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Mitigation of Heavy Oil Production Environmental Impact through Large-Scale Slurry Fracture Injection of Wastes

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Abstract

Slurry fracture injection (SFI) involves placement of solid wastes and water under fracture pressures into deep geological formations. Currently, materials permitted for SFI include oily waste sand, "slops", produced muds, and produced water or waste water. Five years field experience has led to a good understanding of the SFI technology, and a regulatory framework is evolving in Alberta to permit SFI projects to proceed in an environmentally secure manner to meet the goals of the regulatory bodies as well as the goals of the oil companies.

The approach to SFI operations is described, including geological arguments related to environmental security. Security is also based on careful regulatory control, design, site selection, and analysis. The application of SFI to other waste streams should help mitigate environmental issues for heavy oil development, as well as for other oilfield applications.

Heavy Oil Waste Streams

Non-hazardous oilfield wastes (NOW) are produced during exploration, drilling, production, and refining. Depending on heavy metals and certain organic species contents, some streams may be classed as hazardous or mildly toxic. Heavy oil is thought to be environmental problematic because of high sulfur content, but upgrading and removal of sulfur generates a hydrocarbon material suitable for refining as a medium-weight crude oil. The upgrading process generates coke (carbon-rich residue), elemental sulfur, some waste water, and other solids such as spent catalyst. The sulfur is sold. Coke, which is 85-95% carbon, is stockpiled in expectation of low-pollution combustion technology advent. More important environmental issues arise in heavy oil production phases.

Table 1: Non-Hazardous Oilfield Wastes (NOW)

NOW Waste Source	NOW Physical Characteristics
Produced formation water	High chlorides, traces of oil, a few fine-grained clay particles, other dissolved salts...
Produced sand	Fine- to medium-grained sand produced along with heavy oil, > 85% SiO ₂ usually. May have high chlorides content, and up to 4-5% by weight oily residue on grains...
Drilling mud wastes (only back-produced mud currently permitted)	a. Drill chips: high chlorides, sand, shale & lime chips, oily if OBM used... b. Spent aqueous drilling fluids: clays, water, various chemicals, up to 8% emulsified oil, high pH is common... c. Back-produced muds also contain formation fluids, and produced sand
Tank bottoms, sludges, stable emulsion	Sludges from stock tanks, chlorides, clays, briny water, asphaltenes, oil content variable, up to 30-50%, often stable emulsion present...
"Slops" (often called "gorp" if emulsion-rich)	General water and oil waste with solids (clays and sand) from surface clean-up, spills, etc. Chlorides, cyclic HCs...
Refinery solids (not permitted for SFI at present)	Mineral matter, coke (carbon-rich residue) from heavy oil upgrading facilities with high non-combustible minerals content, chloride-rich, various chemicals, may be heavy metals rich...

Because of the development of massive sand co-production as a heavy oil exploitation technique in Canada¹, the major solid NOW stream is fine-grained quartzose sand containing up to 5% heavy oil by weight. Massive sand co-production involves letting sand enter the wellbore during heavy oil production to increase production efficiency. Produced sand settles to the bottom of well-site stock tanks and is removed using vacuum trucks for transportation to disposal locations. It is estimated that in 1997, over 300,000 m³ (at 40% porosity) of waste sand was produced in Canada from

exploitation of heavy oils in the region straddling the Alberta-Saskatchewan border from 51° to 56° latitude. Approximately 60,000 m³ of this sand was injected using SFI, a tripling compared to 1996.

Waste water containing large amounts of chlorides, small amounts of oil and dissolved organic species is co-produced in thermal and non-thermal processes. It is filtered and injected into formations at pressures less than fracture pressure, but some is directly used to make SFI slurries for solids disposal.

Slops is a generic term referring to mixtures of waste water and oil, usually with some solids such as clays. It may also refer to tank bottoms, viscous sludges with high oil and fine-grained mineral solids contents. These accumulate in large heated storage tanks at local oil cleaning and transmission stations. The term slops may also refer to a stable oil-water-clay emulsion generated during heavy oil exploitation. Progressive cavity pumps, gas bubbles, and polar molecules and clay particles are conducive to emulsion generation, and these are prohibitively expensive to treat chemically or thermally. Some proportion of produced stable emulsion is injected through SFI.

Produced muds are largely drilling fluids back-produced during well clean-up. These materials are common in heavy oil exploitation by sand production because sanding leads to low horizontal stresses and lost circulation. The mud and lost circulation material back-produced early in the well life along with formation fluids and sand must be disposed. The "mud" material in Project 2 (see below), for example, contained by weight 50-65% solids, 15-25% oil, and 20-30%. Currently, SFI is only permitted for back-produced aqueous muds.

Slurry Fracture Injection Technology

To date, SFI is permitted for NOWs, including produced sand, tank bottoms and slops (including emulsion), and produced muds. An aqueous slurry is made with solid and liquid waste to a density of ~1.12-1.28 g/cm³ in a flow-through SFI system to produce a controlled density, well-dispersed aqueous slurry. This is injected into deep porous, permeable strata using two triplex injection pumps in parallel. Dual pumps give security against tubing plugging if a single pump should fail, and to triplex pumps reduce undesirable density fluctuations. The slurry density, composition, injection rate, injection period, and other factors depend on the formation, the nature of the waste, and the formation response evolution with time.

The target reservoir is selected based on a number of criteria, discussed later. The well may be a conventional cased vertical oil well with surface casing to protect surficial strata. An old well may be acceptable, but good cement-rock bond must be demonstrated. Purpose-drilled SFI wells using better cement strategies are now being advised, as they give better performance. Target formations to date include oil-free sandstones and depleted reservoirs from 10-40 m thick at depths of 340 to 650 m. In one case, a low-quality oil-containing sandstone at 748 m depth is used for SFI, but this case involves only slow (40 l/min) injection of water and slops at a density of ~1.02 g/cm³, with a minimal amount of solid wastes².

Injection (Fig. 1) follows a careful sequence based on experience, materials, and the evolution of formation response:

- A: Establish rapid clear water injection through tubing;
- B: Initiate formation breakdown (fracture initiation);
- C: Pre-flush fracture at a high rate with clear water;
- D: Slowly increase solids level to target concentration;
- E: Continue SFI operation at average pressure p_{SFI} for 6-12 hours at rates of 0.8-1.5 m³/min typically;
- F: Slowly decrease solids level to zero, then continue with 5-25 m³ of clear water post-flush;
- G: Shut-in the well, recording all pressure data;
- H: Analyze to determine instantaneous shut-in pressure p_{si} ;
- I: Analyze for fracture closure pressure, p_{CL} ;
- J: Evaluate gradual pressure decline toward far-field values to determine reservoir response evolution; and,
- K: Re-initiate SFI after sufficient relaxation time at rates and densities consistent with the target formation behavior

Control and assessment data include p_{SFI} (the SFI operations pressure, Stage E), the pressure at the beginning of injection p_i , the far-field reservoir pressure, p_o , and the shut-in and fracture closure pressure, p_{si} and p_{CL} . These are recorded using down-hole pressure gauges, backed up by at least one surface wellhead gauge and chart recorders. Although p_{SFI} is shown as approximately constant with short-term fluctuations, it is common over the course of a 10-hour injection period for p_{SFI} to climb by 1 MPa, or climb, then decline². Response changes on a day-to-day basis, and values of p_i and p_{CL} evolve over days to weeks. These data all help manage SFI operations, and aid in interpretation of reservoir evolution.

Experience Base

Since ~1988, drill cuttings have been disposed by grinding to a paste and injection under fracture pressures through the annulus between two casing strings. Cuttings injection can lead to problems such as mud blowouts on subsequent wells, activation of shearing leading to casing impairment, and degradation of cement bond quality through high pressure migration along the rock-cement interface.

Massive hydraulic fracturing using well-sorted proppant slurries to increase well productivity is similar to SFI, but there are also substantial differences in magnitude and rate.

Prohibition of injection above formation fracture pressure was adopted decades ago as a regulatory principle, intended to assure well integrity, eliminate fracture impairment of bounding strata, and guarantee waste liquid containment. Liquids must be free of all solids to avoid pressure build-up leading to fracture. If near-wellbore blockage through mineral precipitation impairs the well so that pressures approach the fracture gradient, corrective measures (acids, deliberate hydraulic fracturing) were used. SFI requires that regulators relax these requirements, as it is a continuous fracture process.

The first deep SFI disposal of large volumes of solid NOW took place in Saskatchewan in 1988-90 at the Mobil Canada Ltd. heavy oil Celtic Project. The oil-free Cretaceous Dina Formation of mixed river and estuarine accretion plain origin

was used (Fig. 2). It is a 35 m thick, 30% porosity, 2-5 Darcy permeability quartzose sandstone. A conventional well was recompleted 20-25 m from the top of the Dina at about 670 m depth, and used to episodically inject $\sim 1.12 \text{ g/cm}^3$ sand-water slurry with variable quantities of slops and emulsion. About $10,000 \text{ m}^3$ of sand and slops were injected into a single well over two years; the same well continues to be used for occasional small SFI activity ($2000\text{-}3000 \text{ m}^3/\text{yr}$).

Other projects have operated at similar depths, but in general dealt with higher rates, higher densities, and substantial changes in operational strategy and reservoir use optimization³. These more recent projects, dating from 1994, have been carefully monitored for environmental security⁴.

SFI Case Histories

Projects at eight sites, some revisited several times, have taken place since 1994. Several are summarized here.

Project 1: Over a period of eight months, $\sim 63,000 \text{ m}^3$ of slurry (produced water, sand and slop) were injected into two formations using a well drilled specifically for SFI operations. The well was initially perforated at 439-449 m in the Clearwater Formation. The pressure response to injection was excellent because of high permeability, $>1 \text{ D}$, and a thick section, $>20 \text{ m}$ with a clayey central streak. After daily SFI injection periods averaging 10 hours at rates of $1\text{-}1.4 \text{ m}^3/\text{min}$, pressures quickly dissipated to initial formation pressures. During the first project phase, SFI injection pressures slowly increased by 2 MPa over four months as formation-scale stress changes took place. Far-field reservoir pressures remained constant, as is always the case in SFI using permeable strata.

Wellbore complications resulted in abandonment of the lower zone and recompletion higher in the Lloydminster Formation, perforated between 385.5 and 395.5 m. The river-channel Lloydminster zone is more clayey and less thick and homogeneous than the Clearwater Formation (all SFI formations in Alberta and Saskatchewan are in the Cretaceous Mannville Group, Fig. 2). Though it responded less favorably to SFI, pressure dissipation and formation response remained within acceptable limits. Injection pressures largely dissipated within several hours of injection despite the lowest permeability of all formations used for solids SFI to date, $\sim 200 \text{ mD}$. The pressure did not always drop fully to the initial formation pressure of 3 MPa, probably because of near-well porosity blockage. Well test and surface tilt analysis indicated both planar flow (vertical fractures) and radial planar horizontal flow (horizontal fractures) during and after injection, indicating a combination of vertical and horizontal solids emplacement. Shallow formation depth and modest target zone thickness led different fracture orientations on different days.

Project 2: The Dina Formation in Saskatchewan was used for this project, with $88,000 \text{ m}^3$ of total slurry injected into one SFI well during six months. The perforation interval was at 592-602 m depth, and the baseline formation pressure was similar to other SFI formations ($4\text{-}5 \text{ MPa}$). Properties are similar to the Mobil Celtic Project well. The Dina Formation

is generally the most quartzose ($>95\%$) of the Mannville strata, with quite low compressibilities ($\sim 0.5 \times 10^{-6} \text{ kPa}^{-1}$).

The fracture extension injection rate could not be determined with a step-rate test, despite injection rates of $0.25\text{-}2.25 \text{ m}^3/\text{min}$. Given the thickness and high permeability, there was concern that rapid near-well screen-out could occur, but proper operational sequencing and use of the material streams available allowed successful fracture initiation and solids injection on a daily basis. The Dina has an exceptional ability to accept large volumes of viscous wastes without plugging.

To cope with large material property variations (thick emulsion, mud, clay-free sand, waste water) without negative effects on reservoir response, changes were made to the SFI strategy. Various materials in different concentrations were injected alternately to ensure that formation pressure build-up was minimized. These changes have resulted in smooth pressure fall-off behavior and lower injection pressures, as well as more rapid decay to virgin reservoir pressures.

Project 3: Almost $70,000 \text{ m}^3$ of slurry made from produced sand and water along with slops were injected over six months during this project, also into the Dina Formation in Saskatchewan. (At one time, about 1000 m^3 of snow contaminated with produced water was injected as a waste product!) The perforation depth was 573-592 m, and the fracture extension pressure was measured to be $\sim 10.5 \text{ MPa}$ at an injection rate of fresh water of $\sim 1.0 \text{ m}^3/\text{min}$. The baseline formation pressure was $\sim 4.8 \text{ MPa}$. The formation responded quite similarly to that in Project 2, with bottom-hole pressures generally falling to baseline formation pressures within a few hours after shut in, unless excessive amounts of viscous materials were injected in an uncontrolled manner.

The well had previously been perforated up-hole prior to conversion to SFI, and was patched so that the well could be used as a SFI well. Unfortunately, poor cement bond, large cyclic pressures (4.8 to 14 MPa within 24 hour cycles), and attendant casing deformations caused the casing-formation bond to rupture, allowing pressures to migrate up along the casing to the patch. As soon as leakage was detected from this patched zone, the SFI well was abandoned. Overall, no difficulties were encountered with the SFI operations or injection strategy; wellbore failure was the ultimate cause of well abandonment.

Project 4: This demonstration project involved injection of $5,500 \text{ m}^3$ of slurry (about $1,700 \text{ m}^3$ of HC-contaminated surface soil and mud) in a one-month period into the Upper 99 Zone in the West Coyote field in La Habra, California⁵. This abandoned oil field was exploited by primary, secondary, and tertiary means over a 60-year history. The formation is a thick, arkosic, unconsolidated sandstone of 600 mD permeability. A slotted liner was installed over the injection zone at 1250-1265 m depth in a pre-existing well. Being deeper than other SFI projects, a tiltmeter array was not installed.

The fracture extension pressure and fracture extension injection rate were determined to be $\sim 16.5 \text{ MPa}$ and $\sim 1 \text{ m}^3/\text{min}$. The average SFI injection pressure was 20 MPa , higher than

other SFI injection sites because of the depth effect. Data indicate that SFI fractures were vertical (fracture gradient ~13.2 - 16 kPa/m). The zone reacted well to the injection of soil and mud, pressures dissipated within eight hours of injection, returning to a value of 6 MPa. No changes in this low formation pressure (depleted formation pressure) were noted during a trouble-free operational period.

Project 5: This project involves low-solids slurry injection with an automated injection system; no produced sand is disposed². The injection equipment is remotely controlled by a computer system and slurry material and water are kept in tanks, and injected automatically with valve control. Injection and slurry parameters are collected using data-loggers linked to Calgary by tele-links. The control logic includes emergency shut-down conditions which trigger the post-flush cycle if situations such as high BHP, high WHP, or low tank levels arise.

The McLaren Formation used in this project is actually a low-quality oil-bearing channel sandstone, perforated from 745.5 to 748.5 m. Geology and many operational details may be found in Reference 2. A total slurry volume in excess of 16,000 m³ has been injected over two years, but at injection rates of 40 l/min, far slower than sand-slurry SFI operations into oil-free or depleted strata. The initial formation pressure is high compared to other zones used for SFI (12-13 MPa) because of initial water disposal and injection at some near-by facilities. Pressure analysis show that fractures are being initiated and fracture flow is occurring during injection. Because injection pressures only slightly exceed the formation pressure, the magnitude of pressure fall-off is smaller. The formation has responded favorably to injection operations, and no difficulties associated with the SFI technology have been encountered.

Extension of SFI to Other Heavy Oil Waste Streams

SFI technology seems suitable for other more toxic waste streams associated with heavy oil (coke, heavy metals rich solids, etc.). To implement this, the potential for waste entering the biosphere after disposal must be assessed. This requires addressing SFI environmental security of SFI using geological arguments, understanding of the nature of the wastes involved, and evaluating monitoring to optimize operations and provide a high level of containment assurance to regulatory agencies.

Geological Security of SFI: Geological conditions are the most important guarantee of long-term environmental security for SFI. Sites used in Saskatchewan and Alberta have proved ideal: SFI takes place into a flat-lying sequence of nonfaulted, alternating sand and shale beds of great regional continuity. Such a situation is ideal for the following reasons:

1. High permeability and porosity give good storage capacity and rapid pressure bleed-off potential to limit fractures propagation potential.
2. Once pressures dissipate, solids are trapped under the high effective stresses of the overburden, at least 6-7 MPa at a depth of 500 m. At these stresses, solids are rigid and fully immobilized by frictional forces.
3. Horizontal deep formation fluid flow without mixing with shallow waters in surficial glacial strata is predicated by the flat-lying sequence of sands and shales and the low topography. Deep basin hydrogeology is dominated by slow northeastern fluid flow (cm per year).
4. As with the heavy oil in near-by reservoirs, oily injected material is immobilized because of high viscosity and capillary phenomena in a two-phase liquid system.
5. Deep water is at least 20-30x10⁶ years of age and exit times are at least several million years.
6. Formation and injected waters are more dense than surface waters, predicating against upward flow or mixing.
7. The >200 m thick smectitic Colorado Group clay-shales above the Mannville Group strata form a regional impermeable seal against upward flow.
8. The deep formation water exits over 200 km away to the northeast at springs buried beneath thick glacial strata.
9. Slow transit means that massive dilution by dispersion and diffusion occurs. During exit, additional dilution occurs from groundwater, rainfall, and runoff.
10. The long flow paths contain sands with clays as well as thick shales and clayey silts. Clay minerals provide huge adsorptive capacity ionic and organic species.

SFI has a substantial positive effect on heavy oil development, reducing environmental impact, and virtually eliminating environmental liabilities for the oil companies involved. Though SFI permitted wastes are currently non-hazardous, there exist such robust security factors that we believe SFI can be extended to include solid toxic materials.

A comprehensive set of geological requirements has not been stipulated nor should restrictive regulations be prematurely adopted, as SFI technology is evolving rapidly and the geological bounds for secure application remain to be defined. For example, thick sands with >1 Darcy permeability were first considered necessary; now sands of permeabilities down to 50-100 mD are considered if other criteria are met (e.g. thickness, nature of overlying strata, lateral extent ...). Also, note that the storage capacity for wastes in a large sedimentary basin is essentially limitless. One km³ of 30% porosity sand has a pore volume of 300 million cubic metres, and there are typically thousands of km³ in these basins.

NORM Disposal Using SFI: Given SFI success to date, it is likely that extension to other materials such as NORM (naturally-occurring radioactive materials such as pipe and boiled scale) will be considered in the future. Substantial modifications of the blending injection system will be needed to reduce the risk of particulate emissions, splash, spill, or leakage to levels sufficient to allow materials with some level of toxicity to be handled.

For NORM disposal (or other toxic solids), in addition to all the positive geological factors, dilution and immobilization are additional possibilities. A small-volume NORM stream

can be added as a fraction of a large produced sand stream, providing high dilution (1:10 to 1:30). The adsorptivity of clay minerals in situ is a strongly positive factor: NORMs consist largely of borates, carbonates or silicates, and if the heavier metals are liberated, adsorption will occur.

Further risk reduction can be achieved through incorporation of large percentages (75%-95%) of shale chips, clay, and cementitious material with diluted wastes. As drilling wastes are largely shale chips and clay, it seems natural to use this as a carrier for more toxic material disposal. Once compacted at depth, such a mix would have a permeability 6-8 orders of magnitude less than the sandstones, along with a high adsorptive capacity. The NORM (or other toxic material) is essentially totally immobilized.

Contaminated soil or road asphalts on which PCBs have been spilled, heavy-metal-rich clinkers, foundry sands, and other materials can be easily ground and disposed using SFI. At typical refinery or chemical plant sites, there are thousands of cubic metres of contaminated soils; if site conditions are favorable, these may be injected at depth, without the risk associated with transportation. This has been demonstrated in an injection project within the greater Los Angeles area in California⁵.

Regulatory History of Heavy Oil Waste Disposal

In Alberta and Saskatchewan, it was long permitted to spread produced sand on roadways or fields; however, these practices have become environmentally unacceptable (high chlorides, cyclic hydrocarbons, quality of groundwater). The HCs in produced sand tend to give water a noticeable odor, even in minuscule concentrations. Alternatives are now required, and the Alberta Energy Utilities Board (EUB) has taken a lead role in exploring alternatives. Acceptable alternatives to SFI appear to be:

1. Direct use of oily sand as part of road asphalt formulation or as a feedstock to cement kilns;
2. Biodegradation at surface facilities or managed landfills;
3. Steam, hot water, or chemical washing followed by sand disposal or use as a sand source;
4. Conventional landfill placement; or,
5. Placement in caverns dissolved in salt strata.

There is too limited a market for direct use of any but a small fraction of the produced sand in Alberta and Saskatchewan. Repeated handling and transportation to a user or a cleaning plant add substantial costs, favoring local disposal. Biodegradation is unproven at the large scale, and requires nutrients and sand movement, therefore it is likely to cost more than landfilling. Other approaches are less environmentally secure (landfilling) or more costly (salt caverns, washing). Table 2 contains some rough estimates of the total cost of various approaches.

The Alberta EUB issued its first formal variance to an oil company for SFI in Alberta in 1994. Since then, each new site has been permitted on an ad hoc basis, backed by site studies, operating parameter establishments, reporting requirements,

monitoring proposals to verify containment, and various practices depending on the SFI streams permitted.

Table 2: 1998 Costs for NOW Disposal (\$/CAN)

Method	Estimated cost per m ³ of solid	Comments
Direct sand use in other process	\$20-40/m ³ , mainly handling + transport costs	Limited demand (asphalt, cement)
Conventional landfills	\$30-55/m ³ or more depending on land costs, transportation distance...	Environmentally insecure in the long term, & poor use of land
Biodegradation in landfills	>\$100/m ³ (no experience base yet)	Unproven in practice
Direct cleaning, various methods	>\$70/m ³ not including transportation costs	Sand must still be disposed once it is cleaned
Road or field spreading	\$40-80/m ³ , depending on distance to site	Unacceptable, & sites are often quite distant from the waste source
Solution cavern placement	\$85-105/m ³ not including transportation to site	Currently unregulated, but this will change
Slurry fracture injection (SFI)	\$55-70/m ³ solids (water disposal an additional benefit)	Including well costs, monitoring, analysis, regulatory agency reports.

Recommended Regulatory Approach

In permitting SFI, regulators must protect present or future nearby resources, minimize risks of noxious wastes or leachate interacting with shallow groundwater or the biosphere, and maximize personnel safety in handling the wastes. The following discussion is based on Canadian experience.

Site Choice: NOW are not toxic, thus present site management does not have to be regulated beyond current rules^{7,8,9}. Operators now use enclosed light fabric-rib structures to allow winter operations and sites with concrete pits and lined surface ponds reduce chances of seepage of HCs into groundwater.

Stratum Choice: A sufficiently deep, laterally extensive, porous, permeable reservoir must be identified, characterized, and approved. The stratum must have sufficient thickness and permeability (>5-10 Darcy-metres) and storage capacity, because up to 50,000 m³ of solids and oil in a total slurry volume of 250,000 m³ may be injected over a period several years. A formal reservoir study is invariably executed. If sand and slops are to be disposed together, the amount and nature of the slops must be designed, as some strata are less accepting of slops than others. If sand with less than 2-3% slops will be disposed in a high permeability reservoir, repeated tip screen-out danger exists.

The target may be an oil-free stratum or a depleted reservoir at any depth below shallow groundwater interaction pos-

sibilities. Poorly consolidated or intensely fractured sandstones are preferred, but any formation that can accept large volumes of solids and continue to bleed off fluid pressures rapidly is acceptable.

Well Choice and Completion: SFI requires a conventional vertical oil well with 3-5 m large-diameter ("big-hole") perforations near the stratum base. An old well may be suitable, providing the previous completion and well condition is adequate. A tubing string and packer with a BHP gauge just above the packer are installed.

The major difficulty encountered during generally trouble-free SFI operations to date has been the effects of poor bond between the rock and the cement on the SFI well, or on offset wells close enough to experience the high pressures generated during SFI. Differential pressures can lead to large gradients for considerable times. In one Alberta case, the formation pressure in the producing horizon 85 m above the SFI stratum was 2-2.5 MPa or less, and the SFI BHP of 12-12.5 MPa led to communication along the poor cement of an offset well. Correcting for head, a gradient of about 100 kPa/m existed during SFI, generating the strong potential for upward flow of liquids. Recently, well-specific cement strategies and cement types are being recommended for special SFI wells to reduce the chances of well impairment.

SFI Operations Strategy: The regulatory agency must study and approve a proposed general operations strategy for SFI, including the monitoring activity. For example, the SFI stratum must be allowed periods of "relaxation" for pressure dissipation and collection and analysis of reservoir response data on fracture gradient, transmissivity, and near-wellbore fluid flow impairment. The duration and frequency of quiescent periods depends on the monitoring data: slower pressure decay and changing response must be treated cautiously, compared to rapid decay and consistent response. Typically, SFI periods of 6-12 hours a day are used, injecting perhaps 150-200 m³ sand, 0-150 m³ of slops (extremely dependent on the composition), and 600-800 m³ of total slurry. A single SFI well can be used for injection for several weeks, even months, but long periods of quiescence (while monitoring pressures) allow complete pressure decay and reassessment of reservoir parameters such as.

Permitted Materials: The Alberta EUB, based on their guidelines published in the last few years^{6,7,8}, permits SFI wells for any combination of produced sand and produced water with oily sludges such as slops, tank bottoms or emulsion. In the near future, SFI wells will likely be classified as Class 1b disposal wells, with a relaxation on the maximum allowable pressure to allow injection under fracture pressure³.

One or two-litre samples are taken once a week, but a time limitation on storage is necessary, otherwise they do not meet analysis standards. If there is disagreement on materials within the context of the permit, provisions must be made to sample and analyze it immediately. Occasional random site visits and requests for a detailed audit should be carried out by the regulatory agency each 4-8 weeks. All site operational

data and analyses are filed every 10 weeks.

Monitoring Requirements: Operationally, monitoring is vital for SFI management and to achieve maximum trouble-free efficiency. For regulators, monitoring demonstrates containment, assures personnel and environmental security, confirms best possible practice, and allows full audits.

A continuous reading from a bottom-hole pressure gauge is the most important data source for analysis and evolutionary tracking. Casing annulus pressure, well-head pressure, injection pump manifold pressure, and other data are more important for SFI management than for regulatory control.

Offset well pressure monitoring is advised for up to 3-4 casings penetrating the SFI zone within a radius of 250 m. Production behavior of wells should be monitored and changes in fluid levels or production rates recorded for correlation.

The volume make-up of the SFI slurry (solid NOW, liquid NOW, make-up water) is recorded, and the input stream is continuously recorded for bulk density.

To map where wastes are going requires measurements and inversion of surface deformation data, or continuous microseismic monitoring. At the present time, only the former approach is used. Tiltmeter deformation monitoring involves 12 to 16 precision tiltmeters to record ground surface inclination changes. Analysis gives an estimate of fracture orientation, attitude, and thickness⁴. Repeated measurements allow development of a picture of where the solids were emplaced, and this gives explicit information about containment.

In microseismic monitoring, acoustic emission analysis allows spatiotemporal tracking of processes, helping to delimit the affected zone quantitatively.

Special Reservoir Evaluation Tests: SFI reservoir properties change with time because new materials (sand, oil, fine-grained minerals) are being introduced². Evaluating these changes requires periodic tests and analyses.

Step-rate injection tests involve staged rate increases of clear water injection to assess fracture initiation pressure (fracture gradient). These are carried out before a prolonged SFI period in the well, upon recommencing injection after any shut-down lasting more than three days, and perhaps at two- or three-week intervals during normal SFI operations.

Pressure fall-off analysis is carried out on daily SFI well shut-in pressure responses, which typically provide about 10-12 hours of data before the next start-up. Not all pressure fall-off curves follow "conventional" behavior, and relatively demanding analyses are needed to track reservoir evolution.

Long-term pressure decline analysis is needed for each prolonged shut-down period. Data are analyzed to see if far-field reservoir pressurization is occurring, and if the short-term response (10-12 hours) differs from the long-term response (80-150 hours). Such analyses and a detailed interpretation of their meaning should be required in regulatory reporting.

Tracer and hot water injection tests are used to assess casing integrity to assure that higher zones are not impaired.

Injection tests (constant rate or pressure) are used to delineate reservoir properties such as transmissivity and stora-

tivity. The casing or bond can be examined using various direct observation or acoustic devices. Uphole casing and surface flow system integrity is assessed by regular annulus or loop pressurization, to assure that ratings are being met.

Summary

Slurry fracture injection of non-hazardous oilfield wastes in Alberta and Saskatchewan has mitigated many environmental concerns in heavy oil production. An appropriate regulatory environment is evolving to allow SFI in an environmentally secure manner without engendering prohibitive costs. Experience shows that regulatory bodies are anxious to solve environmental issues economically, and have been extremely cooperative, while fulfilling their mandate of protection of resources and people. Monitoring and analysis turn out to be critically important aspects of SFI. Data include audited waste volumes, pressure recording, deformation monitoring, and repeated re-evaluation of reservoir properties to track evolution.

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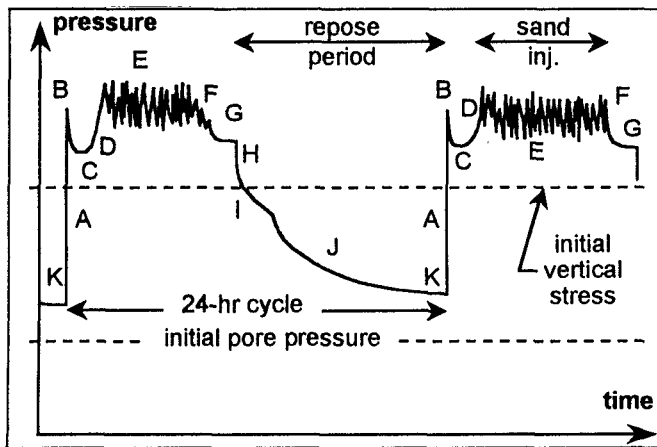


Fig.1: Typical Slurry Fracture Injection Pressure-Time Response for a Complete Day of Solids Injection

Fig 2: Correspondence Among the Formation Names Used in the Text for Alberta-Saskatchewan SFI Activity

DISPOSITION OF STRATA	FORMATIONS NOMENCLATURE USED	
	North-Eastern Alberta	West-Central Saskatchewan
Surficial sediments		Surficial seds (sand, gravel, clay)
Colorado Group	400-900 m	Colorado Grp (smectitic shales)
Grand Rapids Formation		McLaren Fmn. (channel sand)
Clearwater Formation		Lloydminster Fmn. (channel sand)
Rex Fmn. (blanket sand)		
McMurray Formation		Dina Fmn. (quartzose estuarine & blanket sand)
Paleozoic carbonates		Paleozoic carbonates

Table 3: Recommendations for Regulatory Control of SFI Operations

Regulatory Practice	Comments	Recommended Use
Full SFI well and stratum evaluation report	Well casing integrity, cement quality, suitability of proposed stratum for SFI (volume capability, permeability, geographical location, proximity to other wells, resource protection, etc.)	Must be required in any SFI proposal
Site choice and site practices	Protection of surface groundwater, elimination of any air-borne particulate generation, personnel safety issues	Must be required in any SFI proposal
Well completion approach	Nature of the well, use of patching or cement squeezes to close previous perforations, design of new perforations, tubing, packers, downhole and wellhead instrumentation	Not necessary, but a documented plan is desirable for regulatory assessment
Treatment of offset wells (producing or abandoned)	Identification of any casings in an appropriate radius of influence, deciding whether to monitor pressures or other parameters on any of them.	Required for regulatory control, useful for SFI operations optimization
Proposed SFI operations strategy	Injection period and repose period length, injection rates, density of slurry to be injected, percentage slops or sludges, etc.	Part of a documented plan submitted for SFI permitting
Bottom-hole pressures	Continuous pressure-time traces from an operating down-hole gauge sampling the fluid pressure in the injection tubing near the exit point. Data are recorded continuously during active SFI operations and during all shut-down periods as well.	Necessary for both SFI operations control and regulatory supervision
Other pressures (annulus, wellhead, offset wells)	Fluid level gauges or pressures on casings in nearby abandoned or producing wells, annulus and wellhead pressures on the SFI well, pump manifold pressures.	Necessary for SFI operations, not for regulatory control
Surface deformation data and microseismic monitoring	Surface deformations from a tiltmeter array are analyzed to give indications of where solids are going, whether vertical fracture growth is occurring, etc. Microseismic information allows spatiotemporal localization of fracture emplacement.	One or the other should be required to confirm waste containment; both if toxic wastes are disposed.
Volume balance	All volumes of various streams (e.g. sand, produced water, slops and sludges) are estimated from surface measurements and operations, and volumes of injected slurries calculated from the pump stroke rate are recorded continuously.	Necessary for regulatory control
Slurry bulk density	Continuous recording of bulk density after the slurry has left the final mixing tank. Combined with volume estimates of the phases, these data provide information for a detailed audit.	Necessary for SFI operations, not for regulatory control
Step-rate tests	Gradual staged increase in injection rate using clear water to determine the fracture extension (initiation) pressure and thus estimate the minimum in situ stress around the SFI well.	Required before a sequence of SFI episodes or once each month.
Short-term pressure decay tests and analysis	At the end of each daily cycle, the pressure drop off behavior is recorded and analyzed for shut-in pressure, fracture closure pressure, decay rate, well pressure at start-up the next day, etc.	Regular analysis of selected pressure response data is probably necessary
Long-term pressure decay tests and analysis	The pressure decay is recorded for at least 72 hours and analyzed to determine the flow regimes around the SFI well and to measure the far-field reservoir pressure. Comparisons of these data to short-term pressure decay and to previous data give indications of reservoir parameter evolution.	Required once every few weeks (e.g. each three weeks)
Other special tests	Injection tests at constant pressure or rate can be analyzed to give reservoir parameters and estimates of the near-wellbore damage. Casing can be tested, cement bond logs run, etc.	Well integrity should be demonstrated before each SFI period