Implementation of Slurry Fracture Injection Technology for E&P Wastes at Duri Oilfield
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Abstract
The Duri oilfield is one of the 141 oil fields operated in Sumatra, Indonesia by PT Caltex Pacific Indonesia under a production sharing contract with the Government of Indonesia. Discovered in 1941, the Duri field is one of the world’s giant oilfields and the biggest steamflood operation located in the Rokan block with current oil production of 200,000 bpd (31,000 m³ per day). The in situ formations of the Duri field are unconsolidated sands; coupled with a steam flood operation they are susceptible to producing large quantities of oily viscous fluids as a by-product from the oil production. Up to 400 m³/day (2,500 bpd) of oily viscous fluids are generated at five oil production Central Gathering Stations (CGS) in the Duri oilfield.

Slurry Fracture Injection™ (SFI™) is an environmentally viable deep well disposal process for Exploration and Production (E&P) waste streams. The SFI process can be used in the petroleum industry to dispose of produced solids, oily viscous fluids/sludges, tank bottoms, contaminated soils and drill cuttings.

There are a number of environmental advantages associated with the SFI process that make it suitable for E&P waste management strategies that include: permanent disposal of waste materials, zero surface discharge, no adverse interaction with the environment, reduced risk of ground water contamination, and relatively low cost. The SFI process was determined to be the most environmentally viable process for E&P waste management at the Duri oilfield in Sumatra. This SFI project represents the first time that the SFI process was implemented in Indonesia. This paper details the SFI project assessment, development, and field operations related to this deep well disposal process at Duri.

Introduction
PT Caltex Pacific Indonesia (CPI) explored several alternative technologies to replace the surface-based processes used for E&P waste management at the Duri Steam Flood (DSF) oilfield in Sumatra (Figures 1). CPI undertook this study to ensure it employs environmentally sound waste management practices for E&P waste volumes generated at its Duri production operations. After considering several waste management options, CPI decided to use the Slurry Fracture Injection (SFI) process to dispose of E&P waste at the DSF, as this technology is a permanent disposal option at a relatively low cost, and is compliant with zero surface discharge criterion. The SFI process has been used in US and Canada and has been proven to be environmentally acceptable.

The Slurry Fracture Injection - SFI process at the DSF is used for the disposal of oily viscous fluid waste streams. The waste material is screened to pass specified injection criteria. These wastes are then mixed with water to produce a pumpable slurry (for the purpose of this paper, the term ‘waste’ is defined to be any material prior to slurrification and disposal; the term ‘slurry’ is defined to be the waste material that has been blended with mix-water into a slurry stream). The slurry is made with as high a waste concentration as possible, typically 10-33% by volume. Deep disposal wells are used to inject the slurry under pressure into a suitable geological ‘target’ formation deep within the earth. Injection pressures are in excess of the fracture gradient of the disposal formation. The target formation(s) are high permeability, thick, unconsolidated sands.

SFI operations at Duri are conducted on a daily basis (>8 hours/day, continuous injection cycles (> 48 hours/cycle, one cycle 3 days), and long term (12-15 days/month). Under such conditions, as waste material is injected into a formation, an area around the wellbore begins to fill with the injected waste material. The water component of the slurry dissipates into the formation. This waste filling area coalesces and evolves into a ‘waste pod’ (Figure 2). Relatively lower permeability, lower compressibility, and lower porosity than the surrounding formation can characterize this waste pod.

The SFI process incorporates a number of unique monitoring and operating features that allow for effective process control during injection-disposal operations. Process control during SFI operations refers to: a) maintaining optimum formation injectivity; b) maintaining fracture containment; and c) maximizing formation storage capacity.
With effective process control the SFI process is a permanent and environmentally sound disposal technique suitable for a variety of waste streams (Figure 2).

**SFI Project Development**

The SFI project at the DSF is one of the largest deep well disposal projects of its kind for E&P waste streams. Extensive planning was required to address the unique features of this project. The development of the SFI project at the DSF was conducted in four phases starting in early 1999, as follows:

1. Phase 1: Assessment of current and alternative waste management processes.
2. Phase 2: Detailed technical feasibility study of the SFI process for the DSF.
3. Phase 3: Design and implementation study of the SFI process/facility at the DSF.
4. Phase 4: Procurement and installation of the SFI facility.

The Phase 1 assessment evaluated several technologies in order to find the cost effective, reliable, and environmentally acceptable process. Those technologies can be grouped into the following categories:

1. Deep well disposal (SFI).
2. Chemical and Mechanical (sand washing, emulsion breakdown).
3. Solidification.
5. Incineration.

The operating costs, advantages and disadvantages of each alternative were determined for comparison of these various technologies. It was determined that Slurry Fracture Injection – SFI process best met the environmental criteria that CPI has established for waste management at the DSF; i.e. the SFI process was well suited to eliminate the need for surface disposal of E&P waste material, mitigate any adverse interaction with the environment, and provide a permanent disposal method by returning the waste material to its place of origin. The disadvantages of the other alternatives included: the need to provide space/land for storage of the residual material left over after treatment (chemical & mechanical processing); excessive time and land use requirements (bioremediation); prohibitively high processing costs (incineration).

The Phase 2 technical feasibility study determined the suitability of the SFI process for the DSF. The main factors considered were a geological assessment to identify suitable target formations, a waste material audit, and selection of a suitable location for a SFI facility at Duri.

The remaining project development work focused on FEED, implementation, and construction of the SFI facility. Full scale field operations at the Duri SFI project commenced in December 2002.

The Duri SFI Facility is currently fully operational and consists of a waste and mix-water handling facilities, a single Slurry Disposal Unit (SDU) system (for blending and injection of the slurry), and two SFI disposal wells (Figure 3). This facility currently disposes of 7,000 to 12,000 m³/month (44,000 – 75,000 bbls/month) of production wastes generated at the Duri oilfield.

**Waste Material**

The primary production waste streams at the DSF are oily viscous fluids (OVF; oil, sand, and water emulsions) generated by the thermal recovery process. It is beyond the scope of this paper to provide detailed analyses of these waste streams. In summary, these OVF streams vary considerably in terms of composition and rheology.

OVF may have low or high viscosity with varying degrees of ‘waxy’ characteristics, as follows:

- Viscosity of the OVF = varies from 500 cp to 2,000
- Hydrocarbon content = 10-24% by volume
- Solids content (BS&W) = 30-76%

'Sand-slug OVF’ refers to an OVF waste stream with an elevated concentration of sand/solids in it. Produced solids (sands) make up part of these oily emulsions. The produced solids are composed of a range of grain sizes varying between medium grained sands and small quantities of silts and clays. Numerous grain size distribution analyses have been performed, and can be summarized as follows:

- Average grain size (d50) = 0.0016 – 0.0079 inch
- Coarse grain size (d10) = 0.0059 – 0.0270 inch
- Fine grain size (d90) = 0.0015 – 0.0039 inch

Table 1 provides an overview of the DSF waste stream classifications for the SFI project.

**Duri SFI Geology and Wells**

An SFI target formation is the geologic zone in which direct injection of slurry will occur; this formation is the primary disposal zone. The target formation should be properly consolidated with a high compressibility to ensure that the formation yields easily during injection operations. The mechanical yielding of the formation will allow insertion of waste/slurry volumes at optimum formation injectivity. These zones have a high permeability where fluids can drain off quickly during injection. This characteristic prevents high formation pressures and stress gradients from building up, which can cause inadvertent formation fracturing or shearing (potentially increasing the risk of wellbore failure).

A confinement zone is typically an interval of alternating sands and shales above the target formation. Injected fluids/slurry from the SFI operations may ‘leak’ uphole over time due to loss of hydraulic isolation of the disposal well (i.e. loss of cement integrity) or due to vertical growth of the fracturing events during the injection operations. The confinement interval is permitted such that fluid migration into this interval is permissible and acceptable. A confinement zone: is typically a relatively thick (2-5 m) of competent shale that ‘caps’ the confinement zone interval. This confining interval provides an effective seal or cap rock to the deep well disposal operations. Injected fluid is not allowed to migrate past this confining zone.
SFI Operations

The geology of the Duri area contains the necessary geologic stratigraphy for successful SFI operations. The Dalam, Menggala and Pematang formations were all identified as potential target disposal formations, with the Baji-Jaga, Kedua and Pertama zones comprising the containment zone. The confining zone is the shale of the Pertama formation. The Menggala is presently serving as the target disposal zone in the two active injection wells. Menggala/Dalam/Baji-Jaga formations in the area of Duri oilfield are considered to be the primary slurry injection targets. These formations are located below the Duri oilfields common Oil-Water contact. It is expected that the shale sequence above the Pertama will provide the confining cap for injection throughout the project. These zones are identified and correlated to one of the SFI wells in Figure 4.

SFI Wells:

Maintaining the mechanical and hydraulic integrity of the SFI wells is important during SFI operations. Based on past experience, the critical element in any SFI well is the integrity and quality of the cement job. During SFI operations, the cement will undergo high pressure injection cycles on a daily basis. The drilling and cementing program should ensure that the SFI well has a uniform cement sheath, a good cement bond to the casing and formation along the entire well. Good cement placement along the target zone(s) intervals may be difficult (as these are potentially ‘fluid loss’ zones); if possible cement above the SFI target zone should be not brittle and have low shrinkage during set-up time. High quality cement placement across the confining zone is essential. The perforating program must ensure good hydraulic communication with the disposal formation and not impair hydraulic isolation around the wellbore.

SFI project at Duri is comprised of two injection wells. The current well completions for both of the Duri SFI wells are shown in Figures 5 and 6. Some difficulties were experienced in achieving good cement placement (i.e. establishing good cement-to-formation and cement-to-casing contact) for these wells.

SFI Operations

SFI operations at the DSF primarily involve the following factors: a) wellbore design; b) slurry design; and c) injection strategy. These factor need to be optimized continually during large scale SFI operations at Duri.

Wellbore Design:

Review of the performance and response in each SFI well suggest that an optimized well drilling and completion strategy for Duri SFI wells should include the following:

- A larger than normal hole should be drilled so a thicker cement sheath can be achieved.
- A minimum of 75 m (250 ft) rat hole should also be drilled to accommodate any sand influx into the well during SFI operations.
- Employ cementing practices that will give the best possible cement uniformity, and bond to the pipe and formation. Use of appropriate mud and cement for unconsolidated sands that may be encountered during drilling of the SFI well (e.g. careful mud control to avoid wash-outs that could reduce the quality of the cement placement).
- Deep penetration charges must be used to ensure good hydraulic communication between the wellbore and the formation. Cement invasion can occur in permeable sands during the cementing of the well.
- For OVF perforation hole size should be 0.5 inches using 4-6 spf.
- Large injected volumes of OVF waste streams may destabilize and fluidize the formation matrix in the near wellbore area resulting in formation back-flow into the wellbore.
- Formation back-flow into the well (and resultant wellbore plugging), can be managed/minimized through optimized wellbore completion strategies (e.g. tubing placement, perforation strategy, rat hole depth, etc.).

Slurry Design:

Integrating slurry design with the type of waste material being disposed and the geology of the target formation is essential for successful SFI operations. The SFI operations at the DSF have established slurry design criteria as follows:

- No gels or synthetic additives are required for slurry makeup.
- Highly viscous OVF streams can impair formation fluid response during SFI operations and must be limited to no more than 15% by volume of the injected slurry.
- Intermediate viscosity OVF at or below 25-33% by volume of the injected slurry is an acceptable waste stream.
- Low viscosity OVF at or below 40% by volume is an acceptable waste stream.
- Sand-slurry OVF concentrations of 25-30% are acceptable.
- Waxy Sand-slurry OVF is very difficult to inject and must be limited to no more than 15% by volume of the injected slurry.
- Produced solids can be injected at 20% by volume as slurry, or at up to 5% by volume as part of mixed OVF-sand injection slurry.
- The waste material composition and rheology has been highly variable, requiring ‘on-the-fly’ adjustments to continually optimize the injection strategies and slurry design to maintain formation injectivity.

Injection Strategy:

Full scale field operations at the Duri SFI project commenced in December 2002. A daily operation/injection strategy was implemented in the beginning of the project. Daily injection strategy consisted of alternating injection between two wells each day; using a SFI cycle of 9-10 hour daily injection shift per well, followed by 14 hours of shut-in to allow short term fluid bleed-off and pressure dissipation. Such shut-in time was acceptable for the formation to dissipate the high insitu pressures from the injection operations. This
injection strategy continued from December 2002 – August 2003. However, during June – August 2003 an increase in the formation flow back events was noted at well 61A which lead to wellbore plugging events (6 events occurred in this period; Figure 7). Wellbore plugging events are a normal occurrence during SFI operation, but for typical SFI operations such events should occur 3-5 times per year. The reasons for wellbore plugging events were determined to be the short sump of the well and the formation flow back events noted during shut-in time when the daily injection strategy was applied (Figure 8a). Therefore, a workover program was implemented into the 61A well in order to increase the sump and a new ‘continuous’ injection strategy was implemented into both wells in September 2003.

Using a SFI cycle of 3 days continuous injection per well, with 20 hours injection per day; followed by 3.5 days of shut-in. The same continuous injection strategy occurs at the other SFI well during this shut-in period. After the implementation of the ‘continuous’ injection strategy, the frequency of the plugging events was decreased drastically (Figure 7).

Currently, slurry is injected at relatively high rates and pressures. The pressure must be maintained at above the fracture extension pressure (FEP); injection pressures are up to 10-12% higher than original FEP, with bottomhole pressures (BHP) generally between 5,200–6,300 kPa (754-913 psi) for 61A well and between 6,500-7,000 kPa (943-1,015 psi) for 64A well. Preflush and postflush water injection is used to prepare the formation before and after slurry injection, as seen in the pressure plot in Figure 8b and Figure 8c, which illustrate the pressure profiles for the continuous injection strategy.

At this point in the Duri SFI project, a sustainable injection strategy includes the following parameters:

- A different type of SFI wellbore completion dependent on the properties of the injected slurry (mostly OVF injection stream, versus the originally anticipated predominantly sand-plant solid and sand-slurry OVF waste streams).
- A 2.5 m³/min (16 bbl/min) slurry injection rate during SFI operations.
- Typical average bottom hole injection pressures (BHP) of 5,500 kPa (800 psi) and 6,600 kPa (957 psi) for SFI Wells 8Q-61A and 8Q-64A, respectively. Average wellhead injection pressure (WHP) respectively is approximately 4,500 kPa (650 psi) and 5,500 kPa (798 psi).
- While the waste pod development is in the early stages of development, a suitable injection strategy is a day-by-day operation.
- While the waste pod development is in the latter stages of development, a suitable injection strategy is continuous injection operations.
- Switching to such a continuous injection strategy allows the waste pod ‘growth’ to be ‘extended’ in duration, thereby increasing the overall formation storage capacity. Continuous injection also helps to mitigate formation back-flow into the well.
- Formation back-flow into the well (and resultant wellbore plugging), can be managed through optimized OVF injection strategies and shut down procedures.

**SFI Project Performance**

Currently, most of the waste being processed and injected at the SFI facility is from CGS (Central Gathering Station) sites where produced oil is processed. Waste water from the DSF is being supplied to the SFI facility as mix-water. Prior to May 2003 E&P waste streams from existing surface storage pits were also brought to the SFI facility for disposal. These pit based wastes were also classified as OVF, but typically with a high viscosity and solids content.

A process control system has also been implemented for the SFI operations at Duri. Numerous monitoring systems and practices have been installed and implemented. Operating parameters are constantly compared and adapted based on monitoring and analyses. Monitoring systems and monitored parameters include:

- Bottom-Hole Pressure monitoring and analysis at the injection well.
- Tiltmeters for fracture event and waste pod mapping.
- Wellbore Temperature and Oxygen Activation (OA) logs to map fluid movement in the near wellbore.
- Injection operating parameters (slurry and waste injection rates and volumes, slurry density, pressure responses, etc).

The process control program shows that most the injected material and fluids remain contained within the target interval (Menggala formation) with some limited fluid movement up into the containment zone (Figures 9). The monitoring data and analyses (tiltmeters, OA log data and pressure fall-off analysis) indicate that all injected fluid remains contained within the Dalam and Menggala interval. To date, no fluid movement has been seen at or above the Pertama confining zone.

From December 2002 through the end of March 2005, the disposal volumes are approximately 239,000 m³ (1.5 million bbls) of waste materials and 1,033,000 m³ (6.5 million bbls) of total slurry. The monthly injected waste and slurry volumes are presented in Figure 10, with the cumulative injected volumes shown in Figure 11.

**Environmental Performance.**

This SFI facility handles the production wastes generated at the Duri oilfield and has allowed major strides to be made in reducing environmental impact of the Duri oil production operations by significantly reducing the use of surface disposal options to deal with E&P waste streams (Figure 12). The SFI operations at Duri have also facilitated the site remediation of existing surface waste storage impoundment areas. Figure 13 shows the remediation work underway at these areas; establishing the return of vegetation and forest at old OVF storage pits.
Objectives

There are three primary environmental objectives of the monitoring program that has been implemented at the Duri SFI project, as follows:

- To protect the environment and biosphere (i.e. protect ground water, soil/land, and air quality).
- To reduce surface discharge of waste streams generated by the Duri oil production operations.
- To ensure effective process control during the Duri SFI operations (i.e. ensure containment of the injected material, and maximize formation storage capacity).

To date, these objectives have been met. From an environmental protection standpoint, the Duri SFI project has injected approximately 239,000 m$^3$ (1.5 million bbl) of oilfield production wastes and 794,000 m$^3$ (5.0 million bbl) of produced waste-water back into a deep geologic formation sequence (December 2002 to March 2005). This has resulted in a total of 1,033,000 m$^3$ (6.5 million bbl) of oil production slurry waste streams not being disposed of at the surface. The redirection of this waste volume away from previous waste management options (surface pit impoundment area) has effectively resulted in ‘zero discharge’ of these wastes to the environment/biosphere. This fact indicates that the Duri SFI project is an environmentally sound waste management process for the disposal of oilfield production waste streams.

SFI is an environmentally and technically viable process that is being used as part of an effective waste management program at the Duri oilfield. The environmental advantages of the SFI process at the DSF can be summarized as follows:

- Large volumes of oilfield wastes are being returned to ‘place of origin’; eliminating or reducing the need for surface disposal of these waste streams;
- Deep well disposal technology places material far below any usable drinking water source, eliminating the potential for groundwater contamination due to downward percolation from the surface;
- SFI provides a permanent disposal option for the oil production wastes and no long term interaction with the biosphere; i.e. zero discharge’ of these wastes into the environment/biosphere;
- SFI reduces the impact on surface land use; i.e. no need for disposal landfills or storage pits; there is no impairment of future land use;
- Surface odor and emissions problems are reduced; Greenhouse Gas (GHG) and CO$_2$ emissions are reduced.
- SFI provides a flexible, year-round, all weather option for waste management;
- Multiple waste streams can be disposed of with the SFI process; this flexibility allows for concurrent disposal of variable composition waste streams such as waste water, OVF, tank bottoms, produced solids, spent drilling fluids & cuttings, killing fluids, and contaminated soil.

Conclusions

- Overall the geological conditions, waste materials, and waste volumes at Duri make SFI a viable E&P waste management option for the DSF.
- All injected material has stayed contained in the Target Zone and Containment Zone intervals at each disposal well.
- Optimized disposal-well completions, slurry design, and injection strategies are necessary to mitigate formation sand influx/back-flow into the wellbore.
- The process control monitoring program has been successful for evaluating formation response and waste pod development during SFI operations. This program is an essential tool for controlling and optimizing the SFI operations.
- The SFI project has now made the Duri oilfield essentially a ‘zero discharge' oilfield in terms of its OVF waste streams from production operations and a large portion of its waste water. All of these waste injected back into the deep geologic formation sequence, from where these materials originated.
- Duri SFI pilot project is successfully disposing of very large volumes of E&P waste; within a 27 month period, 794,000 m$^3$ (5.0 million bbls) of wastewater and 239,000 m$^3$ (1.5 million bbls) of oil viscous fluid (oily emulsions) waste are disposed in an environmentally sound manner.
- No gels or synthetic additives are required for slurry makeup.

The Duri Slurry Fracture Injection™ project has successfully met the environmental objectives of E&P waste management for Duri oil production operations.

Acknowledgment

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Conversion

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<th>1 m$^3$</th>
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<td>1 kPa</td>
<td>0.145 kPa</td>
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References

3. Gang Han, Mario Ioannidis, Maurice B. Dusseault, University of Waterloo: Semi-Analytical Solutions for the Effect of Well Shut Down on Rock Stability. Presented at the Petroleum Society’s
Canadian International Petroleum Conference 2002, Calgary, Alberta, Canada, June 11 – 13, 2002


Figure 1a: Duri Oilfield location

Figure 1b: Duri oilfield area map
Assessment of formation response = SFI process control

Monitoring formation response

- Slurry injection
- BHP monitoring
- Tiltmeters
- Observation wells
- SFI disposal well
- Pressure sensors
- Shale cap (fluid flow/stress barrier)
- Sand formation
- SFI disposal zone
- Fluid leakoff
- Waste pod

Figure 2: SFI deep-well disposal process

Duri SFI Facility

- Oily Viscous Fluid (OVF) tanks
- OVF pump (OVF tanks to SDU)
- Truck offloading ramp
- Mix water tank (pipelined to facility)
- Access road
- SFI Well #1
- SFI Well #2
- Control room & parts warehouse
- SDU system
- Injection flow line (to wells)

Figure 3: SFI Facility (Duri, Indonesia)
SFI Wellbore & Geology

Figure 4: Geological Zones for SFI Operation at Duri: SFI Well 8Q-64A
Figure 5: Duri SFI Wellbore Diagram: 8Q-61A

Figure 6: Duri SFI Wellbore Diagram: 8Q-64A
Figure 7: Occurrence of plugging events at 61A well

Figure 8a: Typical daily SFI Treatment Pressure Profile
Figure 8b: Typical continuous SFI Treatment Pressure Profile (61A well)

Figure 8c: Typical continuous SFI Treatment Pressure Profile (64A well)
Figure 9: Estimated Depth of Center Fracture using tiltmeter monitoring program

Figure 10: Monthly Injected Volumes of Waste Material & Slurry (both wells)
Figure 11: Total Cumulative Injected Volumes of Waste Material & Slurry (both wells)

Figure 12: OVF pit material at SFI site.
Oily Viscous Fluid (OVF) pits emptied using SFI process

OVF pit facility remediation & land restoration

![Closed pit site](image)

Figure 13: Remediation of surface pits.

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<th>Waste storage cell</th>
<th>Waste type</th>
<th>Description</th>
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| OVF Tank           | OVF        | * Bulk density: 850 - 950 kg/m³  
|                    |            | * Viscosity: < 1500 cp  
|                    |            | * Solid Content: < 10%  |
| Pit Material       | OVF        | * Bulk density: 850 - 950 kg/m³  
|                    | Low viscosity | * Viscosity: < 500 cp  
|                    |            | * Solid Content: < 10%  |
|                    | Intermediate viscosity | * Bulk density: 850 - 1000 kg/m³  
|                    |            | * Viscosity: 500 - 1500 cp  
|                    |            | * Solid Content: < 10%  |
|                    | High Viscosity | * Bulk density: 1000 - 1150 kg/m³  
|                    |            | * Viscosity: 1500 - 3000 cp  
|                    |            | * Solid Content: < 10%  |
|                    | Sand Slurry | * Bulk density: 1150 - 1300 kg/m³  
|                    |            | * Viscosity: 500 - 1500 cp  
|                    |            | * Solid Content: 10 - 40%  |
|                    | Waxy Sand | * Bulk density: 1300 - 1600 kg/m³  
|                    |            | * Viscosity: > 3000 cp  
|                    |            | * Solid Content: 10 - 40%  |
|                    | Sand Plant Sand | * Bulk density over 1600 kg/m³ |

Table 1: Duri SFI Waste Stream Classifications