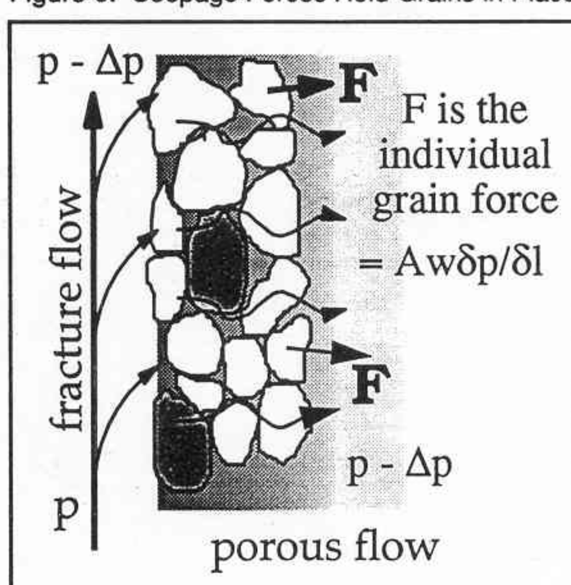


Figure 5: Vertical Fracture Orientation Changes

Figure 6: Seepage Forces Hold Grains in Place



Orientation changes have been detected using tiltmeter monitoring (Dusseault and Simmons, 1982). Such behavior may also be inferred from the high injection pressures required to propagate fractures and to re-initiate SFI after a period of slurry injection (Figure 4). Typically, "stable" injection will continue at $p_{inj} = 1.20\text{-}1.30 \cdot \sigma_v]_{initial}$; it is difficult to reconcile such values with anything but a horizontal fracture process that "lifts" the overburden. Nevertheless, there are probably minor components of vertical fracture propagation, although dominance by horizontal components is evident.

Thus, because the solids being packed into the formation increase local σ_{hmin} and σ_{HMAX}, stresses are altered to the condition $\sigma_v = \sigma_3 < \sigma_{hmin} < \sigma_{HMAX}$. Stress equilibrium dictates that stresses cannot be created or destroyed, only redistributed, therefore stress trajectories are modified by the presence of the waste inclusion. The size of the zone of significantly altered stress is not known, but modeling suggests a region about four times the size of the injected body.

The specific shape of an injected solids body is not known in detail, except that it appears to be relatively compact (near the wellbore) and dominantly horizontal. In a project in Alberta, we placed 17,000 m^3 of sand at a depth of 370 m over a period of 1.5 years, with several prolonged shut-down periods. Pressure-time responses similar to Figure 4 show we lift the overburden, but these overlying rocks have high stiffness and act like a plate. If the curvature is too sharp, a stress concentration will cause plastic extrusion of the sand body; this frictional extrusion is aided by the high pore pressures caused by injection. This, and the lifting effect of the pressure, will likely lead to an approximately axi-symmetrical quasi-horizontal lenticular body of smooth curvature (Figure 3). It will approach axi-symmetry because thick plate curvature cannot be much different in one direction than another, even with some stress or stiffness anisotropy in the horizontal plane. Clearly, a balance between overburden stiffness and the frictional plastic behavior of the sand governs the static shape of the body, but we have not yet analyzed this complex problem fully.

The lenticular body must grow laterally as sand is injected. For example, if one assumes a uniform disc of volume 50,000 m^3, a 10 to 1 thickness ratio (d/h) means that the solids lens is no farther than about 50 m (43 m) from the injection well. We believe these figures are reasonable.

The overburden strata are deflected, and this will induce local compression and tension, depending on the geometry and strains. However, because of the three-dimensional upward spreading of the deformations, strains decay rapidly (though total volume remains almost constant for a horizontal body). For example, at the surface directly above an 50,000 m^3 injection site at 500 m deep, the uplift will be about 800 mm. However, 500 m away from the wellhead, uplift is still several hundred mm, and gradually diminishes until it is less than 5 mm over 1.5 km away from the wellhead. The resultant slopes (0.005 maximum) are much less than the standards for differential settlement of buildings, and can be reduced by the use of a number of injection wells.

What about waste consolidation? High permeability granular wastes consolidate immediately under the effective stresses at depths of several hundred metres. Surface deflection usually stops within hours after stopping injection, thus sites can be returned to prime land use.

Impermeable and fractured strata have serious disadvantages as disposal targets; fluids must travel far to dissipate pressures, leading to fracture plugging and stratum pressurization. High induced pressures in a large volume of shale or other low permeability rock can lead to seismicity. If the fluid potential is not released by porous media flow, the fracturing liquid can generate climbing fractures which break into zones at shallower depths. Thus, placement control is lost, containment is not guaranteed, and well casings can be impaired.

In contrast to previous approaches for radioactive waste disposal by injection (e.g.: Stow et al., 1985), we advocate placement in porous strata isolated from surface groundwaters by thick (>100 m) low-permeability beds. Our reasons are the following:

- Long-term pore pressures do not increase,
- Solid wastes remain near the injection well,
- Lateral groundwater flow minimizes risk,
- High storage capacity and liquid dilution can be easily achieved,
- The strata have low strength and fracture resistance,

- Natural clay minerals exist along potential flow paths to adsorb metallic ions, and
- A large number of potential sites exist.

5 MONITORING OF SFI

Given that SFI can take place at considerable depths, the most important issue after proper site selection and slurry design is process monitoring. Possible approaches to monitoring include P-T-V monitoring of the injection well, borehole geophysical logging, P-T monitoring in adjacent wells, surface deformation (including tilt, uplift, gravimetry), downhole extensometers, electrical methods such as electrical impedance tomography or electromagnetic cross-well tomography, microseismic monitoring, and active seismic probing such as 3-D seismic tomography or VSP approaches. Other than injection well data, we argue that surface deformation and microseismic monitoring are the best methods.

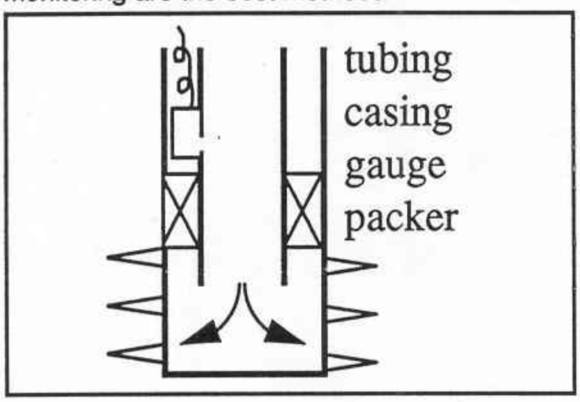


Figure 7: Tubing Quartz Pressure Gauge

Pressures, solid and liquid volumes and temperatures at the SFI well are continuously monitored at the wellhead and pump exit. A quartz pressure gauge is placed into the space between the injection tubing and the well annulus to monitor bottom-hole pressure (Figure 7). These data give valuable insight on formation response changes over time.

If injection is taking place in a depleted oil field, other available wells can be pressure monitored. If pressure monitoring wells are to be specifically installed, it is recommended that they be considered for multiple uses. For example, Figure 8 shows a single well with a non-conductive casing for electrical monitoring, two triaxial geophones for microseismic monitoring, and a perforated interval for pressure monitoring or pump testing. Steel-cased monitoring wells can be converted to SFI wells, so the monitoring investment is not necessarily "lost".

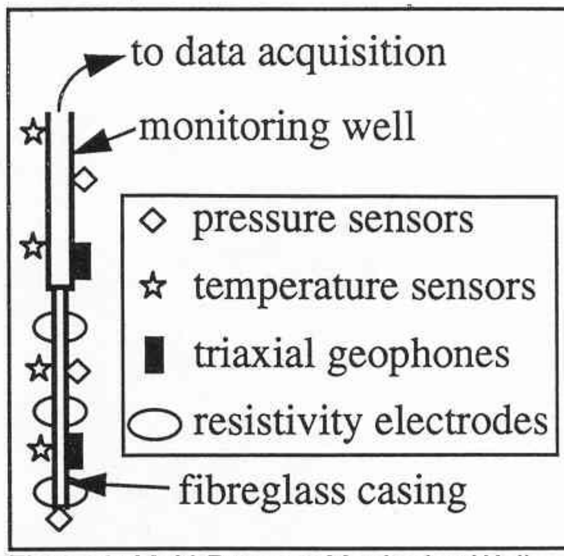


Figure 8: Multi-Purpose Monitoring Well

Actual pressure monitoring in adjacent wells, approximately 100 m laterally distant in one case and 70 m vertically distant in another, has shown that in a thick permeable stratum used for SFI of sand and water, there is negligible pressure response even after hours of injection at pressures 1.3 times overburden weight (initial pressure was 0.4 times overburden).

Deformation monitoring of permanent vertical uplift (Δz) is achieved by periodic leveling surveys of a network of stable benchmarks. Accuracies of ± 0.7 mm are possible, and results are mathematically inverted to give information about the shape and orientation of the injected body. Other technologies such as gravimetry or airborne laser interferometry and satellite radar interferometry currently cannot give the reliability and precision of a ground survey, but may be useful for large deformations over large areas.

With reasonable data quality, good reconstruction of total volume change ($\pm$10-20%) and large-scale shear movements is straightforward (Dusseault et al., 1993), but details of the shape of the SFI body cannot be resolved because of the smoothing effect in deformation transmission to the surface (Wang et al., 1994).

Electronic tiltmeters in shallow boreholes (-6 m) give continuous ground inclination data to accuracies of better than a ten-thousandth of a degree. An array of tiltmeters (12-20) allows reconstruction of the deformed surface, and mathematical inversion gives information about the injected body in "real-time" if required. Tiltmeters were used in a 12-instrument array for monitoring of a 450 m deep SFI project in eastern Alberta (Figure 9). Figure 10 shows the instrument case and the top of the 6-15 m deep installation well for a tiltmeter.

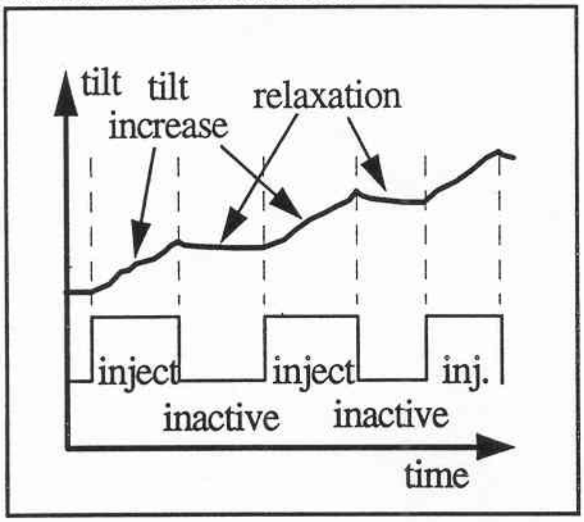


Figure 9: Tilt Response to Injection Episodes

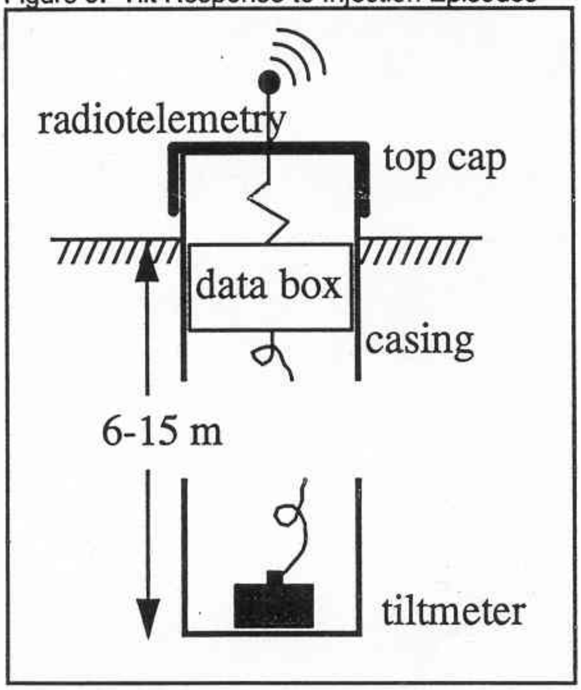


Figure 10: Typical Tiltmeter Installation

Seismic profiling or tomography attempts to delineate spatiotemporal wave velocity or quality differences. Resolution and accuracy are limited by the wavelength sampled, which has to be relatively low because high-frequency energy attenuates over modest distances. Although the usefulness of active seismics in monitoring large-scale conventional and thermal oil recovery processes is well proven, active seismic methods are not considered to be the best option for SFI as containment and spatial details of the solids injection cannot be resolved.

Microseismic (MS) monitoring provides a strong spatiotemporal localization of the solids injection process. Stick-slip shear with MS emission accompanies the frictional plasticity within and on the periphery of the injected sand body during SFI, and localization can be provided by using a two- or three-well transducer strategy. MS activity has been successfully used to track front migration in air injection for in situ combustion (Nyland and Dusseault, 1983), and has been used to track oil-field hydraulic fractures.

It may be possible to track fluid migration spatiotemporally using electrical methods. For example, if fresh water is the carrier fluid and SFI is taking place in a brackish system, a conductivity front migrates through the reservoir as native pore water is displaced. Electromagnetic surface methods are too insensitive (Narayan and Dusseault, 1994), but current injection electrode wells at depth and a combination of surface and well electrodes for measurement can give the necessary resolution to tomographically reconstruct conductivity distribution or to track conductivity front progression through the reservoir.

Geophysical logs are of little use in repeated SFI monitoring as they give information only about the immediate wellbore environment, are expensive to run, and are not sensitive to the types of changes caused by SFI.

6 CONCLUSIONS

Oil field wastes have been successfully disposed of by massive slurry fracture injection into porous permeable sandstones of intermediate depth. The same approach promises to be viable for low-level, large-volume solid radioactive waste. It appears to be far more environmentally secure than many other approaches, does not impair long-term land use, and will be suitable for many types of radioactive wastes. Currently, costs of $CAN50.00/m^3 solids, exclusive of well drilling, apply for most projects. Even including capital costs and extreme care in surface handling and monitoring, costs of less than $CAN200.00/m^3 are reasonable.

Major remaining geotechnical issues are related to the mechanisms of emplacement, stress changes, how rapidly the pressures bleed-off the active fractures and decay, both spatially and temporally, and the surface uplift.

Any hydrogeological risk relates to probability of interaction with potable surface waters, but it appears that proper site selection can reduce this risk to a vanishingly small quantity, and million-year design security is not unreasonable.

Monitoring is necessary to control the process during injection, to demonstrate containment, and to increase the level of environmental security. All injection parameters are continuously monitored, and adjacent wells may be used if appropriate. The surface displacement field is a useful and economic method of monitoring the process at depth. Microseismic monitoring also has promise, but more experience is lacking.

In summary, SFI probably represents a superior solution for entombment of low-toxicity, large-volume, solid radioactive waste.

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