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Engineering the Use of Green Plants to Reduce Produced Water Disposal Volume

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Abstract

In 1990, the Laboratory began an investigation into biological approaches for the reduction of water produced from oil and gas wells. In the spring of 1995, the Company began an on-site experiment at an oil/gas lease in Oklahoma using one of these approaches. The process, known as phytoremediation, utilizes the ability of certain salt tolerant plants to draw the produced water through their roots, transpire the water from their leaves, and thereby reduce overall water disposal volumes and costs.

At the Company experimental site, produced water flows through a trough where green plants (primarily cordgrass) have been planted in pea gravel. The produced water is drawn into the plant through its roots, evapotranspires and deposits a salt residue on the plant leaves. The plant leaves are then harvested and used by a local rancher as cattle feed. The produced water is tested to assure it contains nothing harmful to cattle. In 1996, the Company set up another trough to compare evaporation rates using plants versus using an open container without plants. Data taken during all four seasons (water flow rate, temperature, pH, and conductivity) have shown that using plants to evapotranspire produced water is safe, more cost effective than traditional methods and is environmentally sound.

Introduction

The reduction of produced water at field locations has always been a goal at E&P sites. The prerequisites for reduction of produced water are that the method be safe, environmentally friendly, and economical. The use of phytoremediation (i.e., using plants to reduce the amount of produced water) satisfies all these prerequisites.

This paper discusses the mechanics of phytoremediation as well as problems encountered and resolved at the test site. It also discusses the significance of the acquired experimental data, operational costs, and the successes of the experiment.

Laboratory Phytoremediation Experiments

Costs of current treatment and disposal methods for produced water are increasing. The Laboratory is conducting research on new, cost-effective plant-based systems for volume reduction of produced water prior to disposal.

To develop biological treatment systems for saline produced waters, it is logical to look to the plants that have already developed a natural ability to grow and be highly productive at high external salinity levels, the halophytes. These plants occur naturally in the highly saline habitats along seacoasts, in salt and brackish marshes, in estuaries, and in dry, saline interior habitats. These plants have already undergone strong selection for their ability to tolerate salt. This large pool of plants provides numerous candidates for use in engineered, plant-based systems designed to treat saline wastewater.

For this paper, halophytes are defined as plants found growing under naturally saline conditions (Aronson, 1989). Basically, plants have two fundamentally different mechanisms for tolerating high external salt concentrations. Some halophytes accumulate salt to high levels in their tissues, whereas others typically exclude the salt (Sutcliffe, 1962).

The Company experiment was an outgrowth of the Biotreatment of Produced Waters Project at the Laboratory. The goal of the Laboratory experiment was to develop, investigate and evaluate the principal components of a cost-effective engineered ecosystem, called a contained plant-bioreactor system. Through natural plant processes, the system will reduce the volume of, and contaminant concentrations in, saline wastewater produced in the course of oil/natural gas extraction. The bioreactor system uses natural saltmarsh ecosystems as a model and incorporates salt-tolerant wetland plant species and innovative hydroponic plant growth techniques.

Candidate plant species (see Table 1) were tested at three initial salt concentrations (0%, 1.5%, and 3%) in nutrient solution. Each treatment was replicated three or four times. Each replicate consisted of several plants growing in a plastic bucket with the appropriate nutrient solution bathing the roots.

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The nutrient solution used for the salt-tolerance/evapotranspiration experiments was a slightly modified standard Hoagland's solution (Hoagland, 1950). Greenhouse supplemental lighting, used from November to April, used two banks of 1,000-watt fixtures with broad-spectrum lamps.

After one to several weeks of acclimatization and growth in the nursery trays, a set of transplants (obtained from commercial or research sources) was placed in the experimental buckets to determine salt tolerance and evapotranspiration rates. The plants in each bucket were supported by a styrofoam float. Each plant was placed in a hole in the float that was just large enough to support the plant at the transition between stems and roots. The float fit snugly inside the bucket and maintained root immersion in the nutrient solution regardless of depth. The styrofoam floats also inhibited direct evaporation of water from the surface of the nutrient solution in the buckets. Thus, most water loss from the buckets was assumed to be via transpiration. Another set of replicate buckets containing nutrient solution (but without floats or plants) was used to measure direct evaporation from the open liquid surface.

Total water loss from both the control buckets and the plant buckets was measured directly by using a simple mass-balance technique. The mass-balance technique integrated, over at least a 24-hour period, the highly fluctuating rates of evapotranspiration and evaporation, as well as the major factors that affect these rates (insolation, heat, temperature, humidity, and air movement), which also fluctuate on short time periods. The water depth in millimeters was measured in each experimental and control bucket by using a float gauge developed specifically for this purpose. This value was subtracted from the previous depth measurement for that bucket to obtain the net difference; the net difference was then converted to a volume measurement that represented the amount of water evapotranspired or evaporated during the time interval between measurements. This value was further manipulated mathematically to standardize all readings to 24-hour intervals.

The salt concentration in the nutrient solution of the experimental buckets (both with and without plants) was determined by measuring the electrical conductivity of the solution with a sensitive conductivity meter at 24- or 48-hour intervals. The meter was calibrated against a set of NaCl solutions in a nutrient of known concentration, as well as a certified conductivity standard.

In each bucket, evapotranspiration was allowed to continue until the solution level was either 1 cm or less in the small buckets or 5 cm or less in the large buckets. At this time, solution depth measurements were made and converted to volume amounts to determine water loss via evapotranspiration. Electrical conductivity measurements were also made and converted to salt concentration values. Then, a known volume of nutrient at the same salt concentration as the starting concentration for each bucket was added to the bucket to bring the volume close to the original volume. Volume and conductivity measurements were made again after the addition. The new salt concentration was then higher than the

original (all of the salt added to the bucket remained, only water was lost), but not as high as the concentration just before the addition. Thus, the experimental plants experienced a fluctuating, but generally increasing salt concentration over the course of the experiment. To an extent, this regime paralleled the normal salt fluctuations to which saltmarsh plants are exposed as a result of tidal changes, drying, and the dilution of sea water in saturated wetland soil by rainfall.

By using this procedure, it was possible to measure evapotranspiration over an essentially continuous range of salt concentrations, up to the salt tolerance limit of the species. As this limit was approached, the plants usually underwent changes characterized by a slowing or cessation of growth, severe wilting, drying up of the leaves, and eventual death.

The greenhouse experiments evaluated promising processes and plant species identified during a literature review and database development. Over 80 species were screened for salt tolerance and high evapotranspiration rates. Detailed experimental data on transpiration rates, salt tolerance, nutrient requirements, and maximum salt concentration at which effective transpiration occurs have been generated for 6 species. For all species tested, the mean evapotranspiration rates were consistently above the open water evaporation rates, at least up to a concentration of 2% salt in the nutrient solution. Fig. 1 plots, for each species tested, the mean total plant biomass per container (averaged over the entire experimental run) against the evapotranspiration rate at 2% salinity on a per-container basis. For several species, these high evapotranspiration rates were maintained in salinities up to 6%.

A bioreactor model was developed (Fig. 2) based on conservative greenhouse data, using about 40% of the maximum evapotranspiration rate for the bulrush and cordgrass. The model bioreactor was designed to treat 418.9 barrels (66.6 m³) of produced water using a total surface of 3228 ft² (300 m²), and has two compartments, one containing great bulrush (*Scirpus validus*) and the second saltwater cordgrass (*Spartina alterniflora*). Produced water flows first into the bulrush compartment where the volume is reduced by half through enhanced evapotranspiration. Then, water moves by gravity flow, into the cordgrass compartment where the volume is reduced by half again. The salinity level of each compartment is determined by the tolerance of the plants in that compartment. The water must be removed and replaced by lower salinity wastewater before it begins to have adverse, high-stress effects on the plants in that compartment. The model predicts a 75% reduction in less than 8 days, in the volume of saline produced water. The effluent water will be considerably reduced in both volume and contaminants, while its salt concentration will be increased.

From among the candidate plant species studied in the greenhouse tests, *Scirpus validus* was chosen to grow in the first compartment because of its higher evapotranspiration rates and lower salt tolerance. Highly salt-tolerant *Spartina alterniflora* was chosen to grow in the second compartment, which received wastewater at a higher salinity level.

The use of phytoremediation bioreactors has several

potential advantages over many other methods for the removal of complex saline solutions from water. One advantage is affinity and bioaccumulation, which is the ability of selected hyperaccumulator plant species to adsorb contaminant ions from an extremely broad range of concentrations in the wastewater. The other advantage is selectivity, the ability to adsorb the target contaminant while ignoring other ions present in the solution.

The "ideal" phytoremediation plant for wastewater volume reduction is a large, vigorous, salt tolerant grass or grasslike species that has a large aerial leaf/stem area and a dense fibrous root system with an active rhizosphere to function as a biological filter. The plant-based volume reduction system developed by this research represents a major potential cost saving for the oil/gas industry.

Field Experiment

After reviewing the Laboratory phytoremediation article in a national publication, the Company field-tested the process to determine whether it would be practical for reducing the volume of produced water at a specific well. The first site for the experiment was an oil/gas well in northwestern Oklahoma. Daily production from this well was 220 mcf/day of gas, 5 barrels of oil and 1 barrel of 3% chloride produced water. Using the Laboratory's recommendations, the Company purchased various salt tolerant plant species, primarily two varieties of cordgrass and bulrush. The experiment was set up in the early spring of 1995. Prior to use in the field, some of the plants had been conditioned at the nursery to withstand from 3% to 6% chlorides.

At the experiment site, separate plastic troughs were used to hold the bulrush and two different varieties of cordgrass, which were planted in pea gravel. The bulrush could tolerate up to 3% chlorides; the cordgrasses could tolerate up to 6% chlorides. Initially, fresh water and fertilizer were run through the troughs to sustain plant growth. Produced water was gradually added and water flow rate, temperature, pH, and conductivity were measured each day. Data were submitted to the Laboratory for review and as a basis for recommendations.

The container with the 3% chloride tolerant plants experienced almost a complete loss of plant species and they were not replaced. The container with the 6% chloride tolerant plants experienced a plant loss of approximately 25%.

Within seven days of allowing 100% produced water to flow through the troughs, the leaves on the surviving plants were covered with salt crystals. There was a 75% reduction in produced water in 4 days. To repeat the experiment, the plant leaves were washed with fresh water and fresh water was allowed to flow through the troughs to remove excess chlorides. Then, the process was renewed.

In September 1995, a plastic greenhouse was placed over the experimental area. The greenhouse was heated to 55°F. and a turbine vent was installed to improve air circulation. The flow of produced water continued until the plants went dormant in early November. During the dormancy period, produced water remained in the troughs to maintain growth and root temperature. Initially, due to higher than expected

heat and humidity in the greenhouse, a small species of red spider began to cover the plants, but did not inhibit their growth. During a severe storm, the greenhouse blew over and the red spiders disappeared. There were no other insect infestations.

In the spring of 1996, the greenhouse was removed and the flow of produced water into the facility was resumed. Results were similar to the previous year. The plant leaves eventually were covered with salt crystals and the remaining water transpired.

In the summer of 1996, another site was picked for further experimentation. This oil/gas well, located approximately 35 miles from the first site, has a daily production of 800 mcf/day of gas, 25 barrels of oil, and 20 barrels of produced water with a 6% chloride level. Parallel troughs were set up so salt covered plants could be regenerated while still moving produced water through the other trough. A third trough was set up to compare produced water evaporation rates while exposed to the elements versus transpiration rates through the plants. The containers with plants eliminated the produced water approximately 30% faster than a container open to the atmosphere.

Rather than wash the salt off the plant leaves with fresh water, the salt covered leaves were harvested and given to a rancher for cattle feed. This followed confirmation by a plant material specialist at the Natural Resources Conservation Service in Baton Rouge that the salt covered plant leaves would not harm cattle. Also, a sample of the produced water showed no toxic materials. An expanded metal screen was placed over the troughs and cattle were allowed to come into the area and consume the salt covered plants.

The cost to truck and dispose of the produced water was \$1.20/Bbl. Cost for plants, testing equipment, troughs, data acquisition, etc. was 46¢/Bbl. of produced water (with continued use, this cost will be reduced through re-use of the plants and equipment).

Conclusions

1. The Laboratory's greenhouse studies to date have verified the hypothesis that the primary factors determining the amount of water lost from a closed system (e.g., a plant bioreactor) via plant evapotranspiration are the total aerial biomass of transpiring tissue and its surface area. Larger values for each of these factors (biomass and surface area) result in higher evapotranspiration rates and water loss, as well as more rapid reduction of the water volume from the closed system. This relationship was observed for all species tested and at all salinities of the hydroponic nutrient medium (up to 6% salt).

2. Large, robust species of grasses or grasslike plants (sedges and rushes) best match the "ideal plant" profile that was developed. Those exhibiting moderate to high salt tolerance (halophytes native to salt or brackish marshes or coastal environments) would be appropriate for bioprocessing saline produced water. This bioprocessing includes volume reduction through evapotranspiration and contaminant reduction via the biological filtering effect of the root system and its

associated rhizosphere.

3. The salt tolerant plants used in our field experiment have definite potential use for produced water reduction in remote areas as well as any areas where operational costs for produced water removal exceed the cost of using plants.

4. The experimental sites had a maximum daily produced water rate of 20 barrels. Therefore, we do not know whether this technology would be cost effective at higher flow rates.

5. We hope that other companies in different locations will conduct similar experiments so all of us can learn more about this promising technology.

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Table 1
Species Evaluated:

<u>Scientific Name & Code</u>	<u>Common Name</u>	<u>Plant Family</u>
<i>Spartina alterniflora</i> (Spal)	saltwater cordgrass	Poaceae
<i>Sporobolus virginicus</i> (Spvi)	saltwater dropseed	Poaceae
<i>Salicornia virginica</i> (Savi)	perennial glasswort	Chenopodiaceae
<i>Cladium jamaicense</i> (Cjja)	sawgrass	Cyperaceae
<i>Spartina alterniflora</i> (Spal-V) Var Vermilion	Vermilion saltwater cordgrass	Poaceae
<i>Scirpus validus</i> (Scva)	great bulrush	Cyperaceae

Figure 1
Biomass per Container and Evapotranspiration (ET) at 2% Salt

Figure 2 PLANT BIOREACTOR MODEL

Batch volume = 33.3 m^3 (8800 gallons X 2 = 17,600 gal.)

Evapotranspiration Rate (ET) = 6.1 m^3 (1611 gal./day)

Total volume reduction = 75%
Total time required = 7.6 days

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