11 WASTE TRANSPORT, TREATMENT, DISPOSAL

11.1 Introduction

Disposal of huge volumes of wastes is a crucial aspect of the CHOPS process, and is undoubtedly the major OPEX factor differentiating CHOPS from other technologies for heavy oil production (15-30% of OPEX, and in isolated cases even more). Also, there are environmental ramifications that in the long term will be important to the state of the groundwater and surface conditions in the HOB. For these reasons, waste management is given detailed attention in this chapter, and a full economic analysis of the unit costs of sand management is developed in the next chapter.

Clear differentiation must be made between treatment of CHOPS wastes and disposal of CHOPS wastes. Huge investments have been made in various treatment technologies that promise to produce a fully "rehabilitated" material. Initially, these treatments seem cost-effective and attractive, but the following aspects must be weighed:

- Is the method a final disposal method, or an intermediate treatment method?
- In the execution of the process, will stockpiling, transportation, and disposal still be required or is disposal immediate?
- Will the process result in new waste streams that have to be further treated or disposed?
- Will the process be able to handle the huge waste volumes generated during CHOPS processes?
- Will the treatment or disposal process affect land use in ways that are environmentally questionable, now or in the future?
- Does the treatment or disposal method truly eliminate future environmental liability or merely alter its nature or time frame?

11.2 Stocktank Cleaning and Stockpiling

11.2.1 Stocktank Cleaning Practices

A previous section included a detailed discussion of stocktank management and cleaning practices because of their importance to economically successful CHOPS implementation.

Sand is moved to disposal sites or stockpiles by vacuum trucks or by LHD (load-haul-dump) trucks equipped with sealed boxes (tubs). Even at a disposal site, with the exception of salt cavern disposal, these trucks never unload directly into the disposal facility, but instead dump unto a stockpile. This necessitates additional handling to bring the material to the disposal or treatment facility, to reload the waste sand on trucks for transshipment, or to move and dispose it (e.g. in a landfill site).

11.2.2 Stockpiles, "Eco-Pits", and Concrete Sumps

Large sand stockpiles may be seen in many locations across Alberta and Saskatchewan because regulatory authorities have been lenient in requiring prompt disposal. This leniency was in response to the low heavy oil price in the period 1997-1999[70], and will undoubtedly change with time. The sand that resides in these stockpiles was placed with approximately 20% formation water by weight and 2-6% oil by weight. Because rainfall can help mobilize chlorides in the aqueous phase and dissolve small amounts of HCs, environmentally suitable sand storage sites with careful groundwater protection are now generally required (see previous sections).

Ecology Pits: Once excess fluids have been withdrawal, moist or sloppy sand is dumped onto stockpiles in "ecology pits" ("eco-pits"), either at disposal sites, treatment sites, or regional corporate stockpiles. These serve as a temporary storage locations for sand in transit. A typical design for a 0.4 to 1.0 ha eco-pit (Figure11.1) is as follows:

- Topsoil is removed and placed in a stockpile for future reclamation.
- Subsoil is graded into a shallow, flat-bottomed pit surrounded by berms perhaps one metre high to trap seepage fluids.
- A shallow ditch is installed on the inside of the berm to trap all liquid from the produced sand stockpile.
- A membrane is placed in the bottom of the eco-pit and on the inside slopes of the berms. Usually, this is a fibre-reinforced HC-resistant flexible polymer fabric 2-4 mm thick that can be thermally welded along seams.

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[70] The price per barrel of viscous Alberta crude oil dropped to values of <$USD5.00/bbl temporarily when the world price for conventional oil approached $USD10.00/bbl.

- Normally, a single entrance to the eco-pit is built to allow equipment traffic. As with the berm, the entrance is designed so as to intercept any contaminated water run-off.
- The shallow ditch on the inside of the berm is used to trap water run-off; it is regularly pumped and the liquid is shipped as slops.
- A front-end loader and a medium-sized bulldozer are most commonly used to manage the solids in the eco-pit.
- No protection against wind-mobilization of particulates is implemented because the oil content of the sand usually provides resistance to wind erosion.

Conservation authorities increasingly require careful monitoring of groundwater from oil producers and from treatment and disposal service companies.[71] For example, the Petrovera Elk Point sand stockpile is surrounded by a set of groundwater wells from which samples may be withdrawn. Furthermore, the site is carefully managed to collect and remove run-off.

Several oil companies (e.g. Anadarko, formerly UPR, formerly Norcen) have constructed large, ground-level concrete sumps with loading and unloading facilities to better handle materials movement and reduce ground contamination from uncontrolled seepage. These facilities are environmentally superior to eco-pits, but it is virtually impossible to build any surface facility that does not leak liquids, as the pressure gradients are almost always directed outward from the concrete enclosure (except for high groundwater table periods in the spring). Even high-quality concrete facilities develop small cracks along pour joints and corners, and underlying membranes are also likely to have holes and incomplete thermal welds.

11.2.3 Clean-up of Slops

Slops are treated or disposed of by the following methods:

- Slops that are not viscous stable emulsions are sent to large holding tanks ("slop-tanks") of 100-500 m^3 volume capacity, where gravitational segregation takes place.
- Slop tank oil is skimmed and sent to the local battery.

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[71] For example, the Bromley-Marr facility in Bonnyville was shut down several times over its two-year life because of leaking of liners in pits used to store incoming or effluent streams.

- Slop tank water is sent directly to water disposal wells, although some may be used in slurry injection wells if this sand disposal approach is used.
- Sludge accumulation in the bottom of the slop tanks is periodically cleaned using a pressure truck (stinger) and a vacuum truck.
- Disposal of slops can take place directly as part of the aqueous phase of slurry injection or placed into salt solution caverns.
- Slops can be sent directly to one of the local waste management facilities to be cycloned or centrifuged to separate the phases. Chemicals may be added in such processes to aid segregation.

One company, Anderson Exploration in Saskatchewan (purchased by Devon Energy), has used direct slurry injection of slops and fine-grained sludge into an oil-bearing formation at a depth of ~700 m.

11.2.4 Treatment of Stable Emulsions

This subject was partially addressed previously. Stable emulsions are generated partly as a result of the well pumping activity (PC pumps generate a bit of emulsion) and partly as a result of high-shear stocktank cleaning practices. The approaches to treatment or disposal of the stable emulsion include:

- Treatment in a thermal "flash treater" to drive off water and precipitate solids;
- Treatment in a "cold treater" with emulsion-breaking chemicals and gentle agitation;
- High-speed centrifugation to effect phase separation using gravitational segregation; and,
- Direct disposal by deep well injection or by salt cavern placement.

The fluid residues from hot or cold treatment may be sent for high-speed centrifuge treatment or for disposal in caverns or wells but not directly in landfills or by spreading. Solid residues from separation meet Class II landfill characteristics, providing emulsion-breaking chemicals or other additives have not changed the classification to DOW.

11.3 Sand Disposal by Road Use and Land Spreading

Disposal of produced sand by spreading on roads or fields is a practice dating back to the 1950's in Canada (perhaps even earlier). Incorporation of produced sand into a carefully designed mix for road base construction is more recent. Liquid wastes such as aqueous tank sludge, slops or emulsion cannot be disposed of through road use or land spreading.

11.3.1 Road Spreading: Methods, Advantages and Disadvantages

Alberta has thousands of kilometres of gravel roads throughout the HOB. Because of the dry summer climate, dust suppression has always been an issue on these roads. The heavy oil industry was given permission at an early stage to spread oily produced sand on roads. The produced sand is taken from company stockpiles and transported to the road to be used for spreading, and placed in a layer, generally no more than several inches thick. Because of the oil content of the sand, it tends to reduce dust on these roads.

Road spreading has been dealt with in considerable detail by others (see Short Course Notes by John Newman, CNRL, 1998); only some of the basic advantages and disadvantages will be discussed here. Part F of Guide 58 of the EUB deals at length with road spreading regulatory guidelines in Alberta, and similarly, Guideline GL-97-02 from the SEM (modeled after EUB Guides) contains the Saskatchewan regulations.

The regulatory documents referred to specify limits for chlorides, metals, and so on, as well as all the analyses and reporting that are necessary to apply for, carry out, and verify proper road spreading. As with other activities by oil companies disposing of solid waste, road spreading has not been carefully monitored, and anecdotal reports suggest that abuses have taken place occasionally.

Advantages:

- If the roads are close to the sand stockpile, the method is relatively rapid and economical, the technology is straightforward, and no special facilities are needed.
- Oily sand is an excellent dust suppressor for dirt and gravel prairie roads in Alberta and Saskatchewan.
- If municipal roads are used, the municipality inherits the responsibility for maintenance.

- Long-term scientific study and monitoring indicates that if road spreading is done properly, there is no significant negative environmental impact.

Disadvantages:

- Runoff from the oily sand on the roads can affect the local groundwater. Exceptionally, this may increase chlorides above potable water limits, and give adjacent well water a definite taste and odor.
- With time and more produced solid waste generation as heavy oil production rises, operators have had to go farther and farther from the stockpiles, increasing costs. Basically, operators are running out of roads to use for spreading
- Environmental liability is not eliminated by this disposal method because of potential contamination problems that could arise in the future in adjacent potable groundwater aquifers, despite the approval of the provincial regulatory agencies that permit the practice.
- No liquids, slops, sludges or emulsions may be directly disposed of in this fashion.
- The uniform size sand is not conducive to a stable road surface. It does not compact well and does not bear loads reliably without rutting and deteriorating. Thus, unless it is used in moderate percentages of a designed mix (see next section), it is not a good road base material or a good road surface material.
- Produced sand is not a uniform product; even from a single well oil and clay contents can vary over time, making quality control extremely difficult.
- The produced sand cannot be taken directly from stocktanks and placed on roads; it has to pass through an intermediate stockpile phase, increasing handling costs.

Waste spreading on roads is no longer viewed by any oil company (or waste service company) as a viable long-term strategy for large quantities of produced sand. Provincial regulatory authorities have expressed concerns over the possibility of environmental contamination as quantities of disposed sand increase. Also, the poor quality of the wastes used directly as road material without beneficiation and the maintenance requirements for the municipalities have led to less favorable perceptions of road spreading. During the period 1995-1997, the EUB has stated in forums and in Guide 58-related short courses that the EUB's intent is to gradually eliminate this practice in favor of disposal methods that carry less potential long-term environmental risk.

11.3.2 Sand Incorporation into Road Bases

Produced sand and other oily solid wastes, as well as several other categories of solid waste that cannot be spread directly on the road surface, can be used as part of road base construction material when new roads are built to access well sites, and when local roads are widened or upgraded. In these cases, the principle is to permit incorporation into the road base with view to "encapsulating" the wastes to retard the spread of the partially soluble materials into the biosphere.

Because local county and rural municipality authorities continually seek to upgrade their roads or construct new ones as development continues, opportunities exist for oil companies to work with contractors to build roads, or to become the road-building contractors themselves. With a reasonable quality road base material, the counties can hard-surface the roads with conventional pavement in thin layers, allowing these roads to bear secondary highway loads. This also helps control road degradation as the result of the heavy oil industry trucking needs.

A method of road base construction that uses large amounts of produced sand has been developed. The road base mix is made of:

- ~50% produced sand as mineral matter,
- ~50% appropriately sized gravel without sand,
- Additional heavy oil or asphalt (hot mix), and,
- Elemental sulphur (another "waste" product if there is little market demand for it).

This material can be compacted to reasonable densities if a proper gradation of the gravel is chosen, and to date has shown reasonable stability for long-term traffic. The sand to be used for this application must meet chloride limits, but does not have to be cleaned of heavy oil; it must be heated with the other materials to drive off all water, allowing the grains to become oil wet. The sulphur and small amount of additional asphalt help encapsulate the oil and residual chloride in the hot mix as it is compacted.

The amount of produced sand that can be disposed of through incorporation in road bases depends on the thickness of the road base, the road width, and the specific volume fraction of sand. For example, assuming a 9 m wide two-lane road with a 0.25 m compacted road base layer, about one cubic metre of produced sand per meter length of road will be consumed. Further assuming that local counties and municipalities in the Heavy Oil Belt upgrade 100 km of roads per year, approximately 100,000 m^3 of produced sand could be disposed of in this manner.

Advantages of Road Base Incorporation

- The produced sand is used as an inert mineral fill to generate useful structures, rather than being placed in a landfill as waste.
- The leachable components of the heavy oils on the sand are encapsulated by the additional asphalt, sulfur and by the low permeability and hydrophobic characteristics of the compacted road base.
- Sulfur, another material of little commercial value is used at the same time.
- A substantial part of the costs of disposal can be immediately defrayed because the sand is used as a construction material. In fact, this appears to be the most economical disposal option at the present time.
- Improvements can undoubtedly be made in the formulation and placement of optimum road base mixes, perhaps even incorporating other solid wastes, and also seeking ways to maximize sand use.[72]

Disadvantages of Road Base Incorporation

- The number of kilometers of additional roads that will be available is limited by local demand and availability of municipal financial resources Furthermore, a period of active road building to dispose sand will undoubtedly be followed by a decline in construction (only so many roads can be built), reducing this as a major option, particularly if CHOPS is more widely used.

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[72] For example, sand from two different CHOPS fields with different mean grain sizes could be used in appropriate proportions to increase the placement density in a road base. Sand of 60 µm mean diameter, combined with sand of 150 µm mean diameter, combined with an appropriately graded gravel, could lead to as much as 60% of the mineral matter in a road base mix being produced sand.

- The long-term durability of the road-base mixes that have been used to date is not clear; careful study is needed to assess this issue.
- Quality control of the grain size of produced sand and its oil content is difficult, and this leads to variations in the quality of the placed road base. More careful control would require blending, at additional handling costs.
- If the roads to be surfaced are far from the stockpiles, the transportation costs rise appreciably.

11.3.3 Land Spreading: Methods, Advantages, Disadvantages

"Land spreading" usually refers to a "once-only" application of waste to a field or to non-cultivated land. The term "land farming" refers to a permanent facility where the surface of the land is carefully managed to accept repeated applications of waste. The regulatory authorities are not permitting new land farming or spreading at this time, and it is likely that it will never again be permitted.

The placement of oily solid wastes on the land surface and incorporating it into the soil horizon is basically a process of uncontrolled or non-optimized biodegradation. It is well known that biodegradation is highly effective for HC contaminated soils, provided that most of the HCs are of low molecular weight (light aromatics and short chain aliphatics). Conversely, it is also known that biodegradation is least effective for high molecular weight and sulfur-rich HCs. The heavy oil produced in the Heavy Oil Belt by CHOPS processes is of high molecular weight, high asphaltene content (heterocyclic compounds), and high sulfur content. Furthermore, there is some evidence that the biodegradation of these materials can lead to intermediate compounds (generally sulfur-based) that are toxic.

Nevertheless, particularly in clayey soils, the addition of several inches of sand-sized material improves the texture and air-flow capacity of the soil, improving the crop bearing capabilities of heavy (clay-rich) soil.

To provide an estimate of the land required for field spreading, the approximately 330,000 m^3 of sand produced in 1997 would require about 14-15 square kilometres if placed at a thickness of 25 mm.

Advantages:

- Land spreading has been used for decades throughout North America, and is a well recognized method for disposal of municipal sludges, as well as NOW.
- Providing that disposal fields are nearby, land spreading can be relatively economical, although perhaps not as low cost as road spreading or incorporation into road beds.
- In the right applications, produced sand can be beneficial to soil, particularly to heavy clay soils with insufficient sand sizes.
- There is no doubt that slow biodegradation of the HC components of the produced sand occurs over time, and no negative consequences on animals or crops have yet been recorded.

Disadvantages:

- Land farming at a specific site must be approved by the EUB, as it is classified as a regulated disposal facility, with requirements for measurements and monitoring.
- Even before the prohibition of new sites a few years ago, there was an increasing resistance among farmers, and any reversion to this technology would likely meet more resistance than in the past.
- There are additional costs associated with land spreading related to an intermediate (or in transit) stockpile, reloading into suitable trucks that can deposit a thin layer on fields, and plowing or tilling the produced sand into the top soil to mix it with natural soil and bacteria.
- Environmental liability remains high because of potential contamination problems in the future that may arise in the adjacent groundwater, despite the approval of the provincial regulatory agencies that allowed the practice.
- No liquids, slops, sludges or emulsions may be disposed of in this fashion.
- Degradation of the HC's in the waste is slow, unless costly nutrients and specially-designed bacteria are added.

Pending the results of a comprehensive review that was announced in 1995, the EUB has specifically prohibited the licensing of new field spreading waste treatment facilities and the expansion of existing ones.

11.4 Permanent Landfill Placement

Solid NOW materials can be disposed of in Class II oilfield landfills (and also in Class 1b landfills, although this would constitute underutilization of such facilities). Class II landfills meet design, monitoring and maintenance specifications for non-hazardous oilfield materials as specified by provincial environmental authorities (e.g. AEPA, Alberta Environmental Protection Act) and adopted by the EUB or SEM with minor modifications. In Alberta, NOW landfills cannot be used for municipal or other industrial wastes, nor can any liquids be placed in them. Moist but solid CHOPS wastes (e.g. wet but not "sloppy sand") can be placed directly in approved landfills, but not liquids, slops, aqueous sludges or emulsions.

Approved landfills may be found throughout Alberta and Saskatchewan, operated by towns, counties, or commercial organizations. In the HOB, commercial third-party facilities that are available to separate wastes such as emulsion or treater residues almost always have an adjacent or near-by Class II landfill that receives the solids. However, there is reluctance on the part of the operators of these facilities to use them for the large volumes of produced sand generated by CHOPS wells throughout the region. Some municipal landfills (e.g. Riley and Coronation) accept produced sand that meets specifications, but most do not, and those that do are reluctant to expand their facilities.

The regulations for the design, management, monitoring and closure of landfills are well described in EUB (Section 15, Guide 58) and SEM literature, and there is a long evolution of guidelines for landfill disposal of various NOW materials. For example, landfills suitable for non-hazardous, aqueous-based drilling solids or thick drilling mud sludges have been mandated for some time by the regulatory authorities (see for example SEM Information Guideline GL 99-01). Such facilities are also suitable for produced sand.

As in the case of land spreading, there is an extremely detailed set of requirements for landfills designated for NOW. Because the EUB Guide 58 regulations are considered as part of this report, these requirements will not be detailed. However, the most important one is the chlorides limit of 3000 ppm, as this often disqualifies produced sand from direct disposal, particularly fine-grained sand that tends not to drain easily.

Advantages:

- Landfills are a relatively secure disposal method for NOW. There are decades of experience with Class II landfills.
- The technology is straightforward and surface facilities are low technology.
- Land values in the heavy oil area are low, and there are many sites of little agricultural potential that could be made into Class II landfills.

Disadvantages:

- Landfills do not eliminate environmental liability, as there is a risk that potable aquifers might become contaminated in the future (Figure 11.2).
- Obtaining a permit for a Class II landfill for massive sand disposal requires a careful site investigation and the development of a management plan that meets the needs of all the local stakeholders (farmers, homeowners, companies…). Generally the reaction by local residents is negative.
- Landfills constitute a form of land use that results in a permanent or long-term impairment of quality because of the presence of hydrocarbons on the soils that may interact with groundwater and that cannot be excavated without additional disposal costs.
- Additional costs are associated with stockpiling and transporting produced sand to approved landfills that may be at some distance from the CHOPS field.
- A program of monitoring and reporting is required for all landfills, and the monitoring, although not onerous, must be continued some time after decommissioning.
- Chloride limits mean that sand may have to be "treated" or allowed to reside in eco-pits for longer periods of time to allow chlorides to be washed out by rain.

It is not clear what the future of landfills will be in the Canadian heavy oil industry, although several new landfill sites are under consideration in Alberta at the present time. Whereas the AEUB and the SEM have not indicated any long-term support for landfills (as they once seemed to do for washing facilities), neither are they clearly critical of landfills (as they are with field spreading methods).

Recently there was a lack of suitable landfills close to sand-generating fields. The landfill at Marshall Saskatchewan is 50 km east of Lloydminster, and the West Edmonton Municipal Landfill is 240 km west of Lloydminster. As this method continues to be used, new facilities will be required.

11.5 Sand Washing Approaches

11.5.1 Sand Washing by Thermal and Non-Thermal Methods

Washing removes oil and generates sand that is sufficiently clean to place in a landfill or for secondary industrial use. However, sand washing is not sand disposal: once washing is complete, three streams remain for disposal: sand, oil and "dirty water". Thus, sand washing must be considered to be an intermediate stage in the disposal process. Washing approaches can be roughly divided into thermal and non-thermal methods, although hybrid approaches are possible.

11.5.1.1 Non-thermal washing

Two different approaches are used in non-thermal washing of oily sand: agitation in aqueous solutions with surfactants and perhaps small amounts of solvents; or using solvents to dissolve the oil and remove it from the sand grain surfaces.

To the writer's knowledge, no technologies have successfully reached the field trial stage involving cool water (10-30°C) washing with surfactants or with small amounts of light molecular weight solvents. Verbal reports indicate that various methods have been tried on the bench scale at the Alberta Research Council, at university research laboratories, and elsewhere, but failure to proceed to the field scale is indirect evidence that technological or economic difficulties plagued these methods. The difficulties likely were similar to the issues that have been noted in all washing plants: poor effectiveness and generation of additional waste streams (emulsion, aqueous colloidal suspension, "cleaned" sand). Because asphaltenes adhere tenaciously to silica surfaces once these surfaces have become oil-wet, cool aqueous agitation approaches probably will always remain ineffective in achieving a level of cleaning sufficient to permit the sand to be used as clean fill.

Typical solvent methods involve the addition of a hydrocarbon solvent, usually one or a combination of the following materials: HC mix (naptha), cyclic HCs (xylenes and toluenes), chlorinated HCs (e.g. trichloroethylene), or carbon disulphide. .

These methods have been studied in detail, although rarely has substantial scientific information been made public.[73] Communications with oil industry researchers reveal the following problems:

- Because the asphaltenes in the heavy oil residue are of low solubility in hydrocarbons, the cheap, naphtha-type solvents (mixtures of linear HCs from C_6 to C_9) perform poorly in stripping surface oil off the sand. Other solvents are expensive and must be carefully recovered.
- To recover the solvents as required by environmental guidelines for solvent recycling, a thermal process stage to evaporate liquid solvents and then condense the gases is needed. This is a major additional expense.
- Produced sand invariably arrives at the treatment site with 4-10% by weight of water. This material becomes a "contaminant" in any solvent extraction process that must be removed from the solvent stream at additional cost.
- After a solvent has been used to wash the heavy oil off the sand, the heavy oil in solution must be removed. This can only be achieved through a thermal evaporation stage at additional expense.
- The liquid material remaining after solvent removal is a mixture of oil, water and clay minerals (depending on the process chosen). This mixture must go through a separation process to strip the oil and send it to a local battery.

[73] The reason for a lack of data is puzzling, but may be related to patenting of methods (there are dozens of relevant but totally inactive patents), to issues of competitive advantage, or to the evolving general view that all these washing methods will always be prohibitively expensive.

- The residual water-clay waste, although of small volume, represents a "new" waste stream that must be treated (high-speed centrifuge treatment, long-term pond settlement, flocculation…).

Non-thermal washing with water or other solvents is not used by any full-scale facility that treats large volumes of oily produced sand. These methods may be used at a small scale in the treatment of special oily wastes, such as treater residues or high oil content sludges.

11.5.1.2 Thermal Washing:

To this date (November, 2000), three full-scale thermal sand washing plants in Canada have attempted to use aqueous approaches.[74] All three full-scale facilities used similar approaches: hot water and agitation for phase disaggregation, and gravitational segregation for phase segregation. These washing plants are:

- The Marwayne plant (60 km NW of Lloydminster, Alberta), dismantled in the middle 90's;
- The Bromley-Marr plant (Bonnyville), placed in receivership in September, 1999, and permanently shut down in September 2000 because of pond liner leakage and financial problems;
- The Canadian Environmental Equipment and Engineering Technologies (CE^3) plant (owned by Genoil which is owned by Bow Valley Industries) east of Bonnyville Alberta, a cleaning facility contracted almost exclusively to CNRL and situated on their property (the Bear Trap Field). It experienced technical and financial difficulties during 2000, failed to treat the volumes predicted, or to achieve a consistently clean sand product, and was shut down in late 2000.

Washing appears attractive. From a technology transfer point of view, it appears that the washing plants were all modeled on the large-scale oil sands extraction facilities at the Syncrude Canada and the Suncor mines, north of Fort McMurray. In those large oil sands extraction plants, the Karl A. Clark hot-water extraction process has been modified to extract oil from

[74] There are no known cases of solvent washing using heated solvents and agitation at the bench scale, ad certainly not at the field scale.

feedstocks that average about 12% of 9.5°API gravity oil by weight. An important factor in the success of these plants is that the mined oil sand is water-wet, and does not have time to dry out substantially in stockpiles before extraction.

The Syncrude Canada and Suncor methods use the addition of NaOH, heat, and aqueous froth flotation to bring the oil to the surface of a cell where it is skimmed. Solids and water are removed, and the oil is sent to upgrading. Sand is recombined with clay-rich slurry from a secondary extraction cell and sent to vast tailings ponds (>12 km^2 in the Syncrude case). Extraction efficiency is about 90-93% for the two plants; the clayey water that flows out of the sand into the tailings pond carries an appreciable quantity of oil that leads to slow settling and poor consolidation properties.[lvii,lviii]

Thermal aqueous washing of oily produced sand involves generating slurry with water, sand and surfactant, and then heating it, often by sparging steam directly into the aqueous system. Phase separation is usually gravitational, but may be aided by some version of a cyclone or centrifuge. Surfactants or NaOH may be added to the mix, and paddles or pumps provide agitation. Air may be sparged into the cell, and the oil phase captures the air bubbles and floats more easily to the top where it is removed by skimming. The sand settles to the bottom and is removed. The middle phase is a waste stream that contains clays that have been disaggregated by the agitation, and are well dispersed because of the presence of surfactants and a favorable pH (~8.5-9.5). This aqueous stream is generally high in chlorides from the produced water that accompanied the sand wastes into the treatment plant. Thus, three separate streams are generated as the result of washing.

Various flow processes can be implemented in sand washing to recycle the middle phase, scavenge heat from phases, and facilitate recovery. Each additional process, treatment cell, or thermal exchange device means additional capital expenditure.

Flow charts for the Marwayne and CE^3 plants are not available in the public domain. The flow chart of the Bromley-Marr plant was published as part of a set of public documents that outline interactions between the largest sand washing company, Bromley-Marr, and local and provincial authorities. (Note the high degree of optimism in these documents.). It is widely believed that failure to account for ancillary costs related to the generation of additional waste steams was the major reason for the company's bankruptcy (the facility continued to operate under receivership as late as August 2000 before it was permanently closed).

There is little public information available about the process used in the CE^3 plant, except that it is quite similar to the others, based on agitation and hot water. The plant was designed to wash sand to a level of purity adequate for sale to industrial users, but this has been limited by lack of a large market and by inconsistent results. It was a widely held view in the Heavy Oil Belt that the CE^3 facility would not last through the year 2001, and this indeed happened. There will likely be no further attempts to build large sand washing facilities for produced sand

The concept of mobile plants on skid units or trucks that could go from site-to-site washing small volumes of sand has been discussed in the industry for years, but no such commercial capability yet exists. Apparently, large-volume trucking to a central facility for treatment will always remain more economical for the oily produced sand because of the large volumes that must be treated, and the economies of scale that are needed.

11.5.2 Sand Wettability Issues

The condition of surface wetness of the sand plays a critical role in the technical success of sand washing, and to some degree has been responsible for the technical difficulties that arise in washing sand to a consistent level. In general:

- If produced sand is "entirely" water-wet, aqueous moderate-temperature (50-80°C) washing methods perform well.
- If produced sand is "entirely" oil-wet, water based separation is extremely inefficient.
- In mixed cases with more than 20% oil-wet grains, aqueous washing methods degrade substantially.

In situ, formation sand is undoubtedly > 98% water wet because of the geological history of oil emplacement and because there are few minerals that are hydrophobic. The produced sand from the well-head is initially >95% water-wet even though it has passed through a PC pump. However, drying takes place at the surface. Because of residence in stockpiles or transportation, a condition of oil wetness of the silica and feldspar grains is generated from desiccation, aided perhaps by augering and load-unload activities. Once the rough surface of silica and feldspar have become oil wet, they are almost impossible to fully clean except with solvents[75]. Linear HCs do not dissolve high molecular weight asphaltenes, therefore more expensive solvents must be used in a solvent extraction process, or added in some quantity to an aqueous system. In the latter case, solvent recovery is quite difficult.

11.5.3 Generation of Additional Streams

Washing is not a disposal process; it generates three streams, dirty water, washed sand, and skimmed oil, that each must be handled and disposed of in some manner.

Cleaned sand comprises the solid stream. Clean sand does not require landfill disposal; if it meets environmental guidelines, it can be placed directly on the ground. Three direct ground surface disposal methods are common: the sand may be used as good quality construction backfill where appropriate, it can be used to fill sloughs and low areas, to be covered later by soil and revegetated, or it can be spread on fields and ploughed in. All these disposal methods require ancillary transportation and rehandling activities. Construction sites are not always found nearby, and the demand for clean construction fill is limited in the region. Filling of sloughs near towns remains acceptable, but environmental activists increasingly resist wetland loss, as the wetlands support migratory wildfowl. A fourth possibility for use of clean sand is as a product for industrial processes. This topic requires consideration in detail, and will be discussed in a later section.

The "dirty" water generated during the cleaning process is a colloidal suspension of clay minerals, mainly smectite and illite, stabilized by the high pH and the surfactants present in the water: the same chemical environment that is conducive to cleaning oil off the sand is conducive to suspending clay. The suspension has to be treated by flocculation, filtering, or long-term pond settling to remove solids, and because the supernatant water is chloride-rich, it must be disposed of in salt caverns or in deep injection wells. Alternatively, if an injection disposal operation is located nearby, or if a permitted well is available, the dirty process water could be directly injected into a suitable stratum without further treatment.

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[75] As an example, road asphalt does not strip off the aggregate used in paving mixes because of the strong polarity of the asphaltenic components and because of their high viscosity.

The third stream from washing is not a waste stream, but a valuable product, recovered oil. Before it is trucked to batteries, recovered oil from the washing facility may have to be treated with cyclones or centrifuges, or dewatered using thermal dehydration before it meets specifications. At the batteries, it is blended with the produced oil from stocktanks and the blended materials are treated physico-chemically to remove salt and thermally to remove final traces of water. The effects on battery operations of any residual surfactants in the oil from washing plants are not known.

11.5.4 Summary of Washing Technologies for Produced Sand

- All full-scale washing technologies used to date in Canada have been based on hot water and agitation for dispersal, and gravitational phase separation.
- These methods produce three streams that still must be treated and disposed of, engendering additional costs.
- As of 2001, all three full-scale sand washing operations have failed.No new economically feasible washing technologies are on the horizon.
- It is widely believed that sand washing will never become an integral part of large-scale sand disposal, and it must be remembered that sand washing is not sand disposal.

11.6 Produced Sand as Industrial Feedstock

In principle, produced sand can be used directly as is or cleaned to meet specifications for industrial use (leaving aside road base incorporation, discussed previously). For direct use without washing, there appear to be two possibilities: as part of cement powder manufacture, or as part of asphalt-based surface paving material.

11.6.1 Cement Plant Feedstock

A cement plant uses a finely ground mixture of clay, limestone, and siliceous minerals such as quartz and feldspar in a high temperature kiln where it is turned into clinker. The clinker is then ground to a fine powder to make cement. Large amounts of silica and feldspar are used only when making specialty cements with high silicon oxide content; too much silica impairs the kiln process, generating a poorer quality clinker. Therefore only a limited amount of produced sand can be added to a cement manufacturing process.

Produced sand, along with the clay, oil, and residual water, has been used directly as a feedstock for the cement plant in northwest Edmonton, Alberta. Results have never been published. In their high temperature rotating kiln process, the oil would simply be combusted, and the small amount of chlorides in the residual water would probably be too minor to impair the quality of the product (although high chloride content is always an issue in cement manufacture). In theory, incorporation of produced sand into cement manufacture seems to be practical and environmentally desirable.

However, the cement industry in Alberta and Saskatchewan has only three cement manufacturing plants, and the closest to the CHOPS region is Edmonton, a 2.5 hour drive from Lloydminster. The amount of sand that could be used in one year is a small fraction of the amount produced in the CHOPS industry, and there is little chance of this being increased significantly in the future. Furthermore, the cement industry has its own local sources of very cheap clean sand of consistent properties. Oil industry sand would have to be delivered to the cement plant for only a few dollars per tonne in order to displace other sources of sand.

11.6.2 Road Asphalt Component

Produced sand with oil still on the grains can be used directly in asphalt-concrete for road surfacing. When oily sand is added to asphalt concrete mixes, the oil becomes incorporated as part of the asphalt (road tar) component of the asphalt concrete, and the sand as part of the solid mineral matter. The heavy oil is even improved somewhat by the high temperatures used in the asphalt concrete mix plant, driving off some of the lighter HCs in the heavy oil. However, there are three issues that arise in the use of produced sand in asphalt concrete mixes:

- Even small amounts of heavy oil have a negative effect on the asphalt concrete mix because the tar component becomes less viscous and less cohesive with the addition of heavy oil.[76] Since the tar component is only about 5.5-6% by weight of the mix, only very small amounts of heavy oil may be added before asphalt quality is compromised.[77]

- For high-grade asphalt concrete coverings for major highways, only a small amount of the mix can be the relatively uniform grain size produced sand. For low-grade mixes, a proportionately larger amount is feasible, but likely never more than 25-30% produced sand.
- Finally, the demand for sand for high-grade road asphalt concrete in the region where the sand is produced is limited, and this use is unlikely ever to exceed 5-10% of the produced sand.

11.6.3 Glass and Fiberglass Sand

All produced sand, even if perfectly clean, is unsuitable for conventional clear or colored glass manufacture because of the small percentages of ferruginous minerals present, and because the feldspar and mica contents are variable and sufficiently high to impair the glass quality.

For all glass products, the sand has to be quite free of oil, asphaltenes in particular. The high temperatures used in melting glass can lead to a carbon residue from the HC, and there are traces of heavy metals as well in the asphaltenes that could affect quality. Nevertheless, standards for fiberglass use theoretically can be met by sand-washing techniques.

Neither the Marwayne washing facility nor the CE^3 plant could deliver consistently clean sand that met standards for the manufacture of conventional glass. As for fibreglass manufacture, demand for sand is limited, and commercial fiberglass plants are usually located near major urban centers because it is uneconomical to ship low-weight fiberglass insulation long distances.

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[76] The viscosity of road asphalt is $>10^7$ cP at 20°C, but the heavy oil on the produced sand grains has a viscosity of 1000 – 20,000 cP. Even small amounts substantially degrade the properties of the road asphalts, reducing both cohesion and consistency.

[77] Road asphalt strength (resistance to dynamic traffic loads) arises from a carefully designed, extremely well-graded mix of mineral grains that are angular (the coarser grains are quite angular, and preferably the sand is also angular). The well-graded mix is then compacted to as low a porosity as possible, achieving an exceptional frictional strength because of interlock and high density. The tar component gives some cohesion, particularly in response to dynamic loads, by virtue if its viscosity (many millions of cP). Any decrease in this viscosity is negative, and any decrease in the compacted mix density is negative.

Shipping cleaned sand from the regions where it is cleaned to the regions where it can be used as fiberglass feedstock is not economically feasible (see previous comments in cement section).

11.6.4 Sand Blasting or Other Uses

The comments made in previous sections apply to the use of clean sand as sand blasting sand, or for other uses (architectural, as part of concrete, etc.):

- Shipping costs to major markets are prohibitive; these markets all have local sources that can provide cheap, fully oil-free sand.
- The quality of cleaned sand from washing plants is not consistent enough for sand blasting sand, as even a small amount of asphaltenes can ruin many products for which sand blasting is used (e.g. metal surfaces prepared for painting).
- Grains of produced sand from a single field are usually of uniform size (i.e. poorly graded) and are occasionally somewhat rounded, and therefore produced sands are not suitable as high quality fill or as concrete sand.

11.6.5 Industrial Uses Summary

Advantages:

- Industrial use constitutes permanent safe disposal of a material that otherwise is a waste; this is attractive to governments, oil companies, and citizens.
- If the industry in question will pay for the sand, part of the cost of sand handling and cleaning can be defrayed.

Disadvantages:

- For many uses, the produced sand has to be clean and of very consistent quality; this requires careful washing, a process that has not yet been perfected.
- For specific uses, such as glass making, asphalt concrete road mixes, construction fill, and cement making, the physical, chemical and mineralogical properties of the produced sand are not the best, making it a less desirable additive than other available sands.

- The demand for sand is high, but prices are low because local sources are nearly always available. The demand for sand in the Heavy Oil Belt is small, and urban centers are at least several hours away, which leads to additional transportation charges.

In summary, although industrial uses for produced sand seem to be an appealing solution for disposal, the volumes that are needed are small in comparison with the volumes produced, long-distance transportation is too costly, and the mineralogy and quality of the washed sand is not sufficiently consistent to warrant investment in local factories for products such as low-quality glass products. It is estimated that the entire local market could perhaps absorb from 25,000 to 40,000 m^3 of sand per year, which is around 10% of the produced sand, and much of this would have to be washed sand of consistent quality, which may not be achievable in practice.

11.7 Salt Cavern Placement of Produced Sand

For regulatory purposes, the EUB considers salt caverns used only for disposal to be extensions of disposal wells, and the same regulations apply. If the salt cavern is used as a treatment facility to separate wastes at the surface, it then must also meet EUB approval as a waste processing facility.

11.7.1 Why Salt Caverns?

Salt cavern disposal has two definite advantages over all other disposal methods (Figure 11.3):

- Because of the extremely low permeability of the salt strata and the tendency of a salt cavern to slowly close, it is technologically feasible to place and isolate toxic wastes permanently at a cost far less than with other toxic waste disposal methods. (Note that produced sand and other NOWs are not toxic wastes.)
- The large cavern acts as a huge and effective fluids and solids gravitational treatment and segregation tank (Section 3.4.4).

In addition to NOW, heavy oil production and upgrading operations generate small amounts of DOW, and these are extremely expensive to treat. Because of this, and as background to the use of salt caverns for NOW, a more detailed discussion of the environmental security of salt caverns is presented.

11.7.2 Salt Cavern Potential for Toxic Waste Disposal

Salt strata to be used for disposal of toxic wastes should be no shallower than 500-600 m to eliminate chances of interaction with shallow groundwater. The salt strata should be relatively thick, continuous, and amenable to the creation of caverns.

If toxic wastes are to be placed, the toxic solid material (10-25% by volume) can be blended with granular salt (~50% by volume) and shale chips (25-40% by volume) during placement. This "blended waste" concept greatly reduces long-term environmental risk: when the salt cavern slowly closes, the interstitial pore space will become filled by salt and the shale will provide an adsorbing medium for any toxic cations or molecules that are leached from the solid wastes. Once the solid wastes are in the salt caverns and the access wells are carefully sealed, the salt cavern is essentially decommissioned, except for long-term monitoring.

From this point, natural processes continue to enhance site security. Salt behaves viscously, even at depths as shallow as 500 m. Caverns will therefore close slowly and the cavern volume not filled with granular waste will gradually diminish. Free liquids in this volume will find some escape path from the cavern and enter the permeable strata above the salt cavern. The cavern walls will continue to move inward and apply increasing stress on the blended waste. The granular salt placed with the waste material and shale slowly recrystallizes, flows, and fills the free pore space, expelling most of the remaining fluid. A final porosity of about 2-4% would be a reasonable assumption for a cavern filled with blended solid waste once closure is complete. If the cavern is filled with produced sand or other solids NOW waste without any salt or shale added, the final porosity will not be occluded by the salt, and it will reach a "steady-state" value of 20-30% (the former from well-graded sand, the latter for uniform sand).

Cavern closure from slow creep (Figure 11.4) will be almost complete within several hundred years for shallow caverns (~500 m), within several decades for deeper caverns (>1000 m) where stresses and temperatures are higher. There are methods to accelerate the rate of natural cavern closure by as much as an order of magnitude if deemed necessary.

The compacted blended waste has a permeability that is low ($<10^{-8}$ D), as a result of the salt filling the pores. Furthermore, after cavern closure the compacted blended waste is permanently encapsulated within a salt bed that, by virtue of its low permeability in all directions and its capacity to creep under stress, has exceptionally high environmental security factors. The solid waste is permanently entombed, therefore any waste transport vector that intersects the biosphere must involve transport in the liquid phase of the strata. The geological and physical process factors that act against any interaction with the biosphere are listed here:

- The salt surrounding the wastes is essentially impermeable ($<10^{-10}$ D), and any strata within or adjacent to the salt beds usually has salt-filled pores, which reduce the permeability of these beds to low values ($<10^{-6}$ D).
- Salt strata in Alberta and Saskatchewan have been stable for 300-400 million years; suitable salt beds in other jurisdictions are also millions of years old and stable.
- In stratified sediments, there are always several thick flat-lying low permeability shale beds ($k < 10^{-6}$ D) between the salt cavern and the surface, providing barriers to vertical flow, forcing any generated flow to take place horizontally.
- The formation fluid in and surrounding the salt strata is saturated brine ($\rho \approx 1.19$ g/cm^3). Higher in the sedimentary column, the fluid is unsaturated brine ($\rho < 1.19$ g/cm^3). This density-graded system is extremely stable, and mixing with shallow waters ($\rho \approx 1.00$ g/cm^3) near the surface is hydrogeologically almost impossible, even over millions of years.
- In flat-lying sedimentary strata that are not overpressured, regional pressure gradients are extremely small and flow is extremely slow. Furthermore, flow paths to fluid exit points may be hundreds of kilometres in length, and in many areas (e.g. Gulf of Mexico), fluid exit points are under water.
- The volume of pore space in surrounding strata is so large that any fluid volume expelled from the cavern is a minuscule fraction of the available volume.
- Shale strata, as well as interstitial clays in the sandstones and limestones through which any leachate must pass, provide adsorption sites that trap cations and molecules, attenuating toxic concentrations.
- Even if expelled fluid gradually approaches the surface along some preferred path, the dilution effect near the surface arising from annual rainfall would diminish any biotoxicity to negligible quantities.

In summary, the relevant physical processes and the geological characteristics of typical sites and basins where suitable salt strata are found lead to the conclusion that biosphere contamination will not happen, even for millions of years. Therefore, salt cavern placement is perhaps the most secure of all geological placement methods, and the writer strongly recommends it for DOW, using the blended waste approach.

11.7.3 Cavern Design and Management

In Alberta, many thick, fully secure salt strata underlie the HOB. More information may be found in the literature and from the Alberta Geological Survey in Edmonton (a division of the EUB).

11.7.3.1 Cavern Development and Design

To develop a solution cavern for waste disposal, conventional oil-well drilling is used to drill to the base of the cavern. The well is cased and cemented below the top of the salt bed, and one or two concentric tubings are hung in the casing. Unsaturated water is circulated through the centre tube and brine passes up the annulus between the centre tube and the well casing. Seven volumes of fresh water are required to dissolve one volume of salt. Maximum vertical height is limited to the salt bed thickness; the design height and the cavern shape are controlled using gas or hydrocarbon liquid blanketing techniques that control vertical dissolution. Leached brine is evaporated to make salt, sold as chemical industry feedstock, or disposed of by deep well injection in sub-salt strata.

Purpose-created storage caverns typically have volumes of 200,000 m^3 to 500,000 m^3 with thick roof and floor beams of salt, and are usually well separated from adjacent cavities. In “previously-used” caverns to be converted to waste placement, the current geometry is dictated by the previous use: hydrocarbon storage cavities often have a “tear-drop” or inverted cone shape; old brine exploitation caverns have uncontrolled geometries and often show evidence of roof collapse.[78]

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[78] Exceptionally, uncontrolled solution caverns cave to surface, causing subsidence, impairing groundwater, and alienating the local community. A major design concernis roof stability and caving-to-surface..

Brine exploitation caverns are usually much larger in volume than old storage caverns and tend to be flat with horizontal roofs. They may be hydraulically interconnected with no reliable inter-cavern integrity that might guarantee long-term roof support. The entire salt thickness is usually dissolved, often exposing overlying insoluble strata that fall as rock rubble into the open void space, causing upward migration of the cavity until stable conditions are reached because of rubble bulking. For environmental security, in such cases the cavern use should be limited to NOW. In the case of partly collapsed or unstable caverns, practical limitations to placement of NOW (or DOW) are therefore likely.

11.7.3.2 Waste Placement in a Salt Cavern

After cavern development or conversion, waste slurry (slops, produced sand, emulsion, contaminated soil, etc.) is placed in the cavern through the inner tubing (tailpipe) after screening and mixing. Large size fragments of solid waste must be removed through screening to meet tailpipe injection specifications that guarantee against blockage (see Figures for a diagram of a flow-through slurry system). Mixing guarantees that slugs of high solids content waste do not block the tailpipe. Furthermore, if the waste slurry contains solids, it must be injected at a velocity high enough to keep density waves (solids pile-up) from developing within the time frame of slurry transit from the wellhead to the exit point. In the absence of other criteria, the maximum particle diameter is recommended to be to one-tenth of the inner diameter of the tailpipe, and the velocity in the interior flush tubing should be no less than 1 m/s (~0.5 m^3/minute for 75 mm ID tubing).

Depending on how the cavern is to be used, some of the saturated brine from the slurry can be used to slurry the next increment of wastes, and excess brine (which by now may have traces of materials that render it unsuitable for industrial use) can be disposed of through deep well injection into strata below the cavern site. Of course, the salt cavern must be kept filled with brine to maintain stability and keep closure rates low.

11.7.3.3 Management of Cavern Growth

Salt caverns undergo slow closure, gradually losing volume. Non-saturated aqueous fluids (slops, emulsion) placed in caverns become salt-saturated through contact with the walls of intact salt, and the caverns grow in volume if these new brines are withdrawn to allow space for more waste liquids. For example, if slops ($\rho \approx 1.05$) are injected into a brine-filled cavern, 1 m^3 of salt is dissolved for each 10 m^3 of the slightly saline formation water. For injected non-saturated liquid, the saturation proceeds as follows:

- The low-density fluid rises to the top of the brine in the cavern (where a gas or HC cap should be maintained to control vertical growth), forming a layer with a horizontal upper boundary (e.g. if ~10,000 m^3 could be placed instantaneously in a cavern of ~30 m radius, the layer would be ~3 m thick.).
- Solids suspended in the injected fluid settle to the bottom of the cavern, passing through the saturated brine zone.
- On cavern walls where the fresher water contacts the salt, a thin layer adjacent to the salt face dissolves salt, becomes denser, and flows downward along the wall as a density current (density-driven convection), being replaced by fresher water that flows horizontally to replace it. This density-difference convection drives the liquid flow patterns in the cavern.
- The process slowly continues until the new fluid is totally brine saturated, a process that is rate controlled by the rate of solution, the contact area, the concentration differences, etc.
- If the cavern is used as a treater to take advantage of long-term gravitational segregation, it will continue to grow slowly by virtue of the continued introduction of non-saturated water. The design process should take this into account so that the maximum utility of the cavern is achieved. For example:
- If the cavern is intended only for solid waste placement and the solids are to be introduced as a high-density brine-based slurry, the cavern is initially dissolved close to the expected maximum volume.[79]

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[79] A cavern designed for DOW or other toxic material must be dissolved with a smaller true volume, an unequivocally stable shape, and thicker security barriers of intact salt than a cavern designed to accept NOW. The placement of liquid DOW should be prohibited unless it is fully absorbed on clay, zeolites, or similar absorbent materials, and it should be insoluble in brine.

- If large volumes of non-saturated liquids are to be treated over the life of the cavern, cavern growth must be accounted for, and the initial cavern volume must be much less than the ultimate maximum volume.
- In the latter case, planning must include cavern shape management to avoid generating an unstable shape over the long-term that will promote collapse and loss of the placement wells.

11.7.3.4 Placement of Produced Sand in Caverns

The preferred placement method for produced sand is the following:

- The sand undergoes mixing/blending similar to the slurry injection system described in the next Section (11.8).
- Large particles are sieved out and saturated brine previously displaced from the cavern is added to wash the sand through the sieves.
- The dense slurry enters the mix tank where there is an intense turbulent mixing action, but not intense high velocity shearing that tends to emulsify oil.
- Slops and emulsion are added as part of the make-up fluids, either on the sieve or in the mix tank, to bring the volumetric solids content of the mix to approximately 10-12% (equivalent to one cubic metre of loose produced sand to 6 cubic metres of liquid). Depending on the salinity of the water phase, the density of the slurry is now ~1.16 (fresh water) to ~1.34 (if fully NaCl-saturated brine is used with dry sand).
- This slurry is injected through the central tail pipe into the cavern at a rate of 0.5 – 1.0 m^3/min.
- In the cavern, if the slurry is lighter than brine, it will spread out on top of the liquid column and mineral matter will sink almost immediately through the underlying brine to the bottom. If the slurry is denser than the brine, yet the liquid phase is non-saturated, some interesting phenomena take place:
- The slurry enters the cavern as a density current, falling to the base of the cavern and spreading horizontally to fill the entire cavern area at the interface between solids and the brine column.

- The solids sediment out of the slurry until the remaining liquid is less dense than the overlying brine. (Note that the high salinity will flocculate any clay minerals.)
- The density instability must be overcome, causing the less dense liquid to “float” up through the brine, with some mixing taking place.
- When the liquids are at the top, saturation of the water takes place, facilitating the gravitational segregation of the oil.
- Whether the slurry is lighter or denser than the brine, the water phase becomes salt saturated and the oil phase rises to the top. It is not known at this time which type of placement (less dense or denser than the cavern brine) leads to the best oil separation and emulsion breaking. In most cases, particularly if the liquid phase is partly make-up brine, the slurry should be denser than the brine phase.

For a 500,000 m^3 cavern (neglecting closure effects), perhaps 350,000 – 400,000 m^3 of bulk produced sand could be placed before decommissioning. Note that such a cavern has an area footprint no larger than one-hundredth of a square kilometre if it is approximately spherical, while a typical surface landfill placing NOW materials at a thickness of 8 m (25 feet) has a footprint over six times larger. Once a cavern is filled and is to be decommissioned, the access wellbore is sealed using perforating and squeeze cementation.

11.7.3.5 Liquids Management in Salt Caverns

Because liquids and solids are being added continuously, saturated brine must be withdrawn. Depending on the way that the materials are introduced into the cavern, either the inside tailpipe or the intermediate annulus is used to withdraw brine that is displaced by the introduction of waste streams. Alternatively, if two wells are available, one may serve exclusively as the waste placement well, the second as the clear brine withdrawal well.[80]

With a properly placed withdrawal point, the brine removed is perfectly clear because all oily materials have risen to the top, and the high salinity has caused all solid material to flocculate and settle to the bottom. The cavern volume is typically large enough so that, except near the

[80] There are advantages and disadvantages to a single well strategy or a double well strategy, and the choice depends on how the facility is managed (dominantly as a solids disposal facility or as a “treater tank”).

waste entry point, there is no turbulence to maintain particles in suspension. The brine is disposed of in a water disposal well.

The oily phases combine to form a light phase on top of the brine. Because salt is insoluble in oil, the presence of a hydrocarbon layer on top of the brine suppresses vertical growth. Alternatively, to give better control of cavern dissolution with time, a gas cap may be introduced and managed to promote proper cavern geometry.

There are several ways to skim off the oil. The simplest is to open the outside annulus and allow the gas (air) cap to be displaced until the upper oil phase enters the annulus and rises to the surface. (If there is no gas cap, the outer annulus will automatically fill with the lighter oil, giving a long length vertical separator effect.) This happens quickly because of the large density contrast between oil and brine. If the effluent begins to switch to brine, the process is stopped, and if necessary, a gas cap may be re-established to control vertical growth. The second method is to raise one of the hanging pipes to the level of the oily phase and allow the oil to be displaced to the surface as other wastes are injected. This is harder to control and is more costly because the pipe has to be moved up to enter the oil phase. On the other hand, if the cavern is managed with gas injection and withdrawal, combined with oil withdrawal, it is possible to control the liquid elevation with the gas cap and also to control vertical growth precisely.

Skimmed oil is treated within the facility for more dewatering if necessary (a vertical heated stocktank is adequate) and the oil is sent to a local battery for final treatment.

11.7.4 Rock Mechanics and Geological Engineering Issues

The major aspects of cavern site choice, design, and management are related to the rock properties of the salt and surrounding strata; that is, the *in situ* state as defined by depth (stress), temperature, pressure, and the management requirements of the cavern. In brief, the most important rock mechanics issues are closure rate, dissolution rate if unsaturated fluids are cycled through, and stability of the roof beam. Considerations of rational design include:

- Estimation of the volumetric closure rate of the cavern.
- Estimation of the dissolution rate to be expected, which depends on the planned cavern use.

- Control of the shape of the cavern during the cavern development phase.
- Control of the cavern shape evolution during cavern operation if dissolution is to be part of the operating strategy.

The goal is to achieve a minimum span flat roof beam commensurate with the use of the cavern. This may require careful management of the heavy oil or gas cap that prevents fresh water from directly contacting the overlying salt and dissolving it. If there is no HC cap, vertical cavern growth will continue until an insoluble bed is reached. At that point, the dissolved cavern will mushroom outward just under the insoluble bed until the opening span is large enough that the insoluble bed collapses. Uncontrolled collapse usually ruins the borehole casings and tubings. The HC cap elevation is managed over time to foster salt dissolution at different elevations?? so that a large volume is attained without roof collapse, and also so that decommissioning can be achieved at minimal expense with minimal long-term environmental risk.

11.7.5 Monitoring Salt Cavern Disposal

During all phases of cavern development and use, the amount of salt dissolved must be tracked. This is achieved through careful volume, composition (oil sand water), and density tracking of fluids placed in the cavern, and tracking of the density and volume of brine expelled. The amount of salt dissolved is calculated based on the volume balance and the densities, which give a full mass balance. Densities of fluids can be precisely measured using pycnometer methods, or nuclear densimeters. If nuclear densimeters are used to measure the density of an ingoing slurry of solids and a liquid of unknown density (such as diluted produced fluids at a density of 1.01-1.05 g/cm^3), or if the slurry is composed of three separate phases of different density (oil, water, sand), there is no single method of determining the saturation state of the water phase. Bulk samples must therefore be procured regularly for all ingoing fluids, and the density of the aqueous phase determined using pycnometers.

The cavern may be monitored during its initial dissolution development phase by sonar surveys every few months to insure that the target design shape is being achieved.

If the cavern is designed to be continuously dissolved indefinitely through the controlled introduction of non-saturated aqueous materials (slops, emulsion, clean-up fluids), methods that allow continuous monitoring of the level of the HC in the cavern should be installed. This would aid in the ongoing design procedure used or the cavern roof maintenance, both of which must account for changing geometry.

In any cavern where toxic wastes have been placed, more careful monitoring will be required. If there is concern with respect to the possibility of a roof collapse, a simple microseismic monitoring system can be installed. This will allow the stick-slip processes in the roof to be tracked quantitatively over time, and changes in behavior can predict changes in risk of roof impairment. To assess the effect of slow cavern closure of a single isolated cavern, one or two surface radial lines of 10 survey points each seated at a depth of 6 m below ground should be installed and surveyed each year to determine vertical ground deformation, which can be mathematically inverted to give an estimate of the cavern closure behavior. Other monitoring approaches have little merit in salt cavern management.

11.8 Slurry Injection of Solid Sand and Other CHOPS Wastes

Slurry Fracture Injection™ (SFI™) was developed in Alberta and Saskatchewan as an alternative to surface disposal methods for produced sand. The method involves injection under conditions of continuous fracturing of a slurry of waste sand and water into a stratum that is either a depleted reservoir or permeable oil-free water sand. The water used to generate the slurry can be produced water or slops. A small proportion of emulsion can be included.

An Alberta-based company, Terralog Technologies Limited of Calgary[81], installed the first commercial SFI™ facility in the period 1994-1996. The EUB licensed the six or seven should sites used for injection in the period 1994-1998 under a variance order allowing injection pressures above fracture pressures. In all cases to date a Class II well license has been issued with a variance, rather than an issuance of a Class 1a or 1b well license, which would permit the injection of certain types of more hazardous liquids along with produced sand and NOW liquids.

11.8.1 Principles of Site and Well Selection for Slurry Injection

It is important that an appropriate stratum and injection well be available. Some vital characteristics of the target formation and the injection wellbore are listed here. These

[81] Website www.terralog.com can be visited.

characteristics must be carefully assessed during site selection and design of the well and the injection strategy.

Because an injection site is a waste treatment facility, environmental precautions must be taken on the site, and these are mandated by the regulatory agency for a NOW waste treatment facility (e.g. stockpile isolation, groundwater protection…).

11.8.1.1 Target Formation Selection

The injection stratum must be an unconsolidated or relatively poorly consolidated sandstone or silty sandstone. The following characteristics are desirable:

- The bed must have a thickness of permeable sand sufficient to allow unimpeded injection. Measured as $\Sigma(k \times L)$ in Darcy-m, an aggregate injectivity value of at least 10 is considered to be required to sustain unimpeded injection for repeated injection episodes.
- The minimum thickness of the injection stratum should be about 5-6 m to allow full radial drainage away from the wellbore vicinity, even after repeated injections of clayey or oily wastes.
- The target stratum must be evaluated using well testing and be shown to be capable of maintaining sufficient storativity and injectivity under repeated injection episodes to sustain trouble-free operations for several years.
- Within the target stratum, the presence of shale stringers and lenses less than 1.5 m thickness presents no technical difficulties, except that these zones should not comprise a majority of the thickness of the injection horizon, nor should they impair lateral flow of injected liquids far from the well.
- A low resistance to fracture propagation is required to reduce pressure requirements during injection. For this reason, dense limestone is not considered a suitable candidate rock, even though it may have extremely permeable streaks because of interconnected vugular porosity.
- The reservoir that will accept the waste slurry must have sufficient lateral extent to allow rapid pressure bleed-off over the entire life of the SFI™ well. Narrow channel sands are

not as desirable as widespread, laterally continuous blanket sands, if other factors are comparable.

- It is preferable to have sand stringers above the injection zone separated from it by impermeable shale at least 10 m thick to serve as pressure bleed-off strata (which blunt any tendency for fractures to rise).

11.8.1.2 Geological Conditions for Maximum Environmental Security

In large part, these are similar to the criteria set out for salt cavern environmental security (Section 5.6.1). The target stratum should be in flat-lying stratigraphy with shale barriers in a region of horizontal formation water flow, low gradients, no overpressure, and so on (Figure 11.5 & 11.6). Nevertheless, given that SFI™ is currently licensed for NOW disposal only, a suitable monitoring program to demonstrate waste containment and protection of other resources is installed, it can be used widely. A broad range of geological conditions are suitable, providing there is no risk of affecting surface groundwater quality.

11.8.1.3 Well Perforations

The perforations that establish hydraulic connectivity from the inside of the casing to the formation must be designed and installed properly to maximize well life and minimize blocking possibilities.

- Open-hole completions are not suitable, and the well should not be steeply inclined in the perforated section of the target reservoir.
- Correct perforating does not mean the largest and deepest penetrating perforations; an excessively deep penetration can lead to flow-back and injection control problems because of cross flow in the perforated interval when starting or stopping.
- The zone chosen for perforation must be carefully assessed based on previous well history, or on the geophysical logs. Poor choices may lead to a difficult operation of the injection well.
- Large-diameter ports, >0.75″ diameter, are preferred in all circumstances.

- The perforated interval should be at least 4 m long, but not more than 8 m, and placed at the lower third level of the stratum in the case of a long permeable interval.
- Perforations should be fully phased around the casing, spaced at approximately 26 shots per metre.

11.8.1.4 Wellbore Cementation

The pressure integrity of the wellbore is critical for successful large volume SFI™ over a period of several years. The role of cement is to guarantee that there is a pressure seal between the injection bed and overlying strata (the casing strengthening role of the cement is irrelevant). This prevents elevated injection pressures in the injection well (BHP ≈ 1.15 – 1.25 σ_v) migrating up between the cement and the rock, increasing the risk of casing shear along shale interfaces above the injection stratum.

If an old well is used, all cement bond logs, including a purpose-run one, should be studied carefully to assure suitability of the well for prolonged SFI™.

If poor bond is noted, either the well can be recemented in an appropriate manner, or another old well examined for suitability. There are no specific criteria for the state of the cement bond log; interpretation is judgmental, based on experience in the area.

If a new well is to be designed and used for slurry injection, there are several recommendations to be followed with respect to the cement placement. A genuinely non-shrinking cement slurry of sufficient density should be used so that the rock-cement seal can be maintained through hundreds of pressurization cycles.[82]

11.8.1.5 Tubing and Casing Design and Conditions

Solids injection wells are equipped with 2⅜″ or larger injection tubing held in place with a packer seated at least 1 m above the uppermost perforations. A bottom hole pressure gauge is installed above the packer that, at a minimum, measures the BHP within the injection tubing on a

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[82] There are a number of other recommendations to be followed in the cementing of a dedicated SFI well, available from the SFI operating company.

continuous basis (the BHP gauge can also be configured to measure temperature and annulus pressure at little extra cost).

BHPs will range from 0.45 psi per foot (10 kPa/m) during quiescent periods to values as high as 1.15-1.25 psi per foot (23 – 26 kPa/m) during active SFI™. Furthermore, during the active injection periods, short-term pressure fluctuations of as much as 10% can be expected as fractures change orientations and attitudes at depth. To avoid breakdown of the well, the following casing conditions must be confirmed:

- The casing must be free of serious steel thinning from corrosion, particularly at shallow depths where a breaching of the casing could have more serious environmental implications.
- The casing must be free of patches or squeeze cement jobs used to isolate upper levels, as both of these conditions are susceptible to loss of pressure integrity on repeated cycling.

11.8.2 Operational Practices

Most of these aspects have been addressed in a series of professional papers. A relatively complete reference list is appended; only a brief synopsis is given here.

11.8.2.1 General Approach

Targetr sites should be near a dedicated injection well with a stockpile of sand adjacent to the hopper-feeder unit, and a large source of water (waste produced water or other source). Wastes are stockpiled on site and loaded with a 1.5 m^3 bucket front-end loader into the hopper-feeder during injection.

An instrumentation system helps track and manage the waste injection process. In addition to the instruments that are installed on the flow-through unit (Figure11.7) to monitor the blending process and the density of the ingoing stream, other instruments may be installed. A bottom-hole pressure gauge in the SFI™ well is considered to be absolutely necessary to track the process in real time and to measure the formation shut-in pressure response during periods when active injection is not taking place. Bottom hole or casing pressure gauges in several off set wells (if available) can be completed in the same horizon or in an overlying zone. Finally, an array of tiltmeters (generally from 12 to 16) can be deployed in circles around the well on the site, to monitor fracture parameters such as orientation, width and attitude.

A well is injected for 10-12 hours a day at a slurry rate of 1-1.5 m^3/min, then shut down until the next day (Figure 11.8). Each day, on average, 600-900 m^3 of slurry is injected, composed of 140-200 m^3 of the stockpiled produced sand, perhaps some amount of emulsion or oil-rich slops (only a few percent by volume is acceptable), and produced water or other water to achieve a density 1.16- 1.30 g/cm^3. Injection takes place each day for 10 – 15 days, and then the operation is shut in for 3-4 days while the pressure response of the formation is monitored. The process cycle is then restarted for another 10 – 15 day period.

The bottom-hole pressures during the periods without injection are carefully analyzed to ensure that the reservoir continues to accept the injected wastes without impairment, and that the injection pressures leak off into the surrounding strata at a reasonable rate. Periods without injection also allow the formation to slowly readjust to the changes and pressures imposed during the injection activity.

11.8.2.2 Daily Injection Cycle Procedure (Figure 11.8)

- A step-rate injection test may be carried out initially to assess the fracture gradient, or a limited injection test may be done to assess the formation permeability and injectivity.
- Injection is started with clear water (no solids) and the rate is built up to the normal injection rate and maintained so that the entire system operates smoothly.
- Solids are introduced through the hopper-feeder and the density of the injected slurry rises over a period of a few minutes to the target slurry injection process density.
- Injection is continued for up to 8-12 hours in the injection well, with modification of the process parameters as required during injection to maintain smooth operation without well or formation impairment.
- Once the solids injection process is complete, the solids content is gradually diminished until only clear water is being pumped down the well.
- From 5 to 10 m^3 of clear water is flushed through the system before the wellbore is shut in against the formation pressure.

- The BHP is monitored and recorded at high sampling rates during the period just before shut-in, and for a period of 30 minutes after shut-in, to capture fracture closure and transient pressure decline effects during the period of rapid change.
- The BHP sampling rate is slowed after 30 minutes, but recording is continued until the next injection period begins. If operations are taking place in unprotected winter conditions, all free water is drained and blown from the surface systems to avoid freezing.
- Before the next injection period is started, the pressure vs. time trace from the preceding quiescent period is examined for any anomalous behavior that could affect the injection strategy; if there are no problems, the SFI™ procedure is re-initiated.

11.8.2.3 Flow-Through Waste Mixing System

Slurry injection systems, whether fixed or mobile, consist of the same basic components. The individual parts of the system and their functions are listed here.

- A hopper-feeder system accepts wet, oily sand and feeds it into the flow-through slurry injection system. The feeder unit must be able to handle materials such as rubber gloves, pieces of wood, rocks (3 to 6″ diameter), and so on.
- The "solid" sand is conveyed by conveyor belt or gravel auger to the feed hopper of a vibrating screen system.
- A vibrating screen system with two or three screens sprayed with water removes oversized materials that could block the well perforations. Generally, the smallest screen mesh size used is 3×5 mm. Oversize material is loaded onto LHD trucks and taken to a Class II landfill (or it could be ground and placed into the cycle again).
- The dense slurry that exits the screen is transported by another gravel auger and loaded directly into the mixing tank, where arrays of jets of high-velocity make-up water help to generate a uniform slurry.
- The mix tank volume is 6-10 m^3, and typical injection rates of 1-1.5 m^3/min result in a residence flow-through mixing time of about 4-5 minutes. Feed rates for water, dense

slurry from the screen, and other liquid streams can be varied to achieve the desired consistency and density.

- Slops, emulsion, and other liquid streams that are guaranteed not to have any particles larger than 3 × 5 mm can be emptied from tanker trucks or through flow lines directly into the mixing tank; otherwise, all materials must pass through the screens.
- A centrifugal charge pump provides the suction necessary to charge the main pumps. It withdraws from the base of the mix tank at a zone of exceptionally high turbulence, and after the charge pump is passed, a nuclear densimeter records the specific gravity of the inflow to the main pumps.
- The main injection pump system consists of two sets of motors and triplex or quadruplex injection pumps in parallel but connected to a single injection manifold, so that if one injection line is impaired, the second will continue pumping to clean the wellbore of sand before shutting down. Pumps are typically operated at about 60-70% maximum volume rate capacity during continuous injection for periods of about 8-12 hours.
- The slurry is fed under high pressure into a flow line linked to the injection well.
- All mechanical equipment in the slurry averaging system (for mixing, augering, etc.) is driven by hydraulic motors powered by a central diesel-driven unit.

The final piece of site equipment is the heated control building where the SFI™ operation is remotely controlled, where rates and pressures are continuously displayed, and where data collection for all active monitoring devices takes place.

11.8.2.4 Fixed or Mobile Injection Operations

A fixed injection site is a facility housed in a protected climate environment so that injection operations can be maintained under all weather conditions, independent of local road bans and other limitations. A typical site is adjacent to a regional sand stockpile, and positioned so that sand does not have to be handled again. A permanent site may also have a sand stockpile inside a protected structure maintained at 0°C to +2°C to prevent the wet sand from freezing.. In this case, vacuum trucks emptying stocktanks discharge their loads directly on to the weather-protected stockpile, and injection is initiated only when there is sufficient sand for 5-10 days of daily disposal at an efficient rate. Under ideal conditions, there will be several available injection wells within a pressure flow-line distance of 100-200 m so that slurry disposal operations can switch to another well if the first one is impaired for any reason.

Fixed sites have operated for as long as 14 years in Saskatchewan (MOCAN, now EXXON-Mobil), with total injection into a single well of 30,000 m^3 of sand in 200,000 m^3 slurry, along with some amount of slops and emulsion. Thus, in a fixed site, it is estimated that 100,000 to 150,000 m^3 of sand could be disposed of over a period of three to five years in several wells, along with perhaps 700,000 to 900,000 m^3 of waste water.

A mobile slurry blending and injection unit is mounted on a set of skids that comprise three standard flatbed loads. It is transported to individual sites when sufficient wastes have accumulated to warrant a visit of at least six to eight weeks (3000-5000 m^3); otherwise mobilization and demobilization, preparation and site clean-up push unit costs too high.

11.8.2.5 Slops, Sludge, Drilling Mud, and Emulsion Disposal in Wells

The amount of materials other than produced sand that can be injected in wells is a critical factor. The amount allowed depends on operator experience, the nature of the injection formation, and in particular the day-to-day and hour-to-hour response of the target injection stratum. Too much emulsion blocks the permeability, acting almost as if a rubber membrane is being extruded along the walls of the fracture as it grows. This leads to extension and vertical growth of fractures because it impairs the desirable pressure leak off characteristics of the chosen formation. It can also lead to the maintenance of excessively high pore pressures in the well vicinity after injection is stopped each day, which encourages pressure migration along the casing to upper horizons. In two SFI™ field cases in Canada to date, excessive input of emulsion has led to premature well failure through shear of an interface several metres above the injection zone.

The amount of any viscous or fine-grained material that can be added cannot be predicted a priori by any known means, but there are a few empirical guidelines that can be stated.

- The more coarse-grained the SFI™ stratum, the more viscous material can be added to the stream.[83]
- The lower the viscosity of the material the larger the amount that can be added.
- If there is a progressive decay in the pressure leak off behavior of the reservoir over a few days, viscous additions may have to be reduced or eliminated.
- If pure drilling mud is to be injected, it must be diluted with make-up water so that its viscosity is massively reduced. Because of the viscosity of smectitic clays, the water addition may have to be large, but on the other hand, produced sand can also be added in large quantities to diluted drilling mud (or sludge).

11.8.3 Environmental Compliance and Monitoring for Process Control

To comply with Guide 58 NOW disposal regulations, each slurry injection site must be approved, and a materials audit (material types and volumes) must be provided to the EUB (or the SEM) on a regular basis. Injection operators must assure that no DOW or other unlicensed waste stream is included in the injection process, and that no unaudited, unsupervised, or unmonitored injection takes place in the licensed well.

To date, the EUB has insisted that some monitoring and analysis be done along with SFI™ to confirm that the produced sand and liquid wastes being injected are contained within the target formation and will not impair future access to and extraction of any other HC resource. Among the requirements that must be met are the following items.

- A record of slurry density, composition and injection rates at 15- minute intervals throughout the injection period must be maintained and provided to the EUB if requested.
- A BHP gauge on the injection well is required. This gauge is also vital to control the process and measure reservoir pressure decay, step-rate test response, and any well tests undertaken to characterize the formation.

[83] However, extremely porous formations where k > 3-5 Darcy have additional problems associated with premature screen out leading to sudden blockages and pressure spikes.

- If there are offset wells available in the same injection stratum (i.e. if the injection stratum is a depleted field or a former thermal EOR reservoir), the closest ones must be instrumented with at least a casing pressure gauge, and preferably a BHP gauge to monitor pressure migration through the formation.
- If there are inactive wells in an overlying reservoir with some resource potential, some of these wells should be monitored for pressure response.
- An array of tiltmeters to monitor attitude, orientation and other fracture parameters is not required, but is strongly recommended as a means of tracking the distribution of the solids waste pod, and assuring that the wastes remain in the target stratum.
- Regular step-rate pressure tests should be done to evaluate changes in fracture gradient (perhaps every two weeks).
- Every month or two, thermal tracer tests should be carried out to demonstrate that the slurry injection well retains its integrity.
- Cement bond logs may have to be run again if there is concern that the well is losing pressure integrity.

Other monitoring methods are not necessary, but the EUB encourages detailed monitoring of injection activities so that the industry can learn more about the physical processes taking place.

11.8.4 PanCanadian-Terralog Automated Sludge Injection Well

Terralog Technologies Inc. established an automated slops injection well into an oil-bearing formation in the Provost area of Alberta that was judged a non-exploitable resource. The details are provided in an attached article.

11.8.5 Disadvantages

Slurry injection has its own set of disadvantages that could make it unworkable at specific sites or uneconomic, compared to alternatives:

- A dedicated injection well in good condition is needed for slurry injection.

- The target stratum must be far away from groundwater resources, and must also be an unconsolidated sandstone with no fracture resistance. In some areas, these criteria may be impossible to meet.
- Casing shear and other forms of well impairment have been noted, and these may represent serious cost issues.
- Dedicated injection into a well is prohibitively expensive for disposal of small amounts of waste because of the large mobilization and demobilization costs.
- On-site slurry injection is generally too expensive for a small field comprising only a few wells where the annual total produced sand is only 1000-1500 m^3; in this case, a facility shared by two or more companies is a possibility.

11.9 Other Treatment Options

These methods, similar to washing, are not disposal methods; rather, they are treatment methods designed to destroy, alter or decompose the contaminating agents in the waste so that it meets standards permitting easy disposal or secondary use. The major alternatives are thermal decomposition, biodegradation and chemical treatment.

11.9.1 Thermal Decomposition

There are a number of thermal decomposition technologies that are designed to either directly burn the oil from the sand, or cause it to react with an oxidant that eliminates or greatly reduces the oil content. All these methods involve passing the sand through an insulated kiln where the thermal process takes place on a feed-through basis (batch mode treatment is simply too unrealistic to consider seriously for large volumes of produced sand with small amounts of oil contaminant).

The difficulties with all thermal decomposition methods are appreciable, and are summarized here:

- The sand does not contain enough oil to sustain combustion, and other fuel must be added.
- Because any thermal process also involves heating the sand, which comprises 95-98% of the thermal mass, the additional energy needs are large.

- Scavenging heat from the process, as part of a steam generation process or another heating process, sounds attractive, but is technologically and economically not realistic because much of the heat resides in a solid (i.e. sand), rather than in a more manageable gaseous or liquid form.
- Once “cleaned”, many of the same issues mentioned in Sections 5.4.5 and 5.5.5 still apply; the sand is merely cleaned at this stage, and disposal is still required.

Given the volumes of produced sand, the widespread geographical distribution of the sand producing sites, and the cost of fuel, there is no chance that thermal degradation will become economical for large NOW streams. However, the writer is of the opinion that there is an important niche for mobile thermal treatment units designed to handle those DOW materials that are susceptible to decomposition through thermal treatment. For example, high-T oxidation reaction is already used commercially to decompose polychlorinated biphenyls and similar materials. It will be feasible only for materials for which other disposal methods are not allowed. Furthermore, if placement of blended toxic wastes in salt caverns is permitted by the regulatory authorities, the reasonably low costs associated with that method would displace thermal decomposition approaches.

Similarly, if SFI™ is permitted to dispose of DOW, it could provide disposal with long-term environmental security at a much lower cost than is possible for thermal decomposition.Although economical technology development based on thermal combustion for produced sand is not considered a possibility, a combustion process may be developed for stable emulsions and other oil-rich wastes, with the possibility of using thermal energy from the emulsion (to heat stocktanks?). Such a process would have to cope with the poor combustion qualities and high sulphur content of these liquid streams. Given the opposition to increasing CO_2 emissions by burning poor quality products simply to get rid of them, emulsion burning is unlikely to be an emerging technology in the near future, although this may change.

11.9.2 Biodegradation Cells

In laboratories throughout the western world, batch mode oil product decomposition has been repeatedly demonstrated to be technically feasible. Oily sand can be placed in cells with reasonably controlled conditions, nutrient and bacteria supplied, oxygen made available, and rapid degradation of even difficult materials takes place, often in just a day or two. In the field, nutrient and oxygen access are more problematic, temperatures cannot be optimized, and other natural and man-made factors complicate treatments.

Bacterial breakdown of heavy oil on produced sand has been tried at the field scale in Alberta, and has been shown to be viable from a technical point of view. Twenty-one days in biodegradation pits, carefully controlled and supplied with nutrients, resulted in clean sand. Thus, it seems appealing as a technology for cleaning sand, or for the reduction environmental degradation in facilities such as landfills, where rapid biodegradation could, in principle, be fostered. (Note that biodegradation methods for NOW cannot involve any dilution that is intended solely to reduce the concentration of the contaminating agent so that it can be reclassified.)

Land spreading or land farming is mainly slow uncontrolled biodegradation. Cool temperatures in Canada result in slow natural biological activity for much of the year. If wastes are buried too deeply, the ground temperature may stabilize at 5-8°C, a value too low for degradation within one or two years. (Note that there are other bacteria that are quite active at these temperatures, but apparently not the species that decompose heavy oil.)

Difficulties with biodegradation of the oil in produced sand are substantial, and include the following issues:

- As mentioned previously, the waste volumes are huge, and any batch mode process with a substantial residence time is likely not feasible.
- The polyaromatic, high molecular weight, sulphur-rich heavy oil residues on produced sand are the least susceptible of the HCs to biodegradation, and highly favorable conditions are needed to break down the oily materials rapidly.
- Efficient biodegradation means that both nutrients and bacteria must access the oil efficiently, but the very presence of the oil can block diffusion processes (fluid flow or Fickian diffusion).
- The products of degradation (CO_2, CH_4, other chemicals) must be removed efficiently, and if this requires turning over the waste or re-mixing it, additional handling costs are generated.

- After the sand is cleaned to certain specifications, it still has to be disposed of or shipped to secondary use sites, at substantial expense.

In practice, there are many cases where biodegradation is viable and desirable. Consider the clean up of beach oil from the Exxon Valdez in Alaska, for example. It was found that spreading nutrients on beach oil accelerated the bacterial activity which broke the oil down into harmless components. If relatively small volumes of waste can be allowed to reside in one location for a long time (months to years), spraying nutrients and bacterial inoculants will undoubtedly be effective.

Given the recent improvements in tailoring the genetic material of bacteria to handle difficult conditions, this is a promising treatment possibility that should be monitored. Nevertheless, given the huge volumes of produced sand requiring treatment each year, it is unlikely that any batch mode process needing dedicated environmentally controlled conditions and repeated handling will ever be economically viable. Rather, bacterial processes will likely be used in landfills or in stockpiles.

11.9.3 Chemical Treatments

No large-scale chemical treatments for oily produced sand are known. The same difficulties encountered in other processes (large volumes, small amounts of oil in the sand, type of oil, etc.) act against chemical treatment. Any chemical that could react with the oil to produce totally benign products (gases, or solid material that cannot be leached) is likely to be expensive, and given the small amounts of oil on the sand, is unlikely to be dispersed sufficiently homogeneously to be used efficiently. Given the cost of potential treatment chemicals, combined with the problem of ultimate disposal, no developments are anticipated for CHOPS sand waste treatment with chemicals

Figure 11.1: Cross-Section of an Ecology Pit for Sand Stockpiling

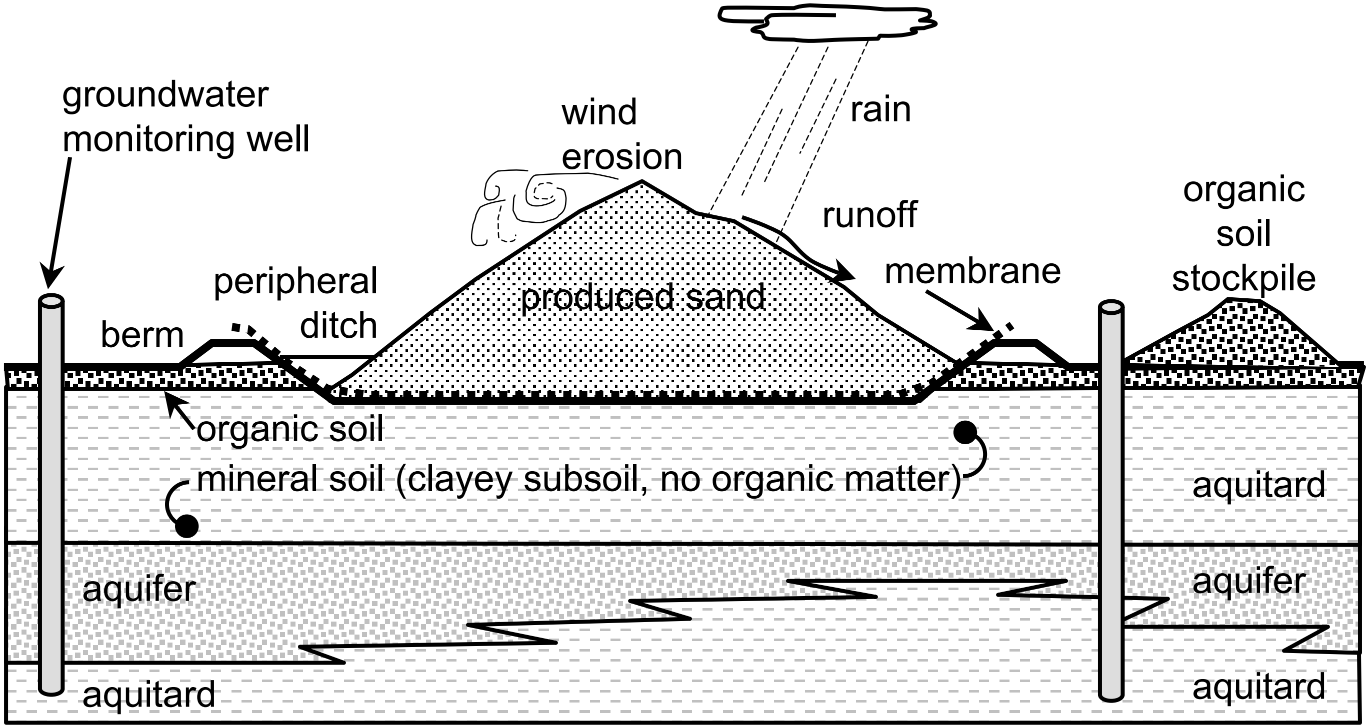

Figure 11.2: Issues Arising in Class II Landfills

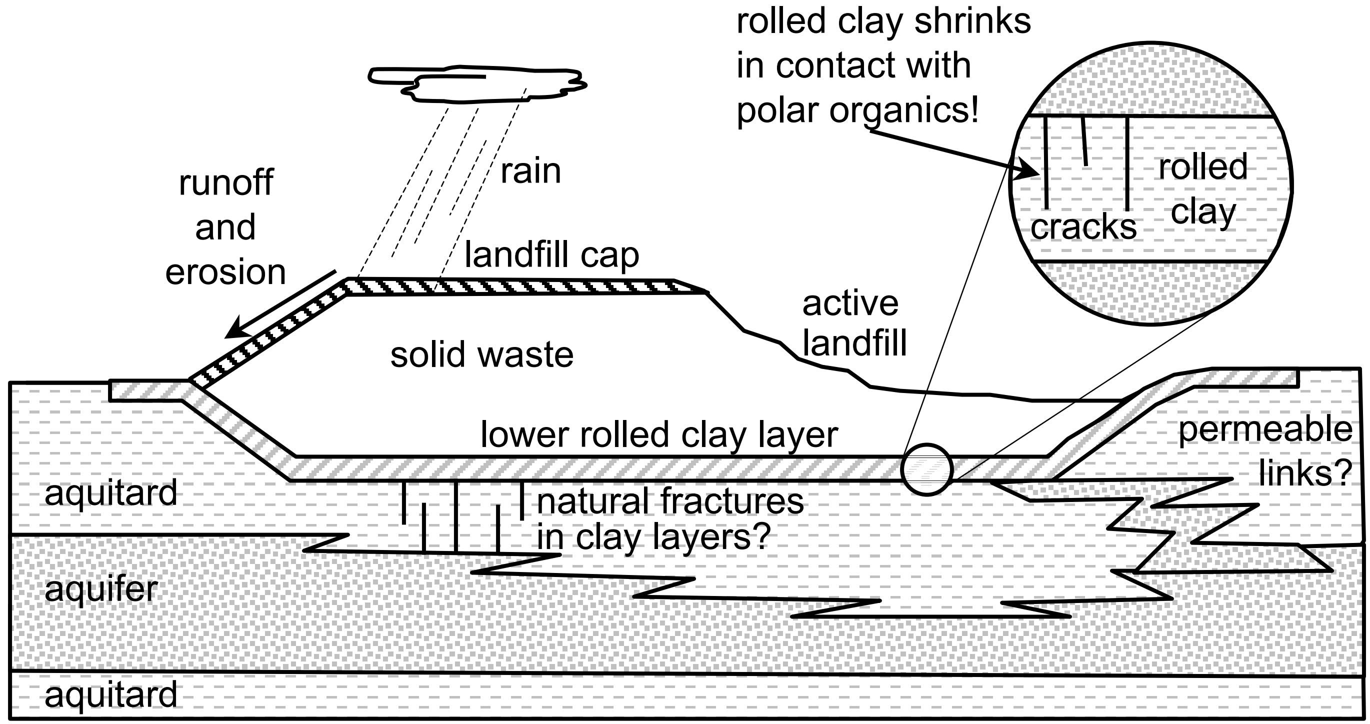

Fig 11.3: Salt Cavern Waste Placement and Management

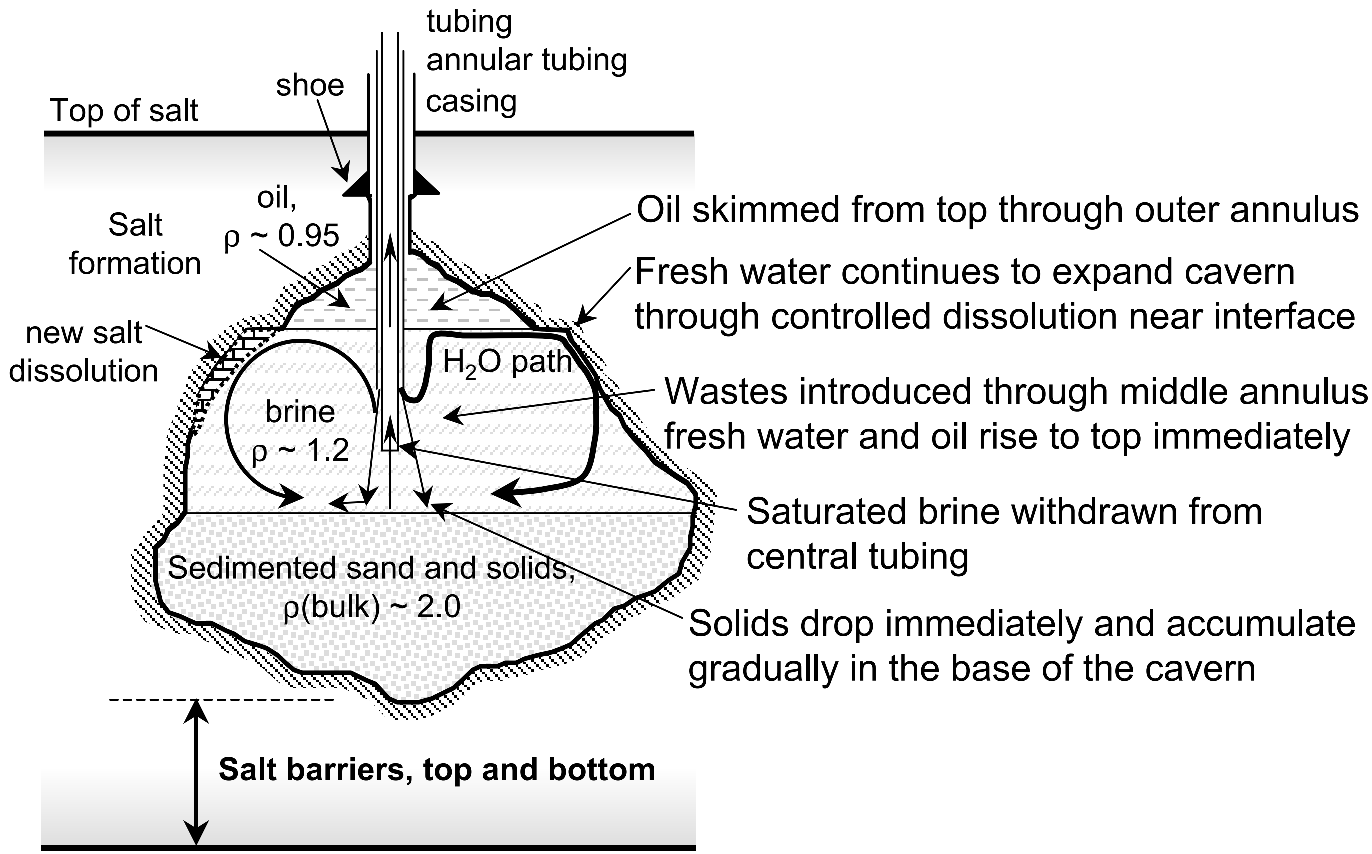

Figure 11.4: Salt Cavern Closure on Solid Wastes

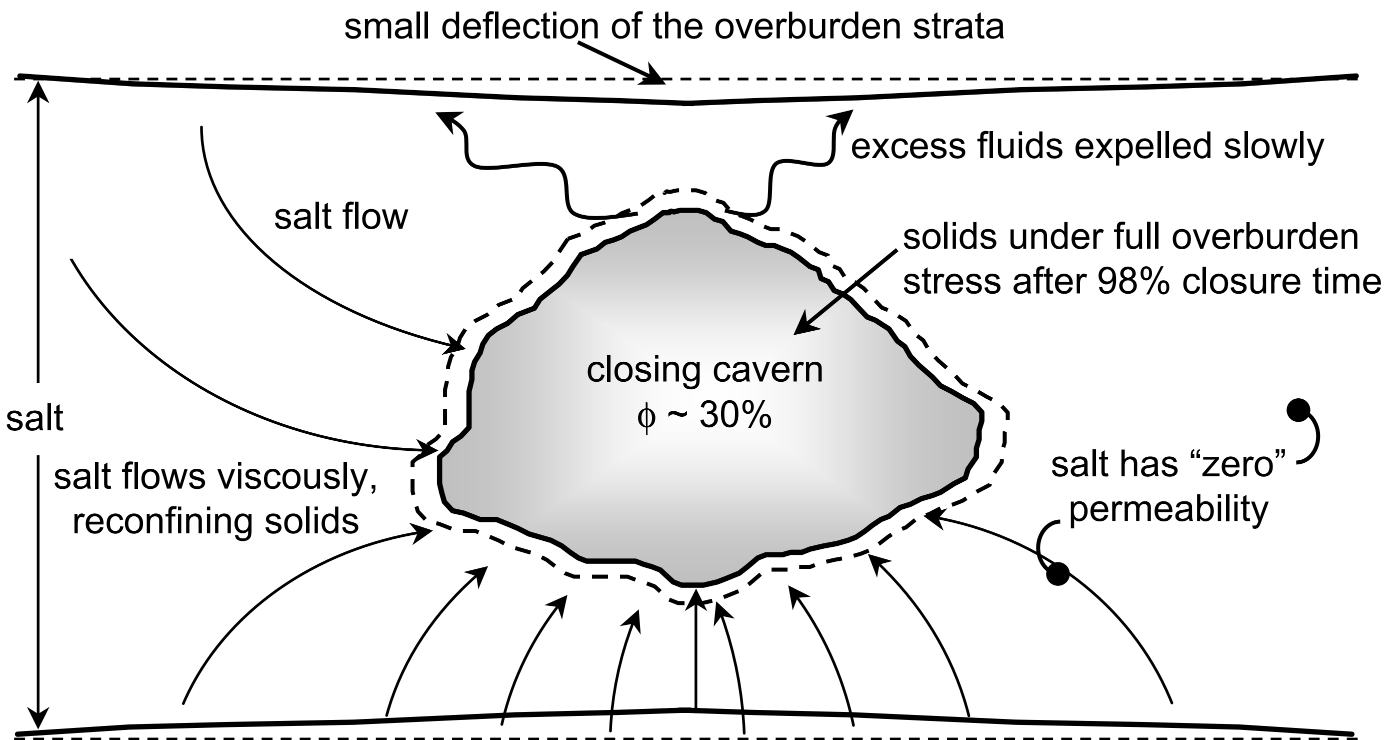

Figure 11.5: Environmental Security of Salt Cavern Placement

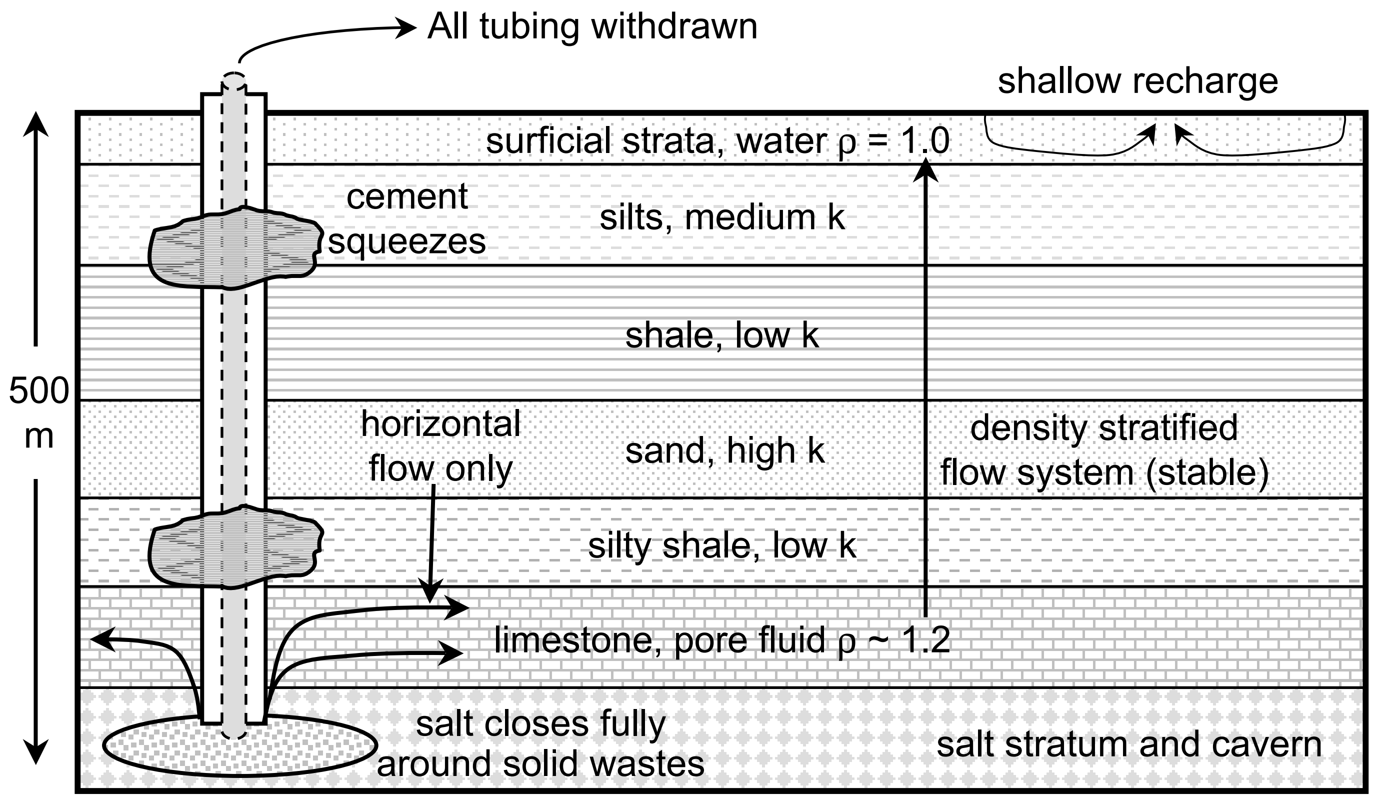

Figure 11.6: Slurry Fracture Injection into Stratified Sediments, Alberta

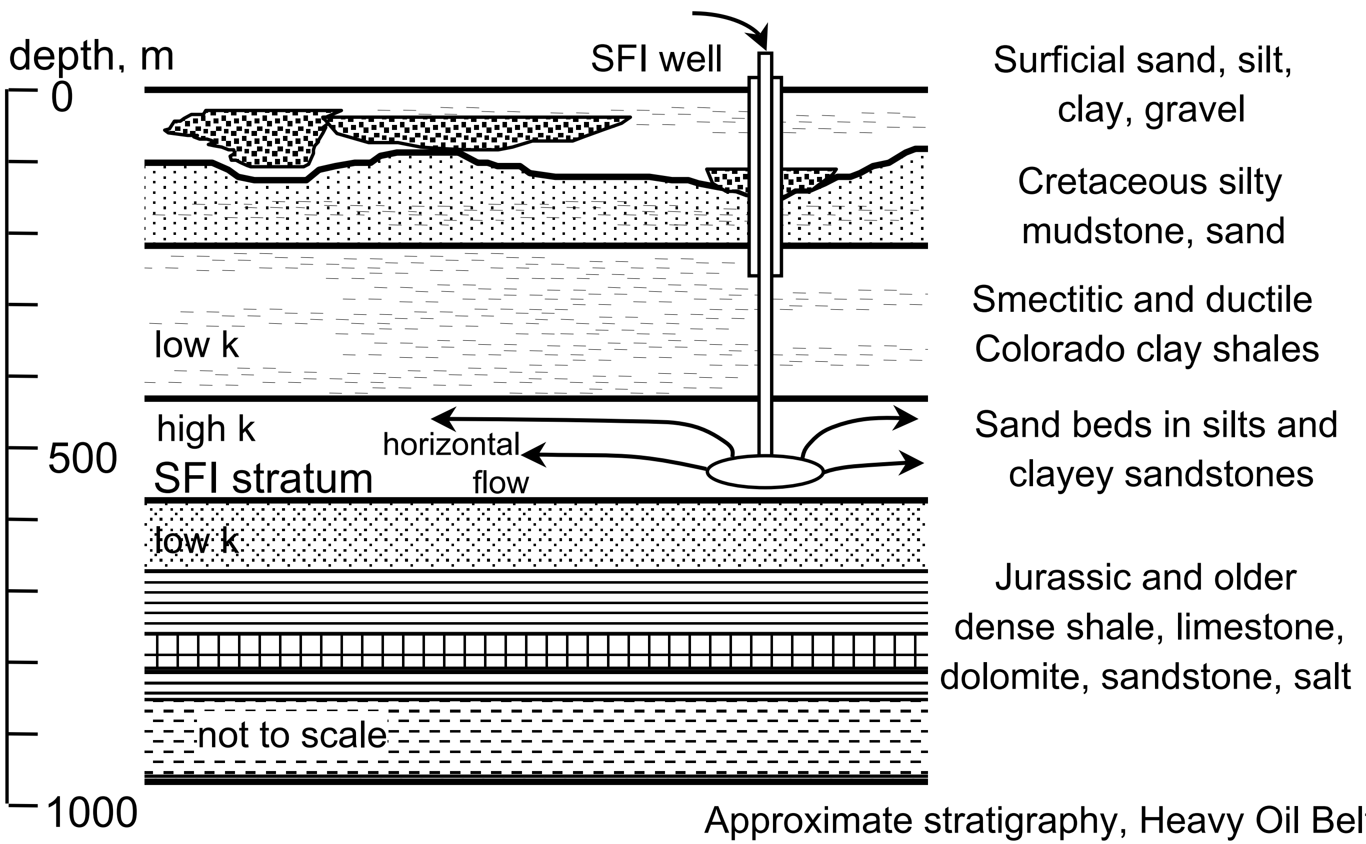

Figure 11.7: A Flow-Through Blending Unit for Slurry Preparation

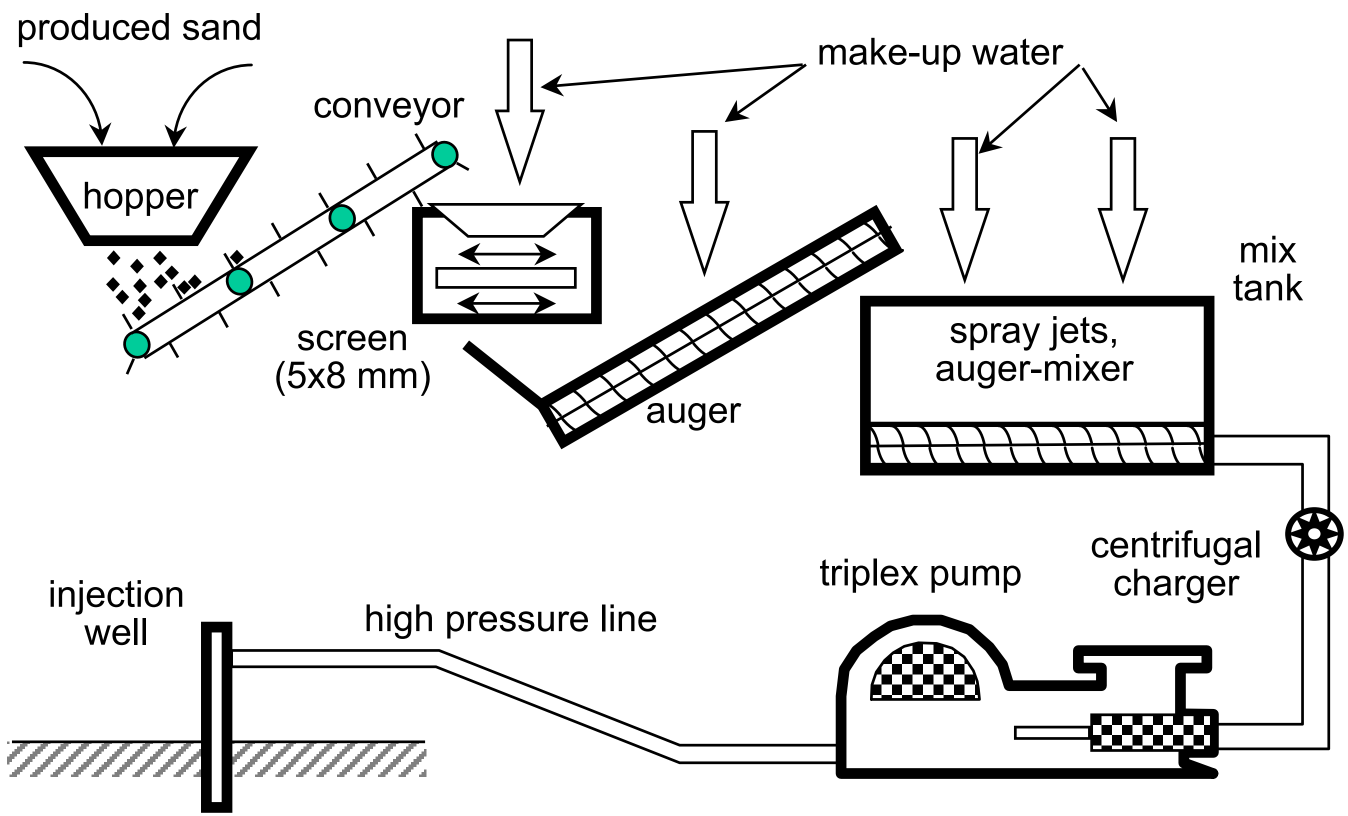

Figure 11.8: BHP Response During SFI Over a Daily Cycle