Geomechanics and Waste Management
Achieving Zero Liquid and Solid Discharge

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Geological Disposal of Solid Wastes

Remember: disposal means disposal; treatment often means new waste streams are generated, but have to be disposed.
Permanent Waste Disposal

- Wastes are: tank bottoms, sand, etc. etc.
- Thermal desorption, incinerating…
- Chemical/washing treatment and land-filling
- Slurry injection (Cuttings re-injection - CRI)
  - Deep placement in porous strata
  - Suitable for solid particulate wastes as well
  - Geological disposal gives permanent isolation
- Some other options for **Zero Discharge**
  - Salt cavern disposal for solids
  - Recycling mud and wastes
Emulsions

Oily Sand

Tank Bottoms

Pit Slops
Advantages of Deep Disposal

- Eliminates landfills & groundwater problems
- Uses many levels of natural barriers
  - Low permeability seals (shales, mudstones)
  - Slow, horizontal flow regimes exist at depth
  - Natural clays absorb cations, organics
- The technology already exists (oil industry)
- No long-term maintenance is needed
- Environmental liability becomes zero
- Two methods: solids injection or salt cavern placement (salt is not everywhere present)
View of an Injection System
Geomechanics becomes an issue if:

- large $+\Delta p$ leads to $\Delta \sigma$, causing shear, etc.
- $\Delta T$ is large, leading to cooling effects

Cooling effect is a thermoelastic stress effect

- Cool H$_2$O injection: thermoelastic shrinkage
- $\sigma_\theta$ drops in the cooled zone until it is below $p_{inj}$
- Radial hydraulic fractures propagate out, following the cooling front
- The well becomes a much better injection well because of the increasing well radius effect

Better cements are important as well (seals)
Cuttings Reinjection

- Ground, slurried cuttings injected through an annulus, usually in shales (mainly offshore)
- Occurs at fracture pressure \( p_{\text{inj}} > \sigma_{\text{hmin}} \)
- Because of low shale permeability, pressures can remain high, two problems can occur:
  - Casings can shear if slip occurs (high \( \sigma_1 - \sigma_3 \))
  - Subsequent wells can have high \( p \) mud blowouts
- These are geomechanics issues, difficult, but possible to monitor and analyze
Slurried Solids Injection

Many areas are suitable for injection.

Possible well locations:
- 300 – 3000 metres
- 5-30 km

- Flat or gently inclined strata
- Surficial deposits
- Mudstone
- Silty shale
- Blanket sand in a thick shale
- Channel sand in a silty shale
- Blanket sand
- Limestone

Horizontal flow regimes:
- Low permeability strata

Not to scale.
Minimizing Risk & Liability

- Reservoirs or deep strata can be easily demonstrated to be remarkably secure
- Solid wastes are permanently entombed by stress once injection ceases
- Thus, solid wastes cannot flow or migrate
- Leachates are low toxicity & flow laterally
- Shale overburden eliminates vertical leakage
- Surface storage is very risky (they all leak!)
- Injection minimizes risk, at modest cost
Slurried Solids Injection Cycles

pressure

24-hr cycle

initial pore pressure = 4.6 MPa

σ_v = 11.4 MPa

sand inj.

repose period

time
Operational Stages

- Begin injection with clear water
- Fracture generation with clear water
- Momentum built up in system with water
- Begin adding solids to clear waste water
- Stable slurry injection, 6-14 hrs.
- Gradually shut off the solids
- Post-flush with clear water
- Stop water injection altogether
- Shut in and get closure pressures
- Obtain long-term $\Delta p$ for analysis
Stress Changes... Reorientation...

Initial Injection  Subsequent Injection  Fracture Re-orientation
One Day’s Injection Record

Daily Pressure vs. Time

(Injection period: 4-12hrs/day)

Injection Bottom Hole Pressure (psi)

start injection

end injection

shut-in period

13-Sep-97
Reorientation During Injection…

Horizontal uplift caused by water fluffing up formation 30 - 50% of uplift volume

Strike orientation of vertical fractures

Project TTI 4 (Saskatchewan, Canada)
In Situ Solids Placement

- Early time slurried solids injection operations
- Wastes fractures into the formation
- Solids deposits causes slight increase in local formation stresses
- Changes in local stresses cause re-orientation of each new fracture (fracture rotation)
Waste Pod Development

- Later time slurried solids injection operations
- Cumulative impact of solids placement and fracture rotation is to create a waste pod.
- Waste pod has different mechanical & flow characteristics (stiffer, lower permeability)

Waste pod development from past cycles (↓ compressibility, ↓ perm)

Today’s fracture

Well

Virgin formation (↑ compressibility, perm)
Waste Pod Growth

Longer fractures:
- access more formation
- waste pod extension

Short fracture:
- contained in waste pod
- waste pod ‘packing’
Waste Pod Development

4-F Waste Management

- Wellhead
- Perforation Locations
- Wellbores
- Core
- True Intersections
- Mapped Fractures

Average azimuth 112°
(1° Thrust)
Waste Pod Growth

Waste pod created by previous fracturing

Overlying Shale

Underlying Shale

Fmn. Thickness (20 - 60 m)

100 - 600 m

Current fracture
Waste Pod Growth

Overlying Shale

Waste Pod

Underlying Shale

Water leakoff into sand formation
The 3-D Shape of the “Zone”

Here, $\sigma_3 = \sigma_{h\text{min}}$, & the other two principal stresses are about equal. Also, the injectate density is assumed to be the same as $\sigma_3/z$, so there is no tendency to climb. (In reality, induced fractures almost always climb.)
In Situ Mechanisms

- Slurry forced in at fracturing pressures
- High k causes rapid pressure bleed-off
- Solids injection changes stress state:
  - Lateral stress ($\sigma_h$) rises
  - Vertical stress ($\sigma_v$) is constant
  - Mixed horizontal and vertical fracturing
  - Fractures change direction, shape, length
- Pressures decay, overburden stress is re-imposed on solids, compaction occurs
Characteristics:

- Low leak-off, high fluid efficiency
- Long, narrow fractures generated
- Little to no filtration of solids
- Slow closure and pressure decay
- Fracture orientation changes develop slowly
- Horizontal components
- Fractures rise because fluid density < \( d\sigma_3/dz \)
Characteristics:
• Medium to high leak-off, medium fluid efficiency (40-90%)
• Shorter, wider fractures generated
• Solids filtration: fracture wall permeability drops
• Rapid fracture closure and pressure decay
• Fracture orientation changes with strains
• Horizontal components develop
• Rise is blunted by fluid leak-off
Control Parameters for Injection

Methods to avoid reservoir impairment

- Surry injection rate can be varied
- The slurry composition (oil%...) can be varied
- Slurry density can be varied (brines used)
- Injection period length and volume of solids/liquids input can be changed
- Relaxation period between episodes can be changed to allow p and ΔV dissipation
- The proper reservoir selection is important
Depending on the liquid and solid wastes and the nature of the strata and potable water zone, higher levels of well security can be chosen, more risk reduction measures taken.
Well and Strata Choice…

**CONFINING ZONE** (Shale)

**CONTAINMENT ZONE** (Sands & Shales)

**TARGET ZONE** (Sand)

Surface sediments (Contain freshwater)

Shale

Sand

Uniform Cement Sheath

Non-contracting, ductile cement.

Bottomhole sensor

Packer

Perforations

Surface Casing

Production Casing

Injection Tubing

Computer

Cable

Underlying Shale
Late Time Behavior

- Slurry: 416 m$^3$
- Sand: 45 m$^3$
- Slurry: 505 m$^3$
- Sand: 80 m$^3$
- Slurry: 498 m$^3$
- Sand: 85 m$^3$
- Slurry: 740 m$^3$
- Sand: 113 m$^3$

Project TTI_3 (Norcen 1997)
Superb Pressure Decay Response
Why a High-k Site?

- Usually high porosity (sandstones > 25% $\phi$), therefore good storativity
- Flow is usually horizontal in high k zone
- High $\phi$ site means high compressibility
- High k means that we will not permanently pressurize a large reservoir volume
- Bleed off almost immediate, no long-distance fracture propagation, waste localized near well
- Much better than injection into a shale!
Conditions for Siting

- Deep, well below potable water sources
- In horizontal strata of great lateral extent
- Stratum must be sufficiently thick & porous
- Permeability must meet certain standards
- Thick ductile overlying shales are desirable
- At least one overlying permeable bed
- Formation water briny, flowing horizontally
- No exploitable resources to be impaired
Ideal Injection Lithostratigraphy

- possible well locations
- flat or gently inclined strata

- Shale barriers to upward flow
- Permeable zones to blunt upward migration
- Zones with good storage
- High k zones
- No reserves

5-30 km

3000-10,000'

not to scale
Solid Waste Injection Site - Duri
Tank Bottom Sludges

50% H₂O
30% oil
20% minerals
Oily Sand Wastes
Typical Surface Uplift

10 cm uplift

max slope ~1:5,000

no uplift at 1.5 km distance

700 m deep

waste site, 100-150 m radius maximum

ΔV ~ 16,000 m³

~symmetric
Well Capacity for Solids

- Proper formation choice is required
- To date, the maximum injected in a single well is 30,000 m$^3$ sand
- Water dissipates into the sediments
- 50,000 to 100,000 m$^3$ of sand (not including the waste water carrier liquid) is quite feasible for a well
- Target stratum tracking during injection allows continuous re-evaluation of capacity
CPI Duri Operations Waste Injection

CPI Duri SFI Well 64A
Jun 30 - Jul 2, 2003

Date/Time

BHP64_kPa

QLYT_m3_per_min

4-F Waste Management

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Step-Rate Test, Injection Well

**Step rate test**

- **Bottom-hole pressure (psi):**
  - 1200 psi
  - 1100 psi
  - 1080 psi
  - 1000 psi
- **Injection rate (m³/min):**
  - 0
  - 0.5
  - 1.0
  - 1.5
  - 2.0

**Injection cycle**

- **24 hours**
- **Begin injection:**
- **Stop injection:**
- **Decay data:**
How Cuttings Are Injected

- Injection is through the annulus between an exterior and interior casing.
- The cuttings are generally ground up to a fine powder and slurries, sometimes even with viscosifying agents.
- Invariably, ground cuttings are injected at the shoe into low-k shales.
- This is **not an optimum approach**.
Cuttings Injection

Injection into annulus

Injection of ground cuttings generally occurs in shale

deeper casing
shallow casing
fracture plane

casing shoe

cement

shale
Cutting Injection Options

1. Annular injection: drill/produce and inject simultaneously
   - Drill and contain top hole cuttings. Inject above reservoir. Drill to TD and produce.

2. Tubing injection: existing redundant well
   - Inject inside redundant well
   - 9¼ in. 4-in. tubing
   - Packer
   - Reservoir
   - Depleted reservoir
   - Injection zone
   - Bridge plug
   - Injection zone
   - Cement
   - Injection zone

3. Tubing injection: dedicated injection well
   - Inject inside dedicated well
   - 9¼ in. 4-in. tubing
   - Packer
   - Injection zone
   - Injection zone

(Courtesy Mi-SWACO Ltd.)
Cutting Re-Injection Problems

- Grinding offshore = a $1-2 million system
- Shales are low permeability, extremely slow bleed-off, strata pressures remain high
- Low bleed-off means vertical fractures climb substantially, fracture extent is large
- Environmental containment is problematic
- Mud blowouts have occurred (BP/Amoco)
- Several reported losses of casing (excessive distortion develops in injected zone)
Best Method for Cuttings, Mud

- Consider using a dedicated slurry injection well, placed away from other well casings
- The well can be slim-hole, economical…
- Or, if you have an available abandonment…
- Choose a permeable stratum, high bleed-off
- Don’t pulverize shale, just grind it to -5 mm
- Dilute slurry with waste water, do not add any other thickening or viscosifying agents
- Carry out injection properly, monitor carefully
Potential Problems

- Well blockages could occur
- Formation could become blocked
- Pressure bleed-off behavior may deteriorate
- Containment could be impaired
- Well casings could shear off (several cases)
- Fortunately, it appears that **properly executed SF can avoid these problems**
- This requires continuous monitoring and analysis of $\Delta p$ and $\Delta V$ data, **proactive**
Stress Changes in Solids Injection

**regions of largest shear stress change**

**regions of largest shear stress change**

**Large stress changes may lead to casing shear if uncontrolled injection allowed**

expansion from slurry injection

liquid leakage to higher zones may occur

region of reduced lateral stress
Waste Disposal

- Slurried Solids Injection is a geomechanics dominated process
  - For cuttings injection
  - For other slurried wastes
  - For emulsions, waste water, other wastes
- The technology is wide-spread offshore
- Increasing onshore
- Proper geology
- Proper geomechanics
- ZERO DISCHARGE is a feasible goal!