DEVELOPMENT OF IMPROVED OIL FIELD WASTE INJECTION DISPOSAL TECHNIQUES

Annual Report
September 30, 2001

Date Published: December 2001

Work Performed Under Contract No. DE-AC26-99BC15222

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Arcadia, California

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National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma
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ABSTRACT

Slurry Fracture Injection (SFI) is a waste disposal technology in which petroleum exploration and production wastes, such as produced sand, drilling muds, tank bottoms, and pit sludge are mixed with water into a slurry and injected into deep unconsolidated sandstone formations above fracturing pressure. The mechanics governing the fracturing of unconsolidated sandstone formations remain poorly understood, and as a result there are few guidelines available to optimize the SFI process. The goals of this DOE sponsored project are to: 1) assemble and analyze a comprehensive database of past waste injection operations; 2) develop improved diagnostic techniques for monitoring fracture growth and formation changes; 3) develop operating guidelines to optimize daily operations and ultimate storage capacity of the target formation; and 4) to test these improved models and guidelines in the field. This Technical Progress Report summarizes Terralog’s efforts and results for testing models and guidelines in the field. The first requirement for this effort has been to identify appropriate sites, design injection operations, and submit required permit applications to regulatory authorities.

A successful SFI project requires cooperation between regulatory agencies, the project operator and engineer, drilling and completions companies, and the site operators. Good communications need to be established between each of these groups. During this period Terralog Technologies has conducted discussions with operators and regulators, and has completed feasibility studies and prepared injection permit applications for three potential injection sites in California. These three sites are:

1. The Guadalupe Dunes former oilfield owned by Unocal Corporation;
2. The South Elwood field operated by Venoco Inc; and,
3. The Aliso Canyon field operated by Southern California Gas Company.

The feasibility studies for each site included geologic reviews to evaluate the availability of appropriate injection formations, detailed well reviews to confirm cement coverage and recommend the appropriate use of existing wells or new wells, and economic reviews to estimate capital and operating costs for waste injection at each site. Appropriate formations were identified at all three sites, and recommendations were provided on appropriate completion designs, operating plans, and monitoring strategies. These were incorporated into permit applications for submission to the California Department of Oil and Gas.
INTRODUCTION

Slurry Fracture Injection is a waste disposal in which produced wastes, such as produced sand, slop, and tank bottoms, are mixed with water into a slurry which is then injected into deep unconsolidated sandstone formations above fracturing pressure. The solids are permanently emplaced within hydraulic fractures generated during the pumping process, and the carrying fluid subsequently drains into the high permeability formation.

The mechanics governing the fracturing of unconsolidated sandstone formations remain poorly understood, and as a result there are few guidelines available to optimize the SFI process. The tasks for this research project have been to:

1. Organize a database of waste injection operations and formation response.
2. Evaluate correlations between waste types, injection pressure, pumping rate, etc.
3. Develop improved pressure analysis and fracture diagnostic techniques for solid waste injection in high permeability granular formations.
4. Develop operating guidelines to improve containment and optimize storage capacity.
5. Verify improved diagnostic tools and operating guidelines in the field.
6. Project documentation and presentations.

The results from Tasks 1, 2, 3, and 4 have been described in detail in previous Topical Reports by Terralog (2000a,b,c; 2001). This report summarizes efforts related to task 5: verifying diagnostic tools and operating guidelines in the field. The first requirement for this effort has been to identify appropriate sites, design injection operations, and submit required permit applications to regulatory authorities.
EXECUTIVE SUMMARY

This Technical Progress Report for the period ending September 30, 2001, summarizes work completed toward verifying improved diagnostic tools and operating guidelines in the field. The SFI well for large-volume waste injection should be located in a formation and area that has sufficient capacity to contain the hydraulic fracture process in a suitable permeable zone. The formation properties should include high permeability (500md or more), high porosity (25% or more), moderate to large thickness (20m or more), and lateral continuity. Special care should be taken to evaluate the mechanical condition and cement coverage for any offset wells within about a kilometer of the proposed injection well. Ideally, the target formation should be overlain by multiple low permeability shale intervals (to provide flow barriers) and high permeability sand formations (to provide a flow sink, or buffer zone, in case of breach).

With this background in mind, Terralog has completed geologic and well reviews for three potential waste injection sites in California, and has prepared injection permit applications for review by the California Department of Oil and Gas and Geothermal Resources. The potential injection sites are:

1. The Guadalupe Dunes former oilfield owned by Unocal Corporation;
2. The South Elwood field operated by Venoco Inc; and,
3. The Aliso Canyon field operated by Southern California Gas Company.

The feasibility studies for each sited included geologic reviews to evaluate the availability of appropriate injection formations, detailed well reviews to confirm cement coverage and recommend the appropriate use of existing wells or new wells, and economic reviews to estimate capital and operating costs for waste injection at each site.

Appropriate formations were identified at all three sites, and recommendations were provided on appropriate completion designs, operating plans, and monitoring strategies. These were incorporated into permit applications for submission to the California Department of Oil and Gas.
EXPERIMENTAL OBSERVATIONS

Our review and analysis of waste injection projects in Canada and the United States has led to a number of critical observations that distinguish large-volume fracture injection from typical short-term fracture stimulation. Some of these observations include:

1. Slurry injection into soft, high permeability formations creates a relatively thick fracture and dilation zone, providing greater storage capacity than traditional thin fractures generated in hard rock;
2. In contrast to normal stimulation operations in low permeability rock, during waste injection in high porosity formations fracture conductivity in the created process zone is often less than or equal to the native formation conductivity;
3. Stresses tend to increase within this fracture and dilation zone, as indicated by increasing shut-in pressure;
4. Reduced fracture conductivity, combined with increased stress within the waste pod, often results in new fractures being created with repeated injection episodes at orientations varying over a range of 30 to 60 degrees;
5. Formation response, fracture behavior, and injectivity can be controlled and optimized by varying injection material content (solids concentration, constituent ratio, density, etc…) and injection rates.

Recognizing some of these unique aspects to large-volume waste injection, and keeping in mind the critical project management requirements for environmental containment, operating cost reduction, and long-term injectivity and well life, allows us to develop optimum design and operating strategies. These insights have been applied to develop appropriate injection project designs and permit applications for the three fields in California. Details on each of these project sites are provided in the following sections.
RESULTS AND DISCUSSION

Guadalupe Field Slurry Fracture Injection

The Guadalupe oil field is located on the California Coast about 12 miles west of the City of Santa Maria. The field was first drilled in 1947. The field produces primarily from the Pliocene age unconsolidated Sisquoc Oil Silt and Oil Sand intervals which occur at a depth of about 3000 ft. Over 30 million bbls of oil were produced from the Guadalupe field over its 50 year history. Most of the 215 wells (DOGGR, 1994) in the field were drilled between 1948 and 1974. The field has been shut in since 1995. All but four wells were abandoned between 1993 and 1995.

Production of the highly viscous crude oil from the field required the use of a number of secondary recovery techniques throughout the production history. Water flooding, steam flooding, and the introduction of diluent into production and well lines was typically used. Diluent, a diesel-like additive, was injected into production lines well annular spaces in volumes of two to three barrels for each barrel of oil produced. Large volumes of this diluent leaked from pipelines and storage facilities over a period of 40 years. The use of diluent to thin heavy produced oil ceased in 1990 and various remediation options, including slurry fracture, are have been proposed to regulatory agencies overseeing cleanup of the site.

Our geologic review evaluated the potential suitability of sand silt intervals within the Foxen, Sisquoc, Monterey, and Knoxville formations. We estimate solids injection capacity for these formations, taking into account net thickness, porosity, and permeability. Our well review included an analysis of historical completion practices throughout the field, with particular attention to cement coverage over potential injection intervals.

The generalized stratigraphy of the Guadalupe area consists of the Pleistocene Paso Robles formation, the Pliocene age Careaga, Foxen, and Sisquoc formations, the Miocene Monterey and Point Sal formations, and the Upper Jurassic Knoxville formation. Figure 1 presents the type section for the Guadalupe Field, as well as a field structure map and cross section.
Figure 1. Type stratigraphy, cross section, and structure map for Guadalupe Field
We have evaluated four formations with respect to the appropriate geologic criteria for successful SFI. These are the Foxen, the Sisquoc, the Monterey, and the Knoxville formations. Volumetric calculations for the Guadalupe field yield approximately 2,938 acres (almost $1.3 \times 10^8$ ft$^2$) in the LeRoy lease. Table 1 contains details of the volumetrics of the main producing zones of the Guadalupe field, the Oil Silt and Oil Sand units.

**Table 1. Sisquoc Formation Volumetrics at the Guadalupe Field**

<table>
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<th>Unit</th>
<th>Volume (acre-feet)</th>
<th>Volume (yd$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Oil Silt</td>
<td>112,161</td>
<td>$1.8 \times 10^8$</td>
</tr>
<tr>
<td>Gross Oil Sand</td>
<td>117,844</td>
<td>$1.9 \times 10^8$</td>
</tr>
<tr>
<td>Net Oil Silt</td>
<td>13,880</td>
<td>$2.2 \times 10^7$</td>
</tr>
<tr>
<td>Net Oil Sand</td>
<td>52,270</td>
<td>$8.4 \times 10^7$</td>
</tr>
</tbody>
</table>

The average original reservoir temperature at a datum of 2,700 ft below surface (generally within the Upper Sisquoc) is 131°F. The estimated original average reservoir pressure of the field in 1947 was 1,205 psi at the same datum. Average reservoir pressure in 1958 was 1,048 psi. Field pressures declined with time due to continued oil production, to a measured average of approximately 740 psi in 1976 (latest data available). The base of fresh water in the vicinity of the Guadalupe field averages 1,320 feet of depth.

There are a number of important criteria used in determining the suitability of a formation for Slurry Fracture Injection (SFI). These include:

- High permeability within the target formation with at least 50 ft of thickness,
- Porosity greater than 20%,
- Poorly consolidated formation sands which can be displaced easily by fracturing,
- The presence of a thick overlying confining unit that is impermeable and resists fracturing, and
- No nearby fault zones that may permit fluid communication to surface.
Both the Oil Silt and Oil Sand of the Sisquoc fit the above criteria, although each unit alone is on the lower end of what we would consider to be sufficient thickness to support injection of large volumes of waste. Collectively, the thickness of the productive Sisquoc zones in sufficient for sufficient volumes of waste injection. We estimate that an SFI well injecting into the Oil Silt through Oil Sand interval will accept about 200,000 yd$^3$ per well, assuming wells are spaced at least 2000 feet apart.

A significant advantage of these intervals is that they are underpressured due to over 40 years of oil production. Low formation pressure provides a reduced fracturing pressure and a natural pressure sink and containment zone for Slurry Fracture Injection operations. Overlying the Oil Silt and Oil Sand units is 250 feet of Sisquoc silts. Injection pressures and rates will be limited due to the limited vertical extent of these units. If large waste volumes (400,000 yd$^3$ or greater) were to be dedicated to an SFI project, a system of multiple wells could be considered to accommodate injection volumes into these thinner units.

The Foxen and the Knoxville formations are not viable candidates for injection due to inappropriate lithology or lack of sufficient localized lithologic data.

Overall, the stratigraphy and previous oil production operations in the Guadalupe Field indicate favorable conditions for use of SFI as a waste disposal technique. We recommend permitting the entire Sisquoc interval for injection. If substantial additional waste volumes are anticipated, further review of well data will indicate where a new well could be drilled to accommodate the added waste into the Sisquoc.

We also evaluated and compared the relative advantages and disadvantages of using one or more of the four existing water disposal wells in the field and the alternative of drilling one or more new wells for solids injection. Finally, we evaluated the costs to modify an existing well or drill a new well in the area, the capital costs for an appropriately sized slurry fracture injection system, and operating costs for a range of waste material volumes. Our review and analysis to date supports the following conclusions and recommendations:
1. The Oil Silt and Oil Sand units of the Sisquoc formation are sufficiently porous and thick to accommodate about 200,000 yd$^3$ of waste solids per well, assuming the wells are spaced at least 2000 feet apart. Slurry injection rates into these formations are anticipated to be about 250 cu-yds/day of soil and about 5000 bbls/day of water per well.

2. The Foxen, Monterey, and Knoxville formations do not seem to be viable injection candidates at this time due to low permeability and uncertainties with regard to their formation properties. There may be highly fractured sections of the Monterey and Knoxville which can provide useful injection targets, but current data is not sufficient for confirmation.

3. From a technical standpoint, the best option would be to drill a new well for waste injection. This well could be used to test the lower Foxen and upper Knoxville, and then completed for injection in the Oil Silt and Sand formations. The costs for drilling, testing, and completing such a well would be on the order of $350,000. In addition to solids injection capability, a new well operating at fracture conditions would provide about 5000 bbls/day additional fluid disposal capacity for the field.

4. Any of the four existing water injection wells at Guadalupe would also be suitable for SFI. From an injectivity and material logistics standpoint, the best candidate would be either well C4-A or YC-4. Re-completion costs for solids injection would be in the order of $100,000. In addition to solids injection, operating one of these existing wells at fracture conditions would also provide about 4000 bbls/day additional fluid disposal capacity for the field.

A slurry fracture injection project application was submitted to the EPA under the project XL program, and a subsequent application was submitted to the California Department of Oil and Gas under the Class II injection program.
South Ellwood Field Slurry Fracture Injection

The South Ellwood field is located offshore of the California coast, west of the City of Santa Barbara. The field was drilled and produced using the Platform Holly, which is located in 221 ft of water. The field was discovered in 1961 and first put into production in 1967. Initial production started with the Rincon Formation, and has produced over 8.3 million barrels of oil. The majority of production in the field has come from the overlying Monterey Formation. The Monterey Formation has produced over 49 MMBO sweet oil and 36 BCF sour natural gas (Venoco Internal Report). Oil and gas production is continuing, with 21 wells currently active in Leases 3120 and 3242. Venoco plans to drill two additional production wells from the Platform Holly in 2001. Disposal of drilling mud and drill cuttings by Slurry Fracture Injection (SFI) is proposed to minimize environmental impact.

The generalized stratigraphy of the South Ellwood Field area consists of the Pliocene to Recent Santa Barbara, Pico, and Repetto Formations; the upper Miocene Sisquoc Formation, the middle Miocene Monterey Formation, the lower Miocene Rincon Formation, the Vaqueros and Sespe Formations of Oligocene age, the Coldwater, the Cozy Dell, Matilija Formations and the Anita Shale of Eocene age on top of Cretaceous Jalama Formation and basement. Figures 2 and 3 present generalized stratigraphic columns and type logs for Blocks 3120 and 3242 respectively.

We have evaluated five formations with respect to the appropriate geologic criteria for successful SFI. These are the Monterey, Rincon, Vasqueros, Sespe and Coldwater Formations. The Monterey and the Rincon Formations as the primary target horizons for injection. There are no wells completed into the Vasqueros, Sespe and Coldwater Formations, and they are relatively deep, therefore these lower formations are more costly alternatives for SFI operations.
Figure 2. Geologic Map – Top Monterey Formation, Cross Section and Composite Electric Log for South Ellwood Field
The Rincon and Monterey Formations are identified as primary potential disposal targets. The best target is the Rincon Formation. The Rincon is underpressured (623 psi). Low formation pressure provides reduced fracturing pressures, and a natural pressure sink and containment zone for Slurry Fracture Injection operations. The Rincon Formation is a well sorted turbidite sandstone with siltstone and shale interbeds. The interbedded nature of the turbidites provides good impermeable cap rock for the SFI project. Average porosity of the sand unit is 29% while permeability is about 150 millidarcy.

Field evidence from previous projects indicates that solids injection can create a fracture and dilation process zone extending up to 1000 ft from the well with an aspect ration of about 2.
to 1 in the direction of maximum stress. Multiple injections create multiple fractures at varying orientation and an extensive dilation zone. About 2% to 5% of the available porosity compacts and accepts solids. Assuming an average 150 ft sand thickness, a single well completed within the Rincon Formation can handle in excess of several hundred thousand barrels of injected waste (much more than needed for this project).

A second potential target is the Monterey Formation, a fractured siliceous formation about 1000 ft thick. Average porosity is about 20%, but it is not interconnected, so that matrix permeability is very low (on the order of a few millidarcies or less). Taking into account fractures common in the Monterey, bulk permeability increases to about 50md. This is on the low end conditions necessary for quick leakoff and limited fracture growth during SFI operations. Since the anticipated volumes for waste injection are relatively small (mud and cuttings from two wells), a fractured interval of the Monterey might be viable for waste injection, but with some risk.

There are no wells completed into the deeper Vasqueros, Sespe and the Coldwater Formations. Hence for economic reason, these three formations are not viable candidates for slurry injection.

In summary, the stratigraphy and previous oil production operations in the South Ellywood Field indicate favorable conditions for use of SFI as a waste disposal technique. We recommend permitting the Rincon interval for injection.

Terralog also analyzed historical completion practices throughout the field, with particular attention to cement coverage over potential injection intervals. Thirty wells are present at the Platform Holly. Many of these wells were re-drilled one or more times to access new production horizons. Twenty-one wells are currently producing oil or gas. Two wells are currently being used as gas injection wells. The remaining seven wells are shut-in.

Of the seven non-producing wells, Well 3120-04 is the best suited for SFI operations. The advantages of using this well are:

1. It has existing perforations in the Rincon formation.
2. The Rincon formation is composed of thick sands of high permeability (~150 md) and high porosity (29%) which are best suited for SFI.

3. No other active wells are present in this zone aside from gas injection well 3120-05.

4. Perforations are present in the Sisquoc, Monterey and Rincon formations, but a tubing and packer can be set so that cuttings are injected into the Rincon only.

The disadvantage of using this well is that it will need to be recompleted prior to SFI to remove the current tubing and electric submersible pump (ESP).

No cement bond log could be found for this well, but casing cement was placed in the Sisquoc, Monterey & Rincon zones (Table 3). Two cement squeezes were also performed to improve cement bond in the Sisquoc (3190 ft) and Rincon shales (5400 ft). The existing cement should be in sufficient condition for a small volume SFI project.

Our geologic and well review and analysis to date supports the following conclusions and recommendations:

1. The Rincon sand is the most suitable target for slurry fracture injection of the drilling wastes. It is a 150 ft thick sand of high porosity (29%) and fair permeability (155 md). It is overlaid by Rincon and Monterey shales of about 700 ft thickness, which will provide good containment of the injected wastes. It is also underpressured due to oil and gas production, which will aid fracturing and containment processes.

2. Because the anticipated waste volume is relatively small, the Monterey formation may also be used for small volumes of cuttings disposal if necessary, but with some risks. The Monterey consists of thinly interbedded layers of fractured chert, porcelanites, siliceous shale, dolomites, and mudstones. Matrix permeability is only on the order 0.1 to 1 md, and even taking into account fractures bulk permeability of this zone is only in the range of 2 to 50 md. Low permeability inhibits fluid leakoff after fracture injection, and results in long-thin fractures rather than thick fracture and dialation zones within permeable sands. The containment ability of the upper Monterey is not well known, and hydraulic fractures may enter the Sisquoc formation.

3. The best well for cuttings injection is Well 3120-04, assuming it is recompleted to inject materials into the Rincon formation. This will require a tubing and packer
assembly set to 5720 ft depth to isolate the Rincon perforations from the Monterey perforation. Current perforations within the Monterey formation can either be isolated with an uphole packer, squeezed, or left open and used for monitoring (subject to approval by the Division of Oil and Gas).

A second option is to inject cuttings into Well 3242-17. This well has existing perforations in the M1 Monterey zone. Unfortunately, there is a fault immediately adjacent to the perforations, which may permit upward movement of injected materials. If this option is pursued, the Monterey and Sisquoc formations should be permitted for cuttings disposal.

A Class II injection permit was prepared for both wells 3120-4 and 3242-17 on behalf of Venoco Inc in August, 2001.

**Aliso Canyon Field Slurry Fracture Injection**

The Aliso Canyon Field is a multi-zone reservoir with commercial oil and gas production from five producing intervals (Aliso, Porter, Del Aliso, Sesnon and Frew) varying from 4,000 to 8,000 ft. in average depth. This field is a southeasterly plunging anticline with structural closure on the south and east, fault closure on the north and west. The Santa Susana fault on the north has a vertical displacement of about 5,000 feet and a horizontal displacement of about 2-3 miles. The Santa Susana fault thrusts Miocene sediments over Pliocene strata and dips from 15 to 80°. A structure map and cross section for the field is presented in Figure 4.

The uppermost producing zone, the Aliso formation is Upper Pliocene age and comprises of poorly sorted, medium to coarse-grained sands with occasional pebbles. This clastic package is approximately 650 to 700 feet thick with average net sand thickness of about 100 feet (DOGGR, 1991). The formation is divided into numerous sand intervals, A1-A42, some with their own oil/water contacts. Porter #27 was the first well completed in the Aliso formation with initial production at 510 barrel per day of 16.5°API oil. Present average production per well has dropped to 30 barrels of oil per day.
Figure 4. Geologic structure map and cross section of the Aliso Canyon Field
Our geologic review evaluated the potential suitability of the Aliso and Porter formations. We estimate solids injection capacity for these formations, taking into account net thickness, porosity, and permeability. Our well review also included an analysis of historical completion practices throughout the field, with particular attention to cement coverage over potential injection intervals.

We evaluated and compared the relative advantages and disadvantages of using one or more of the existing water disposal wells or idle production wells in the field and the alternative of drilling one or more new wells for solids injection. Finally, we evaluated the costs to modify an existing well or drill a new well in the area, the capital costs for an appropriately sized slurry fracture injection system, and operating costs for a range of waste material volumes. Our review and analysis to date supports the following conclusions and recommendations:

1. Both the Aliso and Porter formations are sufficiently porous and thick to accommodate in excess of 250,000 yd³ of waste solids per well, assuming the wells are spaced at least 2000 feet apart. Slurry injection rates into these formations can anticipated to be as high as 300 cu-yds/day of solids and about 5000 bbls/day of water per well.

2. The Porter formation is highly depleted, providing a good pressure sink and containment mechanism. The formation thickness ranges from 600 to 800 feet, and is capped by an impermeable shale interval of at least 300 feet in thickness. The average permeability is on the order of 500md and the porosity ranges from about 23% to 30%. Typical depths, however, are on the order of 6000 to 7000 ft. This would increase pressure and horsepower requirements for slurry fracture injection in comparison to shallower targets.

3. The Aliso formation is also depleted, providing another pressure sink and good containment zone. The gross interval thickness is about 600 feet and provides a good combination of interbedded shales (to act as vertical migration barriers) and high porosity sands (to act as pressure sinks inhibiting vertical migration). The formation depth lies from about 4000ft to 5000ft across the structure, sufficiently deep to be well
isolated from near-surface fresh water yet not too deep to require excessive pumping pressure.

4. We recommend that existing well #43 be used for waste injection at this site. This currently abandoned well is situated downdip of the present oil/water contact and can be re-entered and completed for injection into the Pliocene Aliso formation at approximately 4800 ft depth.

A permit application for injection at Aliso Canyon has been prepared for the Department of Oil and Gas. We examined and provided casing diagrams for all wells within a ¼ mile radius of the proposed injection well. We identified wells to be used for monitoring, and described an appropriate operating plan. About 20,000 barrels of mud and cuttings has been proposed for injection into the Aliso formation over a period of about one month. Proposed monitoring tools include continuous down-hole pressure recording, daily pressure fall-off analysis, periodic temperature and tracer surveys at both the injection well and offset monitoring wells, and periodic step-rate tests.
CONCLUSIONS

The SFI well for large-volume waste injection should be located in a formation and area that has sufficient capacity to contain the hydraulic fracture process in a suitable permeable zone. The formation properties should include high permeability (500 mD or more), high porosity (25% or more), moderate to large thickness (20m or more), and lateral continuity. Special care should be taken to evaluate the mechanical condition and cement coverage for any offset wells within about a kilometer of the proposed injection well. Ideally, the target formation should be overlain by multiple low permeability shale intervals (to provide flow barriers) and high permeability sand formations (to provide a flow sink, or buffer zone, in case of breach).

A typical SFI injection well should include surface casing and production casing cemented to surface. Injection should take place through a tubing and packer system. Good well drilling and cementing practices are critical in providing a good cement bond along the well for the SFI injection well. If a good cement bond exists, particularly in the 60 to 100 m above the target injection zone, the volume of slurry which infiltrates upwards is very small and the volume of waste which can be placed into the target formation can be very large relative to poorly cemented wells.

With these criteria in mind, Terralog has completed technical feasibility reviews and injection permit applications for three projects in California. These are the Guadalupe Dunes oilfield owned by Unocal, the South Ellwood offshore field operated by Venoco, and the Aliso Canyon field operated by Southern California Gas Company. The feasibility studies for each sited included geologic reviews to evaluate the availability of appropriate injection formations, detailed well reviews to confirm cement coverage and recommend the appropriate use of existing wells or new wells, and economic reviews to estimate capital and operating costs for waste injection at each site.

Appropriate formations were identified at all three sites, and recommendations were provided on appropriate completion designs, operating plans, and monitoring strategies. These were incorporated into permit applications for submission to the California Department of Oil and Gas.
REFERENCES


