Geological engineering criteria for deep solids injection

Muhammad Nadeem and Maurice B. Dusseault

ABSTRACT

Slurried solids injection is a procedure for placement of granular solid waste deep into porous and permeable geological strata. This technology is currently used by the petroleum industry in several countries (United States, Canada, North Sea, and Indonesia) to dispose of nonhazardous oil-field waste solids. Granular or ground solids of grain size less than 5 mm (0.19 in.) are mixed with waste liquids to form a slurry that is pumped down a deep well under conditions of continuous hydraulic fracturing pressure ($p_{\text{inj}} > \sigma_v$).

This article discusses rock mechanics aspects and geological engineering criteria for deep slurry injection. Specifically, the geometrical, lithostratigraphical, and physical parameters that characterize a stratum as a suitable target reservoir for slurried waste placement are addressed. The most important criteria are permeability, porosity, reservoir thickness, depth, and structural geology (of the region). A geological assessment model was developed to serve as a screening process to select suitable reservoirs for slurried waste placement. The screening process to select suitable reservoirs is composed of two steps: a decision tree and a semiquantitative ranking system that provides a numerical score for the stratum. The apparently robust assessment model was tested on several sites representing diverse sedimentary geology in the United States, Canada, the North Sea, and Indonesia.

INTRODUCTION

Geological Disposal Options

The conventional means for solid-waste disposal is in landfills. A landfill is a depression in the ground, commonly lined with clay beds or polymer sheeting to reduce hydraulic interaction between wastes and the biosphere. Once full, it is covered with a cap designed to restrict percolation into the waste horizon. Landfills are rarely leakproof because of various factors, including clay liner shrinkage (Philip et al., 2002), hydraulic fracturing of the lower rolled clay seals (see critique below), undetected perforations in polymeric liners, and accidental breaching by other activity.

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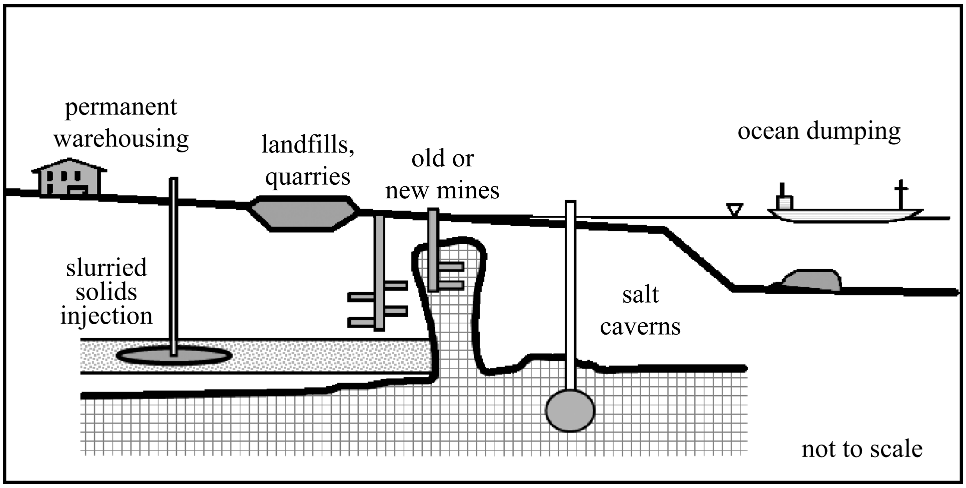

Figure 1. Geological disposal options for waste material. All forms of material (i.e., solid, liquid, and gas) can be disposed of using these options.

Clay liners in class II landfills commonly have a built-in lateral stress (σ_h) on the order of 3050 kPa (4.3–7.2 psi), generated by lateral reaction during compaction. Once the hydraulic head ($p \sim \gamma_w z$, where γ_w is the unit weight of water, 10 kN/m^3, and z is the depth) in the landfill exceeds σ_h, hydraulic fractures can be induced, providing that $\sigma_{hmin} = \sigma_3$. Reduction of lateral stress within the clay liner may occur because of shrinkage (loss of adsorbed water) upon exposure to saline solutions or chemically active leachates. This facilitates hydraulic fracturing, and as fractures propagate downward, paths for leachate access to the clays are generated until the liner is fully breached. Because of these and other problems, landfills are increasingly viewed as unsatisfactory solutions for solid-waste disposal.

More secure geological disposal options for solid waste include mine and solution cavern disposal, ocean placement, and slurry injection (Figure 1), although ocean placement is less and less acceptable. Mines and solution caverns in halite strata are commonly used where such facilities already exist and are scheduled for abandonment. Alternately, a purpose-built dissolution cavern may be developed for solids placement (Veil et al., 1998), a technique used in western Canada and elsewhere for disposal of solid and oily oil-field wastes.

Landfill Selection Criteria

Because injection of solid wastes deep into suitable geological strata is an alternative to near-surface landfill methods, to list and describe several geological and social criteria that are specified for landfills is of direct interest. Some of the important parameters considered for landfill selection criteria (Ontario Waste Management Corporation, 1986a, b; North Dakota Department of Health, 2005) are provided below.

Hydrogeology: Great thickness of uniform fine-grained soils (more than 10–20 m [33–66 ft]) at the base of landfills is considered best because groundwater flow rates and possible leachate are generally slow through fine-grained soils, such as uniform silty clay or clayey sandy soils.

Flood plains and watercourses: The site should not be located in a flood plain because contaminated leachates or surface runoff could move to a watercourse and become a potential risk to downstream users.

Geographical distance: The distance between the waste collection or generation site and the landfill site should be minimized because greater distances mean longer travel times, higher costs, and increased risks.

Site area: The landfill area should be large enough to accommodate the facility and a technical buffer zone for a minimum active landfill life of typically 10–30 yr.

Displacement of residents: Displacement of residents and the use of high-quality residential land should be minimized.

NIMBY (not-in-my-backyard) considerations: Avoiding locations where landfills may interfere with agricultural land use, residential property enjoyment, local traffic movement, airport operations, etc., leading to a public reaction against any siting choice is important.

Rare species: Landfill siting should not adversely affect rare species or critical habitat.

Deep geological placement can eliminate all of these concerns except geographical distance. In particular, deep injection appears to greatly reduce all risks associated with surface and shallow water sources, accidental breaching, or other potential sources of biosphere interaction. However, existing regulations and assessment methods fail to address the particular issues related to deep slurry placement, so new criteria and constraints must be developed. Given the recent emergence of this approach, such regulatory structures have not yet evolved.

Hydraulic Fracturing

The petroleum industry has used injection of slurries to permanently dispose of drill cuttings on offshore platforms since the late 1980s (Veil and Dusseault, 2003), about the same time as the first trials of massive injection of nonhazardous oil-field waste solids and oily liquids or sludges (Dusseault, 1993). Slurry injection technology is based on petroleum industry hydraulic fracturing, a procedure commonly used to enhance well productivity or to inject large volumes of steam into viscous-oil reservoirs. Hydraulic fracturing actually breaks the target reservoir, so that a crack or fracture of a large surface area and a narrow aperture is produced. For this purpose, a fluid (water, oil, gas, or a slurry) is injected rapidly, so that the sustained flow rate exceeds the capacity of the reservoir to dissipate the fluid through porous media flow. The pressure increases because of the inability to sufficiently leak off the injected fluids rapidly. When the bottom-hole pressure reaches a value larger than the characteristic fracture generation and propagation pressure of the target reservoir, commonly assumed to be equal to the minimum principal stress, σ_3, a hydraulic fracture is generated, and fluid moves into the fracture. The fracture propagation is controlled by the transport and geomechanical properties of the formation, the in-situ stresses and pressures, and the nature of the injected slurry. Fluid leak-off from the growing fracture continues because of the high-pressure difference between the fracturing pressure, p_f, and the far-field pressure, p_o.

Need for a Screening Process

Oil industry hydraulic fracture methods have been modified to achieve continuous deep placement of slurried granular solids (Veil and Dusseault, 2003). Thus, this technology is likely to be applied to a broader range of waste materials and also in more diverse geological and geographical circumstances. The disposition, flow characteristics, and geomechanical properties of potential target strata dictate which lithostratigraphic unit may act as the best reservoir for slurry placement; thus, a comprehensive screening process is required to select a suitable target reservoir.

Screening criteria should be able to eliminate unsuitable targets, rank prospective reservoirs, and assure that the lowest reasonable risk levels are attained for waste placement. These criteria must also be flexible, so that more dangerous wastes (e.g., high concentrations of radioactive species, liquids containing chlorinated hydrocarbons or arsenic, and heavy metals in general) can be more securely disposed. Nonhazardous wastes, such as water-treatment sludges (Ca^{2+} rich), oily sand, and municipal biosolids, would be subject to far less stringent criteria than, for example, refinery wastes or solids with significant amounts of cadmium, lead, and selenium. In addition, within generally complex existing sets of regulatory constraints that are different for every jurisdiction (Puder et al., 2003), the disposal process should remain cost effective while providing high levels of environmental security.

Site screening will remain semiquantitative because of the nature of the geological information, which is commonly qualitative and always uncertain. Currently, a probabilistic risk-based calculation procedure does not exist, but the method presented herein may help lead in that direction.

THE WASTE SOLID INJECTION PROCESS

Well and Injection Mechanics

An injection well is drilled, steel cased, and cemented into place with nonshrinking cement to isolate overlying lithologic units that may carry economic minerals or potable water resources; greater security may be achieved through the installation of an intermediate casing string. At the target depth, the casing is perforated over a 3–6-m (10–20-ft) interval, with numerous 25–30-mm (0.98–1.18-in.)-diameter holes. Injection tubing (66–88 mm [2.6–3.5 in.] diameter) is lowered into the steel casing and sealed with a removable isolation packer placed above the perforations. Downhole pressure transducers are installed to continuously measure the pressure on both sides of the packer to provide constant monitoring of the injection well performance.

To initiate slurry injection, water is pumped down the injection tubing at a rate of about 1.5–2.5 m^3/min (53–88 ft^3/min), so that the system acquires full fluid momentum and also achieves the fracture initiation and

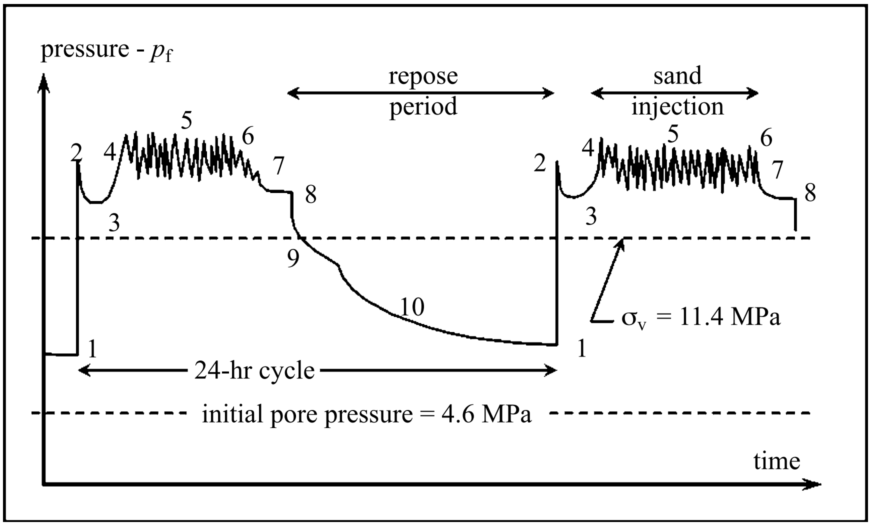

Figure 2. Pressure-time response for a solids injection well. The various terms associated with the graph are explained in the text in the Injection Pressure Response section below.

propagation pressure. Several minutes may transpire before fracture initiation can be observed; then granular waste material is added to the liquid in gradually increasing quantities, so that the desired slurry density is achieved during the next 10–15 min. Depending on the nature of the wastes and the carrying liquid, which could be a mixture of produced water, oil emulsion, and tank sludges, the injection density is maintained at a constant value, commonly 1.20–1.28 g/cm^3 in the case of low-salinity produced water as the liquid phase (~85% by volume).

Steady-state waste slurry injection continues, and one injection episode into a single well lasts for approximately 6–12 hr. At the end of the injection period, the waste feed content in the fluid is gradually dropped until reaching zero concentration during a period of approximately 20 min. Clear water is flushed through the system before the well is shut in, so that the well and perforations are free of solids, and blockage can be avoided during the next injection phase. The shut-in phase commonly lasts for 12–24 hr to allow the wellbore region pressure to dissipate to an acceptable level; downhole pressure is continuously monitored during this shut-in period. Other wells may be used to sustain the disposal operation as a continuous 24-hr process.

Injection Pressure Response

Figure 2 shows a typical $p_f \times t$ response for injection of a slurry of waste sand, formation water, and a small amount of oily waste at a depth of approximately 390 m (1280 ft) in a 15-m (50-ft)-thick, high-permeability ($k \sim 1.5$ d), high-porosity ($\phi = 0.30$) sandstone. Various stages, such as the preinjection period (1), the initial injection response (2), the steady-state clear-water injection phase before solids introduction (3), the stable slurry injection plateau (5), and the system cleanup procedure using clear water (7), are labeled. Note that the slurry injection pressure is substantially higher than the solids-free water injection pressure.

Once slurry injection is stopped (8), the well is closed against the near-wellbore pressure to avoid solids backflow, and a pressure decay period occurs (8, 9), with the bottom-hole pressure gradually approaching the regional (or far-field) formation pressure p_o (1). The pressure decay curve (7–8–9–10) is regularly analyzed to track reservoir-injectivity changes.

For large-scale hydraulic fracturing of slurried waste solids into permeable strata, the bottom-hole injection pressure (5) at steady injection rates of 1.5–2.5 m^3/min (53–88 ft^3/min) is approximately in the range

$$p_f \approx 1.1 - 1.25 \times (\sigma_v), \; p_n \approx p_f - \sigma_v$$

where p_f is the bottom-hole fracturing pressure, σ_v is the initial vertical total overburden stress, and p_n is the net pressure, considered to be the driving force required to sustain the propagating fracture. The condition $p_f > \sigma_v$ arises because additional energy is required to continue to drive a slurry into a fracture and because induced volume changes in the wellbore region increase the lateral stress (σ_h) so that it becomes similar to or greater than σ_v. Under such conditions, induced fractures are complex combinations of vertical and horizontal fracture components, but at any instant, the active fracture remains as a planar feature. It is also clear that the large difference between p_f and p_o sustains a strong pressure gradient in directions away from the fracture. In the hydrostatic pressure case, $p_o = \gamma_w \times z$; therefore,

$$\Delta p = p_f - p_o \approx 1.2 \times \sigma_v - \gamma_w \times z$$

Typical values for a depth of 500 m (1640 ft) are σ_v = 12 MPa (1740 psi) and p_o = 5 MPa (725 psi), giving $\Delta p \approx$ 10 MPa (1450 psi) (γ_w = 10 kN/m^3), which implies that in all slurry injection cases, there is a large pressure gradient that promotes rapid fracture dehydration if the rock permeability remains high. Thus, in a permeable stratum, once injection is stopped, p_f decreases rapidly, the fracture closes, and the bulb of high pressure around the fracture plane continues to dissipate, asymptotically reaching the far-field pressure p_o.

In the petroleum industry, propping agents are commonly introduced into a viscosified fluid for fracturing. Propping agents are strong granular solids, sand, or ceramic beads. Their purpose is to sustain a permeable path when fluid injection ceases. In slurried solids injection, wastes are invariably permeability-impairing agents (fine-grained sand, clayey waste, emulsions, etc.), so each fracture episode slightly affects the general permeability around the well. New fracture episodes, however, access partly unimpaired formation regions as the fractures change orientation, and injection can continue with reasonable postinjection pressure dissipation. Eventually, the injection process becomes increasingly affected by formation alterations in this near-wellbore region called the ''disposal domain,'' and eventually, a new well is required, placed 300 m (984 ft) away in the same stratum. For desirable good zones, injection capacity for a single well may exceed 10^6 m^3 (3.5 × 10^7 ft^3) of slurry, 10^5 m^3 (3.5 × 10^6 ft^3) of solids, 40,000 m^3 (1.4 × 10^6 ft^3) of emulsions, and similar agents that severely impair permeability. The waste water that is carrying liquid is never viscosified because it is unnecessary and expensive. In fact, agents that enhance water viscosity (polymers) are counterproductive in the context of rapid pressure decay goals.

Screening is commonly required for the deep injection process because the solid waste must be less than 5 mm (0.19 in.) in diameter to avoid plugging the well perforations. The screened solids are mixed with water and other wastes (e.g., waste oily liquids or emulsions), and the fluid carries the solids into the stratum where they are permanently deposited, whereas the excess liquid part of the slurry moves away into the porous medium. When injection operations have ceased and pressures returned to normal, the placed solids are under a large effective stress, entombing them permanently at depth.

Mechanics of Hydraulic Fracture

The global and local in-situ stresses control the fracture orientation. The rock mass mechanical properties (Young's modulus, Poisson's ratio) affect the predicted fracture aperture, whereas the stratum transport properties (permeability and storativity) dominate predictions of fracture extent. Fracturing processes in geological strata are reviewed below.

In-situ Stresses at Depth

Subsurface geological formations exist under compressive stresses from all directions having a natural stress state that arises because of gravitational and tectonic loading, as well as geological history (erosion and diagenesis). Stresses are normally reported as the three principal perpendicular compressive stresses, the maximum (σ_1), intermediate (σ_2), and minimum (σ_3). Normally, in the absence of tectonic forces or a geological history of large-scale erosion, σ_1 is the vertical stress, whereas σ_2 and σ_3 act as the maximum (σ_{Hmax}) and minimum (σ_{hmin}) horizontal stresses, respectively. In the presence of compressive tectonic forces (e.g., thrust fault or strike-slip fault environment), σ_1 can be a horizontal stress. Large-scale erosion can lead to a surface layer hundreds of meters thick where $\sigma_v = \sigma_3$, and in cases where the sediments have been buried deeply, mechanochemical effects (diagenesis) may impact the stress state. Principal stresses are generally assumed to be oriented normal and parallel to the ground surface, and their magnitudes vary with depth and can also vary somewhat within a reservoir depending on the tectonic, diagenetic, and production histories. In the case of a complex lateral lithostratigraphy (e.g., distributary-channel system or point bars), the clay beds compact more than the sand beds, and this may lead to local deviations in the stress orientations because of different volumetric compaction potentials. Similarly, in a pressure-depleted reservoir, different local levels of depletion result in small but different amounts of volumetric strain, and this leads to principal stress orientations that, locally, at the scale of the wellbores, may not be parallel or normal to the Earth's surface. However, large-scale solids injection involves volumetric strains that are orders of magnitude greater than those associated with pressure depletion, and in an injection process, the effect of the injected material (ΔV effects plus Δp effects) quickly dominates the stress field orientation.

Before injection, the vertical stress σ_v at depth z is commonly taken to be $\sigma_v = g\int_0^z \rho(z)dz$, where $\rho(z)$ is the density as a function of depth. In a compressive stress regime near a compressional mountain front, the stress normal to the disturbed front is commonly assumed to be the larger one of the two horizontal principal stresses. In a normal faulting tectonic environment, σ_v is assumed to be the major principal stress (σ_1).

The magnitudes and directions of the principal stresses control or affect the following:

- the pressure required to create and propagate a fracture
- the shape, orientation, and dimensions of a fracture
- the compaction of the solids present inside the fracture after injection ceases

Because solids injection introduces large volume changes, the stresses in a region around the injection wellbore will be massively altered. In addition, high pore pressures will be generated in a zone around the well during the injection process, and this can lead to shearing and dilation in weak, high-permeability rocks. These processes are partly amenable to analysis; however, they are beyond the scope of this article. Instead, a brief summary of this issue is presented without detailed discussion.

- Massive solids injection alters stresses near the wellbore, such that horizontal stresses are increased substantially and vertical stresses are increased by a small amount, considering a fracture is vertical.
- Solids injection leads to changes in local stress directions that cause changes in fracture orientation and attitude. After a short period (a few days of injection episodes), a disposal domain develops and grows with individual fractures having components of vertical and horizontal extension (length) and growth (width).
- Regionally, the anisotropic stress field will govern the general shape of the disposal domain, giving an overall ellipsoidal shape with the maximum extension normal to σ_3.
- Shearing and formation uplift alter the formation properties and allow the storage of more solids than can be predicted by conventional petroleum industry models.

Young's Modulus and Poisson's Ratio

The unaltered elastic properties of the distant rock mass affect the injection process, but the highly nonlinear effects of formation alteration (including local shearing), fracture packing, and surface uplift mean that the effect of mechanical properties becomes of second-order importance for a slurry injection process compared with the stresses. Nevertheless, a rock of high stiffness represents a less desirable injection stratum than one of low stiffness, other factors being equal, because it is more difficult to develop both aperture and length in rock of high stiffness. Wide, short fractures are better than long, narrow fractures because the solid wastes remain closer to the injection wellbore (i.e., within a reasonably constrained disposal domain).

In conventional fracture mechanics, after stresses and transport properties, Young's modulus is the dominant geomechanical property for designing a hydraulic fracture and provides a prediction of aperture and length in response to a value of p_n. Mechanical properties are clearly linked to geological history and lithotype, although specific relationships are empirical in nature. Because of the large volumes of solids that are placed in the formation, the lateral stresses increase, whereas the vertical stresses tend to remain approximately the same because of the free surface of the Earth; therefore, horizontal fracturing and overburden uplift are likely to dominate any solids injection process with time. This also means that the volumetric capacity of the reservoir and the stress-strain response are not as strongly linked to formation mechanical properties as a conventional limited-volume fracture process; instead, capacity and volume changes are governed mainly by the uplift of the overburden.

Fracture Growth

The minimum principal stress (σ_3) direction controls the orientation of a fracture, but the stress gradients (induced and natural) will affect the details of fracture growth. Consider the vertical component of a propagating fracture. In the ground, the gradient of the horizontal stress is somewhat less than the gradient of the vertical stress, on the order of 20–24 kPa/m (0.88–1.06 psi/ft). Within the open propagating fracture, the pressure gradient is 10–13 kPa/m (0.44–0.57 psi/ft) depending on the density of the fluid phase within the fracture (ρ_s). Therefore, a potential energy source for upward extension is present because the top of the fracture has a positive driving pressure and the bottom of the fracture has a negative one. For example, given a fracture of height H above the injection point, the excess driving pressure is approximately equal to $H\cdot(d\sigma_v/dz - \rho_s g)$ during the phase when the fracture is open and active.

A clear tendency for upward growth is present, leading to concern over breaching of the overlying rocks that provide a hydraulic seal. This issue affects the screening process, but there are several natural risk-mitigating aspects that should be mentioned.

First, the longer the fracture, the greater the hydraulic energy it takes to drive fluid into the fracture, and this tends to constrain fracture extension in all directions. Second, the negative downward-pressure potential means that significant downward hydraulic fracture growth is improbable; therefore, the integrity of a lower sealing stratum can almost always be assumed, and downward breaching is an issue of far lower risk in all cases. Third, because of uplift and erosion in many onshore sedimentary basins, the upper sediments are under a mild thrust fault stress state ($\sigma_v = \sigma_3$), impeding vertical growth of induced fracture planes. A vertically propagating hydraulic fracture encountering this condition will branch horizontally. Fourth, as a means of reducing risk and managing the process, surface deformation measurements can be used to roughly track fractures (Dusseault and Rothenburg, 2002), and the injection process parameters can be altered to reduce vertical growth components. Real-time monitoring is a valuable means not only to control the process, but to meet regulatory concerns about waste containment.

Transport Properties

Formation permeability and storativity, combined with the cumulative effects of injecting solid particles (clay, sand) and deformable materials (biosolids, oil, emulsions), are dominant factors in any waste disposal scheme.

The permeability of the zone must be sufficient to allow the exudates (waste water used to slurry the solids) to flow away from the injection zone without long-term, large-scale, high-pressure development that could lead to well shearing or local faulting. The zone must have a sufficient porosity to store the exudates relatively near the injection site, and hence, the storativity should be high as well. Other flow factors are important, however, to reduce environmental risk, and these may be more difficult to express in quantitative terms.

The target reservoir should be located far below drinking water aquifers, separated from them by several flow barriers and distant from any other site of economic interest (e.g., petroleum reservoirs or mines). Hydrogeological data indicate that most of the drinking water aquifers are located within 200 m (656 ft) of the ground surface; therefore, a depth less than 200 m (656 ft) is considered a negative factor for slurry injection. However, this figure is strongly dependent on the hydrogeological conditions of an area, and of course, deeper reservoirs provide greater environmental security. In the case of a deep reservoir, any breach in a primary flow barrier (the capping shale, for example), which may of itself be improbable, would be less likely to place any resources at risk because the liquids would take an extremely long time to reach an aquifer (flow rates approximately 10^{-12}–10^{-14} m/s [3.3×10^{-12}–3.3×10^{-14} ft/s] at depth; Boisson et al., 2001; Bradley et al., 2001).

Available storage capacity in other nearby permeable layers, modest regional pressure gradients, and geochemical adsorption of dissolved constituents during regional formation water transit are all factors that can enhance environmental security. For example, adsorption onto mineral surfaces tends to purify liquids in transit (Piwoni and Keeley, 1990), and this process is far more important with greater depths and longer flow paths. Likely, upward-moving liquids would become clean before reaching potable water sources or the ground surface, and this would only occur after many thousands or millions of years in favorable cases. In a porous medium, discrete oily liquids become trapped by capillary forces and, thus, are almost immobilized undoubtedly for periods approaching geological time scales (10^5–10^6 yr).

The northeastern part of the Western Canada sedimentary basin is a useful example of a lithostratigraphic sequence that is generally ideal for waste injection. Deeply buried Mesozoic clastic sequence strata exist with $40–60 \times 10^6$-yr-old formation waters and slow regional northeastward flow at rates of a few centimeters per year or less. The clastic sequences contain 10–15% permeable sandstones and about 85% shales and clayey sandstones, horizontally layered and mainly unfaulted, so that flow is forced to occur horizontally. This means that at least several million years would pass before exudates injected at 500 m (1640 ft) depth would daylight because flow paths are hundreds of kilometers long. By that time, dilution (through dispersion and diffusion) and adsorption would have rendered the water harmless. In the unlikely case of exudates retaining some noxious species when leaving the Mesozoic subcrop far in the future, there are thick glaciofluvial deposits between the subcrop and daylight, and mixing with more rapidly moving groundwater would further dilute them.

However, great depth is a negative factor from an economic point of view. High surface pressure, about $1.2z \cdot (\sigma_v - \rho_s)$, is required to continuously fracture the target formation and to push the injected slurry down the hydraulic fracture. High-horsepower requirements as well as high-pressure pumps and surface equipment are needed, and safety issues become more of a concern.

RESERVOIR CHARACTERISTICS

On the basis of case studies of previous slurry injection operations permeability, porosity (liquid storage capacity), reservoir thickness, depth, and structural geology of the reservoir and the surrounding area are the most important parameters that define the favorability of a target reservoir. Other important parameters include tensile strength and compressibility of the reservoir rocks, cap rock thickness, and the nature of the overlying stratigraphic column specifically; an alternating sequence of permeable and impermeable layers common in undeformed clastic sequences (sandstone and shale) is considered ideal.

Even the geographical distance between a waste collection site and a waste injection facility is important because short distances are more likely to make an injection operation economical and also more environmentally secure (reduced transportation risk, road use, and fuel consumption).

Some of these parameters can be described quantitatively, but others can only be described semiquantitatively or qualitatively. The following paragraphs briefly explain how the important parameters relate to the suitability of a target reservoir.

Slurry injection episodes produce a local zone of abnormally high pore pressure around the wellbore that could pose a potential threat of casing shear; a high permeability allows the liquid phase of the injected slurry to leak rapidly into the porous reservoir and minimize the extent of the local high-pressure zone. Previous slurry injection evaluations (Dusseault et al., 1994; Bruno and Qian, 1995; Bruno et al., 1995; Sipple-Srinivasan et al., 1997, 1998; Reed et al., 2002) indicate that multiple layers of shale (low permeability) and sandstone (high permeability) overlying the target reservoir are best. In addition, a slightly higher pressure is required to fracture the impermeable rock layer as compared with the permeable layer; therefore, a shale layer should also act as a limited stress barrier for hydraulic fracture propagation and help contain them within a limited disposal domain.

Superincumbent low-permeability layers provide flow barriers, whereas high-permeability layers promote rapid leak-off from the fractures (Abou-Sayed et al., 2000). A capping shale or similar low-permeability stratum is a primary hydraulic seal for exudates in the permeable target zone. Cap rock thickness and hydraulic integrity are particularly important for shallow target reservoirs (<1000 m; <3280 ft), less so for deep target reservoirs because a deep injection zone in layered strata commonly has many layers of overlying impermeable and permeable rocks. Impermeable strata provide additional seals; permeable strata tend to dehydrate the slurry within any propagating-upward fractures (called ''blunting''), making any large-scale upward leak-off of injected fluid virtually impossible. The presence of one or more overlying permeable zones is therefore a favorable factor in site selection. Of course, in the extremely fortunate circumstances of a very thick (e.g., 100 m [328 ft]) injection zone, basal injection may never generate fractures that rise to the top of the stratum; in such cases, the high thickness and permeability of the zone provide primary environmental integrity.

High permeability promotes rapid leak-off and solids screen-out (a filtration process) that limit lengthwise growth of the fracture and also promote multiple fractures (Sipple-Srinivasan et al., 1997; Reed et al., 2002; Veil and Dusseault, 2003). A disposal domain with multiple fractures allows a larger volume of solid waste to be placed close to the injection well. An ideal reservoir rock for solids injection should also be weak in tensile strength because it is easier to induce and maintain stable fracturing in weak sedimentary rock using reasonable injection pressures.

In the case of uncommonly high-permeability strata (e.g., more than 10 d), buildup of fracturing pressure during the clear (no-solids) water injection phase is difficult because of rapid leak-off; therefore, permeability values greater than 10 d are considered a negative factor.

High porosity makes a rock compressible: this helps generate thick fractures that ultimately accommodate more solids in a disposal domain of reduced lateral extent. The liquid storage capacity of a geological material depends on its void spaces; thus, high porosity gives high storage volume for exudates, and the solid phase stays entombed inside the domain by stress.

In a fractured porous medium, long-distance fracture propagation and fluid flow are more likely, and storage capacity is less because the matrix blocks are commonly of lower porosity. The classic case of a fractured limestone may be considered a zone of reduced suitability, although the blocks may have some storage capacity.

Permeability of a porous medium strongly depends on the porosity and particularly the pore-throat radius. In the case of granular media, discharge is directly proportional to the fourth power of the pore-throat radius. In the case of a fractured medium, the width of the fracture controls the permeability, with a discharge rate proportional to the cube of the aperture. However, flow through natural fracture systems is less predictable than through porous homogeneous strata; hence, the latter is preferred. Furthermore, we believe that natural fracture apertures quickly become plugged by the injected solids, so the high permeability that is characteristic of a fractured system will be more rapidly impaired than that of a porous medium.

Finally, with respect to permeability and the desirability of pressure dissipation and exudate storage, we emphasize that disposal in thick shale zones, in fractured igneous rock, or in salt and anhydrite should not be considered.

Structural discontinuities and steeply dipping formations could provide favored paths for exudates to migrate toward the ground surface and interact with water sources. A detailed study of the local discontinuities (faults, fractures, etc.) and the inclination of sedimentary strata and folding at the injection site and a regional study of the tectonic framework are necessary to develop a better idea about the large-scale geological fabric at a proposed injection site and the associated zone of influence. An ideal injection site should be tectonically passive and have a relatively simple structural fabric.

Many of the important factors such as tectonic fabric are difficult to rigorously quantify in a conventional manner; therefore, in seeking to make a quantitative assessment, a method must be developed to rank characteristics and classify sites using a mixture of quantitative and qualitative data.

RESERVOIR SCREENING AND RANKING

A screening and ranking process for site selection has been developed for the assessment of prospective disposal sites for deep solid-waste injection operations. This two-step process is based on the importance of several factors involved in site selection. The first step is composed of a decision tree, and the second step comprises the extraction of a semiquantitative numerical relationship expressing site quality.

Critical target stratum parameters and limits have been chosen on the basis of environmental considerations and experience. The decision tree addresses most critical factors that may cause a stratum to be unsuitably classified. In other words, any stratum that cannot comply with these critical limits can be discarded during a comprehensive solids injection site search process. The second part of the process involves calculations that engage the rank and weighting factors of each parameter to obtain a total score for a prospective injection site as an indication of quality relative to other sites that passed the decision tree process.

Decision Tree

A decision tree is based on a postulate of a sequence of events and possible outcomes for each event even if the outcomes have unquantifiable degrees of uncertainty associated with them. A decision tree is a common tool for decision analysis in environmental cases (e.g., site selection) because the logic sequence of the problem-solving procedure is exposed. Various geological and environmental questions and possible responses can be expressed in the form of branches. A decision tree may provide alternative actions that help lead to a more suitable solution (Newendorp, 1975; Moore and Thomas, 1976).

Figure 3 shows the decision tree for deep slurry injection site selection, which is quite simple because issues such as other disposal options, treatment technologies, NIMBY considerations, public discourse, and political factors have not been included. This decision tree is intended only to indicate whether a prospective site is geologically feasible for solids injection operations. Specific parameter values on the tree branches will need modification in particular cases (e.g., the injection of a particularly toxic material where limits would be far more conservative than those suggested).

Branches represent "go-forward" or "reject" decisions based on the values of the parameters defined in each branch. Information from the decision tree can therefore be read as follows:

- if reservoir thickness (T_r) is less than 2 m (6.5 ft), then target reservoir is unsuitable for injection, but
- if reservoir thickness is greater than 2 m (6.5 ft), then target reservoir is suitable for injection; similarly,
- if cap rock thickness is less than $4T_r$, then target reservoir is unsuitable, but
- if cap rock thickness is greater than $4T_r$, then target reservoir is suitable

In the case of depth, the tree information can be read as follows:

- if depth is less than 200 m (656 ft), then target reservoir is unsuitable, but
- if depth is greater than 200 m (656 ft), then target reservoir is economical, and
- if depth greater than 3000 m (9842 ft), then target reservoir is uneconomical

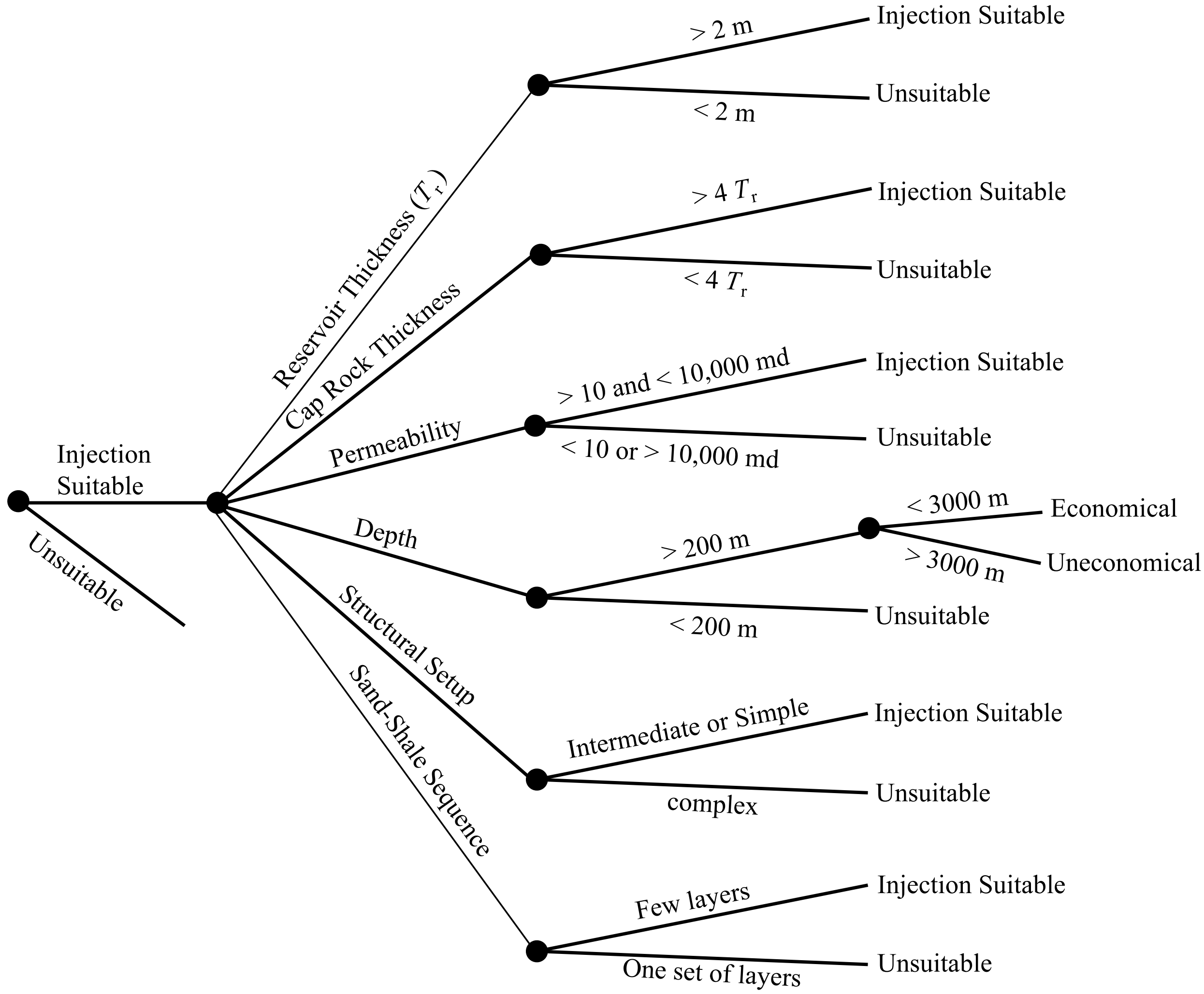

Figure 3. Decision tree for deep slurry injection operation. It comprises critical limits and possible responses for the parameters in the form of alternate actions that help to lead toward a suitable solution. How to read this tree is explained in the text in the Decision Tree section above.

Despite the existence of critical parameter values, some capacity for judgment must remain part of a geological and geomechanical screening system. Therefore, in a case where a prospective site has only one unsuitable rating, assuming other parameters are all excellent, the reason for that failure should be examined in the wider context of costs, volumes of waste, and quality of other factors. A site might be accepted if no other is available, particularly, for example, in cases such as the disposal of a limited volume of solids or for a completely nonhazardous solid waste such as flue-gas desulfurization sludge (U.S. Environmental Protection Agency, 1999). Nevertheless, sites having two or more failures would be unlikely reclassified.

Any site that passes the decision tree test is subjected to the second step of the screening process, which is based on ranks and weighting factors.

Numerical Evaluation

Parameters such as permeability, depth, and porosity are allocated a rank number ($P_1, P_2, \ldots, P_n$) based on the value or the quality of the conditions with respect to solids injection. This scale that leads to a ranking number is not a fixed relationship, but depends on the professional judgment of the evaluator and historical experience. The ranking number for each parameter is a numerical value that can be used to arrive at an overall ranking of sites if used logically and consistently, but the relative parameter importance must be specified.

Some parameters have first-order importance on solid-waste injection operations (e.g., permeability), whereas other parameters are less important (e.g., geographical distance from the waste-generation site). This leads to the adoption of a weighting factor (α_1, α_2,

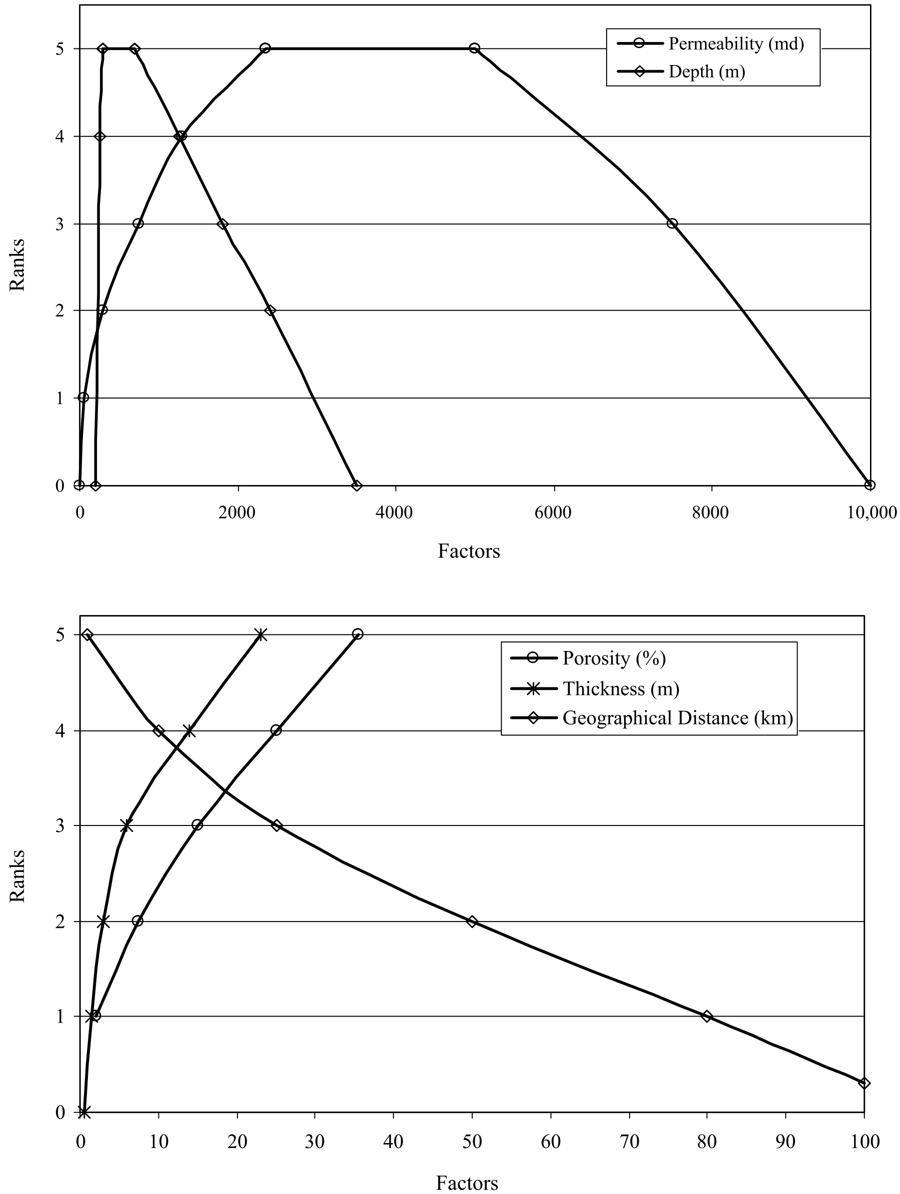

Figure 4. Graphical relationship between rank numbers and parameters, which is used to calculate appropriate rank value for a given value of parameter.

$\alpha_3, \ldots, \alpha_n$) to be applied to the numerical ranking of the parameters. An overall numerical value in terms of a total score (W) for a prospective injection site can be expressed in the form of a mathematical relationship: $W = \alpha_1 P_1 + \alpha_2 P_2 + \alpha_3 P_3 + \ldots + \alpha_n P_n$.

Rank numbers (P_i). Rank numbers are ordinal values (0 as minimum, 5 as maximum) developed to evolve a quantitative rating for deep slurry injection sites. Graphs shown in Figure 4 show the relationship between rank numbers and parameters that have been developed. The graphs are used to find the appropriate rank value for a given quantitative value of the parameter used in calculating a numerical quality value.

Weighting Factors (α_i), A priority scale (Table 1) is defined to assign weighting factors to each of the parameters used in the screening process on the basis of their importance. The following empirical method was adopted to determine appropriate weighting factors:

- Numbers were assigned as weighting factors for each parameter based on its judged priority
- Rank numbers were generated for each parameter for different hypothetical sites; for this purpose, several possible combinations were considered (ranging from excellent to worst case scenarios)
- The weighting factors and rank numbers were used to calculate the total score for each hypothetical site.
- This exercise was repeated for different sets of weighting factors, keeping other conditions and ranking values the same, to refine the assigned weighting

Table 1. Weighting Factor (WF) Scale of Important Parameters Based on Their Priority Level

Parameters and Priority	Remarks	Weighting Factors
Permeability, *k* (1)	Pressure leak-off	7
Reservoir thickness, *T* (2)	Waste amount	4.5
Structural setup, TS (3)	Waste containment	3.5
Porosity, ϕ (4)	Storage capacity, strength, and compressibility	3
Reservoir depth, *D* (5)	Environmental safety	2
Alternating sequence of sand-shale, AS (6)	Flow and stress barrier	2
Reservoir strength, *S* (7)	Breaking pressure	1
Reservoir compressibility, *C* (8)	Fracture width	1
Geographical distance, GD (9)	Hauling and environmental safety	1

factors, until a stable and acceptable set of values was obtained.

In this way, weighting factors were empirically determined for the geological and geomechanical data that were available. Based on this process and on judgment of the importance of geological and geomechanical parameters, these weighting factors are reasonable, although others may arrive at somewhat different factors.

Grading Principle

First, the values of the most critical parameters for the site are checked to confirm their compliance with the limits defined in the decision tree. Almost invariably, prospective sites that fail the decision tree test are discarded. Sites passing the decision tree criteria are then evaluated using the second step of the screening process: numerical evaluation. During this step, a site score is calculated using the previous equation and the ranks and weights. In this study, the maximum score a potential site can achieve is 125 based on the nine parameters and their relative importance (Table 2).

Next, three classifications are defined: below average, average, and above average. Any score less than 85 falls into the below-average category; 85–99 is the average category; and greater than 100 is the above-average category. A site is deemed unsuitable for injection operations if characterized as below average. The best sites will be in the above-average category.

Because of the uncertainties common in geological information, boundaries between categories are approximate. For example, a site achieving 98 points could be reclassified as above average through more careful study. Thus, based on the various cases evaluated, the boundaries can be expressed as 85 ± 3 and 100 ± 3 for this realization.

Finally, the numerical values in the decision tree and factors and weights in the numerical assessment part of the screening process have been chosen to reflect the information available, combined with the knowledge of typical conditions. For example, minimum injection depth in an arid climate with deep, fresh aquifers would be greater than a moist climate with a thin, potable water layer. Similarly, other parameters have to be specified in a manner consistent with the geological and geographical conditions.

EVALUATION

The geological assessment model must be applied in different geographical locations representing diverse geology to determine the performance. For this purpose, several different areas in the United States, Canada, North Sea, and Indonesia were selected. These areas include sites that already have a successful history of deep slurried solids injection.

Table 2. Evaluation Results for Table 3*

		Ranks			
Parameters	WF**	Pematang	Dalam	C1†	C2††
k (md)	7	4.5	4.9	4.7	5.0
T (m)	4.5	4.9	4.1	5.0	4.1
TS	3.5	5.0	5.0	5.0	5.0
ϕ (%)	3	3.3	4.5	3.0	3.8
D (m)	2	5.0	5.0	3.6	3.8
AS	2	5.0	5.0	5.0	5.0
S	1	5.0	5.0	5.0	5.0
C	1	3.0	5.0	3.0	5.0
GD (km)	1	3.7	3.7	5.0	5.0
Total score		113	118	113	112
Category		Above average			

*Above-average category, total score more than 100 of 125, corresponds to the best sites. For definitions of remaining abbreviations refer to Table 1.
**WF = weighting factor.
†C1 = target injection zone completion-1.
††C2 = target injection zone completion-2.

Values for semiquantitative or qualitative parameters are deduced from the overall study of subsurface geology and tectonics, whereas values of those parameters that could not be found using publicly available data (e.g., reservoir strength and reservoir compressibility) are estimated based on knowledge and experience in the public domain. Such estimates are based on empirical functionalities (e.g., the dependence of compressibility on porosity). The rank numbers and weighting factors are then used to calculate the total score for an injection site.

Initially, during the feasibility stage of a study, the quantitative parameters required for the evaluation of an injection site are porosity, depth, and thickness of the target reservoir, which are commonly determined from geophysical logs and drilling data. Pressure values are generally hydrostatic at the depths recommended for slurried solids injection. Parameters such as compressibility and permeability can be calculated more precisely using core data, but initial estimates may also be made using geophysical acoustic log and resistivity log information. Information regarding the tectonic fabric and structural setting of an area can be obtained from geological reports and maps, combined with subsurface structural and stratigraphic cross sections. The other parameters used as input in the assessment model can be estimated based on their relationship with the known parameters.

Duri Oil Field, Sumatra, Indonesia

The Duri region is part of a young, clastics-dominated sedimentary basin lying northeast of the coastal mountain range that forms the southwest edge of the island of Sumatra. The basin is geologically immature because of recent rapid sedimentation and uplift and is composed of alternating sand and shale beds. The shallow (<1000 m; <3300 ft) sands in the sand-shale environment have high porosity (>30%) and are uncemented (i.e., friable). They are suitable candidates for deep slurry injection operations, and all easily pass the first part of the screening process.

Caltex Pacific Inc. selected sandstones of the Dalam and Pematang formations as target reservoirs for solids injection and have performed more than 3 yr of continuous injection of more than 3 million m^3 (106 million ft^3) of slurried oil-field wastes. The important characteristics of the Pematang and Dalam formations are shown in Table 3. The evaluation results (Table 2) show that the total scores achieved by the Dalam and Pematang formations are 118 and 113, consistent with the injection company's experts' views and corroborates the choice of these zones for solids injection.

Table 3. Properties of Different Target Reservoirs in Duri Oil Field, Sumatra, Indonesia, and Port Fourchon, Louisiana*

Target Reservoirs	Pematang Formation	Dalam Formation	C1**	C2†
k (md)	1800	4700	2000	3000
T (m)	21	13	34	13.2
ϕ (%)	18	30	–	23
D (m)	394	370	1469	1352
AS	>2	>2	–	–
GD (km)	~10	~10	~1	~1

*For definitions of remaining abbreviations refer to Table 1.
**C1 = target injection zone completion-1.
†C2 = target injection zone completion-2.

Port Fourchon, Louisiana

The coastal area of Louisiana is a downwarped sedimentary basin formed by deltaic progradation, growth of estuarine accretion plains, and continued subsidence of the general area as sediments accumulate. This part of the Gulf of Mexico consists of thick sequences of clastic sediments of Miocene and younger age that dominantly progress and thicken seaward. Sedimentary formations present in the subsurface of southern Louisiana consist of alternating sand and shale having gentle southward regional dips. Locally, penetrative salt diapirism has warped, faulted, and fractured the sediments.

Chevron Corporation used two poorly consolidated sandstone reservoirs in the Port Fourchon area to successfully inject 1 million bbl of slurried oil-field waste containing small amounts of naturally occurring radioactive material (Reed et al., 2002). Table 3 shows the important characteristics of the two target injection zones referred to as completion-1 (C1) and completion-2 (C2). Table 2 shows the assessment model evaluation results. According to the scores, both reservoirs belong to the above-average category, which is consistent with the performance of the target reservoirs and the assessment of the engineering planning experts for the project.

Southwestern Ontario, Canada

A 2003 study assessed the potential of several areas of southwestern Ontario for deep solids injection. In a case-by-case comparison with all known large-volume injection operations that had occurred up to that time, the southwestern Ontario cases were determined inferior candidates. The current semiquantitative ranking system was used to reassess the sites.

Table 4. Properties of Target Reservoirs in Southwestern Ontario, Canada*

	Towns			
	Enniskillen	Tilbury West	Dunwich	Blenheim
	Guelph Carbonates		Cambrian Sandstone	
k (md)	14	115	21	117
T (m)	86	6	4	4
ϕ (%)	8	5	8	9
D (m)	589	359	1100	877

*For definitions of abbreviations refer to Table 1.

The assessment model is applied to four areas: Enniskillen Township in Lambton County, Tilbury West Township in Essex County, Dunwich Township in Elgin County, and Blenheim Township in Oxford County. Strata in these areas are generally indurated, low-porosity carbonates and siltstones with low matrix porosity (<10–15%) and fluid transport likely dominated by fracture flow. The rocks are stiff and Silurian and Ordovician, and target zones are generally only a few meters thick.

Table 4 shows the average values of the required parameters for the target reservoirs in these four areas, and Table 5 shows evaluation results in the form of the total assessment score for each reservoir. These results show that all areas selected for evaluation belong to the below-average category (scoring below 85 points out of 125), consistent with our original assessment. Injection is not necessarily impossible in southwestern Ontario, but conditions are poor in comparison to other areas. This implies that detailed work is necessary to find the optimum location, and that operations would likely need to be conducted conservatively (e.g., limits on volumes, rates, and slurry constitution) with more careful monitoring and analysis.

Table 5. Evaluation Results for Table 4*

		Ranks			
Parameters	WF**	Enniskillen	Tilbury West	Dunwich	Blenheim
k (md)	7	0.2	1.3	0.3	1.3
T (m)	4.5	5.0	3.0	2.3	2.4
TS	3.5	5.0	5.0	5.0	5.0
ϕ (%)	3	2.0	1.7	2.0	2.2
D (m)	2	5.0	5.0	4.3	4.7
AS	2	5.0	5.0	5.0	5.0
S	1	3.0	3.0	3.0	3.0
C	1	1.0	1.0	1.0	1.0
GD (km)	1	5.0	5.0	5.0	5.0
Total score		77	74	64	72
Category			Below average		

*For definitions of remaining abbreviations refer to Table 1.
**WF = weighting factor.

Murdoch Area, North Sea, United Kingdom

Conoco United Kingdom successfully disposed of approximately 60,000 bbl of oil-contaminated, slurried drill cuttings in the Murdoch area located in the southern sector of the North Sea (Schuh et al., 1993). The target reservoir selected was the Triassic Bunter Group, a sand-shale sequence bounded by thick layers of halite salt above and shale below. In the Murdoch area, the total thickness of the Bunter sequence is 243 m (797 ft), the top is at a depth of 1889 m (6197 ft), and injection was performed at a depth of 1950 m (6397 ft). Average values of porosity and permeability of the Bunter sandstones are 25% and 1000 md, respectively. Structurally, the Murdoch area is simple, and the presence of the overlying halite also likely acted as an additional stress barrier against vertical fracture migration.

Table 6 shows that the Bunter sandstones scored 107 points of 125 using the assessment model and belong

Table 6. Evaluation Results for Different Reservoirs Discussed*

		Ranks				
Parameters	WF**	Bunter Sand	West Coyote	Rex Sand	Dina Sand	Terminal Sand
k (md)	7	3.5	2.4	3.5	5.0	1.8
T (m)	4.5	5.0	5.0	3.3	5.0	5.0
TS	3.5	5.0	5.0	5.0	5.0	5.0
ϕ (%)	3	4.0	4.5	4.3	4.5	3.9
D (m)	2	2.7	4.0	5.0	5.0	3.6
AS	2	5.0	5.0	5.0	5.0	5.0
S	1	5.0	5.0	5.0	5.0	5.0
C	1	5.0	5.0	5.0	5.0	5.0
GD (km)	1	5.0	5.0	5.0	5.0	5.0
Total score		107	103	105	124	97
Category			Above average			Average

*From the section on Murdoch area, North Sea, United Kingdom, to the section on other Canadian basins. For definitions of remaining abbreviations refer to Table 1.
**WF = weighting factor.

to the above-average category, which is again in accordance with the measured performance of the target reservoir. However, the volumes of wastes disposed in this case and most other offshore cuttings disposal cases are minuscule compared to the vast volumes disposed to date in Duri and in other onshore waste injection areas in Canada, Wilmington, California, and the North Slope of Alaska (Veil and Dusseault, 2003). Success in the disposal of small volumes (<50,000 m^3 [<1.76 × 10^6 ft^3] total slurry) is not a guarantee of environmental security for cases of vast volumes (>250,000 m^3 [>8.8 × 10^6 ft^3] total slurry) because of the additional stresses and displacements placed on the strata surrounding the disposal domain.

Wilmington and West Coyote Fields, Los Angeles Region, California

Wilmington Field

In the Long Beach unit area, the Wilmington field (a supergiant oil field) consists of multiple zones of poorly cemented sandstones, greater than 25 m (82 ft) thick, separated by shale layers. The Terminal Sand in this sand-shale sequence was selected as the reservoir for deep injection operations conducted by Atlantic Richfield Company for the Texaco, Humble, Union, Mobil, and Shell group, which operates the Long Beach unit. Average values of porosity and permeability of the Terminal sandstones are 24.5% and 250 md, respectively (Veil and Dusseault, 2003). The slurry injection target involved several sands at different depths ranging from 1400 to 1500 m (4593 to 4921 ft), which were injected with greater than 450,000 bbl of slurried drilling wastes (Hainey et al., 1997). Table 6 shows that the Terminal Sand scored 97 of 125 points on the assessment model, which is within but at the top of the average category. This assessment is consistent with the performance of the target reservoir, where low injection rates were deliberately used to cope with the low permeability; if higher rates had been used, pressure leak-off may have been impaired. Injection has continued since the early 1990s, making this area (along with Alberta, Saskatchewan, and the North Slope of Alaska) one of the oldest large-scale, onshore, solids slurry injection operations in the world.

West Coyote Field

A field trial of a large-volume deep slurry injection of contaminated sand from the surface of an oil field was executed by Chevron Corporation in La Habra, southern California, at the West Coyote field in 1998. The target reservoir selected for the injection was a thick sand reservoir, the depleted and abandoned West Coyote oil field, at a depth of 1250 m (4100 ft), with average porosity of 30% and permeability of 500 md. The solid waste was oily surface sand and soil contaminated from oil production operations over the life of the field (exploitation started in the 1920s). Approximately 50,000 bbl of contaminated soil and fresh water were successfully injected during a period of 3 weeks (Sipple-Srinivasan et al., 1998) in an environmentally sound and economical (US$8.00/bbl of slurry) manner. Table 6 shows the target reservoir scored 103 of 125 points and belongs to the above-average category.

Lindburg Area, Alberta, Canada

Approximately 300,000 bbl of slurried waste, produced sand, and oily waste from heavy-oil production has been successfully injected at Lindburg in east-central Alberta, Canada (Sipple-Srinivasan et al., 1997; Veil and Dusseault, 2003). The target reservoir selected for injection was the Cretaceous Rex Formation of the Lower Grand Rapids Group composed of sandstone with no economic oil reserves. The injection interval sandstone is 8 m (26 ft) thick at a depth of 603 m (1978 ft); average porosity and permeability values for the Rex Formation sand are 28.5% and 1000 md, respectively (Veil and Dusseault, 2003). Table 6 shows evaluation results in the form of the total score for the target sand using the geological assessment model. The result classifies the Rex Formation target reservoir as above average, with 105 of 125 points. The reservoir as a disposal horizon is certainly in keeping with the assessment model results.

Other Canadian Cases

Injection cases are numerous in Canada and Alaska, and thus, not all can be presented here. A final example, the case involving the Dina Formation in Saskatchewan, Canada, is presented as a target reservoir for deep slurry injection operations because of its excellent properties. The first documented solids slurry injection of large volumes of oily waste sand occurred in 1988. The oil-free Dina Formation is dominantly composed of quartzose sandstone of mixed river channel and estuarine accretion plain origin. The reservoir is 35 m (114 ft) thick, with the strata top regionally at about 600–800 m (1968–2624 ft) depth; the average value of porosity for the sand is 30%, and permeability ranges from 2 to 5 d (Dusseault and Bilak, 1998), with exceptional streaks on the order of 5–10 d. The Dina Formation has a total assessment score of 124 of 125 (Table 6), which places the formation in the above-average category. This rating is consistent with injection performance into the formation.

Other Canadian cases, mainly in Alberta, give target strata assessment values invariably greater than 100 (above average) and commonly more than 115 points. This is consistent with the general view that the Cretaceous–age Heavy Oil belt region straddling the Alberta–Saskatchewan border contains many zones that are exceptionally favorable for large-scale solid-waste placement by injection methods. Similarly, targets in the North Slope of Alaska also have relatively high assessment values and are all in the above-average category.

DISCUSSION

Publicly available data show that the assessment system is consistent with practice, and that the numerical ranking value can be used as a reservoir screening tool for solids disposal utility. A brief discussion of the possible future use of the assessment system follows.

Experts opinions are highly regarded in cases of multiple parameter evaluation of complex and uncertain cases, such as those that typically arise in engineering works involving geological targets. The rankings used (Figure 4) may be viewed as professional assessments and quantified in a simple manner. Furthermore, the limits used in the decision tree and the weighting factors used to calculate a score are also chosen on the basis of professional and scientific experience in the general areas of geoengineering and applied geology. Other rankings can be generated based on alternative professional perceptions and experience, allowing comparison among experts. Thus, this approach provides not only a tool for ranking waste injection sites, but also a means of integrating the opinions of multiple experts involved with site selection.

CONCLUSIONS

A method for evaluating formation suitability for waste solids injection has been developed. The method is based on two steps: a go/no-go choice set up as a simple decision tree to decide if further evaluation is warranted; and a numerical evaluation based on the quality of various important parameters that describe the disposition and properties of the stratum.

The second part of the evaluation model uses a ranking for each parameter (reflecting an assessment from excellent to unacceptable). Weighting parameters are then applied to these ranks based on whether the specific parameter is considered to be of first-order or second-order importance. This procedure leads to a score that reflects the suitability of the target formation.

The evaluation procedure was tested against several well-defined cases in the literature to determine if practice corresponds to the numerical ranking achieved. Some results from a more exhaustive study (Nadeem, 2005) are presented here to show that in all cases studied, the rankings corresponded to experts' assessments and were verified by the performance of the operations that occurred.

Therefore, the procedure has merit and can be further extended to a more rigorous statistical assessment procedure by invoking additional statistical techniques and using the geosciences and environmental knowledge of a panel of experts.

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