DOE/MT/92009--17
MT/92009-17

EVALUATION OF THE FREEZE-THAW/EVAPORATION PROCESS FOR THE TREATMENT OF PRODUCED WATERS

FINAL REPORT
(August 1992 - August 1996)

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For
UNITED STATES DEPARTMENT OF ENERGY
Metairie Site Office
900 Commerce Road East
New Orleans, LA 70123
Contracting Officer's Representative: David R. Alleman
US DOE Contract No. DE-AC22-92MT92009
Contract Date: 8/6/92
Completion Date: 8/6/96
Government Award (1996): $82,770

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June 1996

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EVALUATION OF THE FREEZE-THAW/EVAPORATION PROCESS FOR THE TREATMENT OF OIL AND GAS PRODUCED WATERS

ABSTRACT

The use of freeze-crystallization is becoming increasingly acknowledged as a low-cost, energy-efficient method for purifying contaminated water. Freeze-crystallization has been shown to be effective in removing a wide variety of contaminants from water. Water purification by using natural conditions to promote freezing appears to be an extremely attractive process for the treatment of contaminated water in many areas where natural climatic conditions will seasonally promote freezing. The natural freezing process can be coupled with natural evaporative processes to treat oil and gas produced waters year round in regions where subfreezing temperatures seasonally occur. The climates typical of Colorado's San Juan Basin and eastern slope, as well as the oil and gas producing regions of Wyoming, are well suited for application of these processes in combination.

Research sponsored by the United States (US) Department of Energy (DOE), Amoco Production Company, and Gas Research Institute (GRI) is being conducted by Resource Technology Corporation (RTC) and the University of North Dakota Energy and Environmental Research Center (EERC) to evaluate the effectiveness of a combined natural freeze-thaw/evaporation (FTE) process as a water treatment technology. Specifically, the objectives of this research are related to the development of a commercially-economic FTE process for the treatment and purification of water produced in conjunction with oil and natural gas. The research required for development of this process consists of three tasks: 1) a literature survey and process modeling and economic analysis; 2) laboratory-scale process evaluation; and 3) field demonstration of the process.

Results of research conducted for the completion of these three tasks indicate that produced water treatment and disposal costs for commercial application of the process, would be in the range of $0.20 to $0.30/bbl in the Rocky Mountain region. FTE field demonstration results from northwestern New Mexico during the winter of 1995-96 indicate significant and simultaneous removal of salts, metals, and organics from produced water. Despite the unusually warm winter, process yields demonstrate disposal volume reductions on the order of 80% and confirm the potential for economical production of water suitable for various beneficial uses. The total dissolved solids concentrations of the FTE demonstration streams were 11,600 mg/L (feed), 56,900 mg/L (brine), and 940 mg/L (ice melt). An additional benefit of the process is that the treated water produced during the winter months can be used for municipal, agricultural, and industrial development in arid regions.

Executive Summary

Title Evaluation of the Freeze-Thaw/Evaporation (FTE) Process for the Treatment of Produced Waters - Final Report

Contractor Resource Technology Corporation (RTC)
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US Department of Energy (DOE) Contract No.
DE-AC22-92MT92009
Remediation Technologies, Inc. (RETEC) Contract No.
759.12
Gas Research Institute (GRI) Contract No. (to RETEC)
5091-253-2215

Principal Investigator John E. Boysen

Contract Period August 1992 - August 1996

Objective The general research objective is to develop and demonstrate a cost-effective economically viable commercial technology utilizing the FTE process to treat oil and natural gas produced waters. The specific research objectives are to:

- develop process and economic models to determine the FTE process' commercial viability, economically significant parameters, and research issues (Task 1),
- conduct laboratory-scale process simulations to optimize the design of the FTE process (Task 2), and
- conduct an evaluation of an on-location treatment of produced waters that demonstrates the technical feasibility and economic viability of the FTE process (Task 3).

Technical Perspective The use of freeze-crystallization processes for the treatment of water is a low cost and low energy consuming method for the purification of water containing a wide variety of constituents of highly variable concentrations. Water purification by using natural conditions to promote freezing is an attractive freeze-crystallization process for treatment of water in areas where climatic conditions will seasonally promote freezing. The natural processes of freezing and evaporation can be coupled to treat oil and gas produced waters year round in regions with seasonal subfreezing climatic conditions.

Results All tasks of the research program have been completed. A literature survey, environmental regulatory assessment, survey of current disposal practices and economics, and numerical process and economic modeling were completed in Task 1. Twenty one laboratory-scale process simulations were completed in Task 2 and the FTE process economics were re-evaluated using the numerical process and economic models developed in Task 1 and the results of the laboratory-scale process simulations conducted in Subtask 2.1. An evaluation of a field demonstration of the FTE process was completed in Task 3 in conjunction with a separate project entitled "Demonstration of the FTE Process in the San Juan Basin of New Mexico."

The following conclusions regarding the FTE process are drawn based upon the results of this research:

- This research and previous research confirms that freeze-crystallization is effective in removing a wide variety of contaminants and contaminant mixtures from water. This process is capable of simultaneously removing salts, organics, and heavy metals (including NORM) from produced waters.
- This research and previous research also confirms the FTE process is commercially feasible in the Rocky Mountain and Great Plains Regions for treating 500 bbl/day or more of produced water. For a 1,000 bbl/day produced water treatment facility operating in these regions, the cost for produced water treatment/disposal is approximately $0.25/bbl.
- The FTE process is capable of providing significant quantities of water of a quality suitable for various beneficial uses from oil and gas produced waters. Treated waters with TDS concentrations in the range of 200 to 1500 mg/l can be readily produced using the FTE process. Results of sample analyses indicate that organics and metals are also significantly reduced.
- Regulatory and permitting requirements and associated costs for an FTE facility are essentially the same as or slightly less than those of conventional treatment and disposal methods for oil and gas produced waters. Two benefits of the FTE process, that make it more environmentally acceptable are: 1) the treated water may be beneficially used and 2) the volume of brine disposal is small compared to disposal of the produced water by conventional methods. Regulatory constraints for an FTE process design and operation will require a permit for the construction and use of storage pits. An NPDES permit for the surface discharge or beneficial use of the treated water is required to discharge the treated water and acquisition of this permit may require limited monitoring, sampling, and analyses.
- The sensitivity of the base case water treatment cost to the changes in values of the economic parameters investigated also does not impact the commercial feasibility of the FTE process.
- The FTE process is applicable, in regions where subfreezing temperatures seasonally occur, to treat most waste waters contaminated with mixtures of salts, organics, and/or heavy metals in concentrations below eutectic compositions. Potential applications of the process are: oil and gas produced waters, drilling fluids, refinery and gas treatment plant waste waters, groundwater decontamination, groundwater desalinization, industrial waste waters, municipal waste waters, and contaminated waters associated with defense plants.
- A field demonstration of the FTE process was conducted during the winter of 1995-96 at an operating evaporative produced water disposal facility in the San Juan Basin of New Mexico.

During the demonstration, in excess of 10,000 bbl of coal bed methane produced water was treated. The results of detailed analyses of the ice pile created indicated the ice melt would be suitable for various beneficial uses. The demonstration was adversely affected by previous contamination of the holding pond and an unusually warm winter. Despite these problems, the demonstration sponsors were encouraged enough to provide funding for continued operation of the demonstration plant through the next year.

Technical Approach

Project research conducted in Task 1 began with a review of previous research related to water purification processes using both artificially induced and naturally occurring freezing for contaminant removal. The compositions of typical oil and gas produced waters suitable for treatment by the FTE process and the typical range of meteorologic conditions where the process is applicable for treating produced waters were then determined. Next, process and environmental regulatory constraints were evaluated and a preliminary process design was completed. Numerical process and economic models were developed for the evaluation and preliminary economic feasibility and sensitivity analyses based upon the water composition, meteorological conditions, and design were completed. The economic analyses were conducted to assess the commercial economic feasibility of the process and identify future research issues.

The research completed during Task 2 addressed the research needs identified in Task 1. A laboratory-scale FTE process simulator was constructed. An initial series of nine process simulations to optimize the process design were completed. The impacts of produced water quality and climatic conditions were then investigated by conducting nine simulations in which three produced waters of different quality were treated under three differing sets of atmospheric conditions. Finally, a duplicate simulation using each produced water was conducted and the experimental products of these simulations were each subjected to detailed organic, inorganic, and radionuclide analyses. The detailed analytical results were used to determine the effectiveness of the process in removing organic, metal, and salt constituents from mixtures.

The FTE process economics were then re-evaluated based upon the results of twenty one laboratory-scale simulations of the process. The process and economic models developed in Task 1 were used to complete this effort. A Task 1 and Task 2 Final Report was submitted to document the results of this project research.

Project research completed during Task 3 was the evaluation of an on-site demonstration of the FTE process. The objectives of the evaluation (Task 3) of the demonstration project were:

- to confirm the results of the laboratory-scale simulations using atmospheric conditions at a producing well location,
- to evaluate the effectiveness of the process and process design at a larger-scale to better understand the requirements for process scale-up,
- to evaluate the technical and economic viability of the process, and
- to obtain regulatory acceptance of this novel process.

The objectives of the on-site process demonstration were:

- to confirm the technical feasibility and economy of a commercial-scale application of the FTE process,
- to demonstrate the effectiveness of the FTE process for treating produced water under naturally occurring climatic conditions, and
- to demonstrate that the FTE process can be operated at a commercial-scale in an environmentally acceptable fashion.

Conduct of the field demonstration will reduce the amount of time required for commercial-scale application of the process. Demonstration of the technical and economic feasibility of the process was needed to obtain investment capital for commercialization and demonstration of the environmental acceptability of the process was needed to obtain the required permits for a commercial processing facility.

Project Implications

The research issues related to this project are identified by the results of the economic analyses. The results of the economic analyses strongly suggest the process has significant commercial economic potential. The results of economic analyses, based upon the laboratory-scale simulation and the demonstration results confirm the economic potential of the FTE process and also document that it is possible to remove significant amounts of organics and heavy metals using the FTE process. The expected end product of this research is the development and commercialization of a process that mitigates potential water quality issues related to oil and gas production from economically marginal formations, unconventional resources, and continued production from depleted reserves. Other potential impacts of this research are:

- Increased production from depleted and/or marginally economic oil and gas reserves.
- Reduced operating expenses for reserves that are currently economic.
- Development of new coal bed methane reserves.
- Reduced costs for groundwater cleanup by pump and treat.
- Reduced costs for treatment of industrial waste waters.
- Increased municipal and agricultural development in the arid western US.
- Reduced costs for decommissioning defense plants and bases.

US DOE Contracting Officer's Representative:
David R. Alleman

RETEC Project Manager:

1.0 Introduction

The use of freeze-crystallization processes for the treatment of contaminated water is rapidly becoming acknowledged as a low cost and low energy consuming method for purifying water contaminated by a wide variety of contaminants of highly variable concentrations. Water purification using natural conditions to promote freezing appears to be an extremely attractive freeze-crystallization process for the treatment of contaminated water in many areas where natural climatic conditions will seasonally promote freezing. The natural freezing process can be coupled with natural evaporative processes to treat oil and gas produced waters year round in regions with favorable climatic conditions. The objectives of this research are related to development of a commercially-economic natural freeze-thaw/evaporation (FTE) process for the treatment and purification of water produced in conjunction with oil and natural gas. The research required for development of this process consists of three tasks: 1) a literature survey and preliminary economic analyses, 2) laboratory-scale process evaluation, and 3) an evaluation of a field demonstration of the process. This report provides the results of research conducted for the completion of the three tasks: the literature survey and preliminary economic analysis, the laboratory-scale process evaluation, and the evaluation of the field demonstration of the FTE process.

1.1 Objectives

The general objective of the research is to develop and demonstrate a cost-effective, economically viable, commercial technology that utilizes the natural FTE processes to treat the waters produced from conventional and unconventional oil and natural gas resources.

The specific objectives of the research are:

1) to develop an economic model for determining the commercial viability, economically significant process parameters, and research issues of the FTE water treatment,
2) to construct laboratory-scale process simulations for optimizing the design of the FTE process, and
3) to conduct an evaluation of a commercial-scale field demonstration of the FTE process to demonstrate the technical and economic viability of the process.

1.2 Project Description

As previously discussed, the project research consists of three distinct tasks:

1) Task 1: Literature Survey and Preliminary Economic Analysis
2) Task 2: Laboratory-Scale Process Evaluation
3) Task 3: Evaluation of the Field Demonstration of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico

The process development began with a literature survey that incorporated the following objectives: 1) to acquire data related to the reduction of organics, heavy metals, and salts by freeze-purification processes; 2) to determine typical concentration ranges of organics, heavy metals, and salts in water produced in association with energy production from gas wells, oil and gas wells, and methane drainage from coal seams; 3) to determine an expected range of atmospheric conditions where the FTE process might be successfully implemented; and 4) to estimate process discharges, environmental regulatory requirements, and the cost associated with these items.

When the literature survey was completed, sufficient data were acquired to construct a numerical process model and perform a preliminary economic feasibility study and several economic sensitivity analyses. The calculated model results were used to assess the commercial economic potential of the process and to define economically important parameters and research issues.

Since economic modeling results confirmed that the FTE process has reasonable commercial-scale potential, laboratory-scale simulations of the process were conducted, using simulated atmospheric cycles in an existing 200-ft^2 refrigeration cell. The objectives of these simulations were to optimize process equipment design and understand the impacts of produced water quality and atmospheric conditions on the process. Successful completion of these objectives provided improved data to better estimate the performance and economics of using the FTE process for water treatment at a variety of oil and gas production sites. Economic re-evaluation of the FTE process using the laboratory-scale simulation results strongly suggest the process has significant commercial-scale potential. Completion of Task 2 also provided data indicating the process is successful in simultaneously removing salts, organics, and metals from produced waters.

Since the re-evaluated economics continue to indicate significant commercial-scale potential of the process, a field demonstration of the commercial-scale FTE process for on-site treatment of produced waters was recommended. Task 3 of this research was the evaluation of the field demonstration. The objectives of the demonstration were to show the environmental acceptability of the process to state and federal regulatory personnel and to demonstrate the commercial viability of the process so that it may be accepted as an economic method of produced water treatment and disposal.

1.3 Background

Water which is commonly produced along with oil and gas adds disposal costs to the cost of production. In many instances, the water disposal cost in economically marginal, low-productivity formations prevents wells from being completed or causes producing wells to be prematurely shut in. Future production of oil and gas is expected to increasingly depend upon production from economically marginal formations and from unconventional sources of oil and gas. One promising unconventional source of natural gas is methane production from coal seams. Like production from economically marginal resources, the production of methane from coal seams may rely in the future upon a cost-effective method for treatment or disposal of produced water.

Produced waters have traditionally been disposed of by reinjection into an underground formation. However, obtaining a permit for this process is becoming more difficult due to increasingly stringent environmental regulations. In addition, the cost of transporting the water to reinjection wells has also increased. The oil and natural gas industries can expect this situation to intensify and reinjection to become more difficult and costly. The development of cost-effective methods to treat and/or dispose of produced water has become a key concern for the future development of natural gas and oil from economically marginal and unconventional resources. Another factor relating to the need for a cost-effective produced water treatment process is that, in the arid portions of the western United States (US), clean water would be extremely beneficial for municipal, agricultural, and industrial uses.

Oil and natural gas produced waters can contain organics, heavy metals, and salts. Cost-effective treatment of this water is difficult because each constituent presents a unique problem and the combination of constituents complicates the treatment.

Volatile organics can be removed by air stripping, but current and anticipated regulation of atmospheric discharge will significantly increase the cost of this option. Most types of organics can be removed by using activated carbon. However, salts in produced waters dramatically increase the quantity of activated carbon required to eliminate the organics, thereby increasing spent activated carbon disposal requirements and processing costs.

Heavy metals can be removed from water through precipitation and flocculation. However, precipitation processes require pH adjustments that increase the total dissolved solids (TDS) of the already saline water.

The reduction of the TDS concentration in waters is typically an expensive process. Innovations in reverse osmosis (RO) technology have significantly decreased the cost, but it is still expensive when compared to traditional oil and gas produced water disposal methods such as reinjection or evaporation. Furthermore, the presence of organics in salty water can cause operational and maintenance problems in RO units.

As previously mentioned, evaporation is a relatively low cost option for disposing of produced water. A weakness of evaporation methodology is that, for oil and gas production occurring in the northern US, evaporation is ineffective for as many as six months out of the year. These six months, when the effectiveness of evaporation is limited by atmospheric conditions, are the coldest months when the demand for energy is at its peak.

This project investigates a more economical and effective process to treat waters associated with natural gas production by coupling natural freezing and thawing processes with evaporation or solar distillation. This concept utilizes water treatment by freeze-thaw cycling during the winter months, when the demand for energy is at its peak and evaporation is ineffective. The process also uses water disposal by evaporation during the summer months. Thus, the need for water disposal, or contaminated water-storage capacity, is eliminated for continued production during the winter when evaporation and solar distillation are not practical.

The coupling of freezing with evaporation is easily performed and allows natural conditions to be used to purify or dispose of produced water on a continuous basis. The coupled process can be easily and automatically switched from evaporation to freezing, or vice versa, by monitoring the ambient temperature. Purified waters created from the melting ice can also be easily and automatically separated from waters with concentrated contaminant values that are created during freezing. This separation can be achieved by monitoring the conductivity of the water to estimate its TDS content.

A block flow diagram of the coupled process is illustrated in Figure 1. Water produced from a well is placed in a lined holding pond. When the temperature drops below 0°C, produced water is sprayed or dripped onto a freezing pad to create ice piles. Runoff from the freezing pad will be high in TDS and other contaminant concentrations when temperatures promote freezing. This water, which contains concentrated contaminant values, will be identified by conductivity and stored for disposal. When conditions promote melting of the ice, the runoff will be purified water which will be placed in an unlined holding pond and stored for later use. It may also be discharged directly to the surface drainage. The FTE facility operation in the summer will involve continuous use of evaporation. Operation in the winter, spring, and fall will involve intermittent use of both evaporation and freezing with the cycling based upon ambient temperature conditions.

1.4 Project Rationale

The project research investigates the potential of using a natural FTE process for the treatment of waters associated with oil and natural gas production. The research focuses on the elimination of constituents such as salts, organics, and heavy metals that are characteristic of these waters. The research investigates using the natural FTE process to produce water of suitable quality for reuse. Also, evaporation is used to dispose of additional produced water. This research concentrates on the following areas:

- review of previous, related research,
- preliminary economic analyses of the process,
- laboratory-scale studies to simulate the process, and
- evaluation of a commercial-scale field demonstration of the FTE process.

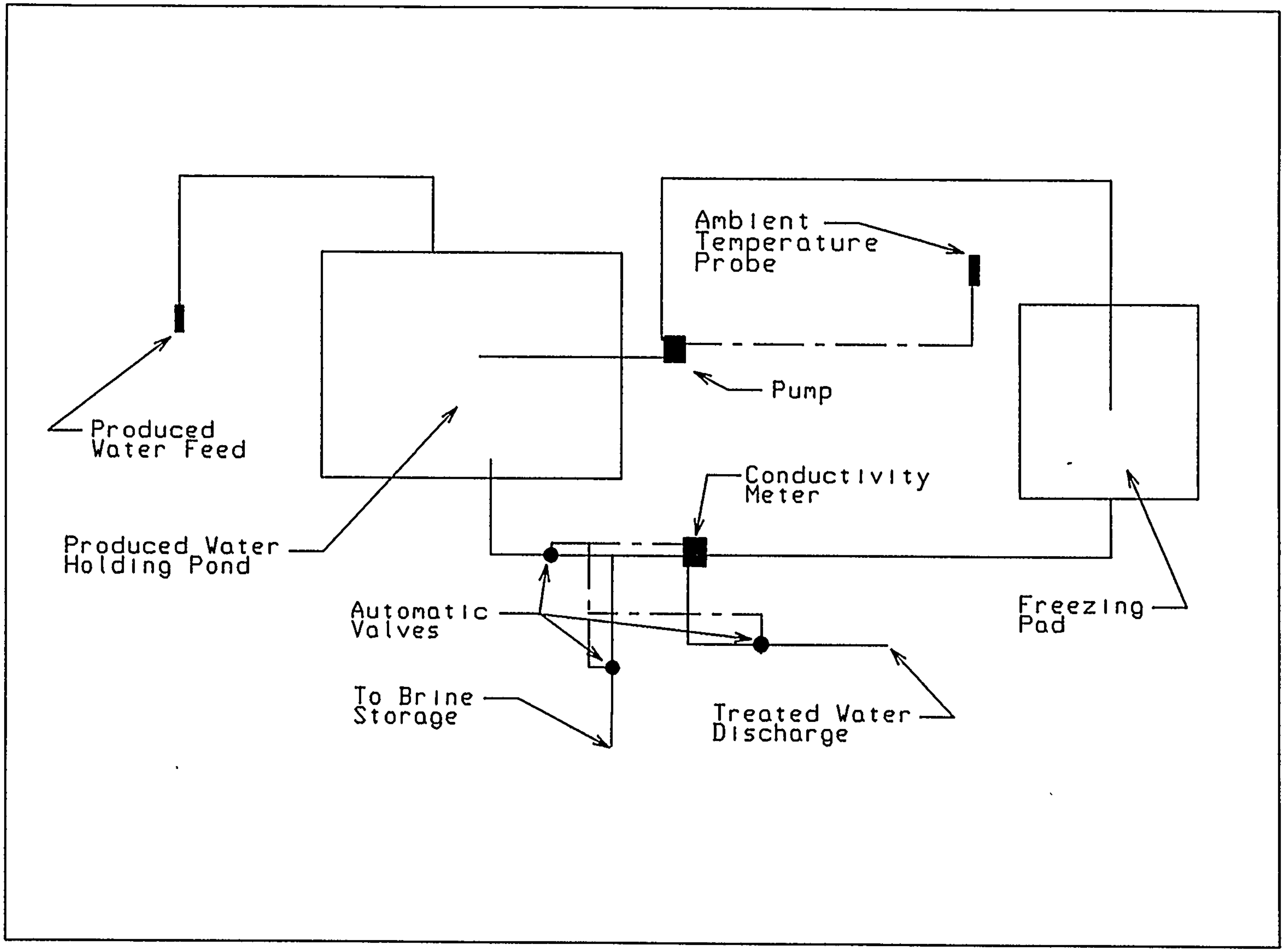


Figure 1. Block Flow Diagram of the Freeze-Thaw/Evaporation Process

The literature review provided a comprehensive review of established FTE technologies. Necessary information on process parameters was obtained for incorporation into the economic feasibility study. An economic sensitivity analysis of the process was used to identify economically significant process parameters whose values must be better defined by experimental research.

Preliminary economic analysis of a probable base-case process design was used to determine the potential economic viability of a FTE plant by incorporating projected regulatory costs and process performance data. The economic sensitivities of the process to parameters such as facility size and location, produced water quality ranges, process design configuration, and atmospheric conditions were determined by varying the value of these variables one at a time and comparing the result to the base case result.

The laboratory simulation series was designed to experimentally determine the expected range of values for important process parameters so that process economics projections and commercial plant design criteria could be refined. A total of twenty-one laboratory simulations were conducted. Treated waters produced in the simulations were sampled and analyzed to determine the end-use potential. The brine produced was also sampled and analyzed to determine disposal requirements.

Results from the initial nine simulations were used to identify the most effective and economic FTE process design. Data required to determine the optimum FTE process design was generated experimentally by simulating three different freezing process design options coupled with three different evaporation process design options.

Nine additional process simulations were completed using the three different produced waters and three different sets of atmospheric conditions. In these simulations, the impacts of produced water quality and atmospheric conditions on the effectiveness of the process were evaluated. The final three laboratory simulations were duplicate simulations in which the experimental products were subjected to detailed organic, inorganic, and radionuclide analyses.

Once the laboratory-scale simulation series were completed, the experimental results were analyzed and used to refine the results of the previous economic analyses. These data were used to develop a basis for determining the optimum plant design and for addressing plant design requirements for different produced water quality and atmospheric conditions. The water treatment costs for commercial processes operating similar to each simulation were calculated using the laboratory results. The economic re-evaluation resulted in significantly improved FTE process economic estimates.

1.5 Benefits of the Research

The long-term viability of the US oil and gas industry is expected to depend increasingly on the development of economically marginal formations and unconventional sources of oil and natural gas. It will also depend upon increased recovery efficiency from reserves currently being produced. The cost of producing oil and gas from most of these resources will strongly depend on the cost of treating or disposing of the water produced in conjunction with the oil and gas. The FTE process is designed to economically treat produced waters by utilizing the natural refrigeration capacity of climates with subfreezing winter temperatures. If a cost-effective produced water treatment process is demonstrated as a result of this research, then development of currently untapped resources will become economically feasible. These resources include economically marginal conventional and unconventional oil and gas resources and extended production from depleted reserves.

The end product of the research was the development and demonstration of a process that mitigates potential water quality issues related to oil and gas production from resources that are economically marginal due to high water disposal costs. Also, natural FTE processes are expected to yield significant quantities of waters with a quality suitable for reuse by industry, agriculture, or municipalities. If successful, the potential end results of this project are increased oil and gas reserves and reduction of future energy production costs. Successful completion of the project tasks will provide oil and gas producers with a commercially viable and environmentally acceptable alternative for treating and disposing of produced waters. The process utilizes naturally occurring atmospheric conditions to generate usable water from what was previously a disposal problem. In addition, approximately ten to twenty percent of current oil and gas production in the US occurs in regions where this process is applicable, and most of the expected future natural gas supply of methane from coal seams is located in these regions. Energy production from these regions is significant to the current and long-term supply situation. The near- and long-term results of this project are economically significant to the gas producers and consumers.

In summary, successful development of the FTE process can potentially impact future energy reserves by extending production from depleted reserves. It may also assist in successful development of future oil and gas production from economically marginal resources because of lower water disposal costs associated with production from these formations. Another important aspect of this research is the applicability of the FTE process to water produced with methane from coal seams. Methane from coal seams is a significant potential source of gas in the US. An estimated 400 tcf of methane is retained in US coal basins and the treatment of water produced with methane from coal seams is a key economic concern related to the development of this resource (GRI, 1989). Therefore, successful development of this treatment process could also greatly enhance the coal-bed methane development. The end result of successful development of the FTE process is decreased oil and gas production costs in the northern US which should result in an increase in economic energy reserves and a decreased energy cost to the consumer.

2.0 Technical Discussion

2.1 Work Plan

A phased approach is being used for the evaluation of the natural FTE process for the treatment of oil and gas produced waters. Each successive task is dependent upon the successful completion of the previous task. The research necessary to develop the FTE process involves the successful completion of three Tasks:

1) Task 1: Literature Survey and Preliminary Economic Analyses
2) Task 2: Laboratory-Scale Process Evaluation
3) Task 3: Evaluation of the Field Demonstration of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico

All tasks of the research have been completed. The following are descriptions of the research effort and objectives of each subtask required for each task of the project.

2.1.1 Task 1: Literature Survey and Preliminary Economic Analyses

A literature survey and preliminary economic feasibility and sensitivity analyses were conducted to evaluate the technical feasibility and commercial viability of the FTE process. The general objective of this task was to develop an economic model for determining the commercial viability, economically significant process and economic parameters, and research issues related to the FTE process. Specific subtasks required for completion of Task 1 are described below:

- Subtask 1.1 - Literature Survey of FTE Research

The research effort and objectives of the literature survey were to: 1) identify economically important FTE process parameters, 2) summarize the response to the FTE process of organics, metals, and salts in contaminated waters, and 3) estimate potential interactions between constituents that may impact the process.

- Subtask 1.2 - Characterization of Natural Gas Produced Waters and Conventional Treatment Costs

The research effort and objectives of this subtask were to: 1) review the literature and databases to characterize typical waters that are generated in association with production from natural gas reservoirs, oil and gas reservoirs, and methane drainage from coal seams, 2) survey meteorological data to establish an expected range of atmospheric conditions at selected production sites where the FTE process is applicable, and 3) survey local producers to determine their current treatment/disposal methods, costs, and willingness to participate in a field demonstration of the process.

- Subtask 1.3 - Evaluation of Process and Environmental Constraints

The research effort and objectives of this subtask were to: 1) estimate FTE discharges and evaluate regulatory requirements for owner operator and commercial type facilities, 2) assess process discharges, regulatory requirements, and costs of conventional methods of disposal/treatment of natural gas produced waters, and 3) compare the environmental acceptability, regulatory requirements, and costs of the FTE process to conventional methods.

- Subtask 1.4 - Conceptual Process Design

The research effort and objective of this subtask was to design a preliminary FTE process based on the results of Subtasks 1.1 through 1.3 to address environmental, regulatory, and process issues for various types of produced waters and assumed operating scenarios.

- Subtask 1.5 - Preliminary Economic Feasibility and Sensitivity Analyses

The research effort and objectives of this task were to: 1) develop an economic model that delineates a numerical discounted cash flow/rate-of-return for the preliminary FTE process design resulting from Subtask 1.4; 2) evaluate the economics of a probable, base case operating scenario which assumes reasonable fixed values for: a) facility location and atmospheric conditions, b) facility size, c) concentration of salts, organics, and heavy metals in the produced water, d) capital equipment costs, e) annual operating expenses, f) debt-to-equity ratio, g) bond interest, and h) return on investment after taxes; and 3) determine the economic sensitivity of the FTE process by evaluating the projected water treatment costs for a minimum of 33 differing operating scenarios.

- Subtask 1.6 - Task 1 Topical Report

The research effort and objectives of the topical report were to: 1) provide a comprehensive analysis of the results of Tasks 1.1 through 1.5 and 2) determine if the FTE process is technically feasible, economically viable, and economically stable.

2.1.2 Task 2: Laboratory-Scale Process Evaluation

Laboratory-scale process simulations were conducted in Task 2 to determine the optimum evaporation and freezing process designs, to determine the impact of atmospheric conditions and produced water quality on the effectiveness of the FTE process, and to demonstrate the feasibility of the process at a laboratory-scale. Data generated as a result of Task 2 research were used to optimize the FTE process design, apply the process to a variety of geographical locations and produced waters, and to improve the accuracy of the economic evaluation of the process. Specific subtasks required for completion of Task 2 are described below:

- Subtask 2.1 - Laboratory-Scale Process Simulation

The research effort and objectives for the laboratory-scale process simulation were to: 1) design and construct a laboratory-scale simulator to test the FTE process; 2) conduct an initial series of nine process simulations to optimize the FTE process design by evaluating the effectiveness of the three different freezing design options (wetted column freezing, conventional water sprays, and atomizing sprays) and three different evaporation design options (conventional evaporation ponds, solar evaporation ponds, and solar distillation ponds); 3) conduct an additional series of nine process simulations, using the optimum process design for treating three different produced waters under three differing sets of atmospheric conditions to determine the effectiveness of the FTE process in removing organic, metal, and salt constituents from produced waters with differing contaminant mixtures and differing local atmospheric conditions; and 4) conduct duplicate simulations for each of the produced waters tested to provide sufficient samples for detailed organic, inorganic, and radionuclide analyses.

- Subtask 2.2 - Re-evaluation of Process Economics Based Upon Laboratory-Scale Simulation Results

The research effort and objective of this subtask was to re-evaluate FTE process economics using the numerical model developed in Subtask 1.5 based upon Subtask 2.1 simulations results.

- Subtask 2.3 - Final Technical Report of Task 1 and 2 Research

A final technical report, "Evaluation of the Freeze-Thaw/Evaporation Process for the Treatment of Produced Waters, Task 1 and Task 2 Final Report" summarizing the results of all FTE process research and simulations was submitted to provide accurate commercial-scale process economic projections and the finalized technical and economic requirements of an FTE process demonstration plant for the treatment of oil and gas produced waters.

2.1.3 Task 3: Evaluation of the Field Demonstration of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico

Task 3 of this research was the evaluation of a demonstration of the FTE process conducted at an operating produced water disposal facility in the San Juan Basin of New Mexico. Task 3 research was conducted in conjunction with a separate project entitled "Demonstration of the FTE Process in the San Juan Basin of New Mexico." The objectives of the field demonstration were: 1) to confirm the results of the laboratory-scale simulations using actual atmospheric conditions at the selected site, 2) to evaluate the effectiveness of the process at a larger scale to better understand the requirements for process scale-up, 3) to evaluate the technical and economic viability of the commercial process, and 4) to obtain regulatory acceptance of this novel process. Demonstration of the technical and economic feasibility of the process is needed to obtain investment capital for commercialization of the process and demonstration of the environmental acceptability of the process is needed to obtain the required permits for a commercial processing facility. Specific subtasks required for completion of Task 3 are described below:

- Subtask 3.1 - Sampling and Analyses of Field Demonstration Process Streams

The research effort and objectives of this subtask were to: 1) collect samples and conduct detailed inorganic, organic, and radionuclide analyses of the produced water in the demonstration holding pond prior to initiation of subfreezing temperatures and 2) collect samples and conduct detailed inorganic, organic, and radionuclide analyses of the ice pile created, treated water produced, brine produced, and the demonstration holding pond during the freezing operation of the demonstration plant.

- Subtask 3.2 - Evaluation of Field Demonstration Operating Data

The research effort and objective of this subtask were to evaluate the operation of the field demonstration based upon operating data collected and the results of sample analyses.

- Subtask 3.3 - Preparation of the Final Report

The research effort and objectives of this subtask were to present a concise summary of: 1) the results of the literature survey and the preliminary economic analysis, 2) the results of the laboratory-scale FTE process simulations, 3) the revised process economics derived from the laboratory-scale simulations, 4) the finalized technical and economic requirements of a FTE process demonstration plant for the treatment of natural gas production waters in the San Juan Basin of New Mexico, 5) the results of the field demonstration process stream analyses, and 6) an evaluation of the demonstration based upon the operating data.

2.2 Work Performed

This document describes the project research conducted to complete Task 1 (Subtasks 1.1 - 1.6), Task 2 (Subtasks 2.1 - 2.3), Task 3 (Subtasks 3.1 - 3.3) of the project. The general research effort and objectives of the tasks and subtasks are described in Sections 2.1.1, 2.1.2, and 2.1.3. During the time period of 8/6/92 through 6/28/96 research efforts related to all three tasks were completed. Subtasks 1.6, 2.3, and 3.3 are the preparation of reports and these subtasks are not discussed further. Following are detailed discussions of the work performed in each subtask required to complete Tasks 1 through 3.

2.2.1 Task 1: Literature Survey and Preliminary Economic Analyses

A literature survey and preliminary economic feasibility and sensitivity analyses were conducted to evaluate the technical feasibility and commercial viability of the freeze-thaw/evaporation process. Specific tasks completed are described below.

2.2.1.1 Subtask 1.1: Literature Survey of FTE Research

In the literature survey, previous research related to the expected concentration ranges of organics, heavy metals, and salts that are responsive to water treatment by freeze-crystallization processes was examined. Research related to the impact of potential interactions between these constituents on the effectiveness of freeze-crystallization water purification processes was also examined. Resources used for the literature survey were the University of Wyoming libraries and database services and Dr. Donald Stinson, a pioneer in the use of natural freezing processes for water purification. In the literature survey, a total of 148 different citations and patents related to the use of freezing as a means of water purification were found. A total of 64 of these references were obtained and reviewed. Twelve of the references dealt with artificial freezing as a method for water purification; the desalination of water by natural freezing was discussed in seven references; heavy metal or organic contaminant removal from water was the subject of three references; and, removal of radionuclides from hazardous waste waters was addressed in two references. A total of 41 patents related to various processes and equipment for water purification by freezing was also reviewed. The majority of patents issued were related to artificial freezing processes; however, a Canadian patent, Methods of Separating Water From Aqueous Solutions, was obtained. This patent, related to a method for the decontamination of water using natural freezing, was issued to Donald Stinson in 1963.

As previously stated, natural freezing as a method of purifying water was the focus of only seven references. All of these references were limited to discussion of the desalination of waters. However, metal and organic removal was addressed in several of the references related to artificial freezing processes. Appendix A provides a listing of the references obtained and reviewed. Also, it should be noted that Dr. Donald Stinson was extremely helpful in assisting in the acquisition of many of the references, especially those from Canada and the former Soviet Union. His assistance is greatly appreciated.

2.2.1.2 Subtask 1.2: Characterization of Natural Gas Produced Waters and Conventional Treatment Costs

Produced water quality data were obtained from the Gas Research Institute natural gas produced water database currently in preparation, the Rocky Mountain Geological Society, the Wyoming Oil and Gas Commission, and the Wyoming Department of Environmental Quality databases. The data for produced water quality are generally limited to pH, TDS, and major cation and anion concentrations. A limited amount of data also was obtained depicting heavy metals concentrations in waters injected into Wyoming Class I disposal wells. In total, 1,680 individual sets of water quality data were obtained from the four databases. However, the data characterizing concentrations of organics, oil and grease, and heavy metals were very limited. The entire data set was reduced by eliminating analyses with TDS concentrations above 75,000 ppm and below 5,000 ppm. The upper limit was considered to be 75,000 ppm TDS because waters with TDS concentrations greater than 75,000 ppm (7.5%) at freezing temperatures are probably near saturation and cannot be effectively treated by a freeze-purification process alone. The lower limit was considered to be 5,000 ppm TDS because many non-toxic oil and gas produced waters with TDS levels less than 5,000 ppm can currently be permitted for surface discharge without treatment. By imposing the TDS limits, the database was reduced to 946 water analyses. Of the 946 remaining analyses, 21 had some type of data describing the concentrations of organics in the waters, and 51 had some type of data describing the concentrations of non-radioactive heavy metals. An additional 381 analyses depicting radium and uranium in injected waters were included in the Wyoming Department of Environmental Quality database which depicts the quality of waters injected into Wyoming Class I disposal wells. This database provides data regarding the quality of waters injected but does not identify the source of the waters. Inspection of the radium and uranium concentration data from this database tends to indicate that the analyses with radionuclide concentration data are probably representative of uranium mining and processing wastes. For this reason, these data were eliminated from further reduction. Median, maximum, minimum, and average values were determined for each analyte in the reduced data set to identify typical ranges of produced water quality that may be suitable for treatment using the FTE process.

The literature survey (Subtask 1.1) provided information describing the geographical regions in the US where natural freeze-thaw water purification processes are applicable. This information provided a starting point for determining states that would significantly benefit from the application of the process, favorable locations for demonstration of the process, and ranges of average meteorological conditions in those states. Initially it was determined that the FTE process would not be applicable in Alaska. Most of the oil production in Alaska is from the North Slope where the temperatures are too extreme. Extreme temperatures cause freezing of the entire solution without thaw or melt cycles. A portion of, or all of, twenty-nine states are geographically located in areas where the climatic conditions appear compatible with application of the natural FTE process (Figure 2).

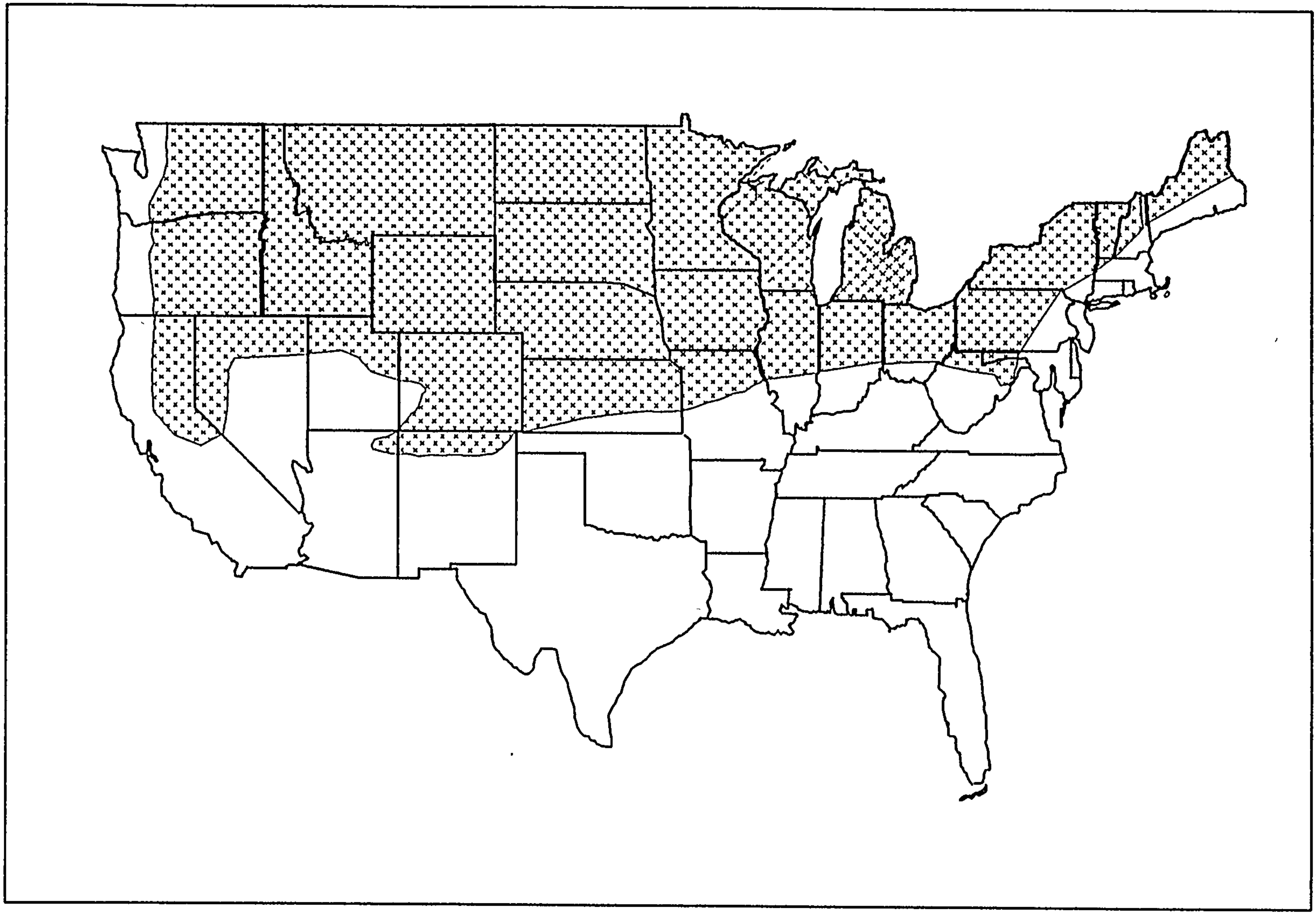


Figure 2. Areas in the US Where the Natural Freezing Process Can Be Used

The oil and gas production statistics of 1987 were used to rank the twenty-nine states by total annual energy production in the form of oil and gas (Table 1). While California ranked number one and Kansas ranked number three in oil and gas production among the selected states, oil and gas production from the regions of these states where the natural freezing process is applicable is less than half of the energy production. For this reason, these states were not considered to have great potential for application of the process. The states of Wyoming, Colorado, Michigan, and North Dakota are considered to have the greatest potential for development of the natural FTE process. Evaluation of expected climatic conditions and the environmental regulatory assessment concentrated on these states.

Using the oil and gas production data for the geographical portion of the US where natural freeze-thaw water purification processes are applicable (Figure 2), three regions were selected to investigate the impact of atmospheric conditions on the process water treatment cost and efficiency. Northeastern Colorado was selected to represent a relatively mild climate, the upper peninsula (UP) of Michigan was selected to represent a severe climate, and central Wyoming was selected as a medium climate where the FTE process is potentially applicable. Meteorological data for the cities of Denver, Co; Sault Ste. Marie, MI; and Casper, WY were selected to provide climatic data representative of these regions.

A search of climatic data was conducted using the US Department of Agriculture National Oceanic Atmospheric Administration National Weather Service databases. These databases included the Climate Dial-Up Service and the First Order Meteorologic Station Data Files. The data acquired contained approximately 25 years of daily average data for the following climatic parameters: precipitation, PAN Evaporation, temperature, wind velocity, and solar radiation. The total number of data points averaged 54,750 per site location. The data were compiled and sorted by location and month, thus the monthly averages for the nominal twenty five year period were calculated. These data were used in the evaluation of the conceptual process design (Subtask 1.4) and in the economic feasibility and sensitivity analyses (Subtask 1.5). These data were also used in the laboratory-scale evaluation of the process (Subtask 2.1) and as a basis for design of commercial processes at differing locations. The raw and reduced data are stored on disk in ASCII format.

Table 1. 1987 Oil and Gas Production for States where Natural Freezing Water Purification Processes are Applicable

State	Oil Production 1,000 bbl	 10^6 Btu	Natural Gas Production 10^6 scf	 10^6 Btu	Total 10^6 Btu
California	364,608	1,701,479,693	424,621	424,621,000	2,126,100,693
Wyoming	115,267	537,904,982	497,980	497,980,000	1,035,884,982
Kansas	59,884	279,454,674	457,050	457,050,000	736,504,674
Colorado	28,802	134,407,413	164,557	164,557,000	298,964,413
Michigan	25,972	121,200,935	146,996	146,996,000	268,196,935
North Dakota	41,351	192,968,577	62,258	62,258,000	255,226,577
Utah	35,788	167,008,281	87,158	87,158,000	254,166,281
Ohio	12,153	56,713,190	166,593	166,593,000	223,306,190
Pennsylvania	3,302	15,409,113	163,318	163,318,000	178,727,113
West Virginia	2,835	13,229,811	160,000	160,000,000	173,229,811
Montana	25,059	116,940,329	46,456	46,456,000	163,396,329
Illinois	23,980	111,905,068	1,371	1,371,000	113,276,068
Nebraska	6,019	28,088,265	1,261	1,261,000	29,349,265
New York	710	3,313,286	25,676	25,676,000	28,989,286
Indiana	3,738	17,443,751	217	217,000	17,660,751
Nevada	3,112	14,522,459	0	0	14,522,459
South Dakota	1,644	7,671,890	3,431	3,431,000	11,102,890
Oregon	0	0	3,800	3,800,000	3,800,000
Missouri	110	513,326	4	4,000	517,326
Maryland	0	0	44	44,000	44,000
Idaho	0	0	0	0	0
Iowa	0	0	0	0	0
Maine	0	0	0	0	0
Massachusetts	0	0	0	0	0
Minnesota	0	0	0	0	0
New Hampshire	0	0	0	0	0
Vermont	0	0	0	0	0
Washington	0	0	0	0	0
Wisconsin	0	0	0	0	0

Also, as a part of Subtask 1.2, contacts were made with six organizations actively involved in disposal of oil and gas produced waters in the selected locations. The contacts were made to identify interest in the project, locate potential sites for a field demonstration of the process, and to acquire data describing disposal requirements and costs. The organizations contacted were: two major oil and gas producing companies, two independent oil and gas producing companies, and two companies currently operating commercial facilities for the disposal of oil and gas produced waters.

2.2.1.3 Subtask 1.3: Evaluation of Process and Environmental Constraints

Based upon the results of Subtasks 1.1 and 1.2, facility locations in Wyoming, Colorado, and Michigan were considered. Contacts were made with personnel from the Wyoming Department of Environmental Quality (WDEQ), the Wyoming Oil and Gas Conservation Commission (WOGCC), the Colorado Water Quality Control Commission (CWQCC), the Colorado Department of Natural Resources Oil and Gas Conservation Commission (DNROGCC), the Michigan Department of Natural Resources (MDNR), and the Michigan Geological Survey (MGS) regarding environmental regulatory jurisdiction and permitting requirements. For the states of Colorado and Wyoming, the permitting process is well understood because alternatives to produced water disposal by deep well injection have been sought and evaporation ponds currently exist for both owner operated and commercial facilities. In the state of Michigan, different climatic and geologic conditions have made water disposal by deep well injection the accepted option. The Michigan regulatory personnel contacted were uncertain of permitting requirements for this process and of the jurisdiction for the permitting process. Through contacts with regulatory personnel in Colorado and Wyoming, the environmental regulations and permitting requirements for design and operation of an FTE facility were determined for owner-operated and commercial facilities, flow charts delineating the steps required to permit the construction and operation of either type facility in Colorado and Wyoming were prepared, and the environmental acceptability of the FTE process, regulatory and permitting requirements for the design and operation of an FTE facility, and permitting and compliance costs for an FTE facility were compared to those of conventional methods for the treatment of oil and gas produced waters.

2.2.1.4 Subtask 1.4: Conceptual Process Design

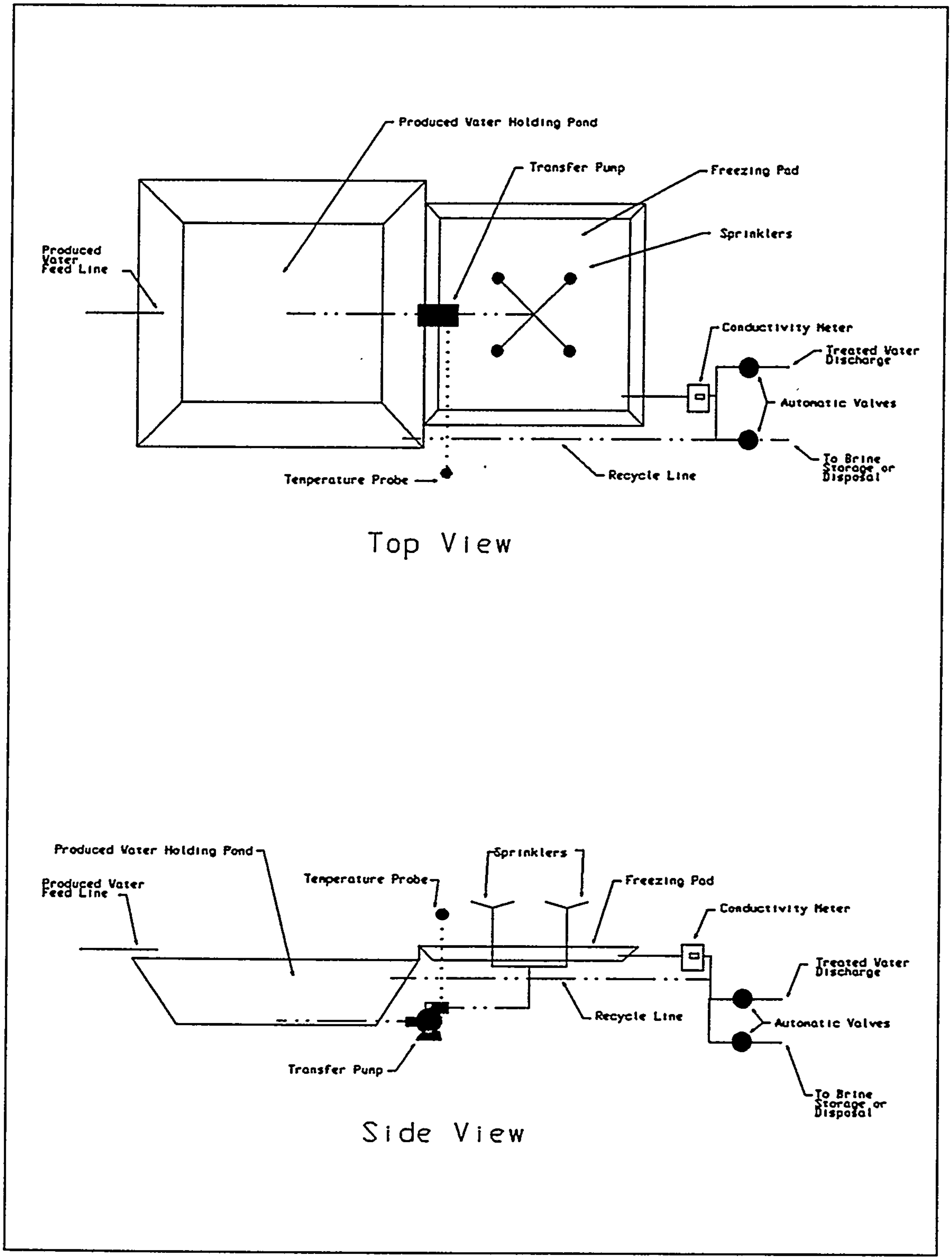
Based upon the results of Subtasks 1.1 through 1.3, a numerical model to design an FTE facility was developed to determine equipment and operating requirements for an FTE facility under a variety of specified operating scenarios. The numerical model is written in Fortran for use on an IBM personal computer. Detailed flow charts describing the process model are provided in Appendix B. Following is a brief description of the model.

The design of the FTE facility is illustrated in Figure 3. The basic units of the FTE process are: 1) a produced water holding pond, 2) a transfer pump, 3) the freezing pad, 4) a conductivity meter operating two automatic valves to direct the run-off from the freezing pad, and 5) a brine storage tank.

This facility is designed to operate as follows: Produced water is continuously fed to the holding pond. The transfer pump operates only when the ambient temperature probe indicates subfreezing temperatures exist. During pump operation, produced water is sprayed onto the freezing pad to create an ice pile. The electrical conductivity (Ec) (proportional to TDS content) of the run-off from the freezing pad is continuously monitored and, based upon conductivity, run-off is automatically diverted to either brine storage, discharge, or the produced water holding pond.

The FTE facility is designed to prevent accidental discharge of water. The holding pond and freezing pad are vertically oriented to guarantee that run-off from the freezing pad flows into the produced water holding pond if line plugging or valve failures cause the freezing pad to overflow. Similarly, if any piping connected to the outlet of the transfer pump becomes plugged or ruptures, water will be contained within the lined areas of the holding pond and freezing pad.

Equipment sizing and specifications for the FTE facility are dependent upon the atmospheric conditions of the location selected, the rate and quality of the produced water feed, the regulated quality of the treated water discharged, the quality of the concentrated run-off, and the specific designs of the holding pond and the freezing pad. Values for each of these process parameters must be specified and are required model inputs necessary to evaluate the design requirements of an FTE facility. Also, due to the absence of data in the literature reviewed that describes the behavior of contaminant constituents other than salts



Top View

Side View

Figure 3. Conceptual FTE Process Design

in a natural freezing process, the model evaluation is based only upon the TDS concentrations in the various process streams. TDS is in effect, assumed to be the indicator of other contaminant species behavior. Experimental data from Subtask 2.1 confirms this assumption to be reasonable (Section 3.2.1).

The location of the FTE facility is the first model input specified in the evaluation. With the location specified, the following atmospheric data are required for the evaluation: 1) the monthly average values for the high, low, and average temperature (°C), 2) the daily precipitation (cm/day), 3) PAN evaporation (cm/day), and 4) solar radiation to a black horizontal surface (langleys). Based upon results of Subtask 1.2, atmospheric data files for locations in eastern Colorado, central Wyoming, and Michigan's upper peninsula were incorporated into the original form of the model. The model can be easily expanded to include additional locations at a later date if the need arises. Atmospheric data files for locations in northwestern New Mexico and eastern North Dakota have already been added to the model as a result of research conducted in Task 2.

Next, the produced water feed rate (bbl/day) and quality (ppm TDS), the regulated quality of the water discharged (ppm TDS), the brine quality (ppm TDS), and the type and design of the produced water holding pond are model inputs that must be specified. Three types of produced water holding pond designs are considered in the model: conventional evaporation, enhanced (solar) evaporation, and solar distillation. Pond design specification requires the following model input data: the maximum allowable water depth in the pond (ft), the slope of the pond sidewall (x:y), the vertical freeboard (ft), the linear feet of liner required to construct the anchor trench and berm, and the pond evaporation efficiency. In every case the ponds are assumed to be lined.

First, the number of hours each month with subfreezing temperatures are calculated using the atmospheric data for the selected location. To estimate the hours of freezing conditions each month, the temperature cycle each day is assumed to be a sine function with the average value equal to the daily mean temperature, the amplitude equal to the difference between the daily average high and low temperatures, and the frequency equal to twenty-four hours.

The FTE facility operation is assumed to be such that the produced water holding pond is essentially empty every spring when subfreezing temperatures cease. The pond fills with produced water during warm months when the freezing pad is not operated. Thus, the pond water volume and level are maximum the day before subfreezing temperatures begin, and the required size of the holding pond is based upon the maximum volume of water.

In the calculation to determine the required size of the holding pond, the volume of water in the holding pond is determined each day of the warm months by considering the rate and quality of produced water fed to the pond and the respective volumes of precipitation to and evaporation from the pond. It is necessary that the dimensions and size of the produced water holding pond be known to determine the amounts of water evaporated and precipitation introduced into the pond. The optimum produced water holding pond size is determined by assuming a specific pond base dimension, performing the day-by-day material balances for the pond operation during the warm months, and determining the maximum depth of water in the pond, the pond volume, and the amount of liner required for the assumed pond base. The assumed pond base dimension is then systematically varied and the calculations repeated until the optimum size of the holding pond is determined based upon the minimum liner required for the pond. Interestingly, if a maximum pond water depth of twenty feet is specified in the pond design basis, a clear optimum pond size results for feed rates less than 100 bbl/day. However, with feed rates in excess of 100 bbl/day, the optimum pond size corresponds to the pond size required with a twenty foot water depth.

Next, the TDS concentration in the produced water holding pond is determined for each day of the warm months. The mass of TDS in the holding pond each day is determined by material balance assuming that the TDS concentrations of the water evaporated and precipitation introduced are negligible. Thus, the cumulative mass of TDS in the holding pond each day is equal to the cumulative mass of TDS in the produced water introduced since the filling of the holding pond began. On any given day, the concentration of TDS in the holding pond is then the cumulative mass of TDS in the pond divided by the volume of water in the pond.

With the size, volume, and quality of water in the holding pond determined when subfreezing temperatures begin, the size of the transfer pump is calculated. The pump is sized based on two criteria: 1) water is withdrawn from the holding pond only during times with subfreezing temperatures and 2) the pond is essentially empty when subfreezing temperatures cease. For the pump sizing, the daily holding pond water volume and quality are determined during times with subfreezing temperatures by considering the produced water feed rate and quality, rates of precipitation and evaporation, and the rate and quality of water pumped to the freezing pad. The pump sizing is another iterative calculation to determine the pump size resulting in an empty holding pond when subfreezing temperatures cease. In the pump sizing calculation, a pump size is assumed. Then, the volume and quality of water in the produced water holding pond are determined each day during the cold months. If the pond is not empty, when the warm months begin, then a larger pump size is assumed and the calculations are repeated. If the pond empties before the on-set of the warm months, then a smaller pump size is assumed and the calculations repeated. The required pump size results when the produced water holding pond empties on the last day of the cold months. When the pump size has been determined, the volume and quality of water in the produced water holding pond are known for each day of the year.

The annual amounts of treated water and brine produced are determined next, based upon the annual amount and quality of water pumped to the freezing pad and the specified qualities of the treated water and brine. The annual amounts of treated water and brine flowing from the freezing pad are determined by a TDS balance. The amount of treated water produced is then used to determine the maximum size of the ice pile on the freezing pad. The ice pile on the freezing pad is assumed to be a maximum height of forty feet, with a circular base and near vertical sides. The base dimension of the ice pile is determined from the height of the ice pile, circular geometry, and the annual amount of treated water required. To determine the base dimension of the ice pile, the ice pile is assumed to have a specific gravity of 0.8 and a volume equal to 80% of the volume of a cylinder of the same height and base. The calculated base dimension is constrained by requiring it be at least twice the height of the ice pile.

The design and sizing of the freezing pad requires that a pad design basis (similar to that specified for the holding pond) be selected and that the base dimension of the ice pile be known. The following freezing pad design basis is used in all cases: a maximum depth of three feet, a sidewall slope of 3 to 1 (x:y), a freeboard of one vertical foot, and six linear feet of liner are required for construction of the berm and anchor trench. The freezing pad is assumed to be square with a base dimension equal to the base diameter of the ice pile. The number of sprays and pipe required for freezing pad operation are determined by assuming each spray covers a sixty foot radius and using the previously determined size of the transfer pump.

Brine run-off from the freezing pad is stored in a standard 400 bbl tank. The brine is then collected, stored, and transported for disposal in the same fashion as produced water from the same location would be. All treated water is assumed to be surface discharged. Water recycled to the holding pond is re-pumped to the freezing pad during the times in the coldest months when excess transfer pump capacity is available.

In summary, the numerical model for the design of an FTE facility provides the following information for each assumed operating scenario:

1) daily water volume and quality in the produced water holding pond,
2) the water volume, dimensions, and liner required for the produced water holding pond,
3) the required size of the transfer pump,
4) the dimensions and liner required for the freezing pad,
5) the maximum volume of ice on the freezing pad, and
6) the annual volumes and quality of treated water and brine run-off from the freezing pad.

Using the model, the impacts of the facility location and size, produced water, treated water, and brine TDS concentrations, and pond design specifications on the FTE design were evaluated by assuming a base case operation and then systematically changing the value of one parameter at a time. A total of twenty nine different operating scenarios for specified process parameters were evaluated. The resulting design data for each case was then used in the economic evaluation of the process (Subtask 1.5) to determine the impact of each parameter on the water treatment cost for the FTE process.

2.2.1.5 Subtask 1.5: Preliminary Economic Feasibility and Sensitivity Analyses

Based upon the results of Subtask 1.4, a numerical model to estimate the water treatment cost was developed for an FTE facility operating according to an assumed operating scenario. The model was used to evaluate the impact of assumptions made for process and economic parameters on the economic potential of the process. Parameters with uncertain values having significant impact on the process economics help identify research issues related to process development. The numerical model was written in FORTRAN for use on an IBM personal computer. Detailed flow charts describing the economic model are provided in Appendix C. Following is a brief description of the model and its use.

The following economic basis is assumed for the analysis of the base case FTE facility: load factor is 1.0, plant life is 20 years, equity required is 50%, bond interest is 10%, return on equity is 15%, state and federal combined corporate tax rate is 35%, depreciation is straight line over the plant life, annual maintenance costs, and property taxes and insurance are 4.0%, and 4.5% of installed capital costs respectively, and the salvage value, plant construction period, and working capital are assumed negligible. In the evaluation of the economic sensitivity of the process to economic parameters, various values for parameters in the basis were investigated to determine the significance of the above assumptions.

Based upon the process design resulting from Subtask 1.4, the installed capital cost (CI) for the FTE facility is:

$$CI = CIPWP + CIPUMP + CIFP + CIOTH + CISIT \qquad \text{(Eqn 1)}$$

where:

CI = total installed capital cost, $
CIPWP = installed cost of the produced water holding pond, $
CIPUMP = installed pump cost, $
CIFP = installed cost of the freezing pad, $
CIOTH = installed cost of the pipe, valves, and meters required for the transfer, discharge, storage, and recycle streams, $
CISIT = installed cost of the site facilities (brine storage, electrical service, sheds, and winterization), $

The installed produced water holding pond cost (CIPWP) is determined using the installed liner in $\$/ft^2$ and excavation costs in $/cuyd excavated. Liner costs considered were based upon vendor quotation and excavation costs used were based upon corporate experience.

The installed pump cost (CIPUMP) is estimated using a base flow capacity in gpm, horsepower, and price. Pump horsepower sizes for different cases are estimated by linear scaling. The transfer pump horsepower required is the ratio of the required pump capacity in gpm to the base flow capacity multiplied by the base horsepower. Pump costs are estimated by standard engineering scaling practices using a 0.61 scale factor (Peters and Timmerhaus 1968). The actual pump cost is the ratio of the required pump size to the base pump size raised to the 0.61 power multiplied by the base pump cost. The installed pump cost is determined by multiplying the pump cost by an installation factor of 2.1.

The installed freezing pad cost (CIFP) is determined as the costs of the installed liner, pipe and sprinklers. The freezing pad design from Subtask 1.4 is such that the base of the pad is located near surface elevation so that if the pad overflows, water flows into the holding pond. Excavation required for the freezing pad is assumed to be conducted as part of the excavation required for the holding pond. The liner required for the freezing pad is determined in Subtask 1.4 and the installed liner cost is the same as that used for the holding pond. Pipe costs are estimated using a base flow rate, diameter, and price from current catalogs. The pipe sizes for different cases are estimated by non-linear scaling. Installed pipe costs are determined by scaling the base price with the 0.61 scale-factor and multiplying by the 2.1 installation factor. Sprinklers required are non-standard and the cost is estimated to be $45 per sprinkler, based upon previous experience.

The installed costs of the pipe, valves, and meters required for the transfer, discharge, storage, and recycle streams (CIOTH) are determined from the results of Subtask 1.4. The installed pipe and control valve costs are again determined by non-linear scaling of base flow rates, diameters, and costs. The installed costs of these items are determined using the 0.61 scale-factor and the 2.1 installation factor. The cost of the conductivity controller, thermal switch for pump controls, and related electrical components are vendor quotations and the installed costs are determined using the 2.1 installation factor. These costs are fixed and do not change with differing operating scenarios.

The installed cost of the site facilities (CISIT) includes the cost of brine storage, electrical service, sheds, and winterization. These factors are estimated from previous corporate experience and are also constant for each operating scenario.

Next, annual operating expenses (AOE) for the facility are determined:

$$AOE = O + V + P + S + M + D + I \qquad \text{(Eqn 2)}$$

where:

AOE = total annual operating expenses, $
O = annual operator salary including benefits and overheads, $
V = annual cost of operator vehicle and fuel, $
P = annual cost of electric power, $
S = annual costs for sample analyses, $
M = annual cost of facility maintenance, $
D = annual cost for depreciation of capital,$
I = annual cost for property taxes and insurance, $

The annual operator salary including benefits and overheads (O) is the sum of the operator compensation, cost of fringe benefits, and general and administrative expenses. The cost is determined assuming the plant requires an operator one day per week only during the times with subfreezing temperatures. During the warm months, an operator is not required to observe the filling of the holding pond. The operator is a seasonal employee working eight hours each week of months with subfreezing temperatures. The operator's compensation is $8.00/hr, fringe benefits are 25% of operator compensation, and general and administrative expenses are 45% of operator compensation plus fringe benefits. The annual cost of the operator vehicle and fuel (V) assumes the operator provides his private vehicle and is compensated for vehicle use and fuel. The estimation assumes the operator travels 200 mi/week. The per diem for the use of the vehicle is $0.30/mi, and the compensation for fuel is determined assuming the vehicle fuel usage is 15 mi/gal and the fuel cost is $1.12/gal. The annual cost for electric power (P) assumes the freezing pump is in operation at maximum capacity during the hours with sub-zero temperatures. Electric power is assumed to cost $0.055/kwhr. The annual cost for sample analyses (S) is estimated as $1500. The annual cost of facility maintenance (M) is specified in the economic basis to be 4% of installed capital costs (CI). Depreciation (D) is straight line over the plant life and, since the facility salvage value is assumed to be zero, annual depreciation is the installed capital costs (CI) divided by the plant life. The annual cost of property taxes and insurance (I) is also specified in the economic basis to be 4.5% of installed capital costs (CI).

The amount of debt and equity required to construct the facility is determined using the calculated installed capital cost and the amount of equity required as specified in the economic basis. The annual loan payment is determined from the amount of debt, the bond interest, and the plant life. In this analysis, the interest rate is assumed continuous and the bond life is assumed equal to the plant life. The required return to investors is determined using the amount of equity required, the return on equity specified in the economic basis, and the plant life using a discounted cash flow/rate-of-return calculation. The annual net profit is determined as the required return to investors minus the annual depreciation. The annual corporate income tax is determined as the annual net profit multiplied by the combined tax rate. The gross income required is calculated as the sum of the required net profit, the annual loan payment, the annual operating expenses, and the annual corporate income tax. The required treatment cost is calculated as the annual gross income divided by the annual barrels of treated water produced.

In summary, the economic model for evaluation of an FTE facility provides the following information for each assumed operating scenario:

- itemized installed capital costs,
- itemized annual operating expenses,
- loan and equity requirements,
- annual loan payment and return to investors,
- annual net profit, corporate income tax, and gross income, and
- the water treatment cost in $/bbl of treated water produced.

Using the model and the results of Subtask 1.4, the impacts of the facility location and size; produced water, treated water, and brine TDS concentrations; and pond design specifications on the FTE process, water treatment costs were evaluated for each of the 29 operating scenarios evaluated in Subtask 1.4. In addition, the model was used to evaluate the impact of the following economic parameters: the estimated installed capital investment and annual operating expenses, equity required, bond interest, return on equity, state and federal combined corporate income tax rate, and the installed liner cost. A total of 40 cases were evaluated to determine the significance of the economic parameters. The economic sensitivity of the FTE process to changes in the value of each selected process and economic parameters was evaluated by comparing each case's water treatment cost to the base case water treatment cost.

2.2.2 Task 2: Laboratory-Scale Process Simulation

Task 2 was the laboratory-scale evaluation of the FTE process for the treatment and/or disposal of oil and natural gas produced waters. Laboratory-scale process simulations were conducted in Subtask 2.1 to determine the optimum evaporation and freezing process designs, to determine the impact of atmospheric conditions and produced water quality on the effectiveness of the FTE process, and to demonstrate the feasibility of the process at a laboratory-scale. Data generated as a result of Subtask 2.1 research were used to optimize the FTE process design, apply the process to a variety of geographical locations and produced waters, and to improve the accuracy of the economic evaluation of the process.

2.2.2.1 Subtask 2.1: Laboratory-Scale FTE Process Evaluation

The following is a summary of the research activities completed in Subtask 2.1:

2.2.2.1.1 Selection and Analyses of Produced Water Samples

Samples of three produced waters were selected, acquired, and stored in a refrigerated environment. Produced water samples from a natural gas producing well in Weld County, CO; an oil and gas producing well near Brighton, CO; and a coal bed methane well in the San Juan Basin were obtained for use in the laboratory-scale FTE simulations. Bill Hall of Silverado Oil provided 55 gallons of sample from a natural gas producing well, Tom Shanor of Thorofare Resources provided 220 gallons of sample from an oil and gas producing well, and Buddy Shaw of Amoco Production Company provided 110 gallons of sample from a coal bed methane producing well. The produced water samples acquired for the laboratory simulations were initially subjected to a comprehensive suite of analyses to determine the concentrations of pertinent organic, inorganic, and radionuclide analytes that are of regulatory interest pertaining to use of waters from oil and gas production. This detailed suite of analyses is provided in Table 2.

2.2.2.1.2 Locations/Climates to be Simulated

Based upon the results of Subtask 1.2 research, the climates of northeastern Colorado, central Wyoming, and the upper peninsula of Michigan were originally selected to represent mild, medium, and severe climates where the FTE process is applicable. However, in Subtask 1.3 research, it was not possible to clearly delineate the permitting requirements and permitting jurisdiction for the FTE process when operating in the State of Michigan. Further, the results of Subtask 1.4 research indicated that an evaporation pond operating in the summer months on the upper peninsula of Michigan would actually gain water because precipitation rates are greater than evaporation rates. While the severity of the winter months on the upper peninsula of Michigan indicate the FTE process could be economically operated there, it was concluded that a freeze-thaw process alone would be more effective. For these reasons, the climatic conditions for Michigan's upper peninsula were not used in the laboratory-scale FTE simulations. Instead, a northwestern New Mexico facility location was selected to represent a location with a mild climate where the FTE process may be applicable.

Table 2. Detailed Suite of Analyses for Simulation Samples

EPA Analytical Method No.	Parameter
200.7	Aluminum (Al)
350.2	Ammonia (NH_3-N)
206.2	Arsenic (As)
200.7	Barium (Ba)
200.7	Beryllium (Be)
200.7	Boron (B)
200.7	Cadmium (Cd)
325.3	Chloride (Cl)
200.7	Chromium (Cr)
200.7	Cobalt (Co)
200.7	Copper (Cu)
335.3	Cyanide (CN)
340.2	Fluoride (F)
376.1	Hydrogen Sulfide (H_2S)
200.7	Iron (Fe)
239.2	Lead (Pb)
200.7	Lithium (Li)
200.7	Manganese (Mn)
245.1	Mercury (Hg)
200.7	Nickel (Ni)
353.2	Nitrate (NO_3-N)
353.2	Nitrite (NO_2-N)
413.1	Oil and Grease
420.2	Phenol
270.2	Selenium (Se)
272.1	Silver (Ag)
375.4	Sulfate (SO_4)
160.1	Total Dissolved Solids (TDS)
a	Uranium (U)
200.7	Vanadium (V)
200.7	Zinc (Zn)
150.1	pH
a	Total Organic Carbon (TOC)
624	Volatile Organic Analyses (VOA)
625	Semivolatile Organic Analyses
a	Sodium Absorption Ratio (SAR)
310.1	Residual Sodium Carbonate (RSC)
a	Combined Total of Radium 226 and Radium 228
a	Total Strontium 90
a	Gross Alpha Particle Radioactivity (including radium 226, but excluding radon and uranium)

a No EPA method applicable.

The reasons for selecting the northwestern New Mexico location were: the significant oil and natural gas production from the San Juan Basin, the large produced water disposal requirements of the basin, and conversations with personnel from a major oil and gas production company operating in the region. While the typical spring, summer, and fall climates in the region are favorable for evaporation, operation of the ponds during the winter months is ineffective due to freezing. The models developed were used to determine if an FTE facility operating in northwestern New Mexico could be profitable at a commercial-scale. The results of this investigation indicated that application of the FTE process in northwestern New Mexico would improve the already favorable economics of evaporative disposal typical of the area.

The final selection of climates to be investigated in laboratory-scale simulations to determine the impact of facility location (climate) on the process efficiency and its economics was: northwestern New Mexico (mild), northeastern Colorado (medium), and central Wyoming (severe).

2.2.2.1.3 FTE Process Simulator Design and Operation

The laboratory-scale FTE process simulations were conducted in a 10′ x 20′ x 10′ refrigeration unit at Resource Technology Corporation's facility. A personal computer interfaced programmable temperature controller was used to regulate hourly temperature changes to cycle the temperature in the unit during the simulations. Sun lamps added to the refrigeration unit were activated for simulation of daylight hours. The refrigeration unit was also equipped with air fans for wind (Figure 4).

The equipment configuration for each FTE process simulator is illustrated in Figure 5. The construction was as follows:

- The required produced water holding and brine ponds of dimensions 19.5" x 15" x 8" deep were fabricated from wood and high density polyethylene (HDPE) pond liners. Pans of dimensions 24" x 18" x 7" deep were used experimentally as the freezing pads. The pans were lined with synthetic (polyethylene (PE)) pond liner. One gallon plastic containers were used to collect the treated water generated. These ponds performed as required in the initial simulation series. However, when the ponds were cleaned after the initial simulation series, leak testing prior to the second simulation series revealed that twelve of the eighteen ponds had developed leaks during cleaning. Similarly, when the six remaining ponds were cleaned after the second simulation series, four of these ponds had developed leaks. It was then decided plastic pans, such as those used for the freezing pads, would be modified and used for the produced water holding and brine ponds. These pans were used in the remaining simulations. Appendix D provides details of the construction of the ponds and freezing pads used.

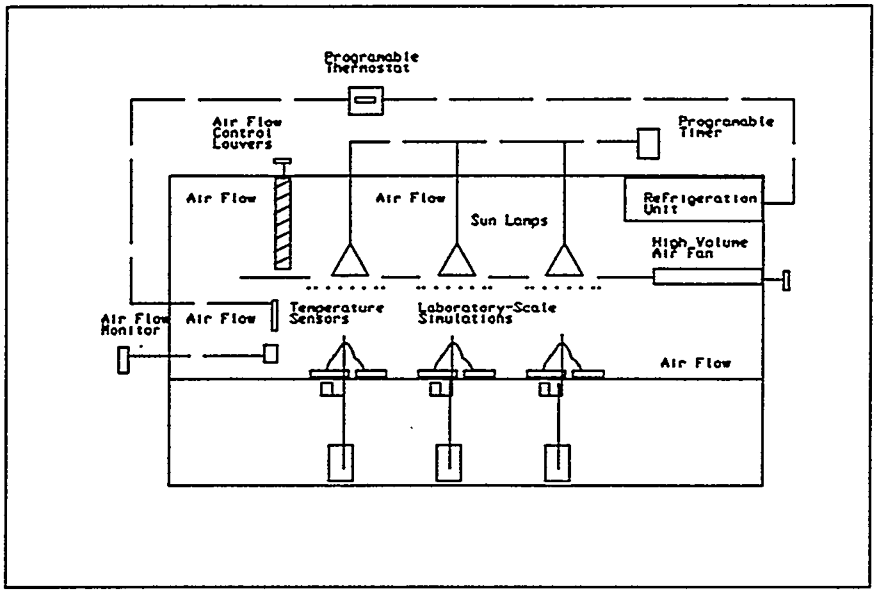


Figure 4. Refrigeration Unit Configuration for the Laboratory-Scale FTE Process Simulations.

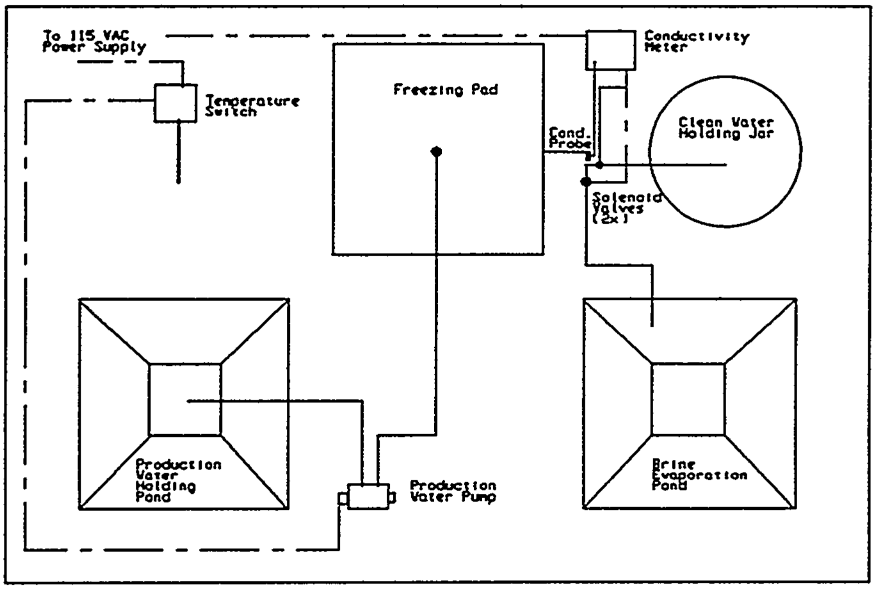


Figure 5. Equipment Configuration for the Laboratory-Scale FTE Process Simulators.

- PE tubing was used for process plumbing. Runoff from the freezing pads was automatically diverted to either the treated water container or brine pond. The solenoid valves were ~~actuated~~ activated by a continuous on-line conductivity meter monitoring the TDS concentration of the runoff.
- Gear pumps were used to recirculate the produced water in the ponds and to supply water to the freezing pads. When the temperature in the simulator was below 0° C, produced water was pumped to the freezing pad. When the temperature was above 0° C, produced water was recirculated in the holding pond. The water recirculated through a pipe into the pond or through sprays in the pond, depending upon the holding pond design being tested. The automatic switching of flows from the pad to the holding pond was achieved using a thermostat in the unit to activate solenoid valves.

After the initial simulation series, the laboratory simulation procedure was as follows:

- Samples of each produced water were collected for compositing and each produced water pond was charged with a known mass of water. The pond levels and mass of produced water added were recorded.
- The temperature controller was programmed to simulate the atmospheric temperature cycles of the location selected. The simulations began with the first month of the year without freezing temperatures. Temperatures were adjusted hourly to simulate daily temperature cycles. The sun lamps and air flow system were timer activated to be on during daylight hours.

The months in which freezing did not occur were simulated first and during those months the simulator operation was as follows:

- Once each day, the level in the produced water pond was measured. Then each forty-eight hours, produced water was added to each pond. The amount added to the pond was sufficient to return the pond water level to its initial value, and samples of the water added were composited with the respective produced water sample. The time the pond was charged with water, the pond water level before and after filling, and the mass of water added were recorded.

When simulation of the months in which freezing did occur were simulated, the simulator operation was as follows:

- Produced water was automatically pumped from the holding pond to the freezing pad when the ambient temperature in the simulator was low enough to promote freezing. When the temperature would not promote freezing, produced water was recirculated to the pond.
- Runoff from the freezing pad flowed to the clean water container if the TDS concentration was less than 2,000 ppm and to the brine pond if the TDS was greater than 2,000 ppm. If the TDS concentration of the brine was greater than 70,000 ppm, it was placed in the brine sample container. If the TDS concentration was less than 70,000 ppm, the brine was recycled to the holding pond. At the end of the simulations, all run-off with a TDS concentration greater than 2,000 ppm was placed in the brine sample container.
- Upon completion of the simulation, the produced water, treated water, and brine composite samples were submitted for analyses.

2.2.2.1.4 FTE Simulation Series 1 - Equipment Optimization

The initial series of simulations consisted of nine laboratory-FTE process simulations to test different FTE process design options. The objective of this series was to determine the best freezing pad and produced water pond designs. Three freezing pad designs were tested:

- wetted column freezing,
- conventional water spray freezing, and
- atomizing spray freezing.

The wetted column freezing design used a pipe located in the center of the ice pile to continuously wet the ice pile by trickling water down the sides of the pile. The conventional spray freezing design used a pipe located in the center of the ice pile with a coarse spray nozzle at the top. The coarse spray nozzle provided a heavy water spray into the air above the pile. The atomizing spray design used a pipe located in the center of the ice pile with an atomizing nozzle at the top. The spray nozzle provided a fine mist water spray into the air above the pile.

Three different evaporation pond design options for the produced water holding pond were also tested in the initial series of simulations. These evaporation pond designs were:

- conventional evaporation pond,
- enhanced evaporation pond, and
- solar distillation ponds.

The conventional evaporation pond design fed recycled pond water through a pipe. The conventional pond design was a deeper pond with steeply sloping pond sidewalls. The enhanced evaporation pond design fed recycled pond water to the pond using sprays. The enhanced evaporation pond design was a shallower pond with more gently sloping pond sidewalls than the conventional design. The enhanced evaporation pond also was equipped with air bubblers in the pond. The solar distillation pond design was similar to the enhanced pond design with two significant exceptions. The solar distillation ponds had a cover so that evaporated water would condense on the cover and the condensate could be collected. The solar pond also did not have air bubblers.

In the initial simulation series, the three different freezing process design options and three different evaporation process design options were thoroughly tested by coupling each pad design with each pond design. Nine simulations resulted from the coupling. The data from these nine simulations were used to select the most efficient and economic pad and pond design combination for the FTE process.

Due to difficulties which occurred during the shakedown testing, it was decided that the experimental procedure for the initial series would differ from later simulation series. In this series, a freezing test was conducted first because it was the most difficult part of the simulations to run. By conducting the freezing portion of the series first, lost time would be minimized if the simulation had to be re-attempted due to operational problems. The temperature cycles during the freezing test were varied as needed to avoid operational difficulties and to promote ice formation so as to maximize the knowledge gained regarding the creation of and behavior of the ice pile. Upon completion of the freezing test an evaporation test was conducted.

The produced water from the oil and gas well (designated "FTE A") was used in all nine simulations. The decision to run the freezing portion of the simulation first proved insightful when the first simulation attempt was forced to abort due to freezing of the sprays which caused significant sample losses in most simulators. Additional insulation was added to the process plumbing and the series was re-attempted. The freezing portion of the second attempt was operated with varying temperature cycles that provided a total of 168.5 hours in which the ambient temperature was below 0°C. The second attempt of the freezing test was operated continuously for fourteen days.

One produced water composite sample was collected during the freezing test of the initial series and nine treated water and nine brine samples were collected, one set from each simulator. These samples were subjected to limited chemical analyses (Table 3). Material and chemical species balances were determined for overall mass, TDS, TOC, and Boron for the freezing test in each of the nine simulations.

Table 3. Limited Suite of Analyses for Simulation Samples

EPA Analytical Method No.	Parameter
[a]	Total Organic Carbon (TOC)
160.1	Total Dissolved Solids (TDS)
200.7	Boron (heavy metal indicator)
150.1	pH

[a] No EPA method applicable.

All nine simulators were then re-charged with produced water "FTE A" prior to the initiation of the evaporation test of the initial series of simulations. During the evaporation test, atmospheric conditions simulated were similar to northeastern Colorado during the months with temperatures above 0°C. The water level in the produced water pond for each simulation was measured daily and no additional produced water was added. The evaporation test was operated for thirteen days. However, during five of those days, the unit was inadvertently down due to a power failure which shut-off the temperature controller.

Samples were not taken during the evaporation portion of the initial series of simulation. Overall mass balances were determined for the freezing test in each of the nine simulations. Performance of the evaporation pond design options were determined based upon the rates of evaporation achieved during the eight days of operation and the best design option was determined by qualitative comparison of the evaporation achieved among all of the simulator design combinations.

2.2.2.1.5 FTE Simulation Series 2 - Northeast Colorado Climate

The second series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of northeastern Colorado. Each of these three simulations used the optimum process design combination determined from the results of the initial series of simulations. The enhanced evaporation pond design and water column freezing pad design were used in these simulations. In the three simulations, one simulator was fed with the coal bed methane produced water (designation "FTE C"), one simulator was fed with the oil and gas produced water (designation "FTE A"), and the remaining simulator was fed with the natural gas produced water (designation "FTE B"). Daily temperature cycles simulating the monthly average cycles for northeastern Colorado were used in the series. The simulations began with temperature cycles similar to the month of April, which is the first month in northeastern Colorado with average temperatures consistently above 0°C. A total of 103 hours with temperatures below 0°C existed during Simulation Series 2.

Four operational problems occurred during the simulation. The four problems encountered during this simulation series were all related to power failure induced temperature controller failures. Four such failures occurred during the simulation series. One of these failures resulted in the need to run the simulation series an additional twenty-four hours. This failure occurred during the scheduled on-set of freezing, and repeating the conditions for that day resulted in the duration of the simulation series being twenty-five days instead of the planned twenty-four. The other three failures had minor impact on the results of these simulations.

The three produced water, three treated water, and three brine composite samples produced during Simulation Series 2 were subjected to limited chemical analyses (Table 3). Material and chemical species balances were determined for overall mass, TDS, TOC, and Boron in each of the three simulations.

2.2.2.1.6 FTE Simulation Series 3 - Northwest New Mexico Climate

The third series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of northwestern New Mexico. These three simulations used similar design and produced waters as Simulation Series 2. In this simulation series, the temperature cycles simulated conditions typical of northwestern New Mexico. The simulations began with the month of April which is the first month in northwestern New Mexico with average temperatures consistently above 0°C. A total of 94 hours with temperature below 0°C existed during Simulation Series 3.

Two operational problems were encountered during the simulations. The two problems encountered during the operation of this simulation series were: 1) a short power-outage-induced controller failure (approximately six hours in duration) occurred during the evening of second day simulating June's conditions, and 2) microbiological activity became so great in the produced water ponds by the days simulating October conditions that the pond sprays in the simulator using the FTE B water (Simulation #3-3) became plugged which caused a large spill. The power outage had minor impact on results from the simulation series and no impact on the duration of the simulation series. The spill impacted both the results from Simulation #3-3 and the schedule of Simulation Series 3. To address as reasonably as possible the problems caused by the spill, the produced water holding pond for Simulator #3-3 was re-charged, and the size of the spill was estimated. Sprays in all three simulators were then shut-off for the remainder of the October simulation. After completion of the October simulation, which was the completion of the evaporation phase, the simulator was shut-down for six days to clean and dry electrical equipment wetted from the spill. This spill added six additional days to the simulation series duration so that the total duration was thirty days instead of the planned twenty-four.

The three produced water, three treated water, and three brine composite samples from Simulation Series 3 were subjected to limited chemical analyses (Table 3). Material and chemical species balances were determined for overall mass, TDS, TOC, and Boron for each simulation.

2.2.2.1.7 FTE Simulation Series 4 - Central Wyoming Climate

The fourth series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of central Wyoming. These three simulations also used similar design and produced waters as Simulation Series 2 and 3 but with temperature cycles that simulated conditions typical of central Wyoming. The simulations began with the month of May, which is the first month in central Wyoming with average temperatures consistently above 0°C. A total of 169 hours with temperature below 0°C existed during Simulation Series 4.

One problem was encountered during the operation of this simulation. During the first day of simulating conditions for January, the evaporator fan failed in the refrigeration unit. This failure resulted in loss of refrigeration in the unit and the simulation was down ten days awaiting parts for repairs. Thirteen and one-half hours with freezing conditions were lost in the series, and the duration of the series was thirty-four days instead of the planned twenty four.

The three produced water, three treated water, and three brine composite samples from Simulation Series 4 were subjected to limited chemical analyses (Table 3). Material and chemical species balances were determined for overall mass, TDS, TOC, and Boron for each simulation.

2.2.2.1.8 FTE Simulation Series 5 - Central Wyoming Climate with Detailed Analyses of Samples

The fifth series of laboratory simulations was to duplicate the operation and conditions of Simulation Series 4 using temperature cycles which simulated conditions typical of central Wyoming. A total of 182.5 hours with temperature below 0°C existed during Simulation Series 5.

One power-outage-induced temperature controller failure was experienced during this series of simulations which required one additional day simulating December conditions. Thus, the duration of this simulation series was twenty-five days.

The three produced water, three treated water, and three brine composite samples produced during Simulation Series 5 were subjected to detailed chemical analyses (Table 2). Material and chemical species balances were determined for overall mass, and every analyte specified in Table 2 that was present in sufficient quantity to allow balances to be determined. These balance were determined for each of simulations.

2.2.2.2 Subtask 2.2: Reevaluation of Process Economics Based on Laboratory-Scale Process Simulation Results

The process and economic models developed in Subtasks 1.4 and 1.5 were used with the results of the laboratory-scale simulations to estimate the water treatment cost. The laboratory-scale simulation data generated was used to select values of the required model inputs. By assuming the field situation will behave similarly to the laboratory-scale simulations, and using the material and chemical species balances resulting from the evaluations of the laboratory-scale FTE process simulations, the following data are provided for input to the models:

- location/climate simulated,
- the quality of the produced water, treated water, and brine, and
- the evaporation pond efficiency.

First, the results of the initial simulations conducted in Subtask 2.1 were used with the process and economic models to select the best design for a commercial-scale FTE process. The design configuration selected and used in the final twelve laboratory-scale simulations was the process design configuration having the lowest water treatment cost.

Next, the results of the remaining twelve laboratory-scale simulations were used with the process and economic models to determine the water treatment cost for those simulations. After completion of all the laboratory-scale simulations, the effect of the produced water contaminant concentration on the process was estimated by comparing results of each series of simulations using the three different waters. Then, the effect of atmospheric conditions on the process was estimated by comparing the results of the simulations using the same produced water and the three different sets of atmospheric conditions. The effects of these variables were used in the economic model to further refine the estimated water treatment costs of the FTE process. A total of twenty-one process and economic simulations were completed using the models developed and the laboratory-scale simulation results.

2.2.3 Task 3: Evaluation of the Field Demonstration of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico

Results of the laboratory simulations completed in Task 2 confirm that the FTE process is capable of providing significant quantities of water, suitable for beneficial use, from oil and gas produced waters. The TDS concentrations of the produced waters tested in the simulations ranged from 2640 to 10,900 mg/l. The treated waters generated in these simulations using the FTE process had TDS concentrations in the range of 200 to 1500 mg/l with, for the most part, similarly reduced concentrations of organics and metals. In addition, the economic analyses using the simulation results continue to indicate that the process has significant commercial economic potential. For these reasons, a field demonstration of the FTE process was conducted to confirm the results of the laboratory-scale simulations using atmospheric conditions at an operating field site. Successful demonstration of the FTE process will confirm: 1) the commercial-scale feasibility of the process, 2) the environmental acceptability of the process in order to facilitate regulatory permitting, and 3) the economic viability of the process in order to obtain investment capital.

The Task 3 research, "Evaluation of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico" was conducted in conjunction with a separate project entitled "Demonstration of the FTE Process in the San Juan Basin of New Mexico". In addition to the objectives listed above, the field demonstration was conducted to provide data to: 1) accurately design and project the economics of commercial-scale operation of the FTE process and 2) facilitate applications of the process to a variety of locations and produced waters. The research conducted in Task 3 supported the demonstration project by evaluating the technical and economic operation of the FTE process. The effectiveness of the demonstration project was determined from operating data, the results of analyses of the process streams, and process economics projected using the model developed in Task 1.

2.2.3.1 FTE Demonstration Site, Produced Water, and Climate

In order to conduct a field demonstration of the FTE process, an oil and/or gas production company that would support the project was identified. Requirements for the demonstration included the use of a operating evaporation facility, funding, and assistance permitting the demonstration project. Amoco Production Company's Cahn/Schneider evaporation facility was provided for the FTE process demonstration. This conventional evaporation facility is located 22 miles south of Durango, CO and 43 miles north of Farmington, NM. Amoco, the US DOE, and GRI provided the funding for the FTE demonstration project and personnel from Amoco's San Juan Operations Center obtained approval from the New Mexico Oil Conservation Division (OCD) to conduct the demonstration project.

Coal bed methane produced water, treated in the FTE demonstration, was trucked to the facility from nearby Amoco wells. This water was from similar sources as the coal bed methane produced water tested in the FTE laboratory-scale simulations completed in Task 2 (Simulations 2-1, 3-1, 4-1, and 5-1). Treated water TDS concentrations from these simulations ranged from 300 ppm to 1400 ppm, treated water yields ranged from 24% to 39%, and evaporated water ranged from 41% to 54%, yielding a corresponding reduction in disposal volumes ranging from 78% to 87%.

The climate at the Cahn/Schneider evaporation facility is similar to that simulated in laboratory Simulation Series 3. Simulation # 3.1 tested coal bed methane produced water under climatic conditions simulating the northwestern New Mexico climate. In this simulation, treated water with a TDS of 1400 ppm was produced with a reduction in the required disposal volume of 78%. Amoco's objective in the demonstration was to generate a water suitable for beneficial use in the area. Based upon the results of Simulation # 3-1, the FTE process appeared to be capable of economically achieving this objective.

2.2.3.2 FTE Demonstration Plant Design and Operation

Based upon discussions with Amoco Production Company and the New Mexico OCD, it was agreed that the FTE demonstration plant would attempt to treat 20,000 bbl of produced water during the winter of 1995-96 and that all products of the demonstration, including treated water generated, would be disposed of by conventional methods.

The original layout of the FTE demonstration plant constructed in the fall of 1995 at the Cahn/Schneider facility is provided in Figure 6. The Schneider evaporation pond is approximately 2 acres in size and was to serve as the produced water holding pond and final depository of the demonstration products. The Schneider pond was evaporated dry in the summer of 1995 and then filled with coal bed methane produced water for the FTE demonstration.

A feed pump, automatic pump controls and a 2500 ft long above ground feed line to the Cahn pond were installed and insulated to transfer water from the Schneider pond to the Cahn pond. The Cahn evaporation pond is one acre in size and was prepared for use as the freezing pad required for FTE process operation. The Cahn pond was also evaporated dry in the Summer of 1995. The pond was then thoroughly cleaned by a vacuum truck to remove the majority of sediment from the pond and the remaining sediment was swept and manually collected. Next, a one-and-one-half foot internal-berm was constructed of sand bags to isolate a portion of the Cahn pond as the freezing pad. The Cahn pond was approximately six times the size required to achieve the project objective of treating 20,000 bbl. Reducing the size of the freezing pad was attempted to improve the ability to separate the freezing pad runoff by improving drainage and pumping capabilities. A variety of pond sprays were installed in the existing spray header to investigate spray performance and the header was connected to the feed line. Then, the freezing pad suction header was installed.

The suction header was connected to a transfer pump to remove the runoff from the freezing pad. The transfer pump was automatically controlled by a level sensor in the Cahn pond. This pump discharged to the transfer shed which contained piping and electrical controls to automatically route the run-off to the proper vessel. Runoff from the ice pile that was created was to be separated into three process streams based upon its electrical conductivity (Ec). Water with an Ec indicating a TDS concentration greater than 50,000 ppm would be pumped to the brine storage tanks, water with TDS concentrations less than 5,000 ppm would be pumped to the treated water storage tanks, and water with a TDS concentration of greater than 5,000 ppm and less than 50,000 ppm would be recycled to the Schneider pond using an existing underground line.

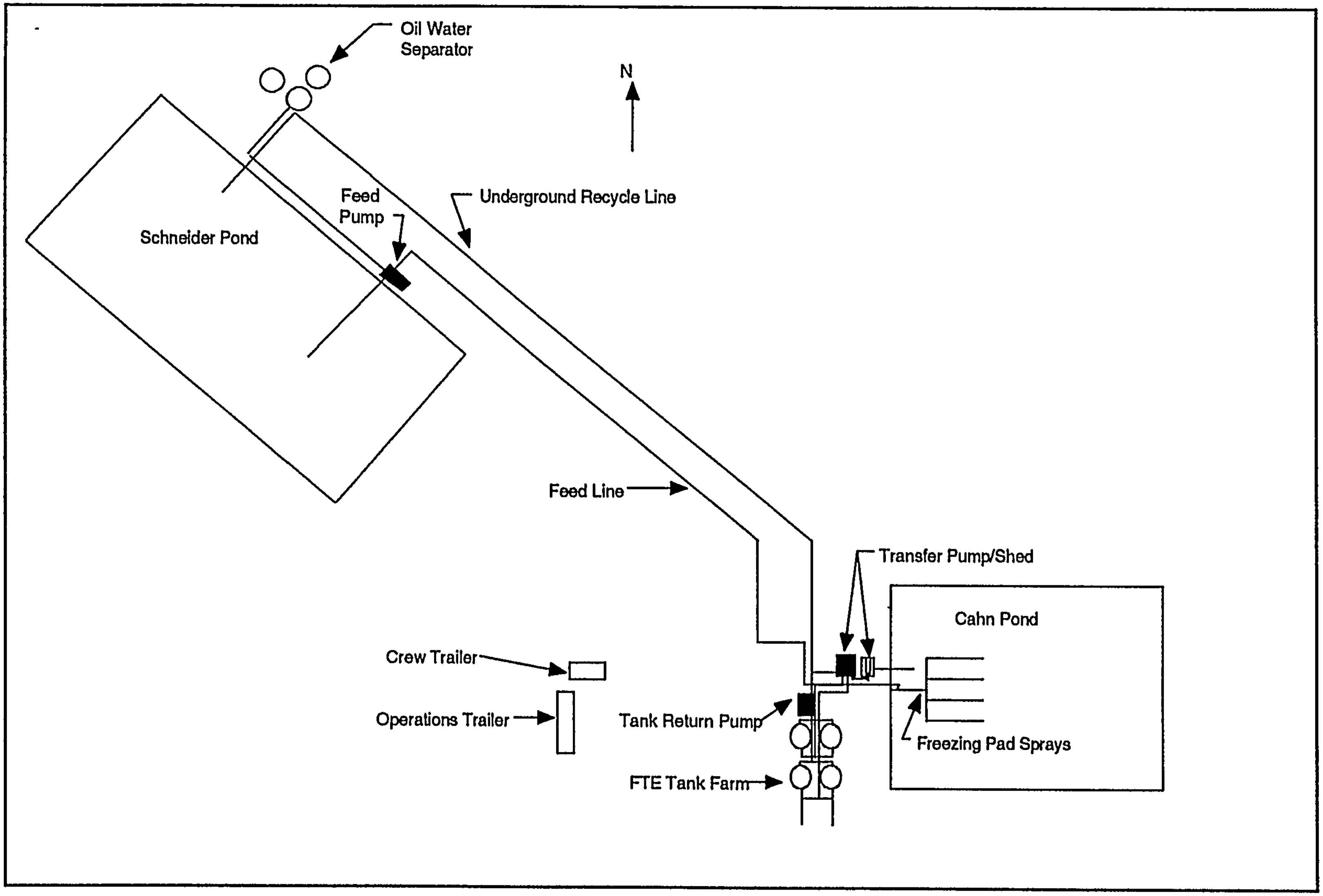


Figure 6. FTE Demonstration Site Layout

The FTE tank farm which included two 400 bbl brine storage tanks and two 400 bbl treated water storage tanks was installed along with piping from the transfer shed to the tank farm. A manually activated pump was also installed to transfer the waters in the brine and treated water storage tanks back to the Schneider pond when full. The transfer of fluids from the tank farm was also piped to utilize the existing underground line.

Shakedown of the FTE demonstration plant was conducted in late November and early December 1995. During the time period from November 28 to December 9, the plant was intermittently operated because of unusually warm weather. Modifications were made to the feed pump suction during this period and all other aspects of the plant design operated as intended. The plant was operated in the fully automatic mode for several days without problems. However, Ec measurements taken from samples of the freezing pad feed and Schneider pond water during this time were exceptionally high. For this reason, samples of the Schneider pond water were collected and analyzed at a local laboratory to determine their TDS concentrations. The results of the TDS analyses revealed that the Schneider pond water had a TDS concentration of 120,000 ppm. It was determined that, since the Schneider pond was not cleaned prior to the introduction of the coal bed methane produced water, salt precipitated in the Schneider pond was redissolved in the produced water causing the significant increase in TDS.

Interestingly, while awaiting the results of the TDS analyses, the plant was operated and a small amount of ice was made. Ec measurements of ice samples, taken immediately after spray operation ceased, indicated the ice contained less than 8000 ppm TDS. Ice samples were taken during the day as the ice melted. Based upon the Ec measurements of the ice melt, the TDS was steadily decreasing during the day and eventually dropped to approximately 900 ppm TDS.

Despite the fact that the FTE process appeared to be successful in generating useable treated water from the heavy brine in the Schneider pond, the decision was made to modify the plant operation so that representative coal bed methane produced water was treated. Treating feed water with a TDS concentration in excess of 100,000 ppm would be uneconomic based upon the results of Task 1 modeling and Amoco had never intended to attempt to treat waters with such high TDS concentrations using the FTE process.

It was apparent that it would not be possible to clean the Schneider pond and refill it with coal bed methane produced water in time to conduct the demonstration during the winter. Therefore, the decision was made to operate the demonstration, during the winter of 1995-96, using only the Cahn pond. As a result of this decision, the following modifications were required to the FTE demonstration plant. The original brine storage tanks, now became feed storage tanks, and were piped to be filled with coal bed methane produced water by truck. The tank return pump was piped to manually feed the freezing pad sprays from the feed tanks and the transfer shed was re-piped to route brine produced to the Schneider pond and recycle water through the freezing pad sprays. The Cahn pond now became effectively the produced/recycle water holding pond and the freezing pad (Figure 6).

These modifications made it possible to test the ability of freeze-crystallization to effectively treat coal bed methane produced water, but made it impossible to demonstrate the design improvements made in the FTE process compared to the natural freezing processes tested over three decades ago. Integral to the FTE process operation is the ability to evacuate runoff from the freezing pad so that the ice pile created can drain and the runoff can be separated into treated water, intermediate (recycle) water, and brine. Since water could no longer be recycled to the Schneider pond, the intermediate process stream had to remain in the Cahn pond. This concession completely eliminated an integral part of the FTE process - the ability to separate brine and treated water on a daily basis. Also, the ability to capitalize on the dynamic freeze/thaw cycling that occurs as a result of the prevailing climatic conditions in the San Juan Basin of New Mexico was lost, due to the loss of process stream separation capability. This had a major impact on plant operations.

Another complication was that the produced water supply was severely limited due to the inability to use the produced water in the Schneider pond. Instead of having the ability to feed the Cahn pond with fresh feed when needed, operations were now, at times, both limited by the quantity of produced water that could be delivered and the need to empty the feed tanks when water delivery was possible.

The general site layout of the modified FTE demonstration plant is similar to the original layout (Figure 6). Figure 7 is provided to illustrate the FTE final tank farm piping. Four 400 bbl tanks, two for

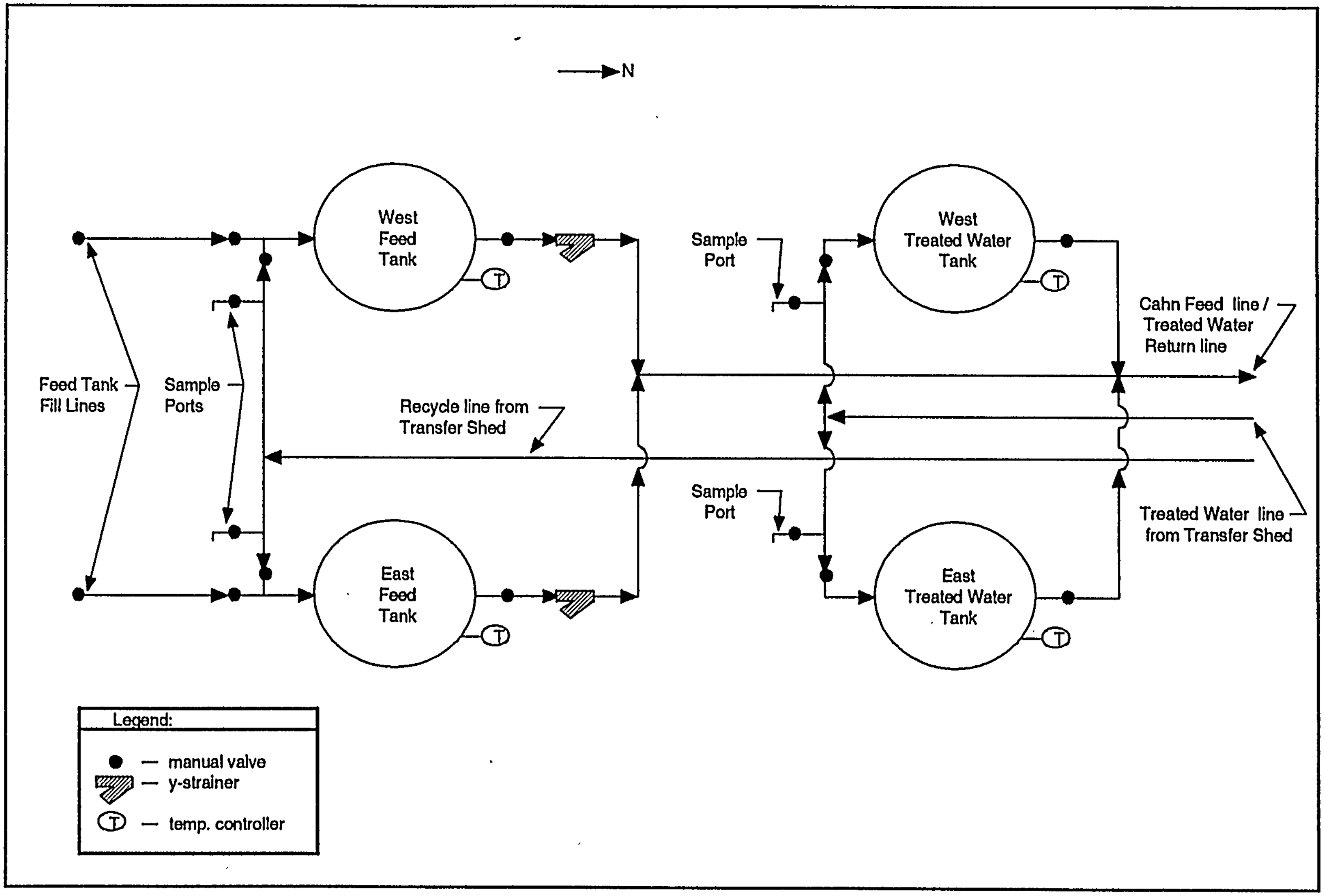


Figure 7. FTE Demonstration Tank Farm Piping

feed water storage and two for brine storage were provided near the southwest corner of the Cahn pond. The tank discharge piping was installed to either feed the freezing pad sprays or transfer treated water to the Schneider pond. Both feed tank inlets were modified to either accept recycled water or produced water from trucks. Both treated water tank inlets are piped as originally designed, accepting treated water from the transfer shed (Figure 7).

Figure 8 is provided to illustrate the FTE feed piping to the Cahn pond and transfer system to evacuate or recycle runoff from the Cahn pond. Piping from the feed tank outlets runs from the tank farm through the return pump to the spray header. The pump and valves in this system were manually activated as a result of the modifications. Feed water introduced from these tanks flows through a solids separator, a feed totalizer, and then to the Cahn pond spray header. Runoff from the freezing pad in the Cahn pond is removed from the suction header using the transfer pump. The runoff can then be either recycled back to the spray header or pumped to the transfer shed.

Figure 9 illustrates the FTE transfer shed piping at the Cahn pond. This piping is as originally designed with the exception of the transfer shed outlet piping, which was modified to transport recycle water to the feed tanks and brine to the Schneider pond. The transfer shed operation was automatically controlled as follows: the conductivity of water from the transfer pump was measured by a conductivity controller (TDS2) to determine the TDS concentrations. Waters with TDS concentrations greater than 50,000 ppm flowed through a solenoid valve (S1), through a flow totalizer, and to the Schneider pond. Waters with TDS concentrations of less than 50,000 ppm flowed through a second solenoid valve (S2), where the TDS concentration of the water is measured by another conductivity controller (TDS3). Waters with a TDS concentration of less than 5,000 ppm flowed through a third solenoid valve (S3), through a flow totalizer, and to the treated water storage tanks. Waters with TDS concentrations of greater than 5,000 ppm but less than 50,000 ppm flowed through a fourth solenoid valve (S4), through a flow totalizer, and to the feed tanks (Figure 9).

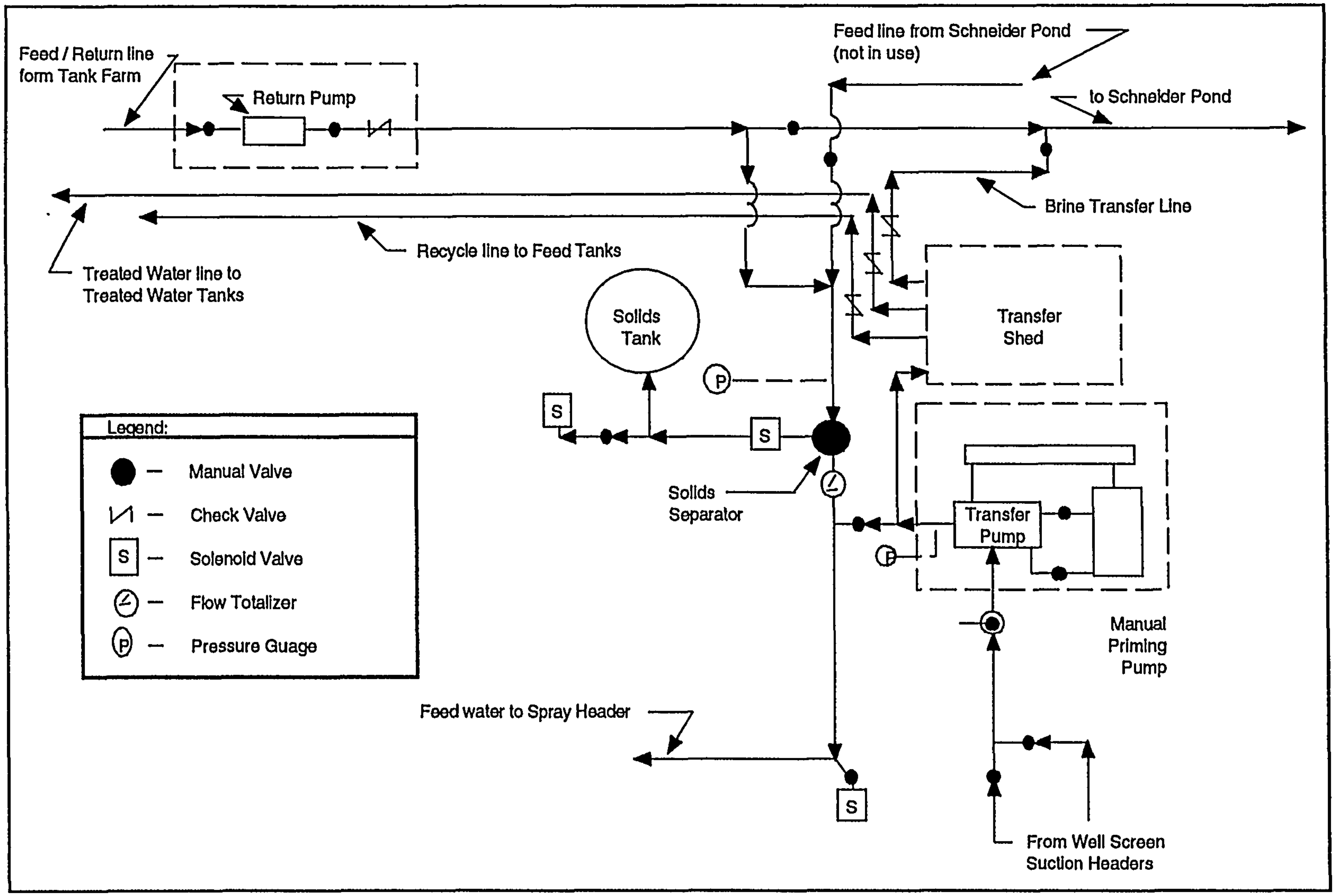


Figure 8. FTE Demonstration Feed and Transfer Piping

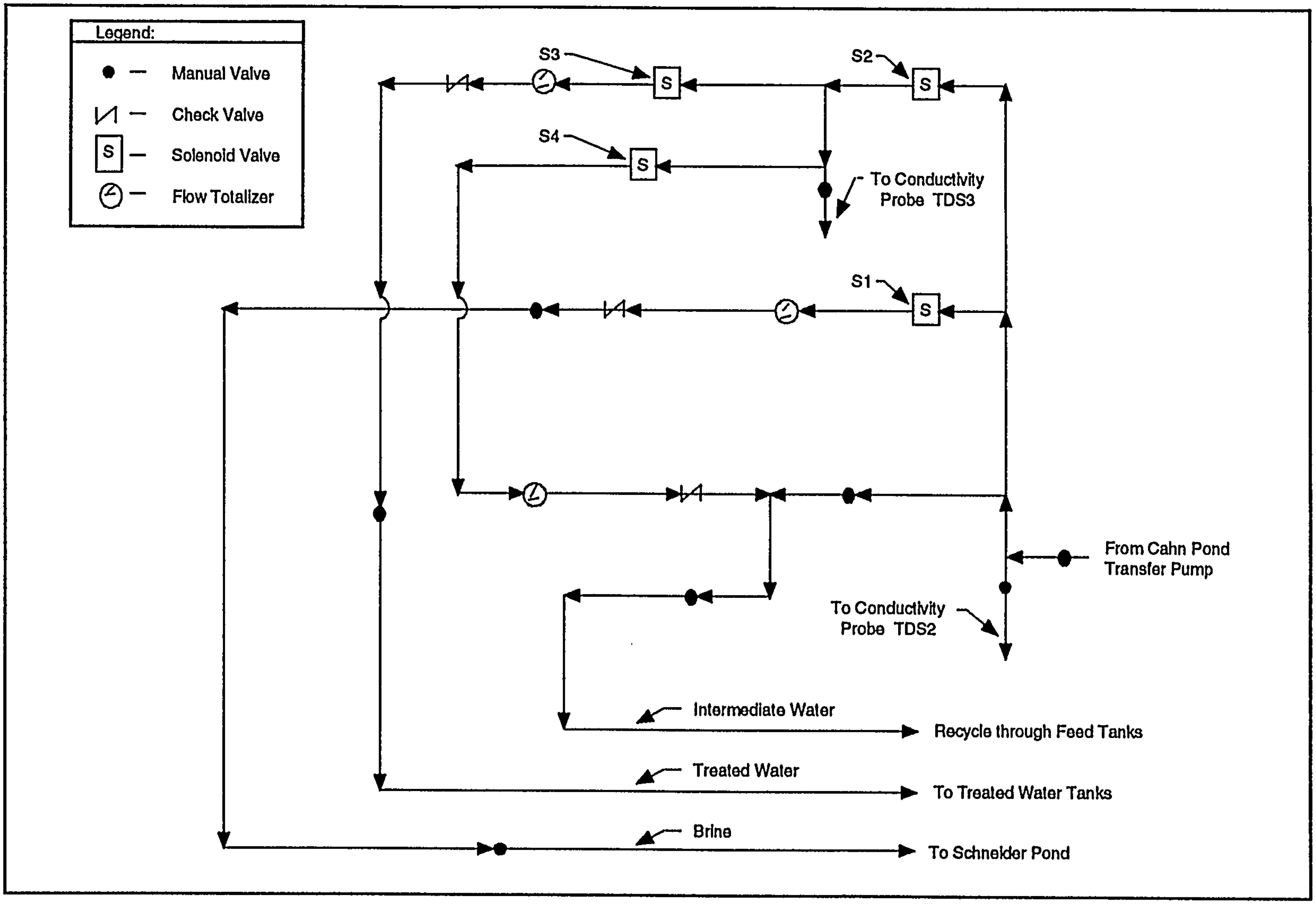


Figure 9. FTE Demonstration Transfer Shed Piping

2.2.3.3 Subtask 3.1: Sampling and Analyses of Field Demonstration Process Streams

Samples of feed water, Cahn pond water, and ice were regularly collected and Ec measurements were taken using conductivity meters in the operations trailer. On-site gravimetric analyses to determine the TDS concentration of selected samples were conducted in conjunction with the Ec readings in order to correlate TDS concentrations for the waters with Ec. The standard method for gravimetric analysis is ASTM method #2540 A. Having plant operators conduct this method at a remote field-site was not practical and the method was modified to be more compatible with field operations. The simplified gravimetric TDS analysis method used at the field site was as follows:

- A weighed filtered volume of sample was placed in a convection oven operating at 130°C. ASTM method #2540 A calls for drying samples at 180°C to convert bicarbonate to carbonate. Field modifications to this method utilized 130°C to minimize conversion of bicarbonate to carbonate. Bicarbonate is a major constituent of this coal bed methane produced water and of potential economic value so destruction of bicarbonate was considered to be undesirable in these analyses.
- The samples were allowed to dry in the oven until all water was visibly evaporated. They were then weighed. Samples were returned to the convection oven for at least thirty minutes and then re-weighed. This process was repeated until the weight loss of the sample during drying was insignificant.
- The solids weight of the sample was determined as the final weight minus the tare weight. The TDS concentration of the sample in mg/l was then determined from the solids weight and the initial sample weight.

Samples of the FTE field demonstration process streams were to be collected and subjected to laboratory analysis as described below:

- A full suite analyses of the feed water was to be performed initially on the feed water stored in the produced water holding pond (Schneider pond) (Table 2).
- Limited suite analyses of composite samples of the produced water, treated water, and brine from the demonstration were to be performed at the end of the first, third and fifth month of operation of the demonstration (Table 3).

- Full suite analyses of composite samples of the produced water, treated water, and brine from the demonstration were to be performed at the end of the second, fourth, and six month of operation of the demonstration (Table 2).

However, due to the inability to use the water in the Schneider pond, delays in start-up of the demonstration operation resulting from the modifications to the plant that were required, and the unusually short winter in the area last year, the sampling scheme was revised to reflect the type and quantity of process streams available for sampling.

After examination of the high Ec measurements of the water samples initially taken from the Schneider pond, three samples were sent to a local analytical laboratory for TDS analysis to confirm the high salt concentrations indicated by the on-site Ec measurements. A local laboratory was selected for the analyses and the limited suite of analyses was reduced to only TDS analyses to facilitate a rapid turnaround of these needed results. Upon receipt of these analytical results it was obvious that the water in the Schneider pond was not desirable for treatment using the FTE process and subsequent modifications to the plant were initiated. After modifications were completed and the plant operation was re-initiated on December 9, 1995, the initial sampling of the produced water pond was not possible.

During the time period of 1/22 - 1/24/96, samples of the produced water feed, Cahn pond recycled water, and ice from the Cahn pond were collected and submitted for analyses at the local laboratory. In addition, another sample of the heavy brine from the Schneider pond was also collected and submitted for analyses. In these analyses, the limited suite was modified. Boron and TOC analyses were not conducted on these samples. Instead, total alkalinity, bicarbonate, and carbonate analyses were conducted along with the TDS and pH analyses originally planned.

Composite samples of the feed water, ice, and brine for the time period of 12/9/95 through 2/1/96 were submitted for detailed analyses (Table 2). As a result of unusually warm temperatures in February 1996, these were the only aqueous samples collected during operation of the freezing process that were submitted for detailed analyses.

Cahn pond water and feed water samples were also collected at the conclusion of the field demonstration (3/18/96) and submitted for detailed analyses (Table 2). Results of these analyses were used to estimate evaporation during the months of February and March.

Solids produced from the gravimetric TDS analyses of the Cahn pond water were crushed, composited, and submitted for detailed analyses. These analyses included all Table 2 parameters except volatile organic analyses. Volatile analyses were not conducted because the heating of the sample required to produce the solids would have likely removed all volatile organics. The solids were also submitted for semi-quantitative XRD analysis. Analytical characterization of these solids were performed to assess the potential economic value and beneficial uses of the solids.

2.2.3.4 Subtask 3.2: Evaluation of Field Demonstration Operating Data

FTE field demonstration operating data collected included: time, wind speed, ambient air temperature, feed tank temperature and water level, Cahn spray header temperature, feed pressure, cumulative feed volume, feed flow rate, feed TDS and Ec, feed temperature, Cahn pond TDS and Ec. These data were compiled in the operations log book, operator's log sheets, and an on-site data logger.

The volume of produced water fed to the Cahn pond and the volume of brine sent to the Schneider were determined from the operating data collected. These data were used in conjunction with the results of the feed, ice, and brine analyses to determine material balances. These data were also compared to the results of the final Cahn pond and feed water analyses to estimate February and March evaporation rates. Estimates of the economics of a commercial-scale FTE operation at this site were also made using the above data and the model developed in Task 1 of this research.

Temperature data were analyzed to determine how many hours of subfreezing conditions occurred during the demonstration period. These data were then compared to the average number of hours of subfreezing conditions that occur annually in the San Juan Basin of New Mexico.

TDS concentration and Ec readings were correlated to provide a method for qualitatively estimating TDS concentrations of these waters from Ec measurements. On-site gravimetric TDS results and analytical laboratory TDS results were correlated to estimate the accuracy of the field method for determining TDS concentration.

3.0 Results and Findings

3.1 Task 1: Literature Survey and Preliminary Economic Analyses

3.1.1 Subtask 1.1: Literature Survey of FTE Research

The following is a summary of literature reviewed. Appendix A provides a listing of the publications reviewed. The summary is divided into two sections: literature related to natural freezing methods and literature related to artificial freezing methods.

3.1.1.1 Natural Freezing Research

Heller (1939) investigated the purification of brackish groundwater in the desert areas of the former Union of Soviet Socialist Republics (USSR). Heller investigated the use of natural freezing to purify brackish groundwater and provide water for agricultural development in these regions. Heller was able to reduce the salt content of the water tested from approximately 15,000 ppm to 400 ppm. Heller also provided data indicating that as the ice formed from this brackish water and was subjected to freeze-thaw cycles, the salt content of the water was dramatically reduced.

Mitin's (1963) research objectives were similar to those of Heller. In Mitin's research, the feed water salt content of approximately 29,000 ppm was reduced to less than 1,000 ppm. Mitin found that water could be effectively purified by natural freezing. The results show that natural freezing did concentrate the salts in the brine and allowed a 70% conversion of the saline water to useable water with the salt content reduced by 96%. Mitin also demonstrated the ability to create potable water using a natural freezing process. The water he produced met the USSR drinking water standards at the time. Mitin also produced a brine with a salt concentration of approximately 180,000 ppm. Mitin estimated the cost of purification to be $0.30 per cubic meter (approximately $0.04/bbl). He also estimated the process to be 70% more economical than purification by evaporation.

Szekely (1964) of the Saskatchewan Research Council performed experimental work related to water purification by freezing in dugouts. Six waters with TDS concentrations ranging from approximately 4,000 to 28,000 ppm were tested, and the salinity reductions ranged from 60 to 80%. The lower salinity reduction from these tests can be accounted for by the fact that the initial ice melt was not drained from the ice. Therefore, the separation of brine from the ice was not as completely achieved as in the Soviet efforts.

Canadian research related to water purification by natural freezing continued, and Spyker (1974), also of the Saskatchewan Research Council, reported on later experimental work related to water purification by freezing in dugouts and by spray freezing. The TDS concentrations of the waters tested were only in the range of 2,000 to 4,000 ppm, but the initial TDS concentration of the melt from one of the spray ice piles was in excess of 50,000 ppm.

Stinson (1968) received a Canadian patent on a process of natural freezing as a method for desalinating waters. Stinson's patent was based upon the concept of spraying water during subfreezing temperatures to maximize ice production and to minimize the space required for the ice pile. While Stinson's process differed from Mitin's and Szekely's, the results of Stinson's research supported their findings. Stinson found that natural atmospheric temperature cycles cause freeze-thaw cycles which improve the purification efficiency of the natural freezing process. Stinson's research confirmed that the freeze-thaw process is effective in purifying saline waters and waters containing acids, bases, sugars, and organic materials. The patent included a claim that this method can also be used to treat oil field brine. The dissolved salts are the most unacceptable component of oil field brine waters, and the method allows the brine (dissolved salts) to be concentrated so that disposal can be more easily and economically accomplished. In addition, the accumulated ice can provide a valuable source of fresh water for wildlife and/or agricultural lands. Stinson's research also indicated that the purest ice is formed as a result of longer holding times because the ice is subjected to a series of re-crystallization (freeze-thaw cycles) which allows more of the contaminants to drain through pores of the ice pile. Stinson estimated the cost of water purification by this method to be less than $0.01 per 1000 gallons.

Research was also successfully conducted by the University of Wyoming Petroleum/Chemical Engineering Department during the 1960s and 1970s to improve the quality of brackish well water to potable water standards by using natural freezing. Elmore (1968), a petroleum engineering graduate student of Stinson's, conducted research related to water purification by spray freezing. During the winter of 1967-1968, ice piles 22 feet high were created using conventional lawn sprinklers. Feed water, with TDS concentrations ranging from 1700 to 2300 ppm, was purified by natural freezing to produce 1.2 million gallons of potable water from the melting ice. The TDS concentrations of the purified water ranged from 60 to 400 ppm. Selected samples indicated that water which did not freeze during the formation of the ice piles probably had concentrated a TDS content of near 50,000 ppm. The results also indicated that the lower the freezing point of a given salt, the more rapid the reduction of that salt in the ice pile. Elmore found that ions such as chloride, nitrate, potassium, and sodium accounted for an 8:1 reduction, and concentrations from ions such as calcium, magnesium, bicarbonate, and carbonate were reduced by approximately 2:1. According to these results, waters containing high concentrations of the latter would be the most difficult to purify and waters containing high concentrations of sodium chloride, calcium chloride, and potassium chloride would be easiest. Elmore's data also show that the purest ice was formed during the highest temperatures, and the ice containing the most contaminants was formed during the lowest temperatures. Elmore estimated the cost of water purification by natural freezing to be $0.27 per 1000 gallons of water purified ($0.01/bbl).

Stinson (1974) also conducted a field experiment on the Big Sandy River in Wyoming to investigate the feasibility of reducing the TDS content of the saline water in this river by natural freezing. The experiment was plagued by equipment failures related to a diesel generator used to supply power to the site. However, one note-worthy achievement of the test was that one of the ice piles had a TDS concentration (30 ppm) less than a nearby snow drift which contained alkaline soil from the area. Apparently, the spraying of the ice pile preventing blowing soil from accumulating in the pile.

3.1.1.2 Artificial Freezing Research

Baker (1967), from the Mellon Institute, used an artificial freezing technique to quantitatively concentrate various organics in aqueous solution in the absence of inorganic salts. Two methods were used in this study: 1) single stage freezing and 2) cascade freezing. Baker found that near complete organic recovery was accomplished by the single-stage freezing. Mixing did not play a role in the recovery rate of the organics, and there was no difference in the type of organic when comparable concentrations were used. Baker also discovered that by using a cascade of single-stage freezing, complete recovery to µg/L levels was accomplished. Initial organic concentrations of 0.1 - 10.0 mg/L were used and complete recovery was achieved. Organics in complex mixtures also made no difference in the recovery of the individual components.

Baker's second study (1967) used inorganics in the presence of organics to see if the inorganics affected the efficiency of recovery and found that the addition of salts to the solutions resulted in reduced recovery and reduced concentration of organic solutes. Contrary to the first study, Baker found that mixing or agitating the solutions did play a role in recovery when inorganic salts are present.

Malo and Baker (1968) found that freezing could be used to increase the recovery efficiency of assorted cations. The cations whose behavior in the freezing process were investigated included Fe, Cu, Zn, Mn, Pb, Ni, Ca, Mg, and K. Within the initial cation concentration ranges of 0.1 to 10 mg/L, the percent recovery did not vary among the cations. Several other variables were studied to determine factors that may play a significant role in the concentration/recovery rate of various cations. The experimental data indicated: agitation improved the recovery rate of all cations studied, increased acidity improved the recovery efficiency of Ca, Mg, and K (alkali metals), and increased alkalinity improved the recovery of heavy metals such as Pb, Ni, and Cu. The results also indicated that as the concentration of TDS increased, the recovery, with regard to specific cations and organics, decreased.

Smith and Tasker (1965), of the National Chemical Laboratory in Great Britain, found that the concentration of inorganic substances (salts and metals) was easily accomplished by artificial freezing. The study was conducted to see whether freezing, as a method of concentration, could be applied to minute (1 ppm or less) solute concentrations. The data show a ten fold increase in the solute concentration following the method of freezing.

Sheng (1969) and co-researchers from Kansas State University, found that the inversion desalination process would be effective in producing fresh water from salt water. A back-mixed type contactor using direct freezing was able to produce 1000 to 2000 liters of fresh water per day from each cubic foot of the contactor. Ice crystals produced by this method were of good quality with low salt content which indicated that the ice washing operation could be carried out effectively.

Several commercial-scale water treatment processes using freeze crystallization have been available for approximately two decades. Interestingly, these processes differ significantly in their basic design and operation. A 100,000 gal/day (69 gal/min) commercial unit was available in the early 1970s. This unit, manufactured by Avco Systems Division, was called the "Crystalex^{TM} Process". The "Crystalex^{TM} Process", a two-stage process, used an immiscible secondary refrigerant (R-114) in a direct-contact crystallizer followed by a surface-type melter/condenser and a pressurized wash column. Data regarding the effectiveness of this process treating a simulated metal-finishing waste containing approximately 100 ppm each of Ca, Cr, Ni, Na, and Zn indicate the percent removal of metals ranged from 99.6 to 99.8 (Ziering, 1973).

Another commercial freeze crystallization unit, the "DirCon^{TM}" process by Freeze Technologies Corp. of Raleigh, NC, is currently commercially available. Freeze Technologies Corp., formed in 1987, is a joint venture between Heist Engineering and the Environmental Systems Company (Roy, 1990).

The "DirCon^{TM}" process also uses direct-cooling of the water to be treated by contact with refrigerant. The process is similar to the "Crystalex^{TM} Process" but somewhat simpler. Freeze Technologies Corp. literature claims the "DirCon^{TM}" process is applicable to reclamation and recycling of pickling liquor, treatment of pharmaceutical and chemical plant wastewaters, reclamation and recovery of munitions plant wastewater, recovery of heavy metals and purified water from metal finishing wastewaters, recovery of acetic, formic, and citric acids from a variety of wastewaters, recovery of solvent and solvent mixtures, including halogenated solvents and aromatics, and separation of pure water from wastewater prior to incineration. Corporate officials claim treated water purity of greater than 99.99% and treated water yields of about 90%. Purification of leachate from interception wells at the Stringfellow Superfund site in Riverside, CA is currently being negotiated with the EPA and company officials claim a 10 gal/min portable unit is ready. The company projects amortized water treatment costs for 25,000 gal/day and 40,000 gal/day modular plants to be in the neighborhood of 9 cents/gal and 4 cents/gal, respectively (Roy, 1990).

The final freeze crystallization process discovered in the literature survey was designed by Horton Process Design Inc. (HPD). Research related to this process began in the 1960s by Chicago Bridge and

Iron (CBI) who produce evaporators and crystallizers. In the 1970s, one of the divisions of CBI formed an independent company, HPD. During the late 1970s and early 1980s, CBI secured over twenty US patents relating to processes and equipment for freeze crystallization. HPD acquired the rights to these patents and, in the late 1980s, began negotiations with Louisiana-Pacific Corp. (LPC) to construct a 1,000 gal/min freeze crystallization plant for the LPC chemical-thermal-mechanical-pulping mill in Chetwynd, British Columbia. The plant is now on line and is the first pulp and paper mill to operate with zero-liquid waste discharge. The plant separates pure water from wastewater containing primarily lignin, organic acids, alcohols, aldehydes and inorganic salts. The 1,000 gal/min plant is approximately 150 ft by 150 ft and requires one full-time operator. HPD has also constructed several 100 gal/min units to process sea water. The HPD freeze crystallization system is relatively straight-forward with respect to standard industrial crystallization technology. A major difference in the HPD design compared to the two commercial designs discussed is that HPD has opted to cool the incoming wastewater using indirect cooling in a heat-exchanger instead of direct refrigerant cooling. HPD testing of pulping wastewater shows a reduction of inorganics from 10,000 ppm and 15,000 ppm to less than 50 ppm, and reduction of organics from 12,000 ppm and 20,000 ppm chemical oxygen demand (COD) to less than 50 ppm. The treated water contains no turbidity or color, and bioassays show no toxicity. HPD claims energy advantages similar to other freeze crystallization processes and indicates capital costs are comparable to evaporation circuits. Other advantages of the process are: applicability to a wide range of wastewaters, production of high quality water, etc (Roy, 1990).

As a result of the literature survey, a comprehensive summary of related research was compiled. The response of salts in waters subjected to natural freeze-thaw cycles is well documented. However, the responses of organics and heavy metals is not well documented for the natural process. The responses of organics, heavy metals, and salts is well documented for artificial processes, but due to the more effective removal of all types of constituents using artificial freezing processes, it is difficult to estimate the response of organics and heavy metals to the natural process. Interactions between contaminant constituents that could impact the effectiveness of the process are also unclear for the natural process. Sufficient information related to process parameters was acquired to conduct preliminary economic analyses by assuming the behavior of the TDS is indicative of the behavior of the contaminant constituents in general.

3.1.2 Subtask 1.2: Characterization of Natural Gas Produced Waters and Conventional Treatment Costs

As previously discussed in Section 2.2.1, produced water quality data were obtained and based upon Subtask 1.1 results and current environmental regulatory practices, analyses to be considered in this research were limited to those with TDS concentrations below 75,000 ppm and above 5000 ppm. The 1680 individual water analyses obtained were reduced to 946 analyses within the TDS limits considered. The median, maximum, minimum, and average values were determined for each analyte in the data set (Table 4). The table also provides the number of water quality analyses in the database containing data for each analyte.

Table 4. Summary of Produced Water Quality Database

Parameter, units	# of Analyses	Median	Concentration Minimum	Concentration Maximum	Mean
TDS, ppm	946	14,700	5007	73,000	20,000
NaCl, ppm	459	13,700	260	72,500	20,000
Na, ppm	858	5,100	4	56,000	6,600
Mg, ppm	798	50	1	2,300	130
Ca, ppm	828	200	1	8,800	500
SO_4, ppm	781	750	1	54,000	2,100
Cl, ppm	911	6,900	3	82,000	11,000
CO_3, ppm	187	150	1	11,000	340
HCO_3, ppm	803	950	13	33,000	1,700
pH, --	792	7.5	3.3	11.6	7.4
Oil & Grease, ppm	21	8	1	778	55
Phenol, ppm	14	0.2	0.04	1.4	0.4
Ethylbenzene, ppm	6	0.4	0.1	4.5	1.2
Benzene, ppm	17	1.5	0.1	30	10
Toluene, ppm	9	2.1	0.06	10	2.6
Xylenes, ppm	10	0.9	0.06	47	8.8
As. ppm	41	0.01	0.01	1.5	0.13
Ba , ppm	58	0.24	0.10	4.2	0.35
Cr, ppm	58	0.03	0.01	5.3	0.31
Pb, ppm	19	0.02	0.01	0.3	0.05
V, ppm	41	38	14	110	50
U, ppm	18	26	0.01	67	28
Ra 226, pCi/L	381	4.5	0.01	280	16

Atmospheric conditions depicting the range of geographic locations where the FTE process is applicable were chosen to be those of the eastern front range of Colorado, representing a relatively mild climate; the upper peninsula of Michigan, representing a severe climate; and central Wyoming, representing a median climate. Meteorological data for the cities of Denver, Co, Sault Ste. Marie, MI, and Casper, WY were selected to provide climatic data representative of these regions. The average meteorological data were obtained from the US Department of Agriculture National Oceanic Atmospheric Administration National Weather Service databases. The data acquired contained approximately of 25 years of daily average data for the following parameters: precipitation, PAN Evaporation, temperature, wind velocity, and solar radiation. The data were compiled and the monthly averages for the twenty five year period were calculated (Table 5). The data in this table were used in the process design evaluation completed in Subtask 1.4.

Contacts were made with personnel from Amoco, Chevron USA, Silverado Oil, Thorofare Resources, and Kissack Water and Oil Services. Amoco and Chevron USA are major oil and gas producers with significant holdings in Colorado and Wyoming. Silverado Oil and Thorofare Resources are independent oil and gas producers with primary holdings in Colorado and Wyoming. Kissack Water and Oil Services operates a produced water disposal facility in northeastern Wyoming (deep well injection). All persons contacted expressed interest in the research, and Amoco, Silverado Oil, and Thorofare Resources expressed a willingness to provide a demonstration site for Task 3.

Currently the most frequently used disposal options are most often used are: 1) to use the water for injection during water flooding of neighboring fields, 2) disposal by Class I or Class II deep well injection, 3) on-site evaporation, and 4) on-site surface discharge. Based upon the information from the contacts, surface discharge is the most desirable option if the produced water is of sufficient quality to permit its discharge. Use of the produced water for water flooding can also be an inexpensive and desirable option. However, the water must be of a chemical composition suitable for flooding, compatible with the geochemistry of the reservoir, and near the water flood injection wells. Transportation costs to ship the water to the water flood injection wells can range from a very small amount to approximately $1.50/bbl.

Table 5. Monthly Average Meteorological Data for Denver, CO, Casper, WY, and Sault Ste. Marie, MI

Month	Precipitation (cm)	PAN Evaporation (cm)	Temperature (° C)	Wind Velocity (cm/sec)	Solar Radiation (langleys)
Denver, Colorado (Monthly Averages for 1948-83)					
January	0.044	0.141	-1.478	387.188	187.586
February	0.055	0.192	0.846	404.643	266.119
March	0.108	0.271	3.282	444.354	345.868
April	0.152	0.434	8.655	455.879	461.922
May	0.211	0.518	13.811	420.230	486.235
June	0.147	0.692	19.314	402.305	567.635
July	0.146	0.716	22.887	375.172	555.663
August	0.117	0.616	21.935	362.027	494.568
September	0.097	0.482	17.151	371.855	424.011
October	0.076	0.320	11.099	357.583	323.347
November	0.070	0.190	3.876	380.340	223.988
December	0.048	0.148	0.109	393.971	179.146
Casper, Wyoming (Monthly Averages for 1949-83)					
January	0.042	0.121	-5.529	733.142	139.152
February	0.047	0.161	-2.762	697.582	215.358
March	0.082	0.226	0.152	625.856	294.562
April	0.129	0.349	5.681	572.211	380.579
May	0.176	0.458	11.203	518.566	437.260
June	0.115	0.654	17.003	491.744	536.797
July	0.092	0.753	21.544	463.994	566.246
August	0.050	0.646	20.609	464.922	494.783
September	0.073	0.458	14.655	491.744	386.920
October	0.075	0.288	8.357	547.666	265.045
November	0.058	0.170	0.726	639.690	174.662
December	0.049	0.131	-3.699	744.229	133.054
Sault Ste. Marie, Michigan (Monthly Averages for 1947-83)					
January	0.186	0.048	-10.427	447.040	99.572
February	0.149	0.064	-9.692	429.181	171.335
March	0.167	0.122	-4.576	460.451	267.006
April	0.208	0.260	3.140	469.392	375.844
May	0.233	0.425	9.731	442.570	463.585
June	0.280	0.493	14.536	389.492	479.735
July	0.231	0.527	17.600	357.713	488.838
August	0.265	0.420	17.241	353.162	407.938
September	0.317	0.255	12.665	388.925	276.400
October	0.236	0.151	7.497	420.172	175.635
November	0.271	0.075	0.356	442.539	101.241
December	0.211	0.050	-6.814	449.558	80.418

On-site evaporation is currently an inexpensive option but is severely restricted by climatic conditions. Amoco is currently operating evaporation ponds in southern Colorado to dispose of an estimated 50,000 bbl/day of water produced from methane drainage wells. Amoco also owns disposal wells in the area and during the winter months is required to use the disposal wells because climatic conditions render evaporation ineffective. In addition, prior to July 1992, on-site evaporation ponds were not required to be lined unless the produced water was toxic. However, new regulations require liners if the water is of TDS concentration greater than 10,000 ppm or is toxic.

All companies contacted used deep well injection for disposal of some of their produced water. Costs for deep well injection ranged from $0.04 to $2.27/bbl when transportation of the water to the disposal well was included. Estimates for the completed cost of a permitted Class I or Class II disposal well ranged from $2.5 to $3.0 million. Costs for using a Class I (commercial) disposal well ranged from $0.60 to $0.85/bbl delivered to the disposal well. Transportation costs ranged from $0.30 to $1.42/bbl. Independent producers generally experience higher disposal costs than the larger companies. The reason for this is that the independent producers generally do not require enough disposal capacity to economically justify the cost of drilling and permitting a disposal well, or to construct a pipeline to transport the water to the well. This is unfortunate because, in many cases, the small independents can operate wells at a lower cost due to lower overhead. They often purchase depleted or economically marginal wells from the majors and continue to operate them. Communication with producers and operators of disposal facilities regarding treatment, handling, and disposal of produced water will continue.

In summary, the research efforts conducted in Subtask 1.2 provided data that characterize the typical concentration ranges of constituents in oil and gas produced waters that are applicable to the FTE process. Daily average meteorological conditions were determined for moderate, median, and severe climates applicable to the FTE process. Information was obtained regarding the current oil and gas produced water treatment and disposal methods and costs. Four of the companies contacted have expressed a willingness to participate in a field demonstration of the FTE process.

3.1.3 Subtask 1.3: Evaluation of Process and Environmental Constraints

Research efforts related to the completion of this subtask were directed toward evaluating the regulatory requirements for implementing the FTE process in Colorado, Wyoming, and Michigan. The following sections provide regulatory and permitting requirements for design, construction, and operation of an FTE process treating oil and gas produced waters in these states. The information is provided by state in the following sections. It is important to note that the type of operation assumed can determine the jurisdiction for the permitting and regulatory processes in some states. When a facility is owned and operated by the company responsible for generating the produced water, the facility will be referred to as an owner-operated type facility. An owner-operated type facility treats only waters produced from wells held by the entity owning and operating the FTE facility. The second type of facility will be referred to as a commercial type facility. A commercial type facility treats produced waters from wells owned by other entities for a fee.

3.1.3.1 Regulations in the State of Colorado for Treating and Discharging Oil and Gas Produced Waters

The information in this section identifies the regulatory requirements and environmental permitting for the design, construction, and operation of a FTE treatment process in the state of Colorado. The Department of Natural Resources Oil and Gas Conservation Commission (DNROGCC) of the State of Colorado is the agency responsible for approving the design, construction, and operation of the FTE facility, whether the facility is an owner operator type or commercial. A permit is also required for the FTE facility to surface discharge the treated water. The Colorado agency responsible for this permit is the Colorado Department of Health Water Quality Control Commission (CDHWQCC) regardless of the facility type.

The following information is based on the regulatory requirements for process discharges and costs associated with conventional methods of treatment. The same criteria is assumed for the FTE process. From consultations with personnel of the Colorado Oil and Gas Commission, it was determined that the FTE treatment process will be viewed to be a more environmentally acceptable option than conventional methods of disposal.

In the state of Colorado, the first step in the permitting process for an FTE facility is the acquisition of a National Pollutant Discharge Elimination System (NPDES) permit to approve the surface discharge of the treated water from the process. Water quality limits for the surface discharge of water are not standardized in the state of Colorado, but are instead set and applied on a site specific basis. Therefore, it is impossible to determine what exact discharge limits would be placed on a FTE facility which operates in the state. Colorado does not have state-wide standards for TDS/salinity, sulfates, or most major cations and anions. The limits are determined on a site-specific basis and are influenced by the major drainage basin in which the discharge is located and the use of that area (aquatic life, agricultural, or drinking water supply). Limits placed on metals concentrations in discharged waters are also dependent upon the type/use of the area of discharge and are again applied on a site-specific basis. This same principle applies to the inorganic, physical, and biological parameters (excluding TDS/salinity). The preceding are referred to as "Table Value Standards." The applicability of the standards is site-specific. Procedures to estimate what the actual limits may be for a given constituent in water discharged at a given location are provided in <u>The Basic Standards and Methodologies for Surface Water</u> by the CDHWQCC. The recommended approach for obtaining an NPDES permit in the state of Colorado is to contact and work with the state regulatory personal as soon as possible because they may use considerable discretion in making their decisions. While all of the rules and regulations discussed will be taken into account for the approval/disapproval of the permit, most of the standards will be implemented on a case-by-case basis. Therefore, it is essential that detailed information be submitted with the permit application to promote understanding and cooperation.

The DNROGCC is responsible for permitting the storage or disposal ponds for waters produced by oil and gas wells. Again, many of the decisions will be made on a case-by-case basis. Filing an application for permit(s) to store and dispose of water produced in oil and gas operations and other oil field wastes in earthen pits is the first step to acquire a permit for the construction and operation of the FTE facility. This application must be filed whether the operation is located on leased land or at the field site. However, if the pit is to receive less than five barrels per day, a permit is not required. If the proposed facility is to involve more than one operator, then a copy of the field operator's agreement must also be submitted. In addition, the following must be included with the application:

1) A legal description of the proposed pit location to the nearest ten acres.

2) A map depicting all natural streams, lakes, ponds, man-made ditches, wells, and irrigation systems. This may be a topographic map with a scale no smaller than 1:24000. A list of wells (location, depth, and yield) can be acquired at the Colorado Division of Water Resources.

3) A soil and stratigraphic description of the area, including the domestic water supply (if one exists). The director may require percolation tests.

4) The amount and source of water/waste that is to be received must be included in a statement, along with evaporation estimates of the area. Calculations must be included that compensate for the annual rainfall.

5) A chemical analysis of both the water to be stored and the domestic water supply below the pit or facilities (if not separated by a natural impermeable barrier). If similar water samples, taken within a five mile radius of the current area, have been submitted in the past, then this requirement may be waived. The chemical water analysis must comply with all of the requirements of API Form 45-1, API Water Analysis Report Form, and be made by a qualified laboratory.

6) A schematic sketch or plan of the proposed pit design for storage, metering, and/or producing system must be submitted, along with the land and location of final separation facilities required in Rule 328 (for on-site pit). Also, the plans for unloading, separating, storage, and evaporation facilities for a central disposal facility must be submitted.

   (NOTE: Because the FTE method of treatment is completely different from conventional methods of treatment, Rule 328 does not appear applicable to this process. Rule 328 requires syphoning from the bottom of the ponds to keep the oil and gas from entering other retaining pits or State waters).

7) If an operator (on-site or central field facility) receives in excess of 100 barrels of fluid per day, and the fluids contain 5000 mg/L or greater of total dissolved solids, then the following information must be supplied in addition to the previous requirements:

   a) If the underlying soil is permeable, the type of material used in constructing the lining of the pit must be submitted. The materials used for lining must be weather resistant, impervious, and resistant to deterioration when exposed to hydrocarbons, aqueous acids, alkalies, fungi, or other substances that are likely to be in the produced waters/wastes.

b) Leak detection plans and plans for corrective action if a leak occurred must be included.

c) The Director must inspect the leak detection system prior to the placement of any fluid into the pit. Therefore, the Director must be notified 48 hours in advance of the fluid placement. The Director must also inspect the liner and cover material after inspection.

d) The method for the disposal of the precipitated solids must be given.

e) The applicant must submit a copy of the application and all other information to the County Commissioner's office for comments. The Commissioners must reply with their comments within 30 days of receipt.

(NOTE: A variance of these provisions will be granted if the applicant can show evidence that the facility will not cause pollution without meeting the requirements.)

8) Other pertinent information that shows the facility will not violate the provisions of the Colorado Water Quality Control Act, C.R.S. 1973, Sections 25-8-101 should also be submitted.

After all required information has been provided and the director determines that the facility will not cause "pollution", the permit is issued. Also, the DNROGCC has the ability to hold meetings with any interested party regarding the permit application. They may also decide to submit a copy of the application to the County Commissioners for approval of the facility location. If the application is submitted to the respective County Commissioners, they have 30 days to respond. The plans may require modification by the director to meet the requirements and regulations for retaining pits. Necessary forms for reporting the information will be supplied by the DNROGCC.

From discussions with personnel at the DNROGCC, it was concluded that the FTE treatment process would be subject to no more than the same rules and regulations as retaining pits for oil and gas produced waters.

3.1.3.2 Regulations in the State of Wyoming for Treating and Discharging Oil and Gas Produced Waters

The information in this section identifies the regulatory requirements and environmental permitting for the design, construction, and operation of a FTE treatment process in the state of Wyoming. When the FTE facility is an owner-operated type facility, the Wyoming Oil and Gas Conservation Commission (WOGCC) is the agency responsible for approving the design, construction, and operation of the FTE facility. When the facility is a commercial type, the responsible agency is the Wyoming Department of Environmental Quality (WDEQ). An additional permit is also required for the FTE facility to surface discharge the treated water. The agency responsible for this permit is the WDEQ's Water Quality Division regardless of the facility type.

Operating an owner-operated type FTE facility in Wyoming is approved and regulated by the WOGCC. The first step in the Wyoming permitting process for an owner-operated type FTE facility is notification to the WOGCC of the intention to build by filing an "Application For Permit To Use An Earthen Pit" (WOGCC Form 14A). A permit for the required pond construction will be issued if the proposed pit(s) shall not cause harm or contamination to the soil, groundwater, or surface waters. A detailed facility design with characterization data for the proposed site must be included with permit application. The site characterization data should include the depths and hydrostatic heads of the near surface aquifers, site topography including drainages, and facility location with respect to nearby communities, ranches or farms. There are no specific design requirements, however, the intended pond design must be described in the application in detail and be approved. After submission of the application, a hearing is scheduled with the WOGCC to discuss the details of the FTE facility design and operation. The purpose(s) of the hearing is discussed in Section 512 of the WOGCC Rules and Regulations. Following the hearing, the WOGCC will perform a detailed characterization of the proposed site (including water table, topography, and geographic location). The proposed FTE process design will then be approved or disapproved. If the design is not approved, it can be modified based upon WOGCC recommendations and resubmitted.

Operating a commercial FTE facility in Wyoming is approved and regulated by the WDEQ's Water Quality Division. The first step in the Wyoming permitting process for a commercial type FTE facility is to file a written application which is provided by the WDEQ, for a permit to construct, install, or modify the facility. This application must be submitted, along with three copies of the Engineering Design Report (EDR), which should include the FTE facility design and specifications, a description of the existing conditions, possible problems and the solutions to the possible problems, a detailed description of the effluent disposal technique, and a monitoring plan.

Details of the specific requirements of the EDR are located in the WDEQ Water Quality Rules and Regulations:

Specific requirements of the EDR - Chapter 11, Section 6,
Pond design requirements - Chapter 11, Section 7,
Maintenance of groundwater standards - Chapter 8,
Monitoring plan requirements - Chapter 3.

Approval of the facility design and specifications is granted by the WDEQ designated engineer. Applications will be acted upon within 60 days and whatever action is decided is given in writing by the administrator. The requirements of the environmental monitoring program are completely up to the discretion of the WDEQ appointed administrator.

Following approval for the process design, it is necessary to apply for an NPDES permit through WDEQ's Water Quality Division. This permit is necessary for both owner operator and commercial type facilities. If the facility is an owner operator type, a General NPDES permit applies. A general permit is much less complicated, and requires fewer details for approval. When applying for a commercial NPDES permit, it is suggested that the complete project design be submitted. Following approval, a schedule of compliance, effluent limitations, and special conditions or restrictions for the specific facility are determined by the WDEQ.

The monitoring requirements for the discharge of oil and gas waters are: TDS shall not exceed 5,000 mg/L, oil and grease must be 10 mg/L or less, chlorides must be no greater than 2,000 mg/L, sulfates must be 3,000 mg/L or less, and total radium limits will be set based upon the surface water class designation. Also, for commercial operations, the WDEQ requires specific inductance measurements to insure an adequate estimation of TDS through a conductivity measurement. Depending upon the type of operation, there is the potential for increased monitoring requirements. This is determined on a "case-by-case" basis. The ponds must be monitored for oil and grease every two months; TDS, sulfates, chlorides, and Ph every six months; and radium each year. Biannual reports that provide the results of oil and grease analyses are required and annual reports that provide the results of all analyses are also required. Details regarding the NPDES rules and regulations are provided in Chapters 2 & 7 of the WDEQ Water Quality Rules and Regulations.

If at any time the operation of the FTE facility exceeds the compliance, effluent, or other limits set by the WDEQ, the facility permit may be revoked, suspended, or modified by the WDEQ.

3.1.3.3 Regulations in the State of Michigan for Treating and Discharging Oil and Gas Produced Waters

After consultation with state agencies in Michigan, the specific permitting procedure for a FTE process in the state is uncertain. Michigan's Department of Natural Resources' Surface Water Quality Division was the first agency contacted. It was determined that an NPDES permit issued from that agency would be required to discharge the treated water. However, the jurisdiction and requirements for additional permits that might be required were not determined through the contacts. The Michigan Geological Survey (MGS) maintains jurisdiction over oil and gas drilling and related permits. RTC contacted personnel from the MGS and found that there does not appear to be binding rules and regulations for the permitting process in regard to treatment ponds for oil and gas produced waters.

3.1.3.4 Comparison of the FTE Method to Conventional Methods

The primary design constraints are related to storage and containment and are no more stringent than current design requirements for a conventional evaporation process. Waters with TDS levels above 10,000 ppm that are either evaporated or held in a pond for injection or some other permissible disposal option, must be stored in a synthetically lined pond. The exact liner specifications depend upon the state's requirements and whether the facility will be the commercial or owner operator type. Waters with TDS values of less than 10,000 ppm are often allowed to be stored in compacted earthen ponds but a synthetic pond liner may be required, depending on local geological conditions and the location and type of the facility. Thus, an FTE facility will require one permit that approves the design, construction, and use of the produced water holding pond and freezing pad.

Regulatory constraints on the operation of the FTE process are primarily related to the quality of discharged water, and are the same as those currently applied to the discharge of oil and gas produced waters. No waters with TDS levels above 5,000 ppm may be surface discharged in any of the states unless an exception is granted. Regulatory personnel contacted by RTC personnel were not familiar with exceptions granted in Colorado or Michigan. Wyoming's regulatory personnel were aware of exceptions to the 5,000 ppm discharge limit that have been granted. The exceptions were requested by the landowners.

Surface discharge of waters with TDS levels less than 5,000 ppm, chlorides below 2,000 ppm, sulfates below 3,000 ppm, oil and grease below 10 ppm, and pH between 6.5 and 8.5 are generally allowed in Wyoming but in Colorado stricter limits are placed on many of the major drainage basins. In any case, the water discharge will require an NPDES permit.

Consider a commercial FTE facility located in Colorado or Wyoming, which treats the median produced water from Subtask 1.2 (14,700 ppm TDS). The facility has on-site tank storage of the concentrated brine run-off, disposes the brine in a permitted disposal well, and surface discharges the treated water. This facility will require permits for construction and use of the produced water holding pond and the freezing pad and issuance of these permits will require approval of the facility design. The agency responsible for approving the facility design and issuing the permits will depend upon whether the facility is the owner operator type or commercial. In Colorado, pond permits will be issued by the DNROGCC of the State of Colorado. In Wyoming, pond permits will be issued by either the WOGCC (owner operator) or the WDEQ (commercial). An NPDES permit for the surface discharge or beneficial use of the treated water will also be required from either the CWQCC or the WDEQ.

In summary, the environmental acceptability, regulatory requirements, and associated costs are similar to those of a conventional disposal facility using evaporation. Two benefits of the FTE process that make it more environmentally acceptable are: 1) the treated water may be beneficially used and 2) the volume of brine disposal is small compared to produced water disposal by conventional methods.

3.1.4 Subtask 1.4: Conceptual Process Design

The calculations required in the facility design are discussed in Section 2.2.4. The numerical model developed for this subtask was used to determine the facility equipment and operating requirements for a base case and 28 other assumed operating scenarios. The results of this effort are presented in the following sections.

3.1.4.1 Base Case Design

A base case operating scenario was assumed and used to evaluate the commercial feasibility of the process. The following values for parameters as model inputs were selected for the base case: a central Wyoming location, 1,000 bbl/day of produced water feed with a TDS concentration of 14,700 ppm, and the quality of treated water for discharge and brine are 2,000 and 50,000 ppm TDS, respectively. In addition, the base case pond design selected was a conventional evaporation pond with a maximum water depth of 20 ft, a 2 to 1 sidewall slope, 3 vertical ft of freeboard, 6 linear ft of liner required for the berm and anchor trench, and pond evaporation was 80% of PAN evaporation.

The results of a base case plant design are presented in Figure 10. The base case equipment requirements are presented in this figure. The base case facility requires a produced water holding pond with a maximum water depth of 20 ft and base and surface dimensions of 178 and 270 ft, respectively. The maximum pond water volume is 169,000 bbl and 85,000 sqft of liner are required. The freezing pad base dimension is 237 ft and the pad requires 75,000 sqft of liner. The maximum ice accumulation on the pad is 1.8 million cuft. The pump required to operate the pad is 10 HP with a flow rate of 165 gpm at 90 ft of head. The average pumping rate during freezing hours is 100 gpm and four sprinklers are required.

The base case daily average stream flows are: 1,000 bbl/day of produced water feed, 689 bbl/day of treated water production, 266 bbl/day of brine production, and net evaporation of 45 bbl/day. The averages are determined on an annual basis. The only flow that doesn't vary from day to day is the produced water feed rate which is constant. In summary, the base case operation would provide 689 bbl/day of water for use and reduce the volume required for disposal by 73% (Figure 10).

The base case water depth in the produced water holding pond during the year is illustrated in Figure 11. For the central Wyoming location, subfreezing temperatures cease in May and begin in November. Thus, the depth in the produced water holding pond is near zero on May 1st.

The level in the pond increases during the warm months and reaches maximum level on October 31st. On November 1st, subfreezing temperatures begin and water is pumped from the pond to the freezing pad. During this time, the water depth of the produced water holding pond decreases. For the Wyoming location, the hours per day with subfreezing temperatures are few during the month of April, and the rate at which water must be removed from the pond to keep it empty during April actually determines the size of the transfer pump. The result is that excess transfer pump capacity is available during the months of January, February, and March. This excess capacity will be utilized if significant recycling is required during the cold months to obtain the desired ice purity.

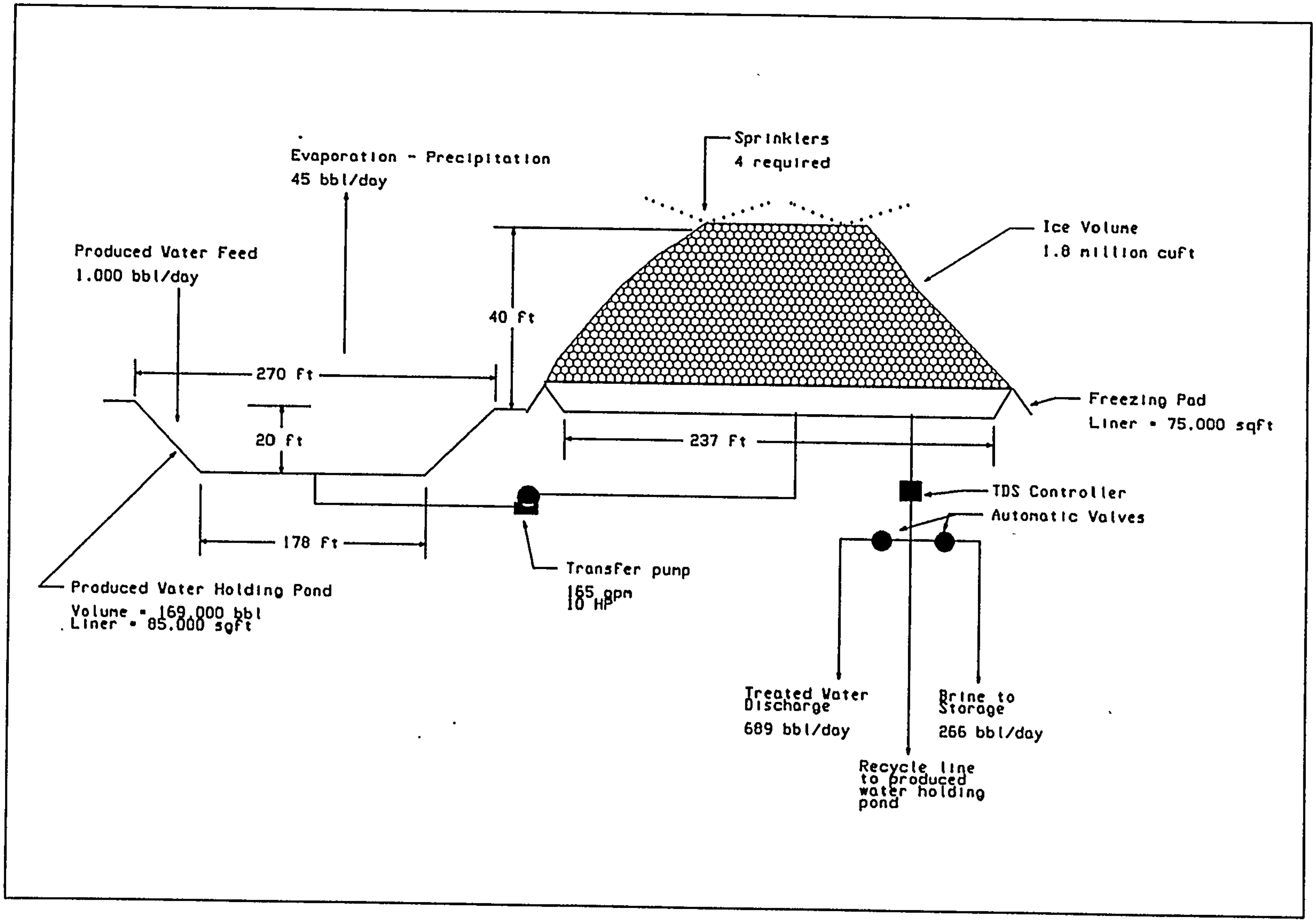


Figure 10. Base Case FTE Facility Design

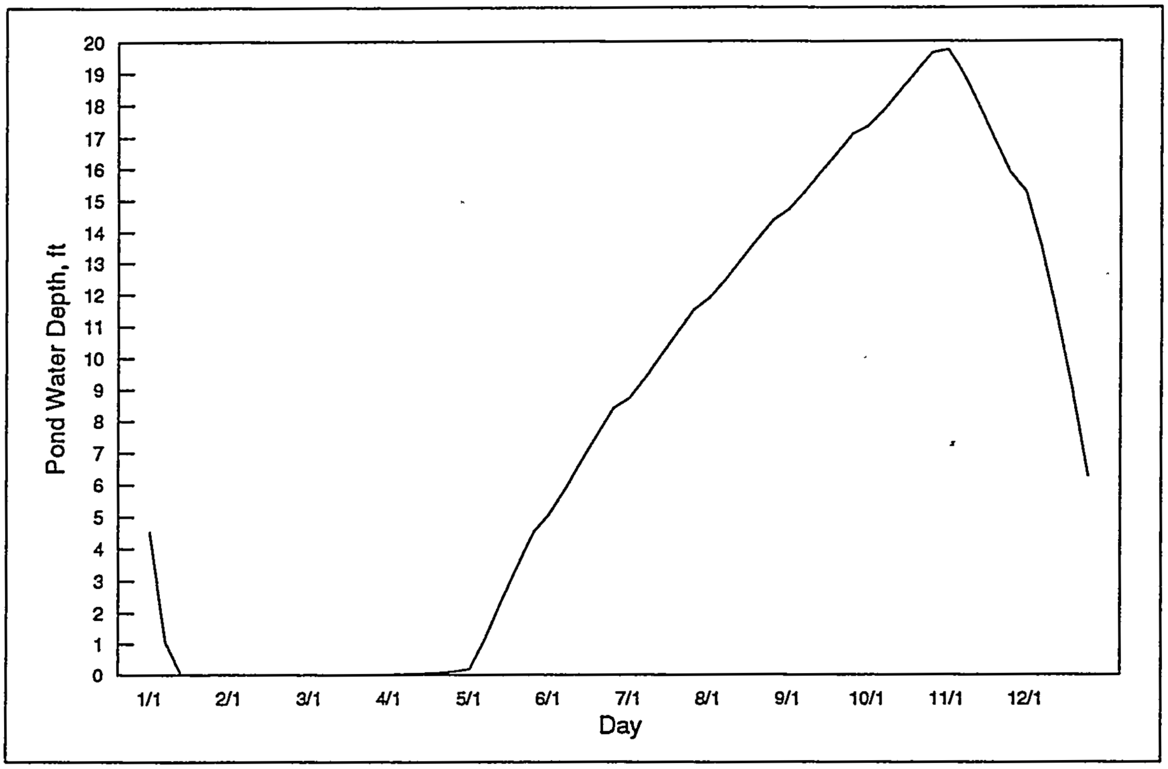


Figure 11. Base Case Produced Water Holding Pond Depth versus Time

The daily facility stream flows for the base case are illustrated in Figure 12. As illustrated, the feed rate is constant. The rate at which water is pumped from the pond to the freezing pad is also constant. However, the daily rate at which water is pumped is not constant because the number of hours with subfreezing temperatures per day varies each month and water is only pumped when subfreezing temperatures exist.

It is, perhaps, more obvious from this figure that the significant excess transfer pump capacity results from the design assumption. This was intentional because the effect of recycling on the produced water quality is not well understood and cannot be quantified, but it is known to be beneficial and the capacity for recycling is considered desirable. This excess capacity also turns out to be economically insignificant as shown in Section 3.1.5. Also note, the rates of precipitation and evaporation are small compared to the feed rate and the flow rate of water to the freezing pad during the winter months. The evaporation rate is maximum in July, in spite of the fact that the pond water level is not maximum. Also, precipitation is maximum in April for this location.

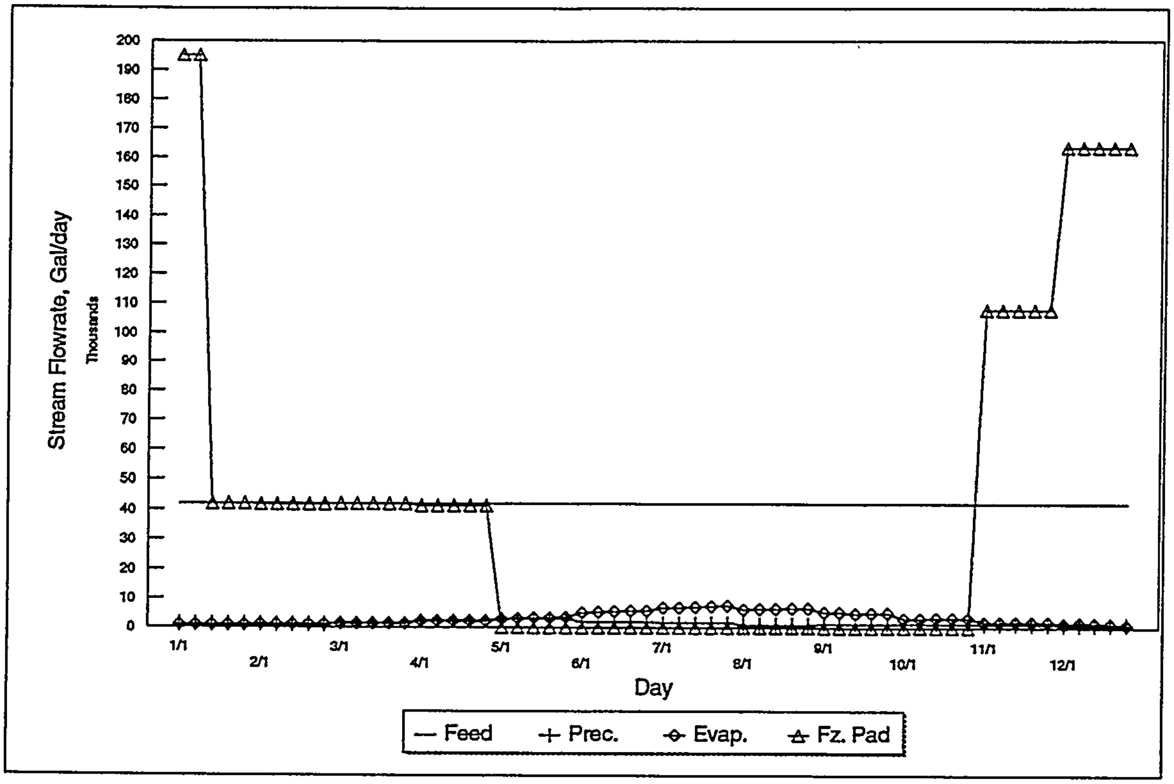


Figure 12. Base Case Stream Flows versus Time

The daily TDS concentration of water in the produced water holding pond is illustrated in Figure 13. This figure illustrates that the TDS concentration of the water in the pond increases during the warmer (5/1 - 10/31) months because evaporation is greater than precipitation. In the months with subfreezing temperatures (11/1 - 4/30), the TDS concentration of the water in the pond decreases because of the transfer of water from the produced water pond to the freezing pad.

3.1.4.2 Design Sensitivity to Process Parameters

The sensitivity of the design to process parameters provides data to evaluate the economic sensitivity of the FTE process (Section 3.1.5). The produced water feed rate; the produced water, treated water, and brine TDS concentrations, the facility location atmospheric conditions, and the design of the produced water holding pond were selected as the process parameters in the sensitivity analyses. Produced water feed rates of 50, 100, 500, 1,000, 5,000, 10,000, and 50,000 bbl/day were considered to be a reasonable range of values. The low value was

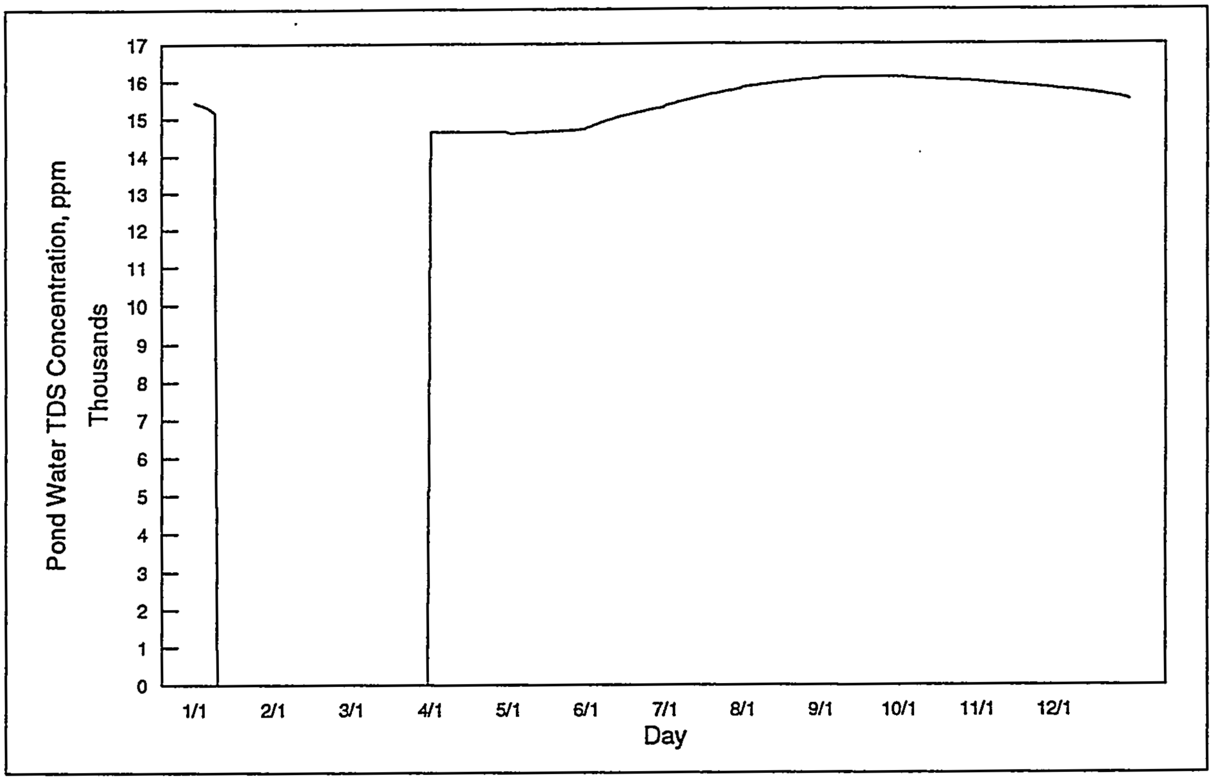


Figure 13. **Base Case Produced Water Holding Pond TDS Concentration versus Time**

selected to represent a single economically marginal producing well and the high value was selected to equal large evaporative facilities in the San Juan Basin. Produced water TDS concentrations of 6,000, 14,700, 20,000, 30,000, and 40,000 ppm were considered to be a reasonable range of values. The low value was selected because many waters with TDS less than 5,000 ppm can be surface discharged without treatment and the high value was selected to be less than the base case brine TDS concentration. Treated water TDS concentrations of 500, 1,000, 2,000, and 5,000 ppm were considered to be a reasonable range of values for waters that may be discharged based upon Subtask 1.3. Brine TDS concentrations of 30,000, 50,000, 60,000, and 75,000 ppm were considered based upon the results of Subtask 1.1. Locations of eastern Colorado, central Wyoming, and the UP of Michigan were selected based upon Subtask 1.2 results. The pond designs selected were a conventional evaporation pond, an enhanced evaporation (solar) pond, and a solar still. The design criteria for the ponds are presented in Table 6.

Table 6. Design Criteria for Produced Water Holding Pond Options

Parameter	Conventional	Pond Design Option Solar Pond	Solar Still
Max. Water Depth	20 ft	10 ft	10 ft
Sidewall Slope (x:y)	2:1	3:1	3:1
Vertical Freeboard	3 ft	2 ft	2 ft
Anchor and Berm Liner	6 ft	6 ft	6 ft
Evaporation Efficiency[a]	80 %	90 %	95 %

[a] Conventional pond evaporation efficiency is 80 % of PAN evaporation. Solar pond and still evaporation efficiency are determined as % of solar radiation absorbed to a horizontal black surface.

The results of the design sensitivity analyses are presented in Tables 7, 8, and 9. The data in these tables illustrate the change in equipment requirements resulting from the respective changes in the values of the process parameters. The required produced water holding pond base dimension, water depth, water volume, and liner size are presented for each case in Table 7 and the size of the transfer pump, freezing pad base dimension, liner size, and ice volume are presented for each case in Table 8. The daily average treated water discharge and brine production rates are presented for each case along with the disposal volume reduction resulting from the FTE process in Table 9.

Examining the design sensitivity of the process provides insight that will be useful to optimize the process. The produced water holding pond requirements increase in a non-linear fashion with increasing produced water feed rate, indicating an economy of scale for that equipment. The produced water, treated water, and brine TDS concentrations do not effect the requirements of the produced water holding pond. Interestingly, central Wyoming and its climate result in the minimum holding pond requirements. This is because the warmer climate in eastern Colorado provides fewer months of subfreezing temperatures than Wyoming and more produced water must be stored. The UP of Michigan has more months with subfreezing temperatures than Wyoming, but higher precipitation means more water is stored. The requirements for solar evaporation ponds and solar stills are greater than those of the conventional evaporation ponds at all three locations. The conventional evaporation ponds must store a larger volume of water

Table 7. Design Sensitivity Impacts on Produced Water Holding Pond Size

Process Parameter/ Value	Produced Water Holding Pond Requirement			
	Base Dimension, ft	Water Depth, ft	Water Vol., Mcuft	Liner Size, Msqft
Produced Water Feed Rate/				
50 bbl/day	31	13	46	13.2
100 "	38	17	93	19.3
500 "	112	20	474	51.6
1,000 " (BC)	178	20	950	85.3
5,000 "	446	20	4,727	314.6
10,000 "	647	20	9,435	580.8
50,000 "	1493	20	47,012	2,585.7
Produced Water TDS/				
6,000 ppm	178	20	950	85.3
14,700 " (BC)	178	20	950	85.3
20,000 "	178	20	950	85.3
30,000 "	178	20	950	85.3
40,000 "	178	20	950	85.3
Treated Water TDS/				
500 ppm	178	20	950	85.3
1,000 "	178	20	950	85.3
2,000 " (BC)	178	20	950	85.3
5,000 "	178	20	950	85.3
Brine TDS/				
30,000 ppm	178	20	950	85.3
50,000 " (BC)	178	20	950	85.3
60,000 "	178	20	950	85.3
75,000 "	178	20	950	85.3
Location - Pond Design/				
CO - Conv.	194	20	1,102	95.4
CO - Solar	245	10	756	110.8
CO - Still	230	10	681	101.4
WY - Conv. (BC)	178	20	950	85.3
WY - Solar	231	10	648	101.9
WY - Still	222	10	635	95.8
MI - Conv.	189	20	1.058	92.4
MI - Solar	254	10	803	116.6
MI - Still	229	10	675	100.7

(BC) base case

Table 8. Design Sensitivity Impacts on Transfer Pump and Freezing Pad Sizes

Process Parameter/ Value	Transfer Pump, gpm	Freezing Pad Requirement		
		Base Dimension, ft	Liner Size, Msqft	Ice Vol., Mcuft
Produced Water Feed Rate/				
50 bbl/day	8	53	8.2	88
100 "	17	75	12.7	178
500 "	84	168	42.1	886
1,000 " (BC)	165	237	75.3	1,766
5,000 "	825	527	318.5	8,726
10,000 "	1647	744	610.7	13,912
50,000 "	8204	1660	2,881.0	69,256
Produced Water TDS/				
6,000 ppm	165	266	92.2	2,229
14,700 " (BC)	165	237	75.3	1,766
20,000 "	165	217	64.8	1,483
30,000 "	165	174	44.6	950
40,000 "	165	115	23.3	417
Treated Water TDS/				
500 ppm	165	233	73.3	1,712
1,000 "	165	235	73.9	1,729
2,000 " (BC)	165	237	75.3	1,766
5,000 "	165	245	79.6	1,883
Brine TDS/				
30,000 ppm	165	202	57.1	1,279
50,000 " (BC)	165	237	75.3	1,766
60,000 "	165	245	79.6	1,883
75,000 "	165	252	83.8	1,999
Location - Pond Design/				
CO - Conv.	165	235	74.2	1,735
CO - Solar	122	187	50.1	1,094
CO - Still	114	175	45.2	964
WY - Conv. (BC)	165	237	75.3	1,766
WY - Solar	130	197	54.8	1,217
WY - Still	124	188	50.7	1,108
MI - Conv.	182	253	84.1	2,007
MI - Solar	149	219	65.5	1,501
MI - Still	129	195	54.0	1,195

(BC) base case

Table 9. Design Sensitivity Impacts on Treated Water Discharge Rate, Brine Production Rate, and Reduction in Disposal Volume

Process Parameter/ Value	Evap. - Precip. bbl/day	Treated Water Discharge Rate, bbl/day	Brine Production Rate, bbl/day	Reduction in Disposal Volume, %
Produced Water Feed Rate/				
50 bbl/day	2	35	13	74
100 "	3	70	27	73
500 "	21	346	133	73
1,000 " (BC)	45	689	266	73
5,000 "	262	3,407	1,331	73
10,000 "	546	6,792	2,662	73
50,000 "	2,883	33,799	13,318	73
Produced Water TDS/				
6,000 ppm	45	870	85	92
14,700 " (BC)	45	689	266	73
20,000 "	45	579	376	62
30,000 "	45	371	584	42
40,000 "	45	163	792	21
Treated Water TDS/				
500 ppm	45	668	287	71
1,000 "	45	675	280	72
2,000 " (BC)	45	689	266	73
5,000 "	45	735	220	78
Brine TDS/				
30,000 ppm	45	499	456	54
50,000 " (BC)	45	689	266	73
60,000 "	45	735	220	78
75,000 "	45	780	175	83
Location - Pond Design/				
CO - Conv.	56	677	267	73
CO - Solar	296	427	277	72
CO - Still	345	376	279	72
WY - Conv. (BC)	45	689	266	73
WY - Solar	251	475	274	73
WY - Still	291	433	276	72
MI - Conv.	-46	784	262	74
MI - Solar	145	586	269	73
MI - Still	260	466	274	73

(BC) base case

than the solar ponds and stills. But, because of the greater water depth assumed for the conventional evaporation ponds, the liner requirements are less for these ponds than for solar ponds and stills (Table 7).

The freezing pad requirements also increase in a non-linear fashion with increasing produced water feed rate. The non-linear rate of increase indicates a significant economy of scale for that equipment. As the TDS concentration assumed for the produced water is increased, the freezing pad requirements decrease significantly because the treated water yield decreases significantly (Tables 8 and 9). Conversely, as the assumed treated water TDS concentration increases, the treated water yield increases and the freezing pad requirements increase (Tables 8 and 9). Similarly, as the brine TDS concentration increases the treated water yield increases and the freezing pad requirements increase (Tables 8 and 9). Freezing pad requirements also increase as the location's climate becomes colder but the freezing pad requirements decrease with pond designs that increase the net evaporation rate (Table 8).

The flow rates of the process streams also change with the values of the parameters. Net evaporation increases in a non-linear fashion with increasing produced water feed rates which implies an economy of scale. The corresponding increases in treated water yield and brine production is linear. Increasing TDS concentration in the feed water decreases the reduction in disposal volume, increasing TDS concentration in the treated water increases the reduction in the disposal volume as does increasing TDS concentration in the brine. The reduction in disposal volume changes only slightly with location and pond design, but as the pond size increases the evaporation the treated water yield decreases. One final point to note is that, in the UP of Michigan, the annual net evaporation rate from a conventional pond is negative. This is consistent with the information received from the Michigan regulatory personnel contacted in Subtask 1.3.

3.1.5 Subtask 1.5: Preliminary Economic Feasibility and Sensitivity Analyses

3.1.5.1 Economic Feasibility Analysis of the Base Case

The base case operation, defined in Subtask 1.4, is used with the economic basis (Table 10) to determine the economic feasibility of the process. The base case operation assumes a central Wyoming location, 1,000 bbl/day of produced water feed with a TDS concentration of 14,700 ppm, and the quality of treated water and brine are 2,000 and 50,000 ppm TDS, respectively. The base case assumes a conventional evaporation pond with a maximum water depth of 20 ft, a 2 to 1 sidewall slope, 3 ft of freeboard, 6 ft of liner required for the anchor trench, and evaporation is 80% of PAN evaporation.

Table 10. Economic Basis Used for the Base Case

load factor = 1.0
plant life = 20 yr
equity required = 50%
bond interest = 10%
return on equity = 15%
state and federal combined corporate tax rate = 35%
depreciation is straight line over the plant life
annual maintenance costs = 4.0% of installed capital costs
property taxes and insurance = 4.5% of installed capital costs
facility salvage value is negligible
plant construction period is negligible
working capital required is negligible

A summary of the economic analysis results for the base case is provided in Table 11. The installed capital cost for the base case is $176,000, annual operating expenses are $31,000, and the required gross income is $49,000 yielding a water treatment cost of $0.20/bbl of water treated and a 73% reduction in disposal volume. The economic results presented below do not address the cost of transporting the produced water to the disposal facility. Nor do they include the cost for the disposal of the brine produced.

Table 11. Base Case Economic Analysis Results Summary

Total installed capital cost = $176,400
Annual operating expenses = $ 30,893
Annual gross income required = $ 49,358
Water treatment cost = $ 0.20/bbl of water treated
Reduction in disposal volume = 73.4%

Figure 14 is presented to provide details regarding the base case capital investment, annual operating expenses, and gross income

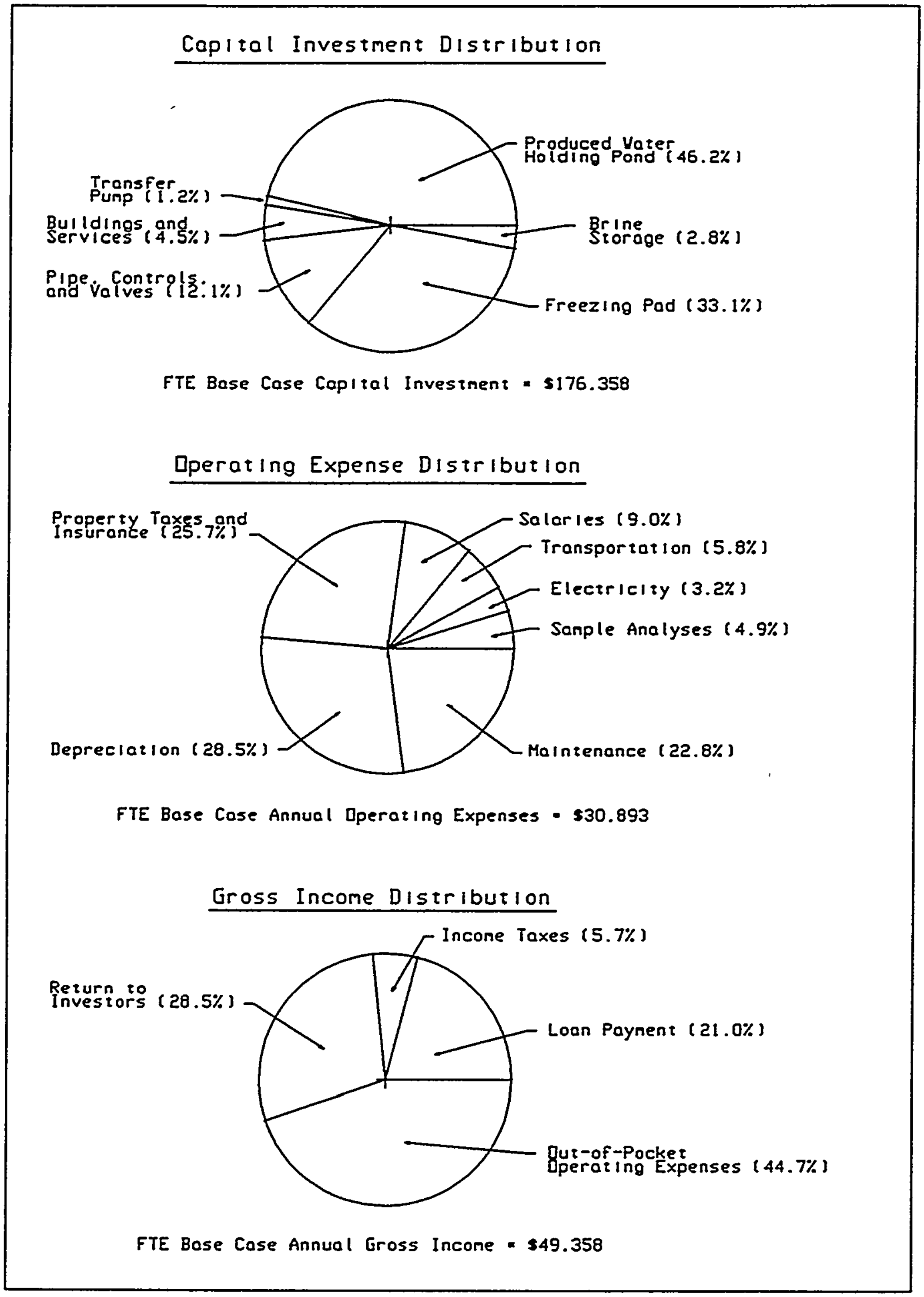


Figure 14. FTE Base Case Capital Investment, Annual Operating Expenses, and Income Distribution

distribution. The major capital investment items are the produced water holding pond and the freezing pad which comprise 46% and 33% of the capital investment, respectively. The major annual operating expense items are depreciation, property taxes and insurance, and maintenance, which comprise 29%, 26%, and 23% of the annual operating expenses, respectively. Figure 14 also provides details regarding the distribution of the base case gross income. The out-of-pocket operating expenses are the annual operating expenses without depreciation, and require 45% of the annual income generated by the facility, the return to the investors requires 29%, the loan payment requires 21%, and income taxes require 6%. Based upon these results, the FTE process is economically feasible if operated as specified. Current disposal cost data acquired in Subtask 1.3 indicate that the cost of $0.20/bbl, which is less than one-third of the current costs independent producers are paying for disposal at commercial injection wells, is very favorable.

3.1.5.2 Economic Sensitivity Analyses

The sensitivities of the base case economics to changes in values of uncertain process parameters and important economic parameters are determined to evaluate the impact of process uncertainties and economic parameters on the process's commercial feasibility. Process parameters considered in the sensitivity analyses are: produced water feed rate, produced water TDS concentration, treated water TDS concentration, brine TDS concentration, facility location, and pond design.

The economic sensitivity analyses are conducted by assuming base case values for all process and economic parameters except the sensitivity variable investigated. The changes in the water treatment cost when each respective parameter is varied reflect the magnitude of impact of that variable on the process economics. The results of the sensitivity analyses of the process parameters are provided in Table 12. It should be noted that the water treatment cost for all cases presented in Table 12 are competitive with current disposal practices.

The sensitivity of the water treatment cost to changes in the produced water feed rate is also illustrated in Figure 15. As illustrated in the figure and eluded to in Section 3.1.4, the FTE process water treatment cost indicates a strong economy of scale. However, the economy of scale is almost fully realized at produced water feed rates of 5,000 bbl/day. Increases beyond that value have only a minor impact

Table 12. FTE Economic Sensitivity to Changes in the Values of Selected Process Parameters

	Produced Water Feed Rate, bbl/day						
	50	100	500	1,000	5,000	10,000	50,000
Water Treatment Cost, $/bbl:	1.21	0.70	0.26	0.20	0.13	0.12	0.11

	Produced Water TDS Concentration, ppm				
	6,000	14,700	20,000	30,000	40,000
Water Treatment Cost, $/bbl:	0.17	0.20	0.22	0.32	0.65

	Treated Water TDS Concentration, ppm			
	500	1,000	2,000	5,000
Water Treatment Cost, $/bbl:	0.20	0.20	0.20	0.19

	Brine TDS Concentration, ppm			
	30,000	50,000	60,000	75,000
Water Treatment Cost, $/bbl:	0.25	0.20	0.19	0.18

	Water Treatment Cost, $/bbl		
Location:	Eastern Colorado	Central Wyoming	UP of Michigan
Pond Design:			
Conventional Evaporation Pond	0.21	0.20	0.19
Solar Evaporation Pond	0.31	0.27	0.25
Solar Distillation Pond	0.52	0.45	0.43

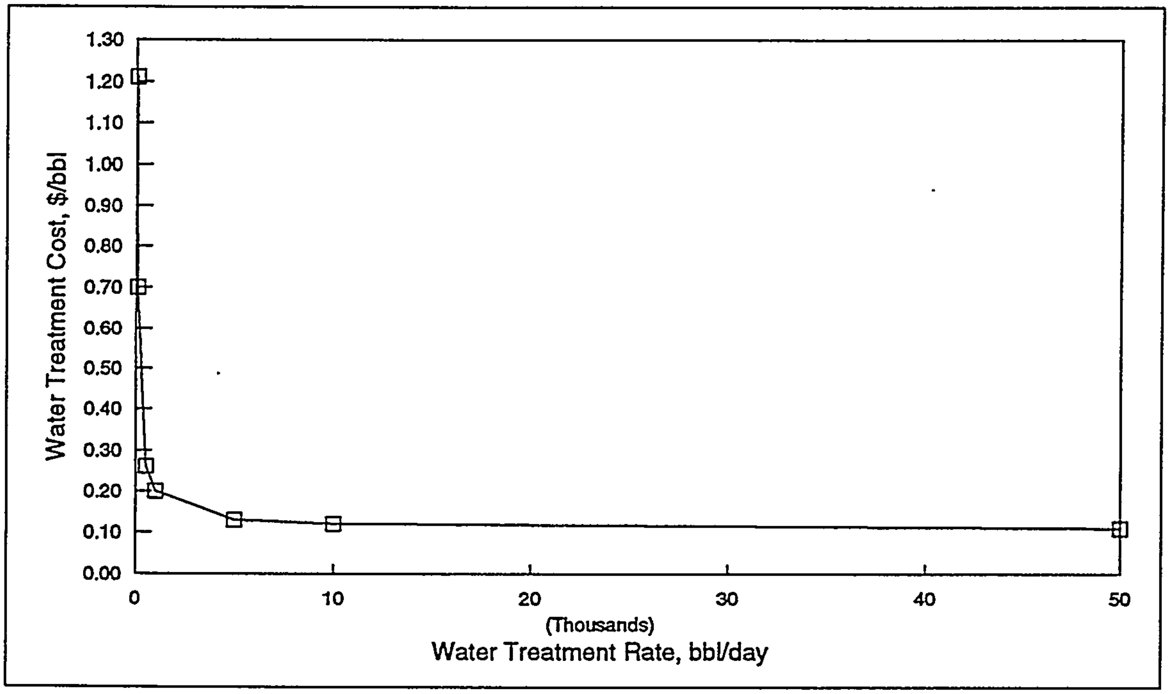


Figure 15. FTE Water Treatment Cost Sensitivity to the Produced Water Feed Rate

on the water treatment cost. Also, for feed rates below 500 bbl/day the water treatment cost rises dramatically as the feed rate decreases. However, at feed rates of less than 100 bbl/day the facility would probably be located at a producing well site and transportation costs related to disposal would be eliminated. Thus, the $1.21/bbl water treatment cost for a 50 bbl/day facility would probably be less than the cost of disposal by deep well injection plus water transportation costs. The $0.70/bbl treatment cost is near the current cost for water disposal at a commercial injection well. Thus, commercial FTE facilities of sizes greater than 100 bbl/day are competitive with current disposal practices.

The water treatment cost sensitivities to the TDS concentration of the produced water feed, the treated water discharge, and the brine are illustrated in Figure 16. The TDS concentration of the discharge and brine have minor impact on the treatment cost. The TDS concentration of the feed water is more severe as the feed concentration approaches the brine TDS concentration. If produced waters with high TDS concentrations are to be economically processed, the TDS concentration of the brine will need to be significantly greater than the feed TDS concentration.

The sensitivities of the FTE water treatment cost to pond design and facility location are illustrated in Figure 17. There is some advantage to operating in a severe climate, but this advantage is small. The data in this figure also illustrate that the simpler, and less expensive the pond design, the lower the water treatment cost. However, the water treatment cost is conservatively determined based upon barrels of treated water produced and does not credit increased water disposal by evaporation. By considering the water disposed of or annual disposal costs, the pond designs can be more accurately compared (Table 13).

Table 13. FTE Water Treatment Cost Corrected to Include Water Disposed of by Evaporation for Conventional and Solar Ponds and Solar Stills

	Corrected FTE Water Treatment Cost $/bbl of Water Treated or Disposed of		
Pond Design	**Colorado**	**Wyoming**	**Michigan**
Conventional Evaporation	0.19	0.18	0.20
Solar Evaporation	0.18	0.18	0.20
Solar Distillation	0.27	0.27	0.28

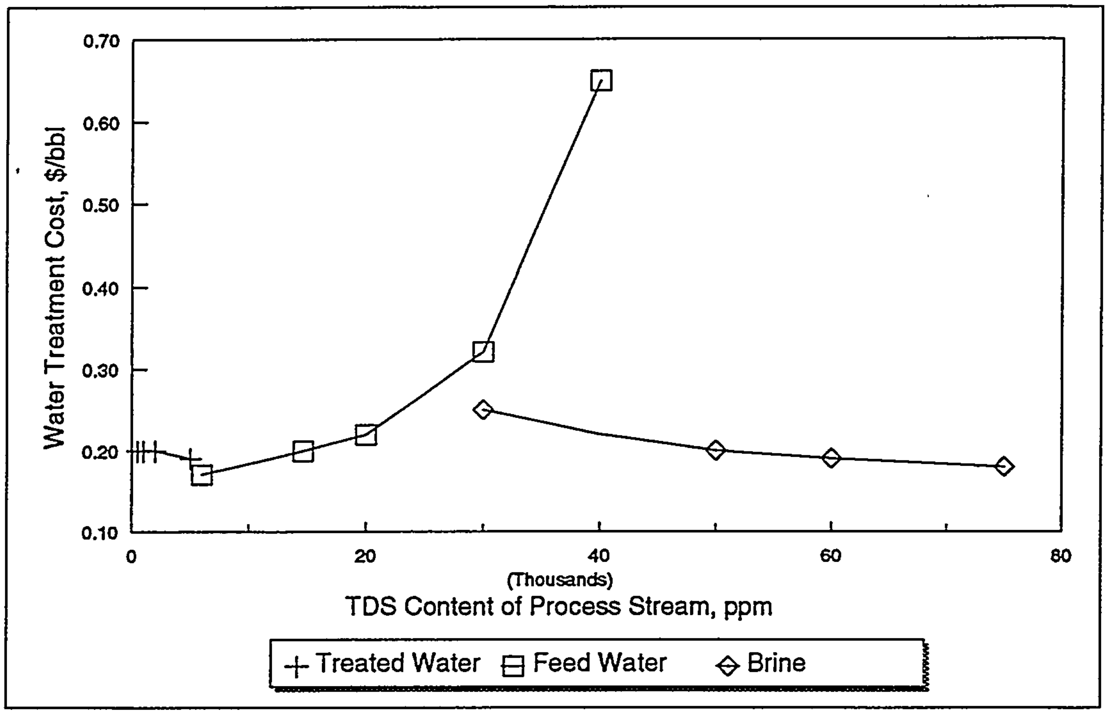


Figure 16. FTE Water Treatment Cost Sensitivities to the TDS Concentrations of the Produced Water Feed, Treated Water Discharge, and Brine

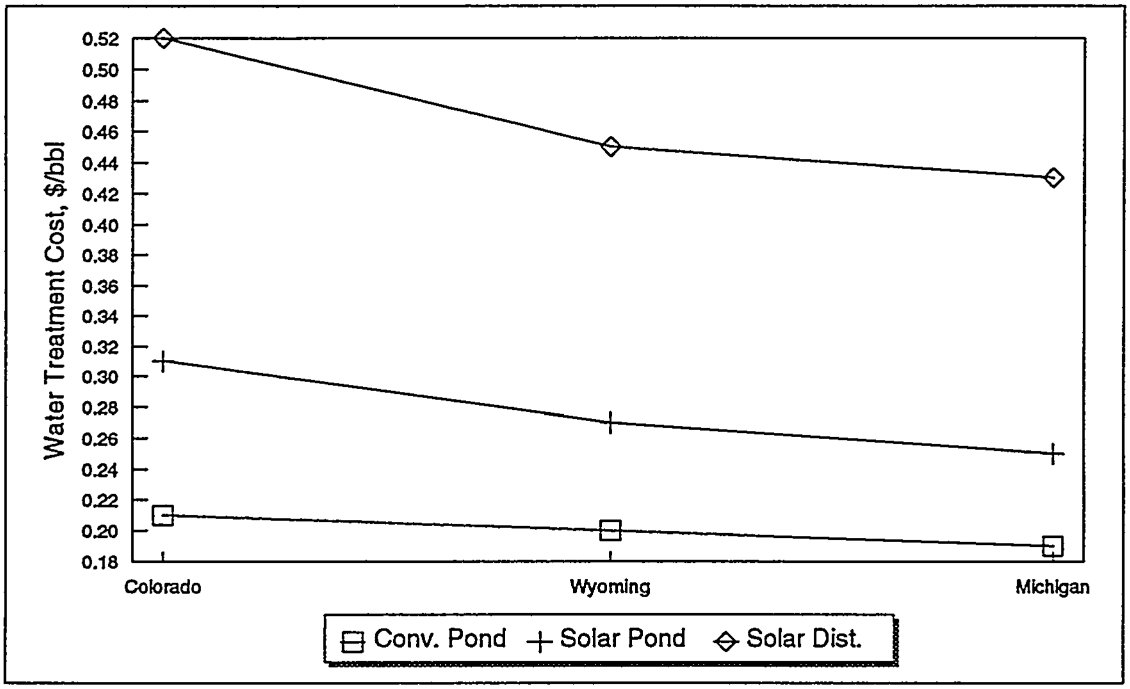


Figure 17. FTE Water Treatment Cost Sensitivities to Pond Design and Facility Location

For the base case Wyoming location, the conventional pond disposes of a net of 45 bbl/day by evaporation and produces 689 bbl/day of treated water. The required annual gross income for the base case is $49,358. Thus, the cost is reduced from $0.20/bbl of treated water produced to $0.18/bbl of produced water treated or disposed of. By similar calculation, the data presented in Table 13 was developed. The FTE water treatment costs corrected to include disposed water illustrate that: 1) the process becomes even more economic when credit is taken for evaporative disposal, 2) the conventional pond and the solar pond yield similar costs for water treatment or disposal costs when evaporation is considered, and 3) all locations considered yield similar water treatment or disposal costs when evaporation is considered (Table 13).

The results of the sensitivity analyses of the FTE water treatment costs to process parameters indicate that: 1) the process is economically stable, 2) the process is competitive with current disposal costs for all cases considered, and 3) the process appears to have a significant economic advantage to current disposal methods for facility sizes greater than 500 bbl/day.

Economic parameters and the cost of the pond liner are also considered in the sensitivity analyses. The economic sensitivity of the process to changes in the values of the following economic parameters are investigated: installed capital cost, annual operating expenses, equity required, bond interest, return on equity, corporate income tax rate, plant life, and liner cost.

Results of the sensitivity analyses to the estimated capital costs and annual operating expenses are illustrated in Figure 18. Both the sensitivities in this figure are linear. The capital costs have a slightly greater impact on the water treatment cost than the operating costs when both are varied by the same percentage. Neither of these economic parameters impair the commercial competitiveness of the FTE process when increased by 50% over the base case value.

Results of the FTE water treatment cost sensitivity to the equity required is illustrated in Figure 19. In this figure, equity required is expressed as a debt to equity ratio. The sensitivity in this figure is also near linear and this economic parameter does not impair the commercial competitiveness of the FTE process when varied over its entire range of possible values.

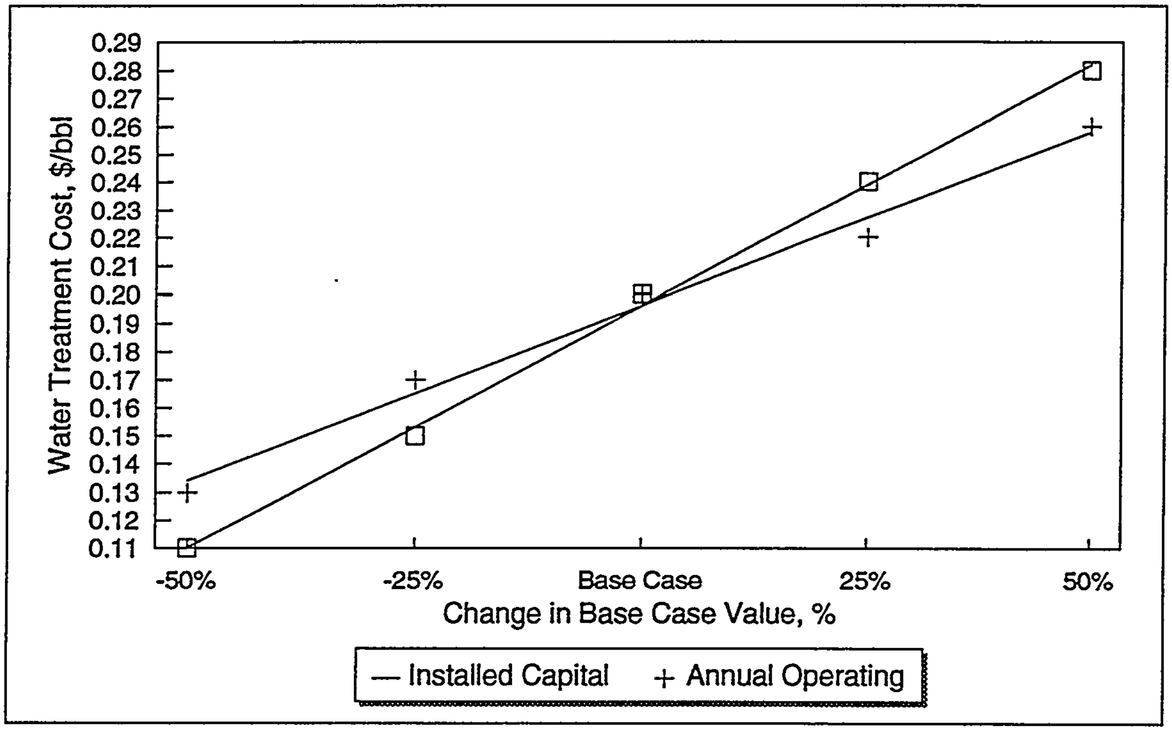


Figure 18. FTE Water Treatment Cost Sensitivities to the Estimated Capital Costs and Annual Operating Expenses

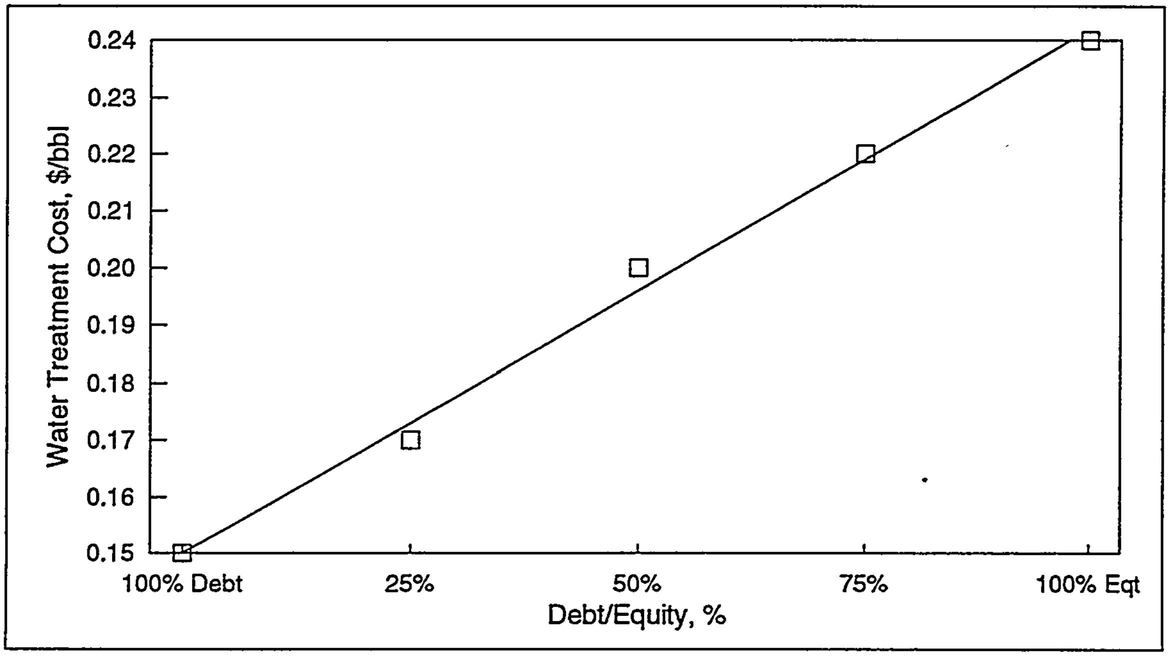


Figure 19. FTE Water Treatment Cost Sensitivity to the Equity Required

Results of the FTE water treatment cost sensitivity to the return on equity, bond interest, and corporate income tax rates are illustrated in Figure 20. All the sensitivities in this figure are near linear and these economic parameters do not impair the commercial competitiveness of the FTE process when varied over the ranges of values considered. The rate of return on equity range considered was 10 to 30%, the bond interest rate range considered was 6 to 15%, and the corporate tax rate range considered was 30 to 45%. The strongest economic sensitivity to these three economic parameters is to the return on equity.

Results of the FTE water treatment cost sensitivity to the assumed plant life is illustrated in Figure 21. The sensitivity in this figure is clearly non-linear. However, for plant life greater than five years this parameter does not impair the competitiveness of the FTE process.

Results of the FTE water treatment cost sensitivity to the cost of the pond liners for the holding pond and freezing pad are illustrated in Figure 22. The sensitivity in this figure is linear. When the installed liner cost is varied from $0.50/sqft to $2.00/sqft, the water treatment cost is increased, however, even with the $2.00/sqft assumed liner cost the water treatment cost of the FTE process is commercially competitive.

The sensitivities of the base case water treatment cost to the changes in values of the economic parameters investigated also tends to confirm commercial feasibility of the process. The results of the base case and sensitivity economic analyses strongly suggest the process has commercial economic potential. However, assumptions are made regarding the qualities of the treated water and brine that effectively assume technical feasibility of the process. Since the design and operation of the FTE process differ from processes reported in the literature, the technical feasibility of the FTE process must be experimentally confirmed. Also, the behavior of organics and heavy metals could not be addressed in these analyses because data, depicting the behavior of these types of species in a natural freezing process, are not available. Removal of organics and heavy metals are documented for artificial freezing processes, but demonstrated removal of these types of contaminants from waters using the FTE process is needed. Finally, consideration needs to be given to make the process economics less sensitive to the produced water feed rate so that on-site facilities serving one well can be economically achieved in order to reduce transportation related disposal costs and fuel usage.

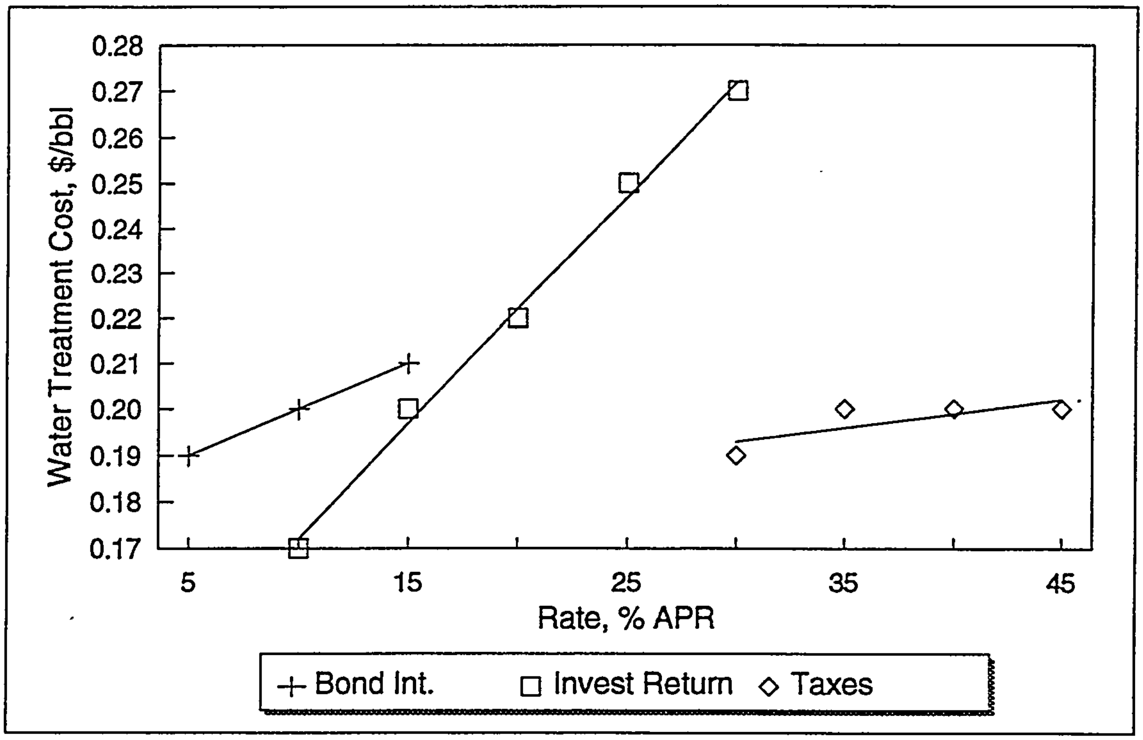


Figure 20. FTE Water Treatment Cost Sensitivities to the Return on Equity, Bond Interest, and Corporate Income Tax Rates

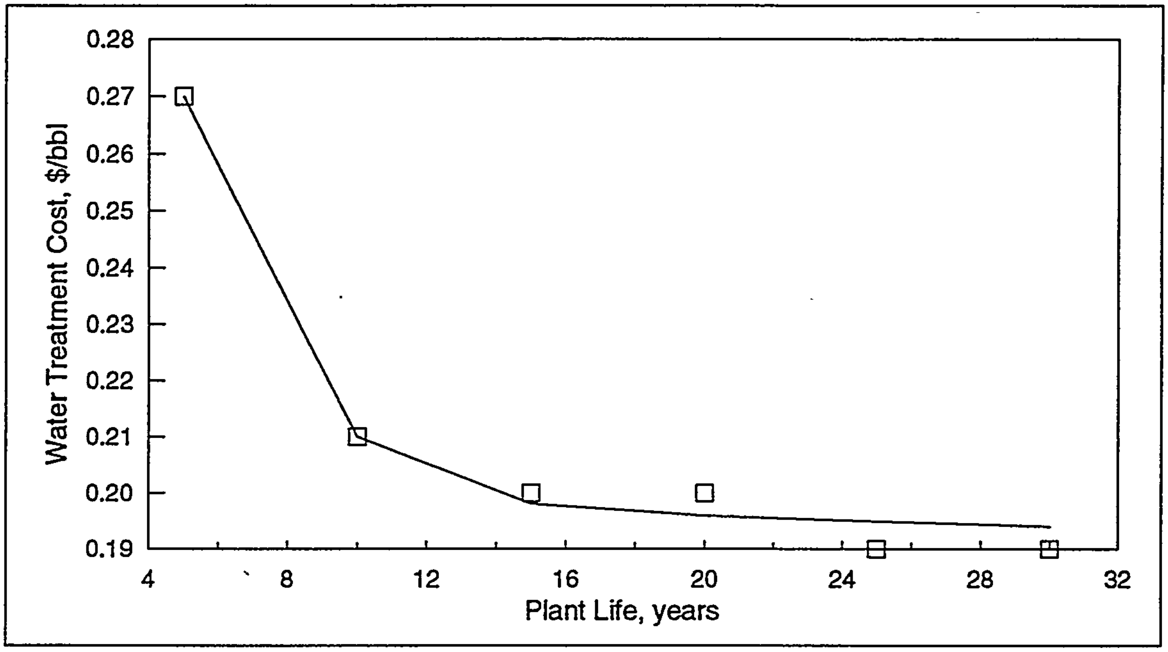


Figure 21. FTE Water Treatment Cost Sensitivity to the Plant Life

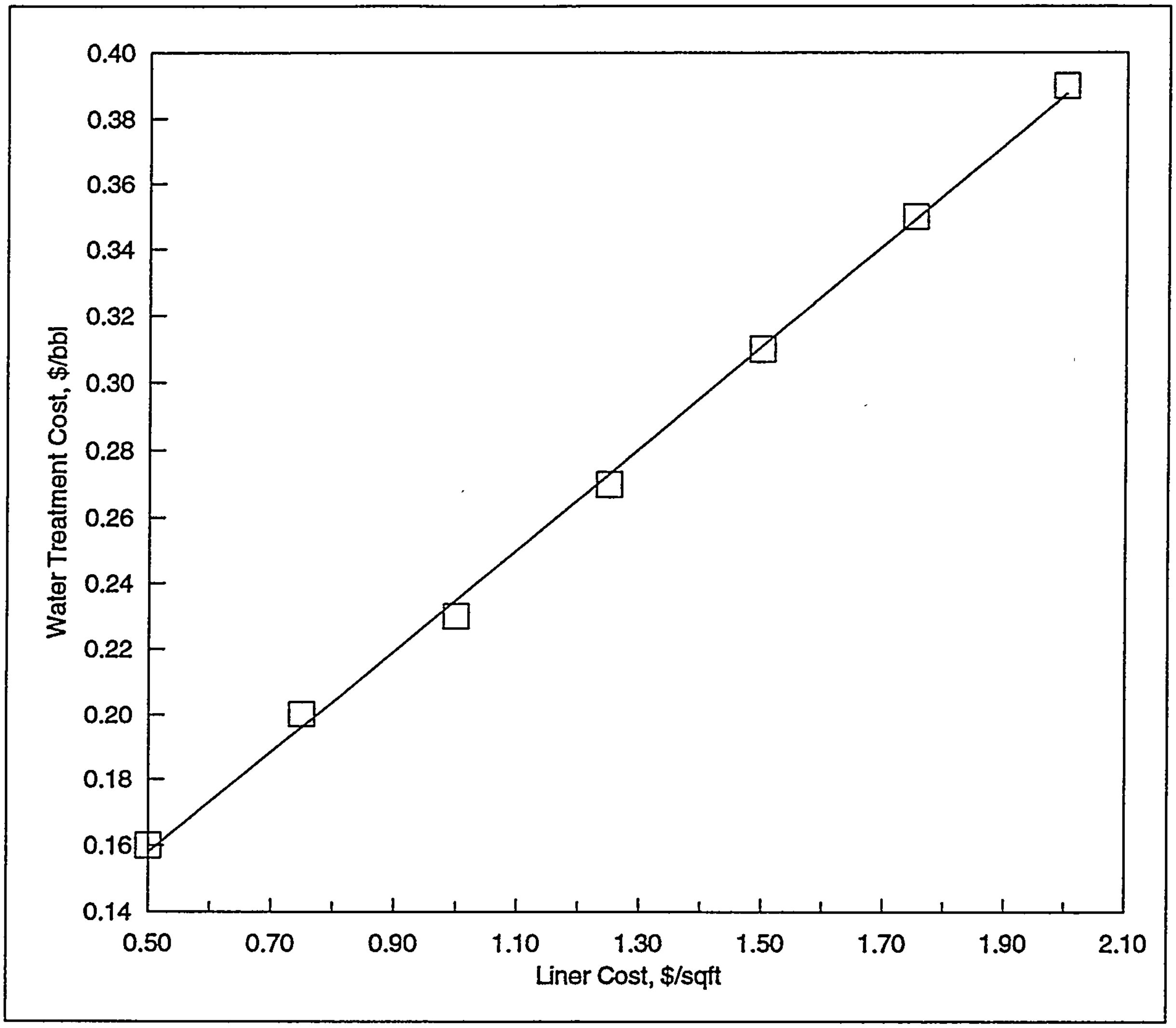


Figure 22. FTE Water Treatment Cost Sensitivity to the Pond Liner Cost

3.2 Task 2: Laboratory-Scale Process Simulation

3.2.1 Subtask 2.1: Laboratory-Scale FTE Process Simulations

In Subtask 2.1, samples of three differing produced waters were obtained for use in the laboratory-scale FTE process simulations conducted in this subtask's research. Produced water samples were collected from a natural gas producing well in Weld County, CO; an oil and gas producing well near Brighton, CO; and a coal bed methane well in the San Juan Basin. Samples of each of these produced waters were then submitted for detailed chemical analyses (Table 2). Nine laboratory-scale FTE process simulations were then simultaneously conducted to determine the optimum evaporation pond and freezing pad designs. Nine additional simulations were conducted to determine the impacts of produced water quality and atmospheric conditions on the effectiveness of the FTE process. All samples from these eighteen laboratory-scale FTE process simulations were subjected to limited chemical analyses (Table 3). Finally, three additional simulations were conducted to provide sufficient samples for detailed chemical analyses (Table 2). The following sections provide details regarding the results of these simulations:

3.2.1.1 Initial Analyses of Produced Waters

Produced water samples were collected from an oil and gas producing well near Brighton, CO (FTE A); a natural gas producing well in Weld County, CO (FTE B); and a coal bed methane well in the San Juan Basin (FTE C). Samples of each of these produced waters were then submitted for detailed chemical analyses (Table 2). The results of analyses of these samples are presented in Tables 14, 15, and 16.

The results of the inorganic analyses show that: the salinity, as represented by the TDS, varies significantly between the three produced waters with the TDS of the FTE B (natural gas) produced water having the lowest concentration (2700 mg/l), the FTE A (oil and gas) produced water having an intermediate concentration (7600 mg/l), and the FTE C (coal bed methane) produced water having the highest concentration (11,000 mg/l). The FTE A and FTE C waters are both mildly basic with pH values of approximately 8.1. The FTE B water is mildly acidic with a pH value of 6.7. The FTE A water is predominately a sodium chloride based water with a substantial TOC concentration (6600 mg/l) and significant concentrations of sulfate, ammonia, cyanide, and phenols. The FTE B water is also predominantly a sodium chloride based water with significant concentrations of ammonia and cyanide; and a small, but detectable, concentration of phenols. However, the FTE B water contains concentrations of TOC and sulfate below the analytical detection limits. The FTE C water is the most alkaline of the three waters and is predominantly a sodium carbonate based water with concentrations of TOC, sulfate, cyanide and phenols all below the analytical detection limits for the analyses. The FTE C water does contain a detectable concentration of ammonia, but the concentration is significantly lower

Table 14. Results of Initial Produced Water Characterization - Inorganic and Radionuclide Analyses.

Produced Water:	Coal Bed Methane FTE C (mg/l)	Oil & Gas FTE A (mg/l)	Natural Gas FTE B (mg/l)
TDS	11000	7600	2730
Alkalinity	8360	1130	159
Ammonia	3.2	15.0	14.7
Cyanide	<0.1	0.69	0.57
H2S	<0.05	<0.05	<0.05
TOC	<100	6610	<100
Tot. Phenols	<0.01	5.25	0.60
Na	3700	2510	716
Ca	16.3	86.9	78.1
Mg	25.5	17.1	5.86
Fe	0.26	11.8	2.33
SO4	<10	101	<10
NO3	11.9	4.0	6.3
NO2	12	<0.5	<0.5
Cl	875	3630	1230
F	<1	<1	<1
Al	<1	<1	<1
As	<0.05	<0.05	<0.05
Ba	31.2	0.1	1.5
Be	<0.05	<0.05	<0.05
B	2.33	12.2	3.53
Cd	<0.01	<0.01	<0.01
Cr	<0.05	<0.05	<0.05
Co	<0.01	<0.01	<0.01
Cu	<0.1	<0.1	<0.1
Pb	<0.01	<0.01	<0.01
Li	<1	1.2	<1
Mn	<0.01	0.9	0.2
Hg	<0.0001	<0.0001	<0.0001
Ni	<0.1	<0.1	<0.1
Ra 226(a)	1.2(+/-0.7)	(b)	3.6(+/-1.5)
Ra 228(a)	3.9(+/-2.1)	(b)	(b)
Se	<0.01	<0.01	<0.01
Sr	11	4.6	7.6
Ag	<0.01	<0.01	<0.01
U	<0.002	<0.002	<0.002
V	<0.1	<0.1	<0.1
Zn	<0.05	0.07	<0.05

(a) - Concentration in pCi/l.

(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

Table 15. Results of Initial Produced Water Characterization - Volatile Organic Analyses.

Produced Water:	Coal Bed Methane FTE C (µg/l)	Oil & Gas FTE A (µg/l)	Natural Gas FTE B (µg/l)
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	U
Acetone	U	15000	140
Carbon Disulfide	U	190	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	120	12
1,2-Dichloroethane	U	U	U
2-Butanone	U	1400	U
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	U	15000	1800
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	1	9100	870
Chlorobenzene	U	U	U
Ethyl Benzene	U	180	U
Styrene	U	U	U
Total Xylenes	U	1700	470
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 16. Results of Initial Produced Water Characterization - Semi-Volatile Organic Analyses.

Produced Water:	Coal Bed Methane FTE C (µg/l)	Oil & Gas FTE A (µg/l)	Natural Gas FTE B (µg/l)
Base/Neutrals:			
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl)Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	39	6
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	29	33
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenyl ether	U	U	U
Fluorene	U	49	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	6
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 16. Results of Initial Produced Water Characterization - Semi-Volatile Organic Analyses. (Continued)

Produced Water:	Coal Bed Methane FTE C (µg/l)	Oil & Gas FTE A (µg/l)	Natural Gas FTE B (µg/l)
Base/Neutrals:			
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	15	U	200
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	23
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U
Acids:			
Phenol	U	3100	110
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	930	220
4-Methylphenol	U	650	10
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	200	150
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

than the ammonia concentrations of the FTE A and B waters. The FTE C water is the only water of the three to contain a detectable quantity of nitrate and also has the highest concentration of nitrite. Analyses to determine the concentrations of trace metals in the waters indicate that with few exceptions the waters contain low levels of metals (Table 14).

The results of the radionuclide analyses indicate: none of the three produced waters contained detectable quantities of Uranium or Radium 228, detectable quantities of Gross Alpha radiation were found only in the FTE C (coal bed methane) produced water, detectable quantities of Radium 226 were found in the FTE A (oil and gas) and FTE B (natural gas) produced waters. All three produced waters contained detectable quantities of strontium: 4.6, 7.6, and 11 mg/l in FTE A, B, and C, respectively (Table 14). Results of the volatile organic analyses indicate: Benzene, Toluene, and Xylenes in the low ppm range (15 mg/l benzene, 9 mg/l toluene, and 2 mg/l xylene) and Carbon Disulfide (190 ug/l), 2-Butanone (1,400 ug/l), and Ethyl Benzene (180 ug/l) were present in the FTE A water only; benzene was present in the low ppm range (2 mg/l benzene) and toluene (870 ug/l) and xylene (470 ug/l) were present in the ppb range in the FTE B water; and essentially no volatile organics (only 1 ug/l toluene) were found in the FTE C water (Table 15).

Results of the Semivolatile organic analyses indicate: quantities of Naphthalene (39 ug/l), 2-Methylnaphthalene (29 ug/l), and Fluorene (49 ug/l) along with phenols (3,100 ug/l Phenol, 930 ug/l 2-Methylphenol, 650 ug/l 4-Methylphenol, and 200 ug/l 2, 4-Dimethylphenol) were present in the FTE A water; quantities of Naphthalene (6 ug/l), 2-Methylnaphthalene (33 ug/l), and Phenanthrene (6 ug/l) along with phenols (110 ug/l Phenol, 220 ug/l 2-Methylphenol, 10 ug/l 4-Methylphenol, and 150 ug/l 2, 4-Dimethylphenol) were present in the FTE B water; and no semi-volatile organic compounds were present in FTE C water (Table 16).

3.2.1.2 Equipment Optimization - Results of Laboratory-Scale Simulation Series 1

The initial series of simulations consisted of nine FTE process simulations to test of different process design options. The objective of this series was to determine the best freezing pad and produced water pond designs. The three different freezing pad designs tested were:

- wetted column freezing (WCF),
- conventional water spray freezing (WSF), and
- atomizing spray freezing (ASF).

Three different evaporation pond design options for the produced water holding pond were also tested:

- conventional evaporation pond (CEP),
- enhanced evaporation pond (EEP), and
- solar distillation pond (SDP).

In the initial simulation series, the three different freezing process design options and three different evaporation process design options were thoroughly tested by coupling each pad design with each pond design. Nine simulations resulted from the coupling. The data from these nine simulations were used to select the most efficient and economic pad and pond design combination for the FTE process. As previously mentioned, experimental procedures were modified for this simulation in order to economically achieve the experimental objectives. The produced water from the oil and gas well (FTE A) was used in all nine simulations because the combination of moderately high TDS and TOC concentrations, coupled with the physical appearance and odor of the water, made it appear to be the most difficult water to treat.

As previously discussed the initial simulation series was conducted as two separate tests: a freezing test and an evaporation test. One produced water composite sample was collected during the freezing test of the initial simulation series and nine treated water and nine brine composite samples were generated and collected, one set from each simulator. These samples were subjected to limited chemical analyses (Table 3). Using the logged data and chemical analyses data, overall mass, TDS, TOC and boron balances were determined for the freezing test in each of the nine simulations. The results of these balances are presented in detail in Appendix D, Section D-1 and are summarized in Table 17. As the data in the table illustrate, each of the treated waters produced in the nine simulations would be suitable for surface discharge, based upon the limited chemical analyses data. (Note: In a commercial facility, more detailed organic and inorganic analyses would be required prior to permit approval for surface discharge.)

Other key observations regarding the data, are that the reduction in the concentrations of organics and boron in the treated waters produced are similar to the TDS concentration reductions. Further, the TDS concentrations of the brines produced and the reductions in disposal volumes achieved are economically favorable based upon the results of Task 1 research.

Table 17. Results Summary for Simulation Series 1 - Freezing Test

Simulation #	1-1	1-2	1-3	1-4	1-5	1-6	1-7	1-8	1-9
Pond Design[a]	EEP	SDP	EEP	EEP	SDP	CEP	CEP	SDP	CEP
Pad Design[b]	WCF	WSF	WSF	ASF	WCF	ASF	WSF	ASF	WCF
Treated Water Analyses:									
TDS, mg/l	780	710	1580	580	620	930	830	1140	1040
TOC, mg/l	<100	<100	<100	<100	<100	<100	<100	<100	<100
Boron, mg/l	0.82	0.76	1.48	0.61	0.62	0.89	0.81	1.09	0.98
Brine Analyses:									
TDS, mg/l	55300	31000	42000	44000	25400	32300	33000	42300	55300
TOC, mg/l	990	650	610	660	430	530	540	550	720
Boron, mg/l	51.5	32.0	38.7	38.1	22.3	28.4	29.3	28.2	39.1
Produced Water Analyses:									
TDS, mg/l	11900	11900	11900	11900	11900	11900	11900	11900	11900
TOC, mg/l	250	250	250	250	250	250	250	250	250
Boron, mg/l	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5	10.5
Mass of Contaminant in Treated Water (% of Contaminant Mass in Produced Water Feed):									
TDS	2.5%	1.5%	4.6%	1.3%	1.1%	2.5%	2.1%	2.8%	3.8%
TOC	0%	0%	0%	0%	0%	0%	0%	0%	0%
Boron	3.0%	1.8%	4.9%	1.6%	1.3%	2.8%	2.3%	3.0%	4.1%
Mass Yield (% of Produced Water Feed):									
Treated Water	38.4%	24.9%	34.6%	26.8%	22.0%	32.5%	29.9%	29.2%	43.6%
Brine	18.0%	34.1%	23.0%	20.2%	35.2%	24.6%	23.2%	20.0%	13.8%
Pond Inventory	5.9%	3.8%	3.1%	12.6%	6.7%	7.0%	9.9%	7.9%	6.2%
Evap. + Losses	37.6%	37.2%	39.3%	40.4%	36.1%	35.9%	37.0%	42.9%	36.4%
Reduction in Required Disposal Volume (% of Mass of Produced Water Feed):									
	76.1%	62.1%	73.9%	67.2%	58.1%	68.4%	66.9%	72.1%	80.0%

[a] CEP = conventional evaporation pond, EEP = enhanced evaporation pond, and SDP = solar distillation pond.

[b] WCF = wetted column freezing, WSF = conventional water spray freezing, and ASF = atomizing spray freezing.

The overall mass balances for each of the nine simulations in this series were forced to closure by determining the evaporation plus experimental losses by difference. Evaporation and losses in the freezing test were determined by difference because it was not possible to accurately measure the volume of ice on each freezing pad. However, it was possible to measure the total volume of moisture that was condensed on the refrigerant evaporator during the freezing test of the initial simulation series. This volume is an approximate representation of the total volume of water evaporated from all nine simulators during the freezing test. The total mass of evaporation plus losses in the nine simulations was 33,500 g. The total mass of water condensed and collected from the refrigerant evaporator was 32,200 g. Thus, the losses from the nine simulations are 1,300 g which is 1.5% of the total produced water feed during the simulations.

Samples were not taken during the evaporation portion of the initial series of simulations. Performance of the evaporation pond design options were determined based upon the rates of evaporation achieved during the eight days of operation. The best design option was determined by projected process economics and by comparison of the evaporation and freezing performance achieved among all of the simulator design combinations.

Economic projections for each of the nine simulations in the initial series were made using the model developed in Task 1. The produced water, brine, and treated water TDS concentrations from each simulation; the treated water and brine yields from each simulation; and, the PAN evaporation efficiencies achieved from each simulation were used along with climatic conditions as the required model inputs. In order to achieve the most accurate comparison, similar holding pond design criteria were assumed for the conventional and enhanced evaporation pond designs. The difference in design between these two options was that the enhanced evaporation pond design had sprays while the conventional design did not. The results of the economic projections for the initial simulations are summarized in Table 18 and provided in detail in Appendix E, Tables E-8 through E-70. The data in Table 18 illustrate that the treated water cost projected for the conventional and enhanced evaporation pond designs are similar and significantly less than the projected treatment costs for the designs testing the solar distillation pond design.

Table 18. Projected FTE Water Treatment Costs based upon the Results of the Initial Simulation Series

	Water Treatment Cost, $/bbl (Simulation #)		
Evaporation Pond Design[a]	CEP	EEP	SDP
Freezing Pad Design[b]			
WCF	0.20 / (1-9)	0.21 / (1-1)	0.56 / (1-5)
WSF	0.22 / (1-7)	0.22 / (1-3)	0.47 / (1-2)
ASF	0.23 / (1-6)	0.22 / (1-4)	0.41 / (1-8)

[a] CEP = conventional evaporation pond, EEP = enhanced evaporation pond, and SDP = solar distillation pond.

[b] WCF = wetted column freezing, WSF = conventional water spray freezing, and ASF = atomizing spray freezing.

The PAN evaporation efficiencies achieved for the various designs tested in the initial nine simulations are illustrated in Figure 23. The data in this figure illustrate that the enhanced evaporation pond design performs better than the other designs tested. Since the economic model developed in Task 1 calculates the process water treatment cost based upon the volume of water treated, the enhanced evaporation pond design is more economic than the conventional pond design when the cost per barrel of water treated or disposed of is considered. For this reason, the enhanced evaporation pond design was selected for use in later simulations.

The FTE process performance for the initial simulations conducted using the enhanced evaporation pond design is summarized in Figure 24. These data illustrate that the performance of the water column freezing pad design was the best with the conventional spray freezing pad design a close second. For this reason, the water column pad design was selected for use in later simulations. However, it should be noted that the limited space in the refrigeration unit required that the water sprays be set so that the height of spraying was only approximately nine inches. The water column freezing pads were operated at a height of twelve inches. Further, the, atomizing sprays had to be set with a spray height of approximately four inches in order to contain the spray in the simulators. This probably explains the difference in the results between simulations using the various designs.

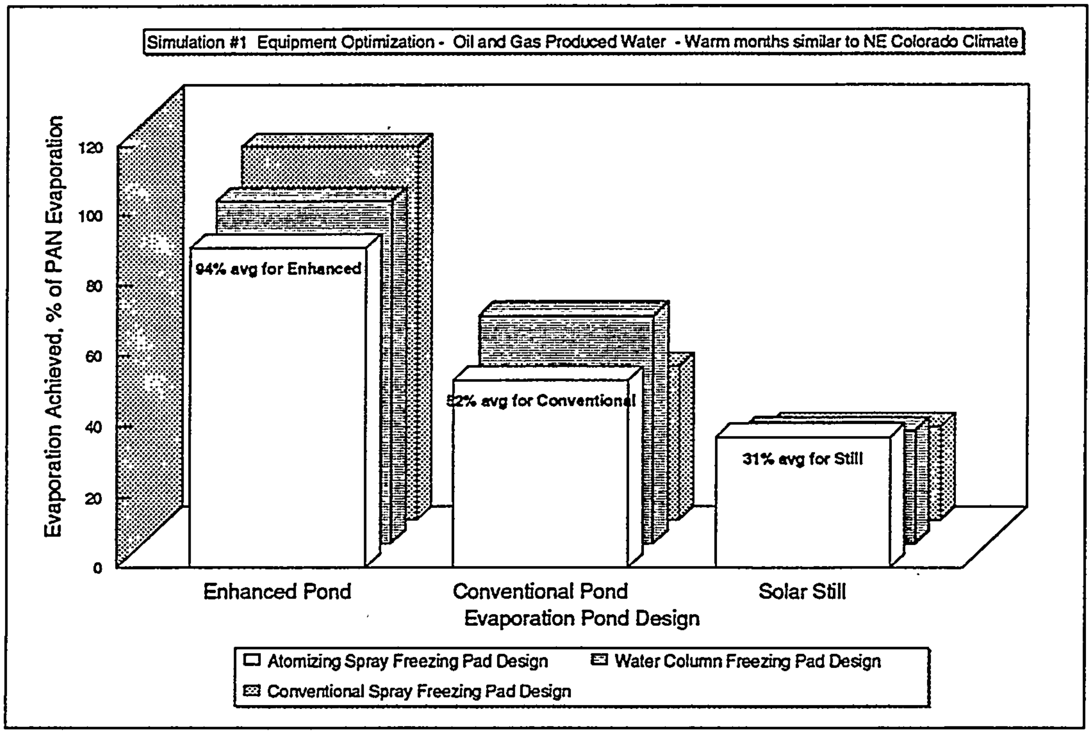
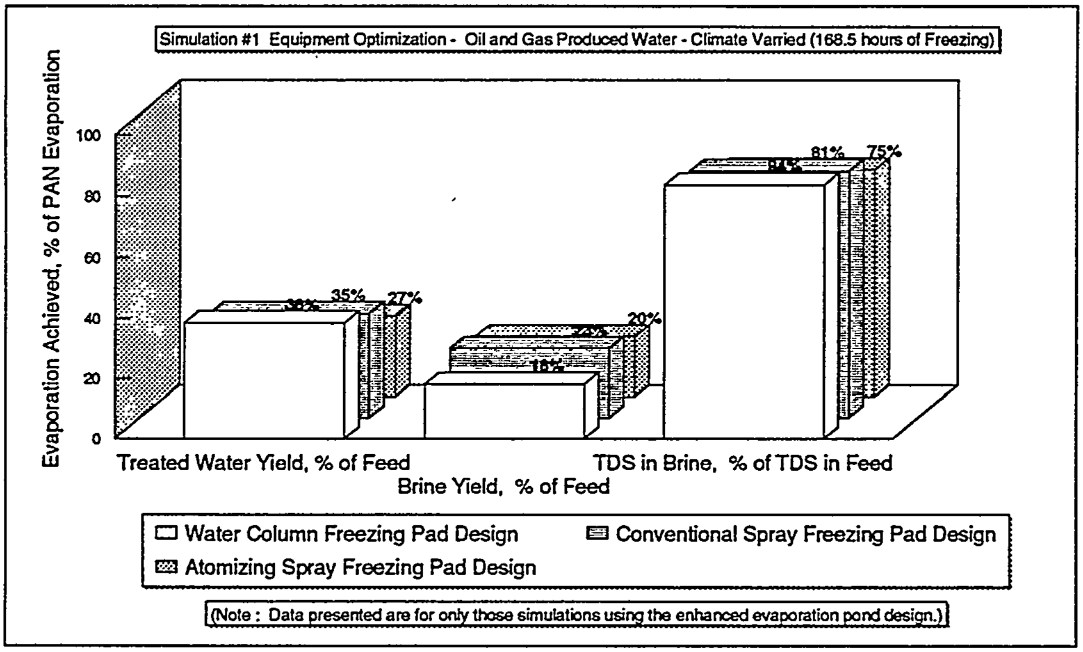


Figure 23. PAN Evaporation Efficiency Achieved for Various Designs



(Note : Data presented are for only those simulations using the enhanced evaporation pond design.)

Figure 24. FTE Performance for Various Freezing Pad Designs

Based upon observations made during the simulations, it is concluded that atomizing sprays would be difficult to contain in a field situation and are not recommended. Further, while the water column design is workable and has favorable results it is suspected that conventional sprays would probably perform better in a field situation where space and containment problems, that occurred during the simulations, are greatly reduced.

3.2.1.3 Impacts of Produced Water Quality and Atmospheric Conditions on the Effectiveness of the FTE Process - Results of Laboratory-Scale Simulation Series 2, 3, and 4

The second, third, and fourth laboratory-scale series of FTE process simulations were conducted with the objectives of determining the impacts of produced water quality and atmospheric conditions on the effectiveness of the FTE process. Each of the three produced waters were tested in Laboratory-Scale Simulation Series 2, 3, and 4 resulting in a total of nine simulations being conducted. The enhanced evaporation pond design and water column freezing pad design were used in these simulations. In the three simulations in each series, one simulator was fed with the coal bed methane produced water (designation "FTE C"), one simulator was fed with the oil and gas produced water (designation "FTE A"), and the remaining simulator was fed with the natural gas produced water (designation "FTE B").

The second series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of northeastern Colorado. Daily temperature cycles simulating the monthly average cycles for northeastern Colorado were used in the series. The simulations began with temperature cycles similar to the month of April, which is the first month in northeastern Colorado with average temperatures consistently above 0°C. A total of 103 hours with temperatures below 0°C existed during Simulation Series 2.

The third series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of northwestern New Mexico. These three simulations used similar design and produced waters as Simulation Series 2. In this simulation series, the temperature cycles simulated conditions typical of northwestern New Mexico. The simulations began with the month of April which is the first month in northwestern New Mexico with average temperatures consistently above 0°C. A total of 94 hours with temperatures below 0°C existed during Simulation Series 3.

The fourth series of three laboratory simulations investigated the impact of produced water quality on the effectiveness of the FTE process when operating under climatic conditions similar to those of central Wyoming. These three simulations also used similar design and produced waters as Simulation Series 2 and 3 but with temperature cycles that simulated conditions typical of central Wyoming. The simulations began with the month of May, which is the first month in central Wyoming with average temperatures consistently above 0°C. A total of 169 hours with temperature below 0°C existed during Simulation Series 4.

The nine produced water, nine treated water, and nine brine composite samples produced during Simulation Series 2, 3, and 4 were subjected to limited chemical analyses (Table 3). Material and chemical species balances were determined for overall mass, TDS, TOC, and Boron in each of the nine simulations. The results of these balances are presented in detail in Appendix D, Section D-2 (Series 2), Section D-3 (Series 3), and Section D-4 (Series 4). These results are also summarized in Table 19. Based upon the data in Table 19, it is obvious that cross-contamination of organics occurred in many of the simulations. In addition, it was also found that the TOC analytical procedure used was less than optimum. The detection limit of the analytical TOC procedure was too high and it is also suspected that the microbiological activity occurring during the simulations interfered with the results of these analyses. In Simulation Series 2 and 4, the microbiological activity in the simulators was significant. In Simulation Series 3, the microbiological activity in the simulators was excessive, with respect to equipment operation, and resulted in the large spill during Simulation 3-3. This spill was caused by plugging of holding pond sprays with the microbial slime generated. However, while these problems did impact the ability to perform TOC balances on the simulations and draw conclusions regarding the portioning of organics, these data were adequate to estimate the impact of produced water quality and atmospheric conditions on the effectiveness of the FTE process in removing TDS and metals.

Table 19. Results Summary for Simulation Series 2, 3, and 4 - Impacts of Produced Water Quality and Atmospheric Conditions

Simulation # Produced Water[a]	2-1 C	2-2 A	2-3 B	3-1 C	3-2 A	3-3[b] B	4-1 C	4-2 A	4-3 B
Treated Water Analyses:									
TDS, mg/l	386	484	308	1380	866	240	430	410	240
TOC, mg/l	<100	220	<100	110	620	120	<100	180	<100
Boron, mg/l	0.11	1.14	0.83	0.61	1.27	0.69	<0.2	0.35	0.28
Brine Analyses:									
TDS, mg/l	54300	50700	42300	41200	27900	12500	69500	47900	37800
TOC, mg/l	7040	32300	1460	370	14000	380	1170	17750	680
Boron, mg/l	10.9	53.2	51.0	8.0	28.8	15.5	10.1	27.0	33.4
Produced Water Analyses:									
TDS, mg/l	10800	8530	2680	10340	8180	2600	10700	8690	2705
TOC, mg/l	140	2640	100	130	8000	100	360	9000	<100
Boron, mg/l	3.0	10.5	3.7	2.2	9.9	3.5	2.2	7.8	3.4
Mass of Contaminant in Treated Water (% of Contaminant Mass in Produced Water Feed):									
TDS	0.9%	1.2%	4.0%	3.1%	2.1%	2.4%	1.5%	1.7%	3.6%
TOC	0%	1.8%	0%	19.9%	1.6%	30.8%	0%	0.7%	0%
Boron	1.0%	2.3%	7.9%	6.7%	2.6%	5.0%	0%	1.6%	3.3%
Mass Yield (% of Produced Water Feed):									
Treated Water	25.1%	21.5%	34.8%	23.6%	20.2%	25.7%	38.4%	35.6%	40.1%
Brine	19.1%	16.0%	5.5%	21.9%	26.7%	8.3%	14.8%	14.9%	6.6%
Evaporation	53.5%	55.8%	59.0%	54.1%	49.4%	64.8%	41.3%	42.8%	43.7%
Losses	2.3%	6.7%	0.8%	0.4%	3.7%	1.2%	5.6%	6.7%	9.6%
Reduction in Required Disposal Volume (% of Mass of Produced Water Feed):									
	80.9%	84.0%	94.5%	78.1%	73.3%	91.7%	85.2%	85.1%	93.4%

[a] Produced Waters: A = Water from an oil & gas well, B = Water from a natural gas well, C= Water from a coal bed methane well.

[b] Data presented represents the large water spill that occurred during the simulation (See pages 40 and D-3-7). The mass yield of evaporation shown is reflective of the mass evaporated plus the mass lost in the spill.

Further, the detailed analyses of experimental products from the three simulations conducted in Simulation Series 5 were to determine in detail the fate of individual inorganic, organic, and radionuclide species. The results of Simulation Series 5 are discussed in the Section 3.2.1.4.

The data in the table also illustrate that all treated waters generated are suitable for surface discharge and/or beneficial use, with respect to the TDS concentration. Significant contaminant reductions in the treated waters and contaminant concentrations in the brines resulting from the FTE process are also evident. In addition, the reduction in the required disposal volume resulting from the FTE process is evident.

The impact of produced water quality on the effectiveness of the FTE process is graphically illustrated in Figures 25 and 26. Figure 25 provides the non-dimensional TDS concentration in the treated water produced from the laboratory-scale FTE process simulations conducted in Series 2, 3, 4, and 5 as a function of the TDS concentration of the freezing pad feed water. The non-dimensional TDS concentration is determined by dividing the estimated TDS concentration of the feed water to the freezing pad. The TDS concentration of the freezing pad feed is estimated by assuming that water evaporated during the first part of the simulations contains no TDS. The TDS concentration of the feed to the feeding pad is then determined by considering the TDS in the feed to the holding pond and the amount of water pumped from the holding pond to the freezing pad. Results from Series 5 are included in the figure to provide three additional data points for the correlations. Simulation Series 5 was conducted with 183 hours of subfreezing conditions occurring during the simulations. (Note: A more detailed discussion of the results of the three simulations conducted in Series 5 will be presented in the Section 3.2.1.4.

The data illustrated in Figure 25 is difficult to consider alone. Figure 26 is then provided to further illustrate the impact of produced water quality on the effectiveness of the FTE process. The data presented in Figure 26 illustrates the non-dimensional TDS concentration in the brine produced from the FTE process simulations conducted in Series 2, 3, 4, and 5 as a function of the TDS concentration of the freezing pad feed water. The data in the two figures indicate that the lower the TDS concentration of the feed to the freezing pad the greater

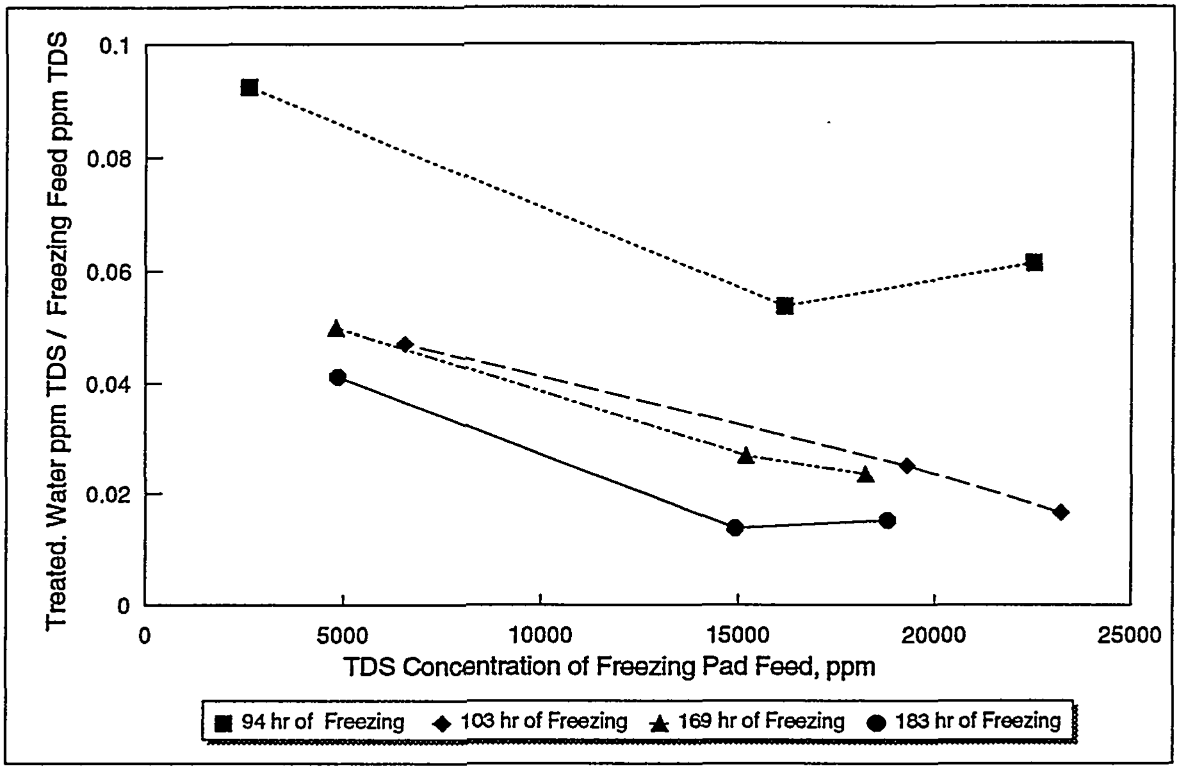


Figure 25. Non-Dimensional Treated Water TDS Concentration versus TDS Concentration of Freezing Pad Feed

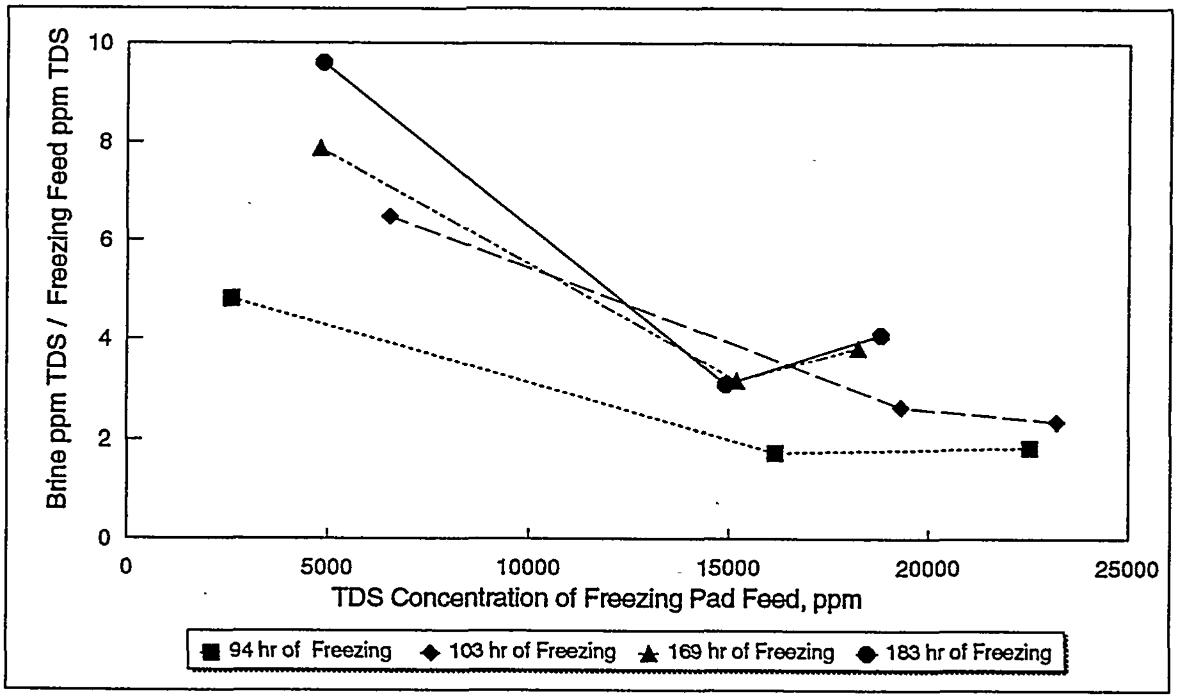


Figure 26. Non-Dimensional Brine TDS Concentration versus TDS Concentration of Freezing Pad Feed

the TDS concentration increase in the brine. However, in the cases of a low TDS concentration in the feed to the freezing pad the non-dimensional TDS concentration is higher. These impacts are mathematical and related to dividing by a smaller numbers. However, the nature of the curves in the figures do suggest that the equilibrium chemistry of the water at subfreezing temperatures also impacts the process effectiveness. The data in the two figures also illustrates that the more hours with subfreezing temperatures occurring during a simulation the lower the non-dimensional TDS concentration in the treated water and the higher the non-dimensional TDS concentration in the brine (Figures 25 and 26).

Figures 27 and 28 are provided to further illustrate the impact of the atmospheric conditions during the simulations completed in Series 2, 3, 4, and 5 on the effectiveness of the FTE process. Figure 27 provides data illustrating the non-dimensional TDS concentration of the treated water as a function of the hours of freezing occurring during the simulation for each of the three produced waters tested. Similarly, Figure 28 provides data illustrating the non-dimensional TDS concentration of the brine as a function of the hours of freezing occurring during the simulation for each of the three produced waters tested. The data in these two figures clearly illustrate that the more hours of freezing during the simulation the more effective the FTE process is in treating all of the waters.

Figures 29 and 30 are provided to compare the effectiveness of metals removal using FTE process to the effectiveness of the overall TDS removal using the FTE process. Boron was selected as an indicator of heavy metal behavior during the simulations because it was the only heavy metal present in sufficient quantities in each of the three produced waters to permit quantification during analyses. Figure 29 provides data illustrating the non-dimensional boron concentration of the treated water as a function of the hours of freezing occurring during the simulation for each of the three produced waters tested. Similarly, Figure 30 provides data illustrating the non-dimensional boron concentration of the brine as a function of the hours of freezing occurring during the simulation for each of the three produced waters tested. If the effectiveness in removing metals using the FTE process is similar to the effectiveness of removing salts using the FTE process, Figures 27 and 29 should be similar in shape as should Figures 28 and 30. Inspection of the figures indicate the shape of the curves are similar.

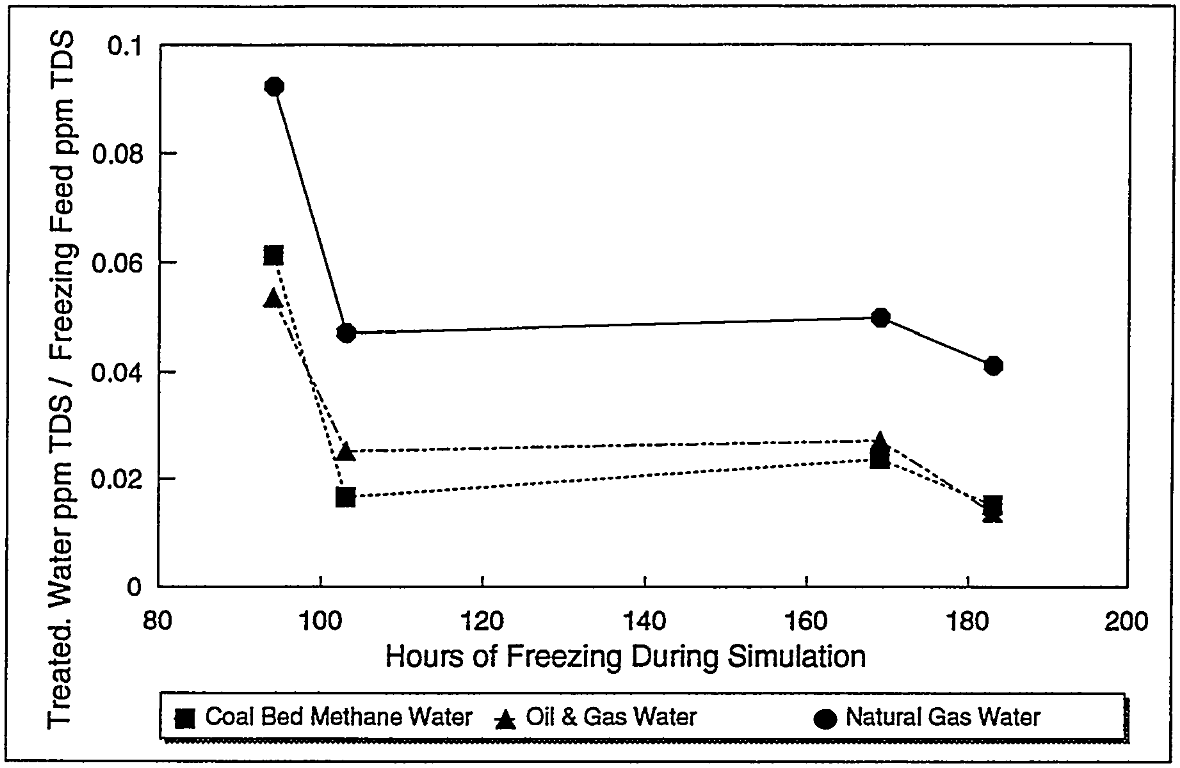


Figure 27. Non-Dimensional Treated Water TDS Concentration vs. Hours of Freezing during the Simulation

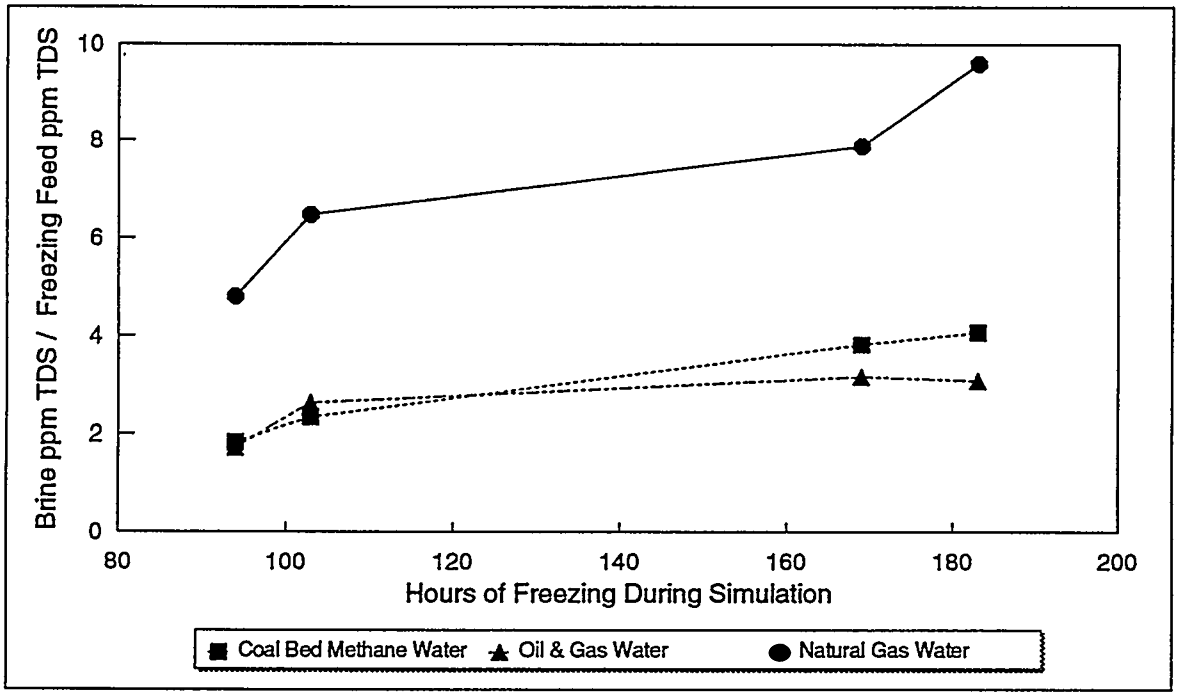


Figure 28. Non-Dimensional Brine TDS Concentration vs. Hours of Freezing during the Simulation

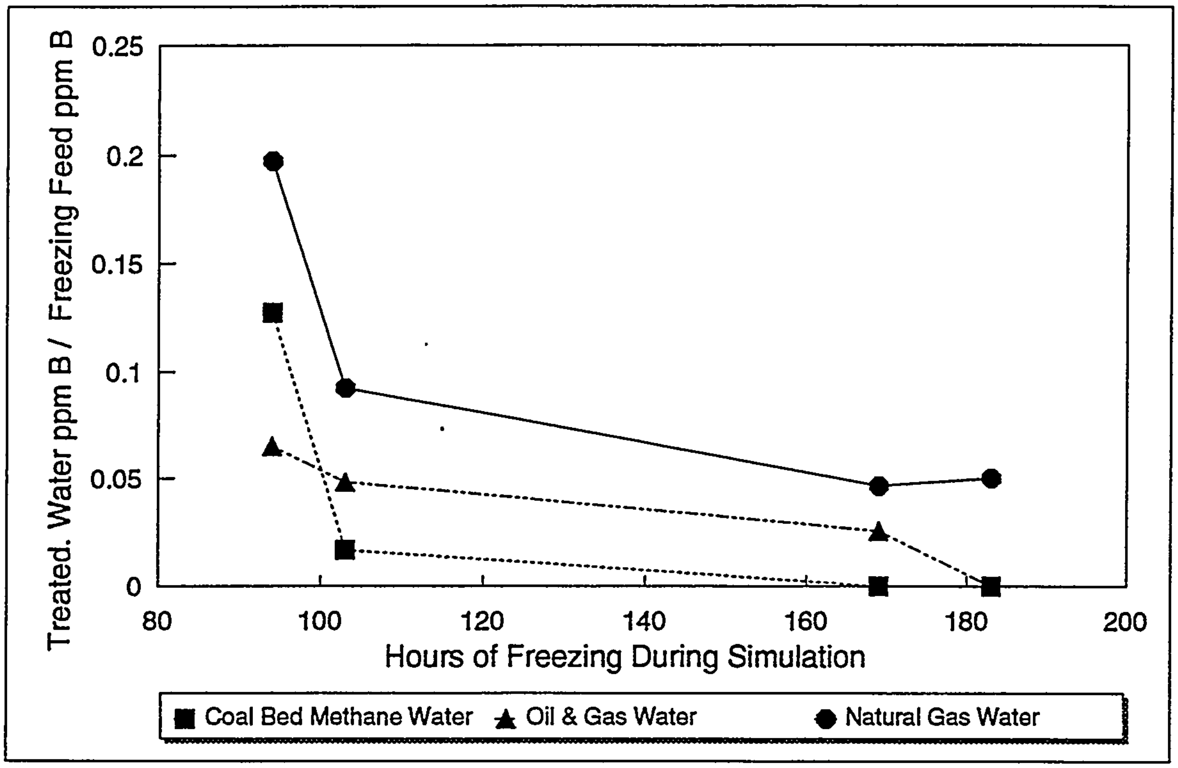


Figure 29. Non-Dimensional Treated Water Boron Concentration vs. Hours of Freezing during the Simulation

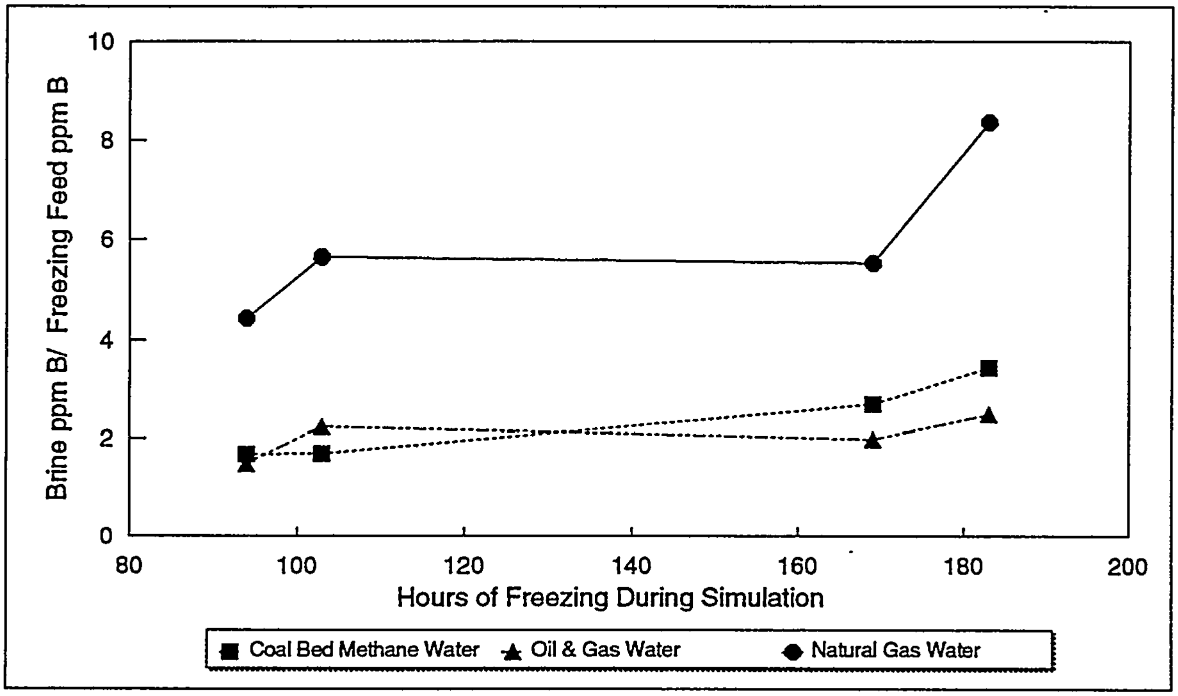


Figure 30. Non-Dimensional Brine Boron Concentration vs. Hours of Freezing during the Simulation

Figures 31 and 32 are also provided to further investigate the comparison of the effectiveness of metals removal using FTE process to the effectiveness of the overall TDS removal. Figure 31 provides data illustrating the non-dimensional boron concentration of the treated water as a function of non-dimensional TDS concentration of the treated water from the simulations and Figure 32 provides data illustrating the non-dimensional boron concentration of the brine as a function of non-dimensional TDS concentration of the brines from the simulations. If the effectiveness of removing metals using the FTE process is identical to the effectiveness of removing salts using the FTE process, the data in Figures 31 and 32 should both illustrate linear functions with slopes equal to 1. The data illustrated in Figure 31 are somewhat linear. A linear regression analysis of these data yields an R^2 of 0.79 and a slope of 1.7. Further, regression analyses of the data yields that: in the two simulation series in which warm or mild atmospheric conditions were examined (Simulation Series 2 and 3), the regression analyses yields an R^2 of 0.86 and a slope of 2.0; and, for the two simulations series in which cold atmospheric conditions were examined (Simulation Series 3 and 4), the regression analyses yields an R^2 of 0.89 and a slope of 1.0.

These data suggest that boron salts do not drain from the ice pile as rapidly as other salts such as sodium or calcium salts which are known to melt ice. If this is the case, the age of the ice pile is an important factor impacting the effectiveness of the FTE process. Further, this would imply that the freezing is as effective in removing metals from the ice as it is in removing salts but the physical separation of the heavy metal salts from the ice requires more time than the physical separation of salts with lower molecular weight cations. If this is the case, in a field situation this would limit the application of the process to climates with less than 169 hours of freezing per year. It should be noted here, that all the areas where the freezing process is believed to be applicable (Figure 2) have far in excess of 160 hours of freezing per year.

Figure 32 provides data illustrating the non-dimensional boron concentration of the brine water as a function of non-dimensional TDS concentration of the brine during the simulations. These data are useful to further investigate if the effectiveness of removing metals using the FTE process is similar to the effectiveness of removing salts using the

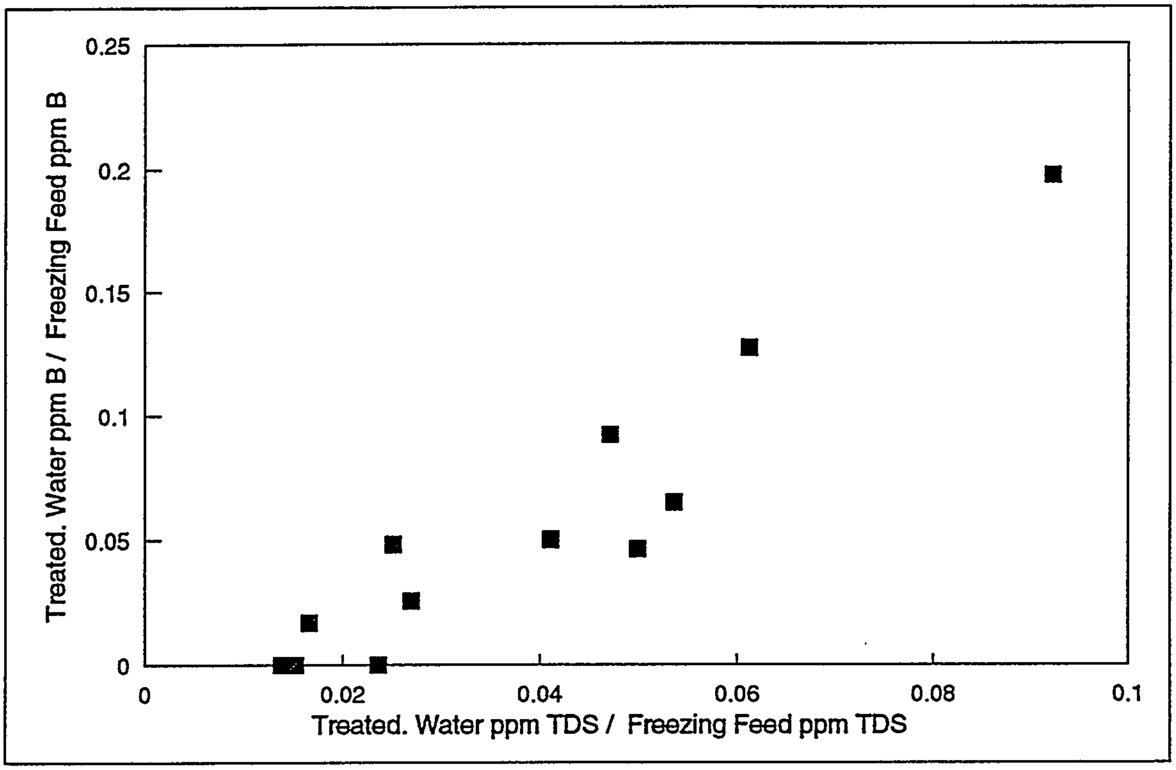


Figure 31. Non-Dimensional Treated Water Boron Concentration vs. Non-Dimensional Treated Water TDS Concentration

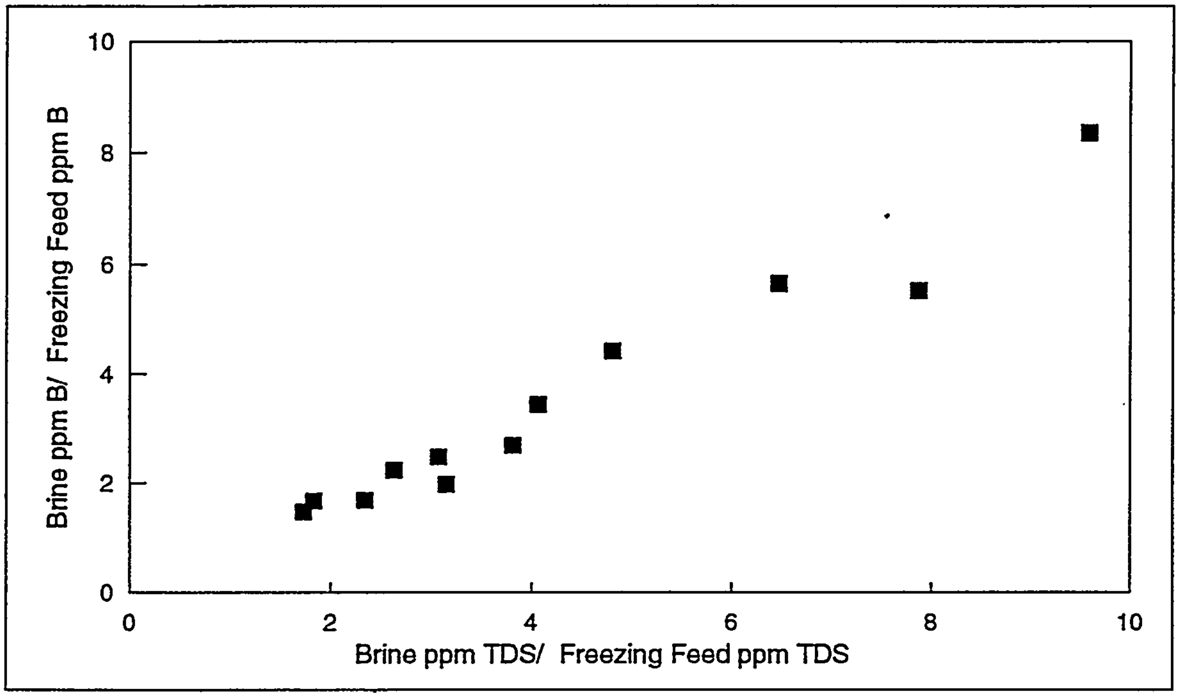


Figure 32. Non-Dimensional Brine Boron Concentration vs. Non-Dimensional Brine TDS Concentration

FTE process. As previously stated, the data in Figure 32 should also illustrate a linear function with the slope equal to 1. However, the data illustrated in Figure 32 is reflective of the brine compositions which are more concentrated with chemical constituents than the treated waters. The brine analyses to determine boron concentrations should be somewhat more accurate than the treated water analyses to determine boron concentrations because they are not near or less than the detection limits for boron analyses as the treated water compositions were. Again, the data illustrated in Figure 32 appears linear. A linear regression analysis of these data yielded an R^2 of 0.96 and a slope of 0.82 which statistically supports the assumption regarding the direct relationship of salt and metals removal using the FTE process. An explanation for the slope of the line being less than one may be precipitates found in the colder simulations (Simulation Series 4 and 5). In preparing the brine samples for analyses, the brines were allowed to warm to room temperature and stirred in an effort to re-dissolve as much of the precipitate as possible. However, it was not possible to re-dissolve all the precipitates. This caused some problems with specific ion balance closures in the material balance for the simulations and was most evident in the balances related to cations with divalent or trivalent states. Salts composed of monovalent cations are typically more soluble than those salts composed of divalent cations.

3.2.1.4 Detailed Chemical Analyses of Simulation Products - Results of Laboratory-Scale Simulation Series 5

The fifth laboratory-scale series of FTE process simulations was conducted with the objectives of providing sufficient treated water and brine samples for detailed inorganic, organic, and radionuclide analyses. Each of the three produced waters were tested in Laboratory-Scale Simulation Series 5 using similar equipment and procedures as those used in the previous three simulation series. The fifth series of laboratory simulations was performed to duplicate the operation and conditions of Simulation Series 4 using temperature cycles which simulated conditions typical of central Wyoming. However, a total of 182.5 hours with temperature below 0°C existed during Simulation Series 5 because serious operating problems did not occur as they did in Series 4.

The results of the inorganic and radionuclide analyses of the process streams from Simulation #s 5-1, 5-2, and 5-3 are presented in detail in Appendix D Section D-5 along with overall mass and individual ionic species balances. In addition, the results of the inorganic and radionuclide analyses for Simulation #s 5-1, 5-2, and 5-3 are summarized in Tables 20, 21, and 22, respectively. Simulation #5-1 tested the coal bed methane well produced water(FTE C), Simulation #5-2 tested the oil and gas produced water (FTE A), and Simulation #5-3 tested the natural gas produced water (FTE B). The data in these tables illustrate that:

- The treated waters are all suitable for agricultural use.
- With a minor polishing process, such as activated carbon filtration, all of the treated waters produced would be suitable for municipal use. Such polishing steps are economic due to the dilute concentrations of analytes found in the treated waters.
- The concentrations of all inorganic and radionuclide analytes considered were significantly reduced in the treated waters produced compared to their respective concentrations in both the produced water and feed water to the freezing pad.
- The concentrations of all inorganic and radionuclide analytes considered were significantly increased in the brines produced compared to their respective concentrations in both the produced water and feed water to the freezing pad. In fact, many analytes considered, specifically Al, F, Cd, Pb, Li, Hg, Se, and Ra^{228}, were below their respective analytical detection limits in the produced water but were sufficiently concentrated in the brines produced by the FTE process to be detectable in the brines.

The results of the volatile and semi-volatile (BNA and PNA) organic analyses of the process streams from Simulation #s 5-1, 5-2, and 5-3 are presented in detail in Appendix D Section D-6. In addition, the results of the volatile organic analyses for Simulation #s 5-1, 5-2, and 5-3 are summarized in Tables 23, 24, and 25, respectively; and, the results of the semi-volatile organic analyses for Simulation #s 5-1, 5-2, and 5-3 are summarized in Tables 26, 27, and 28, respectively. The data in these tables illustrate that:

- External contamination and cross-contamination of the experimental products with Chloromethane, Bromomethane, Methylene chloride, Acetone, 2-Butanone, and 1-1-2-2 Tetrachloroethane occurred. Traces of these species were detected in some of the treated waters but were not present in the produced water in sufficient concentration to explain the concentration found in the treated water.

Table 20. Results of Chemical Analyses of Process Streams for Simulation # 5-1.

Process Stream: Analyte	Produced Water Feed (mg/l)	Est. Pond Water prior to Freezing (mg/l)	Treated Water (mg/l)	Brine (mg/l)
TDS	10900	18808	286	76570
Alkalinity	8500	14667	188	38750
Ammonia	0.89	1.54	0.48	5.27
Cyanide	<0.1	<0.1	<0.1	<0.3
H2S	<0.05	<0.05	<0.05	<0.16
TOC	1400	2416	<100	8804
Tot. Phenols	<0.01	<0.01	<0.010	0.84
Na	3750	6471	111	26288
Ca	6.3	10.9	2.0	12.4
Mg	23.5	40.6	0.84	163.7
Fe	0.26	0.45	<0.1	0.90
SO4	1.5	2.6	1.5	19.2
NO3	42.4	73.2	<1	163.7
NO2	<1		<1	<3
Cl	1100	1898	22.5	6107
F	<1		<1	28.5
Br	5.2	9.0	<1	39.7
Al	<1		<1	<3
As	<0.05		<0.05	<0.16
Ba	27.9	48.1	0.86	22.6
Be	<0.05		<0.05	<0.16
B	2.14	3.69	<0.2	12.74
Cd	<0.01		<0.01	0.05
Cr	<0.05		<0.05	<0.16
Co	<0.01		<0.01	<0.03
Cu	<0.1		<0.1	<0.3
Pb	<0.01		<0.01	0.124
Li	<1		<1	4
Mn	0.017	0.029	<0.01	<0.03
Hg	<0.0001		<0.0001	0.0015
Ni	<0.1		<0.1	<0.3
Ra 226(a)	2.8(+/- 1.8)	4.8(+/-3.1)	<0.3	11.8(+/- 6.5)
Ra 228(a)	(b)		(b)	17.1(+/- 6.5)
Se	<0.01		<0.01	<0.03
Sr	15	25.9	0.39	16
Ag	<0.01		<0.01	<0.03
U	<0.1		<0.1	<0.3
V	<0.1		<0.1	<0.3
Zn	<0.05		<0.05	<0.16

(a) - Concentration in pCi/l.
(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

Table 21. Results of Chemical Analyses of Process Streams for Simulation # 5-2.

Process Stream: Analyte	Produced Water Feed (mg/l)	Est. Pond Water prior to Freezing (mg/l)	Treated Water (mg/l)	Brine (mg/l)
TDS	8360	14927	206	45900
Alkalinity	1040	1857	39	6730
Ammonia	7.63	13.62	3.80	66.3
Cyanide	2.5	4.5	<0.1	9.6
H2S	<0.05		<0.05	<0.15
TOC	6050	10803	100	27300
Tot.Phenols	1.51	2.70	<0.01	9.51
Na	2240	4000	51.4	17040
Ca	66.6	118.9	12.4	126.6
Mg	12.0	21.4	<0.5	95.1
Fe	1.41	2.52	<0.1	47.4
SO4	87.1	155.5	3.0	621
NO3	<1		<1	<3
NO2	<1		<1	<3
Cl	4020	7178	83.0	29970
F	45.6	81.4	1.3	247.8
Br	26.3	47.0	<1	188.1
Al	<1		<1	4.2
As	<0.05		<0.05	<0.15
Ba	0.22	0.39	<0.1	122.1
Be	<0.05		<0.05	<0.15
B	8.80	15.71	<0.2	39.0
Cd	<0.01		<0.01	0.075
Cr	<0.05		<0.05	<0.15
Co	<0.01		<0.01	<0.03
Cu	<0.1		<0.1	<0.3
Pb	<0.01		<0.01	0.069
Li	1.1	2.0	<1	6.6
Mn	0.43	0.77	<0.013	2.61
Hg	0.0002	0.0004	<0.0001	0.0015
Ni	<0.1		<0.1	<0.3
Ra 226(a)	2.5(+/- 1.2)	4.5(+/-2.1)	(b)	5.7(+/- 3.3)
Ra 228(a)	4.2(+/-1.7)	7.5(+/-3.0)	(b)	(b)
Se	<0.01		<0.01	<0.036
Sr	5.7	10.2	0.55	29
Ag	<0.01		<0.01	<0.01
U	<0.1		<0.1	<0.1
V	<0.1		<0.1	<0.1
Zn	<0.05		<0.05	<0.05

(a) - Concentration in pCi/l.

(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

Table 22. Results of Chemical Analyses of Process Streams for Simulation # 5-3.

Process Stream: Analyte	Produced Water Feed (mg/l)	Est. Pond Water prior to Freezing (mg/l)	Treated Water (mg/l)	Brine (mg/l)
TDS	2640	4863	200	46620
Alkalinity	225	414	17	6370
Ammonia	6.81	12.55	2.20	83.3
Cyanide	0.2	0.4	<0.1	2.1
H2S	<0.05		<0.05	<0.35
TOC	<100		<100	1680
Tot. Phenols	0.13	0.24	<0.010	5.67
Na	757	1395	72.6	13650
Ca	63.6	117.2	11.0	791.0
Mg	5.7	10.4	0.7	105.0
Fe	0.21	0.39	<0.1	3.5
SO4	2.6	4.8	1.3	36
NO3	<1		<1	<7
NO2	<1		<1	<7
Cl	1350	2487	125.0	22050
F	<1		<1	<7
Br	10.3	19.0	<1	284.9
Al	<1		<1	<7
As	<0.05		<0.05	<0.35
Ba	2.2	4.1	0.17	17.4
Be	<0.05		<0.05	<0.35
B	3.05	5.62	0.28	46.9
Cd	<0.01		0.13	0.175
Cr	<0.05		<0.05	<0.35
Co	<0.01		<0.01	<0.07
Cu	<0.1		<0.1	<0.7
Pb	<0.01		<0.01	<0.07
Li	<1		<1	13.3
Mn	0.11	0.20	0.018	0.48
Hg	<0.0001		<0.0001	0.0042
Ni	<0.1		<0.1	<0.7
Ra 226(a)	3.1(+/- 1.2)	5.7(+/-2.2)	(b)	34.3(+/-18.2)
Ra 228(a)	(b)		<2.0	(b)
Se	<0.01		<0.01	<0.07
Sr	8.4	15.5	0.81	133
Ag	<0.01		<0.01	<0.07
U	<0.1		<0.1	<0.07
V	<0.1		<0.1	<0.7
Zn	<0.05		<0.05	<0.05

(a) - Concentration in pCi/l.
(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

Table 23. Volatile Organics Summary Data for Simulation #5-1

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	1	1
Acetone	210	3800	630
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	U	U
1,2-Dichloroethane	U	U	U
2-Butanone	U	2900	850
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	U	U	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	U	U	U
Chlorobenzene	U	U	U
Ethyl Benzene	U	U	U
Styrene	U	U	U
Total Xylenes	U	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 24. Volatile Organics Summary Data for Simulation #5-2

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	1
Acetone	43000	2800	3100
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	13	14	U
1,2-Dichloroethane	U	U	U
2-Butanone	1200	2100	U
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	U	U	U
Dibromochloromethane	1300	9	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	1
Toluene	470	12	U
Chlorobenzene	U	U	U
Ethyl Benzene	6	U	U
Styrene	U	U	U
Total Xylenes	79	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 25. Volatile Organics Summary Data for Simulation #5-3

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Chloromethane	3	2	7
Bromomethane	1	U	5
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	2
Acetone	320	2100	2100
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	U	U
1,2-Dichloroethane	U	U	U
2-Butanone	U	1900	200
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	140	2	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	64	1	1
Chlorobenzene	U	U	U
Ethyl Benzene	U	U	U
Styrene	U	U	U
Total Xylenes	29	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 26. Semi-Volatile Organics Summary Data for Simulation #5-1

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Base/Neutrals:			
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl)Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 26. Semi-Volatile Organics Summary Data for Simulation #5-1 (Continued)

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Base/Neutrals:			
3,3′-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	1	U	5
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U
Acids:			
Phenol	U	2000	78
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	48	4
4-Methylphenol	U	45	2
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 27. Semi-Volatile Organics Summary Data for Simulation #5-2

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Base/Neutrals:			
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl)Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 27. Semi-Volatile Organics Summary Data for Simulation #5-2 (Continued)

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Base/Neutrals:			
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	U	U	U
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U
Acids:			
Phenol	2200	1000	U
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	U	U
4-Methylphenol	U	U	U
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 28. Semi-Volatile Organics Summary Data for Simulation #5-3

Compound Name	Produced Water Concentration (µg/l)	Brine Concentration (µg/l)	Treated Water Concentration (µg/l)
Base/Neutrals:			
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	4	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl)Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table 28. Semi-Volatile Organics Summary Data for Simulation #5-3 (Continued)

Compound Name	Produced Water Concentration (μg/l)	Brine Concentration (μg/l)	Treated Water Concentration (μg/l)
Base/Neutrals:			
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	3	U	1
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U
Acids:			
Phenol	4	2100	53
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	87	6
4-Methylphenol	U	84	5
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	300	11
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	4
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

The presence of Chloromethane, Bromomethane, Methylene chloride, and 1-1-2-2 Tetrachloroethane indicates that a small leak in the refrigerant evaporator must exist, probably resulting from the severe icing which occurred in the evaporator during the fan failure in Series 4. These species can all be found in significant or trace quantities in R-12 refrigerant.

Acetone must have been introduced in the analytical laboratories, since it was found in the blank. Further, the levels of acetone in treated water samples from Simulation #s 5-1 and 5-3 indicate that cross-contamination of acetone from Simulation #5-2 must have occurred. The acetone concentration in produced water tested in Simulation #5-2 was two orders of magnitude greater than the acetone concentrations of the produced waters used in the other two simulations.

The presence of 2-Butanone in two of the treated waters is easily explained. 2-Butanone is a solvent used in thermal welding of poly vinyl chloride (PVC) plastics. PVC fabrication was in progress in RTC's facility during the time that Simulation Series 5 was in progress and some limited thermal sealing of PVC piping in the simulator also occurred during the simulation. The thermal sealing of the piping was required because the solvent bonds in the piping did not withstand the repeated thermal cycling during the simulations.

3.2.2 Subtask 2.2: Re-Evaluation of Process Economics Based on Laboratory-Scale Simulation Results

In this subtask, the process and economic models developed in Subtasks 1.4 and 1.5 were used along with the results of the laboratory-scale simulations to estimate the water treatment cost. The laboratory-scale data generated in the simulations provided data for selecting the values of the required model inputs. By assuming the field situation will behave similarly to the laboratory-scale simulations, and using the chemical analysis results of the process streams and the material balance data resulting from the evaluations of the laboratory-scale FTE process simulations, the following data are provided for input to the models:

- location/climate simulated,
- the quality of the produced water, treated water, and brine, and
- the evaporation pond efficiency.

The value of all other model parameters were equal to the base case values assumed in Section 1.5.

First, the results of the initial laboratory-scale simulations conducted in Subtask 2.1 were used with the process and economic models to select the best design for a commercial-scale FTE process. The design configuration selected and used in the final twelve laboratory-scale simulations was the process design configuration having the lowest water treatment cost. The results of the economic projections for the initial simulations are summarized in Table 18 and provided in detail in Appendix E, Tables E-8 through E-70. The data in Table 18 illustrate that the treated water cost projected for the conventional and enhanced evaporation pond designs are similar and significantly less than the projected treatment costs for the designs testing the solar distillation pond design.

Next, the results of the remaining twelve laboratory-scale simulations were used with the process and economic models to determine the water treatment cost for those simulations.

After completion of all the laboratory-scale simulations, the effect of the produced water contaminant concentration on the process was estimated by comparing results of each series of simulations using the three different waters. The results of the economic projections for the FTE process Simulation Series 2, 3, 4, and 5 provided in detail in Appendix E, Tables E-71 through E-154. The impact of produced water quality on the FTE process water treatment cost is illustrated in Figure 33. The data illustrated in the figure suggest that water with a TDS concentration near 9000 ppm is the most expensive to treat. This is misleading. The water tested with a TDS concentration of approximately 9000 ppm was the oil and gas produced water (FTE A) which contained considerable concentrations of organics. If the total contaminant concentration (inorganic plus organic) is considered, the FTE A water is the most contaminated and this explains the inflection in the curves illustrated in Figure 33.

Then, the effect of atmospheric conditions on the process was estimated by comparing the results of the simulations using the same produced water and the four different sets of atmospheric conditions. The impact of atmospheric conditions on the FTE process water treatment cost is illustrated in Figure 34. With one exception, the data illustrated in the figure suggest that the greater the number of hours with subfreezing temperatures during the simulation the more economic the FTE process.

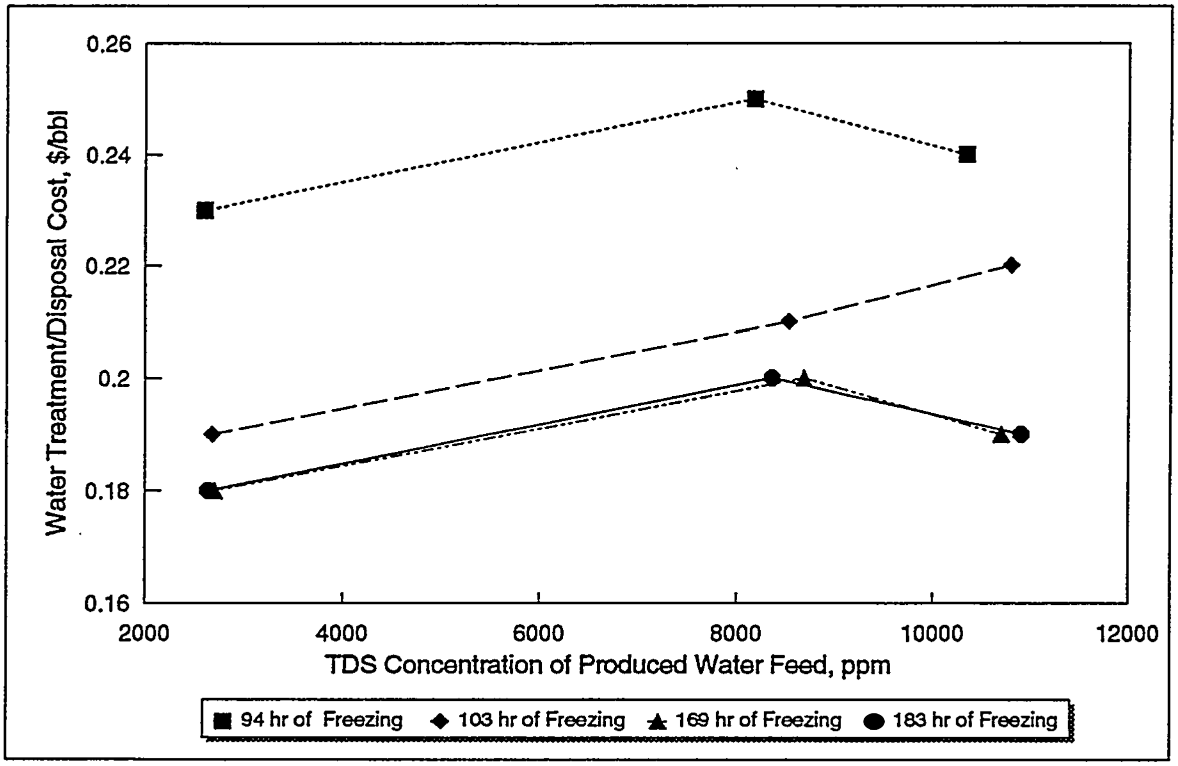


Figure 33. FTE Water Treatment / Disposal Cost vs. TDS Concentration of the Produced Water Feed

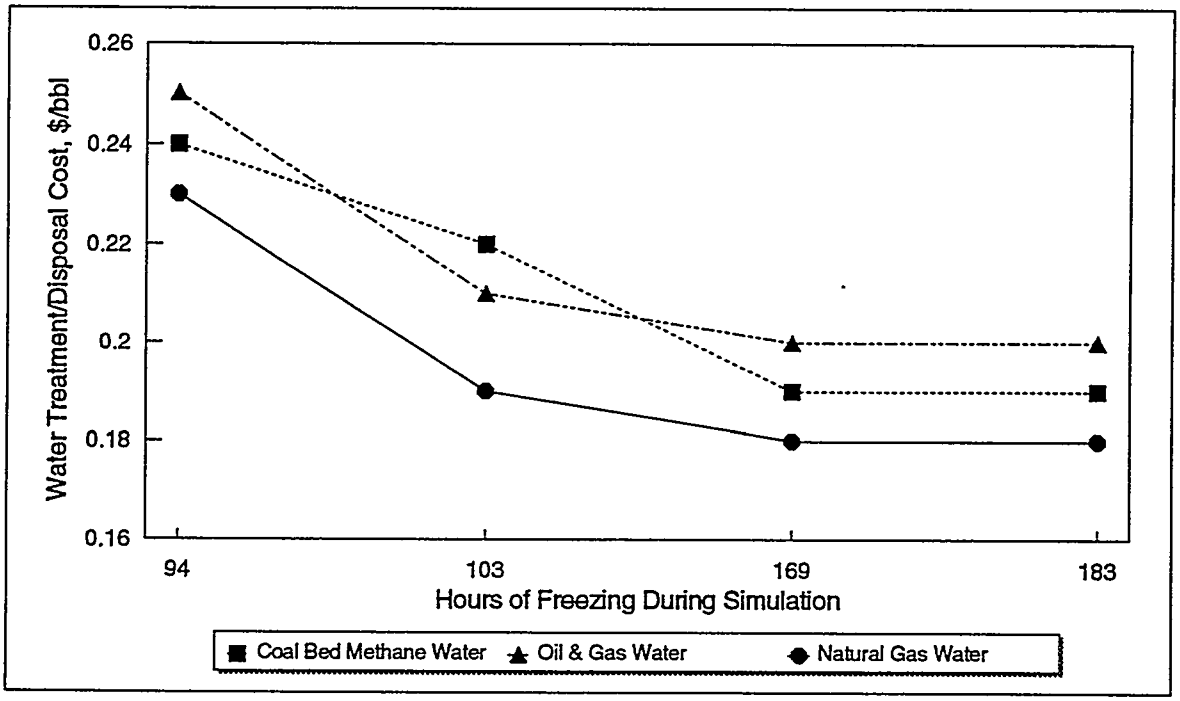


Figure 34. FTE Water Treatment / Disposal Cost vs. Hours of Freezing During the Simulation

A final observation is that once the optimum freezing pad and holding pond design were determined from the initial series of simulations, all economic projections based upon the results of the final twelve simulations yielded water treatment costs ranging between $0.18/bbl and $0.25/bbl, regardless of water quality and atmospheric conditions. The FTE process economic projections based on the results of the laboratory-scale process simulations continue to strongly indicate the commercial economic potential of the process.

3.3 Task 3: Evaluation of the Field Demonstration of the FTE Process for the Treatment of Produced Waters in the San Juan Basin of New Mexico

Task 3 of this research was the evaluation of the FTE process demonstration conducted at an operating evaporative produced water disposal facility in the San Juan Basin of New Mexico. Task 3 research was conducted in conjunction with a separate project entitled "Demonstration of the FTE Process in the San Juan Basin of New Mexico." The construction, start-up, and shakedown of the FTE field demonstration in the San Juan Basin of New Mexico was completed. Operation of the demonstration was initiated in December 1995 and was prematurely terminated in March 1996 due to financial difficulties at GRI. Originally, the demonstration plant was scheduled to run through the spring and summer of 1996 to obtain evaporative data for the evaluation. Agreement has been reached with GRI to resume operation of the FTE demonstration plant in October 1996 and to continue operation through the summer of 1997.

As previously discussed, the design of the FTE demonstration was significantly modified due to the inability to use the Schneider pond as the produced water holding pond. This modification critically impacted the operation of the FTE demonstration. The results of the evaluation of the field demonstration of the FTE are summarized in the following sections.

3.3.1 Subtask 3.1: Sampling and Analyses of Field Demonstration Process Streams

Seven samples from the FTE demonstration were subjected to limited chemical analyses. On 11/28/96, one sample of the Schneider pond and two samples from the oil/water separator tanks feeding the Schneider pond were collected and submitted for TDS analyses to confirm the unexpected high field Ec measurements of the feed to the freezing pad. The results of these analyses indicated that the TDS concentration of the water in the Schneider pond was in excess of 100,000 ppm and that the TDS concentration of the feed to the pond from the oil/water separator tanks was in excess of 40,000 ppm (Table 29). The following conclusions were drawn from these data:

- The TDS concentration of the water fed to the Schneider pond had been substantially elevated from precipitated solids in the pond that redissolved when the pond was filled with water. Treatment of the water in the pond using the FTE process was possible but would be uneconomic. For this reason, the water in the Schneider pond would not be suitable for demonstration of the FTE process.
- The TDS concentration of the feed to the pond was presumably elevated from build-up in the oil/water separator tanks rendering them unsuitable as feed tanks for the demonstration.

Table 29. Results of Limited Suite Analyses of Schneider Pond Water, High Flow and Low Flow Feed Water, and Feed Water, Recycle Water, Ice, and Brine

Sample/Date	Alkalinity[a]	Bicarbonate[a]	Carbonate[a]	pH	TDS
Schneider Pond/ 11/28/95					120000
Schneider Feed/ 11/28/95					42500
Schneider Feed/ 11/28/95					42900
Cahn Recycle Water/ 1/24/96	24200	13000	11200	9.02	40300
New Ice/ 1/22/96	4150	2450	1700	9.31	7950
Cahn Feed/ 1/22/96	8200	5600	2600	8.94	10800
Schneider Brine/ 1/24/96	42400	9600	32800	9.39	81400

[a] Alkalinity, bicarbonate, and carbonate are reported as CaCO3.

Based upon these conclusions, the decision was made by project personnel to modify the FTE demonstration plant design and operation as discussed in Section 2.2.3.2.

During the time period from 1/22-1/24/96, grab samples from the feed water, Cahn pond recycle water, ice, and heavy brine from the Schneider pond were collected and subjected to limited chemical analyses. The purpose of these analyses was to provide qualitative data indicating the status of the demonstration at that time and also to provide data needed for correlation of analytical TDS concentration versus on-site TDS analytical results. The following conclusions were drawn from these data:

- The TDS concentration of the water fed to the Cahn pond was approximately 11,000 ppm with bicarbonate and carbonate being the dominant anions. The bicarbonate-to-carbonate ratio was 2.15:1 (Table 29).
- The TDS concentration of the unaged ice formed the night before sampling was approximately 8,000 ppm which was reduced 25% compared to the feed to the pond. The bicarbonate-to-carbonate ratio was 1.44-to-1 indicating bicarbonate is removed from the ice faster than carbonate (Table 29).
- The TDS concentration of the recycle water in the Cahn pond was approximately 40,000 ppm which was increased 270% compared to the feed to the pond. The bicarbonate-to-carbonate ratio was 1.16-to-1. These ratios for the recycle water and ice may suggest that bicarbonate is removed from the ice by chemical precipitation or by evolution of CO_2 (Table 29).
- The TDS concentration of the water in the Schneider pond was approximately 81,000 ppm which was reduced 32% compared to the previous analysis of water in the Schneider pond. This reduction was probably due to precipitation of solids in the pond as the pond water cooled. The bicarbonate-to-carbonate ratio was 0.29-to-1 confirming that the water in the Schneider pond was not representative of the chemistry of coal bed methane produced water (Table 29).

Six samples from the demonstration were subjected to detailed chemical analyses. On 2/1/96 composite samples of feed water, ice, and brine were submitted for analyses. The feed and brine samples were composited over the time period from 12/9/95 to 2/1/96. The composite of the ice was collected on 2/1/96 by sampling the ice pile in the Cahn pond. In addition, samples of feed water, Cahn pond water, and solids were collected and submitted at the conclusion of the demonstration.

The results of the detailed analyses of the 2/1/96 composite samples of feed, ice, and Cahn pond recycle water are presented in Tables 30 through 33. The results of these analyses indicate:

- Melt produced from the ice would apparently be suitable for various beneficial uses (Tables 30, 31, 32, and 33).
- The TDS concentration in the ice produced was reduced by 92% and the TDS concentration in the brine was increased 390% compared to that of the feed (Table 30).
- The concentrations of all inorganic constituents analyzed were significantly reduced in the ice produced compared to their respective concentrations in the produced water feed. In general, the constituent concentration reductions were in excess of 90%. Exceptions were: boron which was reduced 82%, chloride which was reduced 86%, potassium which was reduced 66%, and sulfate which was reduced 76% (Table 30).
- The concentrations of most inorganic analytes were significantly increased in the brine sample compared to their respective concentrations in the produced water feed with the exceptions of ammonia, barium, and calcium. Ammonia is believed to have been removed from the system through volatilization. It is suspected that calcium and barium were removed from the system by scaling and possibly by chemical precipitation (Table 30).
- Radionuclide concentrations in the feed were at very low concentrations. Germanium and radium-226 were the only radionuclides present in the feed sample in detectable and quantifiable concentrations considering the analytical detection limit and laboratory precision. None of the radionuclide constituents analyzed for were present in the ice sample in detectable and quantifiable concentrations. Germanium, radium-226, and uranium were the only radionuclides present in the brine sample at detectable and quantifiable concentrations (Table 31).
- Acetone was detected in all three samples (feed, ice, and brine) and is suspected to have been introduced either during field sampling or by the analytical laboratory since historically acetone has not been present in these coal bed methane waters. Acetone is a common laboratory solvent for cleaning the glassware and laboratory equipment (Table 32).

Table 30. **Results of Inorganic Analyses of Feed Water, Ice and Brine Composite Samples for the Time Period of 12/9/95 - 2/1/96**

	Feed (mg/l)	**Ice (mg/l)**	**Brine (mg/l)**
Alkalinity ($CaCO_3$)	8670	555	33700
Alkalinity (CO_3)	122	155	7970
Alkalinity (HCO_3)	10200	363	24900
Alkalinity (OH)	0	0	0
Aluminum (Al)	< 1	< 1	< 1
Ammonia (NH_3)	7.00	<0.5	2.89
Antimony (Sb)	<0.01	<0.01	<0.01
Arsenic (As)	<0.05	<0.05	<0.05
Barium (Ba)	22.1	0.95	0.93
Beryllium (Be)	<0.05	<0.05	<0.05
Boron (B)	3.5	0.60	34.4
Bromide (Br)	12.1	1.1	79.2
Cadmium (Cd)	<0.01	<0.01	<0.01
Calcium (Ca)	12.3	< 1	11.2
Chemical Oxygen Demand	90	20	1300
Chloride (Cl)	1500	207	2340
Chromium (Cr)	<0.05	<0.05	<0.05
Cobalt (Co)	<0.01	<0.01	<0.01
Copper (Cu)	<0.1	<0.1	<0.1
Cyanide (CN-)	0.56	<0.1	1.94
Electrical Conductivity	14100	1627	37300
Fluoride (Fl)	1.2	< 1	6.5
Hardness as $CaCO_3$	103	4	248
Hydrogen Sulfide (H_2S)	< 1	< 1	< 1
Iodide (I)	< 5	< 5	< 5
Iron (Fe)	0.5	<0.3	3.63
Lead (Pb)	<0.01	<0.01	<0.01
Lithium (Li)	1.2	< 1	8.1
Magnesium (Mg)	17.5	0.98	53.4
Manganese (Mn)	0.04	<0.01	0.17
Mercury (Hg)	<0.0005	<0.0005	<0.0005
Nickel (Ni)	<0.1	<0.1	<0.1
Nitrate (NO_3)	< 1	< 1	< 1
Nitrite (NO_2)	< 1	< 1	< 1
Oil and Grease	1.5	< 1	3.0
pH	8.42	9.80	9.11
Phenols	<0.01	<0.01	0.2
Phosphate	< 1	< 1	< 1
Potassium (K)	28.6	9.8	651

Table 30. **Results of Inorganic Analyses of Feed Water, Ice and Brine Composite Samples for the Time Period of 12/9/95 - 2/1/96**
(Continued)

	Feed (mg/l)	Ice (mg/l)	Brine (mg/l)
Selenium (Se)	<0.01	<0.01	<0.01
Silicon (Si)	10.0	0.5	23.8
Silver (Ag)	<0.01	<0.01	<0.01
Sodium (Na)	4150	331	19000
Sodium Absorption Ratio	178	71.8	525
Strontium (Sr)	7.8	<0.5	10.2
Sulfate (SO_4)	62.8	15.2	1000
Total Carbon	2230	180	7480
Total Dissolved Solids	11600	940	56900
Total Inorganic Carbon	2080	< 100	7020
Total Kjedahl Nitrogen	8.23	0.05	4.11
Total Organic Carbon	150	< 100	460
Total Suspended Solids	160	< 5	1970
Vanadium (V)	<0.1	<0.1	<0.1
Zinc (Zn)	<0.05	<0.05	<0.05

Table 31. **Results of Radionuclide Analyses Feed Water, Ice, and Brine Composite Samples for the Time Period of 12/9/95 - 2/1/96**

	Feed (pCi/l)	Ice (pCi/l)	Brine (pCi/l)
Germanium (mg/l)	0.14	DNQ	0.10
Gross Alpha	DNQ	DNQ	DNQ
Gross Beta	DNQ	DNQ	DNQ
Ra 226	1.9(+/-0.8)	DNQ	1.8(+/-0.8)
Ra 228	DNQ	DNQ	DNQ
Total Radiostrontium	DNQ	DNQ	DNQ
Uranium	DNQ	DNQ	2
Uranium (mg/l)	DNQ	DNQ	0.003

DNQ: Indicates parameter was detected, but not quantifiable.

Table 32. Results of Volatile Organic Analyses of Feed Water, Ice, and Brine Composite Samples for the Time Period of 12/9/95 - 2/1/96

	Feed (µg/l)	Ice (µg/l)	Brine (µg/l)
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	U
Acetone	3900	NQ	1100
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	U	U
1,2-Dichloroethane	U	U	U
2-Butanone	U	U	NQ
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	NQ	U	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	NQ	NQ	NQ
Chlorobenzene	U	U	U
Ethyl Benzene	U	U	U
Styrene	U	U	U
Total Xylenes	U	U	1
Trichlorofluoromethane	U	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 33. Results of Semi-Volatile Organic Analyses of Feed Water, Ice, and Brine Composite Samples for Time Period of 12/9/95 - 2/1/96

	Feed (µg/l)	Ice (µg/l)	Brine (µg/l)
Base/Neutrals:			
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl)Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	NQ
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenyl ether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	NQ	U	NQ
Anthracene	U	U	U
Di-n-Butylphthalate	NQ	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 33. Results of Semi-Volatile Organic Analyses of Feed Water, Ice, and Brine Composite Samples for Time Period of 12/9/95 - 2/1/96 (Continued)

	Feed (µg/l)	Ice (µg/l)	Brine (µg/l)
Base/Neutrals:			
3,3′-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	NQ	NQ	NQ
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U
Acids:			
Phenol	U	U	U
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	NQ
2-Methylphenol	U	U	NQ
4-Methylphenol	U	U	NQ
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

- Other than acetone, the volatile organics detected were: benzene and toluene in the feed sample; toluene in the ice sample; and toluene, butanone and xylenes in the brine, however these analytes were below the EPA Estimated Quantitation Limit (EQL) (Table 32).
- The only semi-volatile organic constituent detected in the ice sample was bis (2-ethylhexyl) phthalate but was below the EPA EQL. Semi-volatile organic constituents found in the feed sample were phenanthrene, di-n-butylphthalate, and bis (2-ethylhexyl) phthalate. Again, these analytes were below the EPA EQL. Semi-volatile organic constituents found in the brine sample were 2-methylnapthalene, phenanthrene, bis (2-ethylhexyl) phthalate, benzylalcohol, 2-methylphenol, and 2-methylphenol. Concentrations of these analytes were also below the EPA EQL. Many phthalates are common contaminants from plastic and these constituents are suspected to have been introduced from either the pond liner, process piping, or composite storage drums (Table 33).

The results of analyses of the final feed water and Cahn pond water samples are presented in Tables 34 through 37. The results of these analyses indicate that:

- The concentrations of most of the inorganic and radionuclide analytes were significantly increased in the Cahn pond water compared to their respective concentrations in the produced water feed. This suggests that either significant evaporation from the Cahn pond occurred during the months of February and March or that produced water from other than coal bed methane wells was fed directly into the Cahn pond rather than through the feed system (Tables 34 and 35).
- Volatile organic analyses detected acetone in both the produced water feed and the Cahn pond. However, acetone was also detected in the analytical blank and the presence of acetone is attributed to laboratory contamination (Table 36).
- No semi-volatile organics above the EPA EQL were detected in either the produced water feed or the Cahn pond water (Table 37).
- Phthalates were detected in the Cahn pond water, but were not detected in the produced water feed. However, phthalates were detected in the analytical blank. Phthalates are common contaminants from plastic and could have been introduced from the pond liner, process piping, or composite storage drums (Table 37).

Table 34. Results of Inorganic Analyses of Feed Water and Cahn Pond Water Samples taken 3/18/96

	Feed Water (mg/l)	Cahn Pond (mg/l)
Alkalinity ($CaCO_3$)	7170	15100
Alkalinity (CO_3)	0	3300
Alkalinity (HCO_3)	8750	11700
Alkalinity (OH)	0	0
Aluminum (Al)	< 1	< 1
Ammonia (NH_3)	10.4	0.25
Antimony (Sb)	<0.01	<0.01
Arsenic (As)	<0.05	<0.05
Barium (Ba)	17.1	4.8
Beryllium (Be)	<0.05	<0.05
Boron (B)	3.7	18.4
Bromide (Br)	10.7	32.5
Cadmium (Cd)	<0.01	<0.01
Calcium (Ca)	13.2	9.7
Chemical Oxygen Demand	82	696
Chloride (Cl)	1470	6270
Chromium (Cr)	<0.05	<0.05
Cobalt (Co)	<0.01	<0.01
Copper (Cu)	<0.1	<0.1
Cyanide (CN-)	0.40	0.92
Electrical Conductivity	13800	32200
Fluoride (F)	11.5	3.8
Hardness	96	144
Hydrogen Sulfide (H_2S)	< 1	< 1
Iodide	< 5	< 5
Iron (Fe)	0.98	0.60
Lead (Pb)	<0.01	<0.01
Lithium (Li)	1.9	4.5
Magnesium (Mg)	16.0	30.4
Manganese (Mn)	<0.01	<0.01
Mercury (Hg)	<0.0001	<0.0001
Nickel (Ni)	<0.1	<0.1
Nitrate (NO_3)	< 1	< 1
Nitrite (NO_2)	< 1	< 1
Oil and Grease	34.3	21.4
pH	8.23	9.28
Phenols	<0.01	<0.01
Phosphate	< 5	< 5
Potassium (K)	22.7	343
Selenium (Se)	<0.01	<0.01
Silicon (Si)	10.20	9.90
Silver (Ag)	<0.01	<0.01

Table 34. Results of Inorganic Analyses of Feed Water and Cahn Pond Water Samples taken 3/18/96 (Continued)

	Feed Water (mg/l)	Cahn Pond (mg/l)
Sodium (Na)	3950	10700
Sodium Adsorption Ratio	175	387
Strontium (Sr)	8.8	7.8
Sulfate (SO_4)	< 1	549
Total Carbon	1860	3260
Total Dissolved Solids	10500	26400
Total Inorganic Carbon	1860	3030
Total Kjedahl Nitrogen	9.02	1.20
Total Organic Carbon	<100	230
Total Suspended Solids	10	20
Vanadium (V)	<0.1	<0.1
Zinc (Zn)	<0.05	<0.05

Table 35. Results of Radionuclide Analyses of Feed Water and Cahn Pond Water Samples taken on 3/18/96

	Feed Water (pCi/l)	Cahn Pond (pCi/l)
Germanium (mg/l)	0.08	DNQ
Gross Alpha	DNQ	380(+/-280)
Gross Beta	DNQ	DNQ
Ra 226	3.5(+/-1.9)	DNQ
Ra 228	DNQ	DNQ
Total Radiostrontium	DNQ	DNQ
Uranium	DNQ	DNQ
Uranium (mg/l)	DNQ	DNQ

DNQ: Indicates parameter was detected, but not quantifiable.

Table 36. Results of Volatile Organic Analyses of Feed Water and Cahn Pond Water Samples taken on 3/18/96

	Feed Water (μg/l)	Cahn Pond (μg/l)
Chloromethane	U	U
Bromomethane	U	U
Vinyl Chloride	U	U
Chloroethane	U	U
Methylene Chloride	U	U
Acetone	B	NQ B
Carbon Disulfide	U	U
1,1-Dichloroethene	U	U
1,1-Dichloroethane	U	U
Trans-1,2-Dichloroethene	U	U
Cis-1,2-Dichloroethene	U	U
Chloroform	U	U
1,2-Dichloroethane	U	U
2-Butanone	U	U
1,1,1-Trichloroethane	U	U
Carbon Tetrachloride	U	U
Bromodichloromethane	U	U
Vinyl Acetate	U	U
1,2-Dichloropropane	U	U
Trans-1,3-Dichloropropene	U	U
Trichloroethene	U	U
1,1,2-Trichloroethane	U	U
Benzene	NQ	NQ
Dibromochloromethane	U	U
Cis-1,3-Dichloropropene	U	U
2-Chloroethylvinyl Ether	U	U
Bromoform	U	U
4-Methyl-2-Pentanone	NQ	U
2-Hexanone	U	U
1,1,2,2-Tetrachloroethane	U	U
Tetrachloroethene	U	U
Toluene	NQ	NQ
Chlorobenzene	U	U
Ethyl Benzene	U	NQ
Styrene	U	U
Total Xylenes	NQ	8
Trichlorofluoromethane	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 37. Results of Semi-Volatile Analyses of Feed Water and Cahn Pond Water Samples taken on 3/18/96

	Feed Water (μg/l)	Cahn Pond (μg/l)
Base/Neutrals:		
bis(2-Chloroethyl)Ether	U	U
1,3-Dichlorobenzene	U	U
1,4-Dichlorobenzene	U	U
1,2-Dichlorobenzene	U	U
bis(2-chloroisopropyl)Ether	U	U
N-Nitroso-Di-n-Propylamine	U	U
Hexachloroethane	U	U
Nitrobenzene	U	U
Isophorone	U	U
bis(2-Chloroethoxy)Methane	U	U
1,2,4-Trichlorobenzene	U	U
Naphthalene	U	U
4-Chloroaniline	U	U
Hexachlorobutadiene	U	U
2-Methylnaphtalene	U	U
Hexachlorocyclopentadiene	U	U
2-Chloronaphthalene	U	U
2-Nitroaniline	U	U
Dimethylphthalate	U	U
2,6-Dinitrotoluene	U	U
Acenaphthylene	U	U
3-Nitroaniline	U	U
Acenaphthene	NQ	U
Dibenzofuran	U	U
2,4-Dinitrotoluene	U	U
Diethylphthalate	U	NQ
4-Chlorophenyl-phenyl ether	U	U
Fluorene	NQ	U
4-Nitroaniline	U	U
N-Nitrosodiphenylamine	U	U
4-Bromophenyl-phenylether	U	U
Hexachlorobenzene	U	U
Phenanthrene	NQ	U
Anthracene	U	U
Di-n-Butylphthalate	U	U
Fluoranthene	U	U
Pyrene	U	U
Butylbenzylphthalate	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 37. Results of Semi-Volatile Analyses of Feed Water and Cahn Pond Water Samples taken on 3/18/96 (Continued)

	Feed Water (µg/l)	Cahn Pond (µg/l)
Base/Neutrals:		
3,3'-Dichlorobenzidine	U	U
Benzo(a)Anthracene	U	U
bis(2-Ethylhexyl) Phthalate	U	NQ
Chrysene	U	U
Di-n-Octyl Phthalate	U	U
Benzo(b)Fluoranthene	U	U
Benzo(k)Fluoranthene	U	U
Benzo(a)Pyrene	U	U
Ideno(1,2,3-cd)Pyrene	U	U
Dibenz(a,h)Anthracene	U	U
Benzo(g,h,i)Perylene	U	U
Acids:		
Phenol	U	U
2-Chlorophenol	U	U
Benzylalcohol	U	NQ
2-Methylphenol	U	U
4-Methylphenol	U	U
2-Nitrophenol	U	U
2,4-Dimethylphenol	U	U
Benzoic Acid	U	U
2,4-Dichlorophenol	U	U
4-Chloro-3-Methylphenol	U	U
2,4,6-Tricholorophenol	U	U
2,4-Dinitrophenol	U	U
4-Nitrophenol	U	U
4,6-Dinitro-2-Methylphenol	U	U
Pentachlorophenol	U	U
2,4,5-Trichlorophenol	U	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

The results of analyses of the composite solid sample produced from the on-site gravimetric analyses are presented in Tables 38, 39, and 40. The results of chemical analyses of the solid produced indicate:

- These solids appear potentially suitable as a source for a low-grade industrial sodium carbonate/bicarbonate liquor. The significant concentration of chloride in these solids would make the economic production of a high grade sodium carbonate/bicarbonate solid or liquor difficult (Table 38).
- No radionuclides were detected in the solids in quantifiable concentrations given the detection limits of the analyses and laboratory precision (Table 39).
- No semi-volatile organics were detected in the Cahn solids except for phthalate. Again, contamination by phthalates is often associated with plastics and their presence is probably from external sources (Table 40).

The powdered solids were also subjected to X-ray diffraction (XRD) analyses to identify the major mineralogical phases. The results of the X-ray powder diffraction analyses indicate that:

- The Cahn pond solids are primarily composed of sodium carbonate (>80%) (thermonatrite and natrite). However, significant sodium chloride (natrite) is also present along with a nominal composition of potassium chloride (sylvite).

Finding a market for the brine produced by the FTE process is of significant economic importance to the cost of operating a commercial-scale FTE operation. One potential market for the brine may be power plant operators. Sodium carbonate solutions have been shown to increase the effectiveness of SO_2 removal and opacity control in power plant SO_2 scrubbers. Consequently, this option could decrease or eliminate the need to pay for brine disposal. Therefore, the beneficial use of the brine will be investigated in FTE research to be conducted next year.

3.3.2 Subtask 3.2: Evaluation of Field Demonstration Operating Data

In this subtask, operating data collected from the FTE demonstration are analyzed along with the results of the sample analyses discussed in the previous section. The following sections provide details regarding the results of these analyses.

Table 38. Results of Inorganic Analyses of Solids

	Solids (mg/kg)
Aluminum (Al)	<70
Ammonia (NH_3)	38.2
Antimony (Sb)	< 1
Arsenic (As)	0.54
Barium (Ba)	647
Beryllium (Be)	<0.5
Boron (B)	628
Bromide (Br)	610
Cadmium (Cd)	<0.03
Calcium (Ca)	317
Chemical Oxygen Demand	19400
Chloride (Cl)	212000
Chromium (Cr)	0.13
Cobalt (Co)	< 5
Copper (Cu)	< 10
Cyanide (CN-)	30
Fluoride (F)	130
Hydrogen Sulfide (H_2S)	< 1
Iodide	< 80
Iron (Fe)	92
Lead (Pb)	<0.2
Lithium (Li)	150
Magnesium (Mg)	927
Manganese (Mn)	3.8
Mercury (Hg)	<0.01
Nickel (Ni)	< 7
Nitrate (NO_3)	< 250
Nitrite (NO_2)	< 250
Oil and Grease	220
Phenols	1.1
Phosphate	< 250
Potassium (K)	12200
Selenium (Se)	< 4
Silicon (Si)	< 10
Silver (Ag)	<0.03
Sodium (Na)	355000
Strontium (Sr)	206.0
Sulfate (SO_4)	13800
Total Carbon	5.96 %
Total Inorganic Carbon	5.29 %
Total Kjedahl Nitrogen	180
Total Organic Carbon	6700
Vanadium (V)	< 4
Zinc (Zn)	8.0

Table 39. Results of Radionuclide Analyses of Solids

	Solids (pCi/g)
Germanium (mg/l)	DNQ
Gross Alpha	DNQ
Gross Beta	DNQ
Ra 226	DNQ
Ra 228	DNQ
Total Radiostrontium	DNQ
Uranium	DNQ

DNQ: Parameter detected but is below analytical detection limit and is not quantifiable.

Table 40. Results Semi-Volatile Organic Analyses of Solids

	Solids (µg/kg)
Base/Neutrals:	
bis(2-Chloroethyl)Ether	U
1,3-Dichlorobenzene	U
1,4-Dichlorobenzene	U
1,2-Dichlorobenzene	U
bis(2-chloroisopropyl)Ether	U
N-Nitroso-Di-n-Propylamine	U
Hexachloroethane	U
Nitrobenzene	U
Isophorone	U
bis(2-Chloroethoxy)Methane	U
1,2,4-Trichlorobenzene	U
Naphthalene	U
4-Chloroaniline	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 40. Results Semi-Volatile Organic Analyses of Solids

(Continued)

	Solids (µg/kg)
Base/Neutrals:	
Hexachlorobutadiene	U
2-Methylnaphtalene	U
Hexachlorocyclopentadiene	U
2-Chloronaphthalene	U
2-Nitroaniline	U
Dimethylphthalate	U
2,6-Dinitrotoluene	U
Acenaphthylene	U
3-Nitroaniline	U
Acenaphthene	U
Dibenzofuran	U
2,4-Dinitrotoluene	U
Diethylphthalate	U
4-Chlorophenyl-phenyl ether	U
Fluorene	U
4-Nitroaniline	U
N-Nitrosodiphenylamine	U
4-Bromophenyl-phenylether	U
Hexachlorobenzene	U
Phenanthrene	U
Anthracene	U
Di-n-Butylphthalate	U
Fluoranthene	U
Pyrene	U
Butylbenzylphthalate	U
3,3'-Dichlorobenzidine	U
Benzo(a)Anthracene	U
bis(2-Ethylhexyl) Phthalate	NQ
Chrysene	U
Di-n-Octyl Phthalate	U
Benzo(b)Fluoranthene	U
Benzo(k)Fluoranthene	U
Benzo(a)Pyrene	U
Ideno(1,2,3-cd)Pyrene	U
Dibenz(a,h)Anthracene	U
Benzo(g,h,i)Perylene	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

Table 40. Results Semi-Volatile Organic Analyses of Solids
(Continued)

	Solids (µg/kg)
Acids:	
Phenol	U
2-Chlorophenol	U
Benzylalcohol	U
2-Methylphenol	U
4-Methylphenol	U
2-Nitrophenol	U
2,4-Dimethylphenol	U
Benzoic Acid	U
2,4-Dichlorophenol	U
4-Chloro-3-Methylphenol	U
2,4,6-Tricholorophenol	U
2,4-Dinitrophenol	U
4-Nitrophenol	U
4,6-Dinitro-2-Methylphenol	U
Pentachlorophenol	U
2,4,5-Trichlorophenol	U

U: Compound not detected above the reporting limits.
NQ: Not quantifiable indicates that the compound is detected, but is below the EPA Estimated Quantitation Limits.
B: Compound found in blank and sample.

3.3.2.1 Ambient Temperatures during the Demonstration

The winter of 1995-96 was one of the warmest winters in the San Juan Basin in the past 25 years. Historical temperature data for Farmington, New Mexico reveals that every month from November 1995 through, March 1996 were much warmer than typical. Figure 35 illustrates the hourly average temperatures at the FTE demonstration site and the twenty year monthly average high and low temperatures at Farmington, NM. Table 41 provides the 20 year average winter high and low temperatures for the time period from 1968 through 1988, and also the average high and low temperatures for the winter of 1995-1996 for Farmington, NM.

The warm temperatures occurring in November and early December did not impact the FTE demonstration because modifications to the plant were being conducted during this time period. The warm temperatures occurring from December 9 through December 21, 1995 did limit operation of the demonstration significantly (Table 41 and Figure 35).

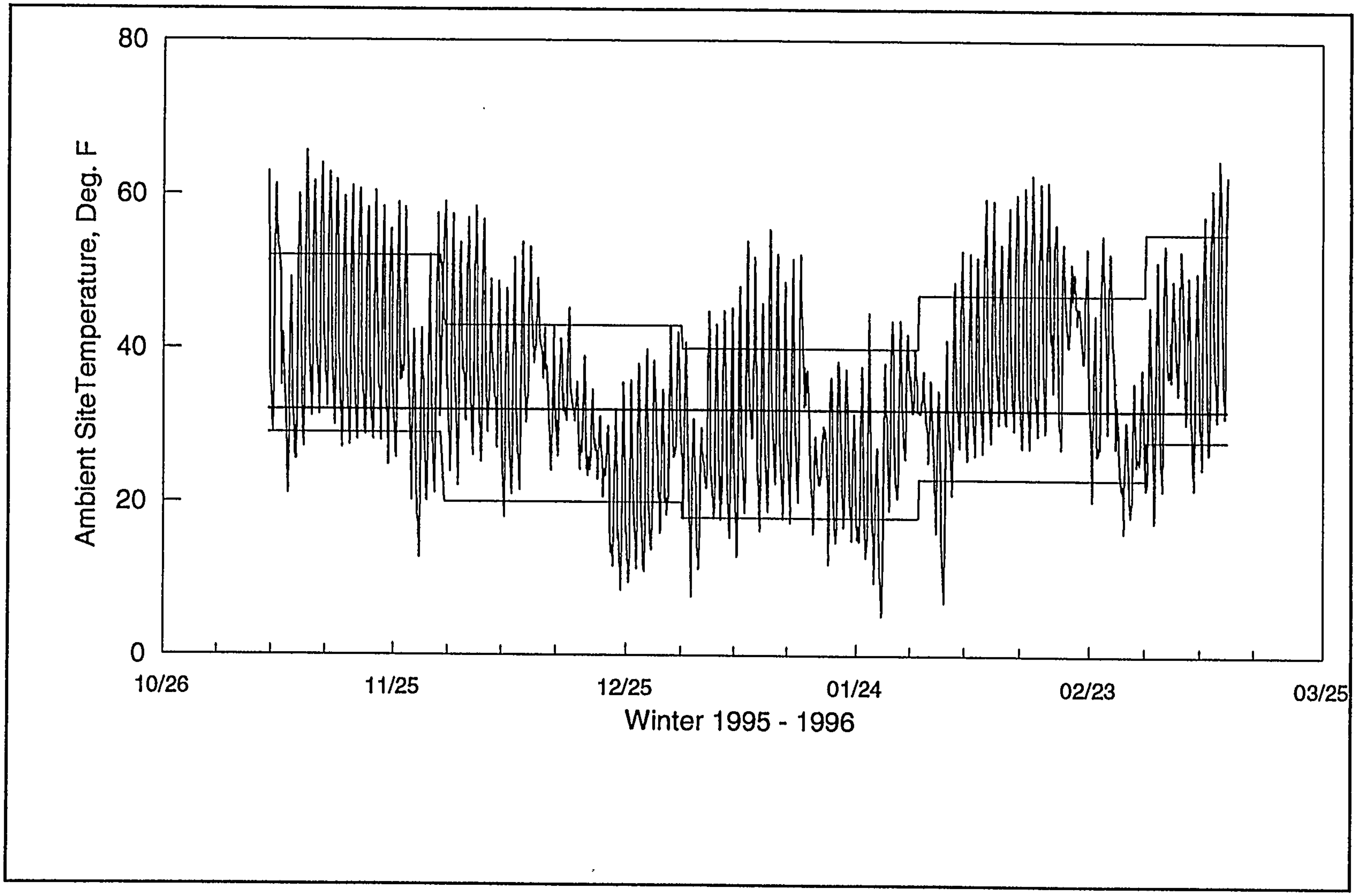


Figure 35. FTE Demonstration Site Temperature Compared to Farmington, NM Average Temperatures

Table 41. Average Winter Temperature Data for Farmington, NM

Month	20 Year Average[a]		1995-1996[b]	
	High	Low	High	Low
November	52	29	59	29
December	43	20	47	23
January	40	18	45	19
February	47	23	54	28
March	55	28	58	29

[a] Gregory et al. 1989.
[b] E.J. Gregory, personal communication, 1996.

Even though January 1996 was warmer than usual, temperatures were sufficiently cold to allow for operation of the demonstration during most of the month and a significant ice pile was created. In fact, the FTE demonstration was operated thirty of the thirty-one days in January 1996. Although, on three of these days temperatures were such that the demonstration plant could only be operated for a few hours (Table 41 and Figure 35).

February, however exhibited much warmer average high and low temperatures than typical. In fact, the average low that occurred in February 1996 was the warmest February average low temperature recorded in the 20 years of data reviewed (1968-1988) and had only occurred two other times; in 1976 and in 1980. The unusually warm temperatures in February severely impacted the operation of the FTE process demonstration which was able to operate only sixteen of the twenty-nine days. Eight of these days that the demonstration was operated were after the ice pile had completely melted, and operation of the demonstration was only for a few hours at a time on most of the other eight days of operation. The effect on the demonstration was a complete loss of the large ice pile created in January and dilution of the brine that was not transferred in January. Attempts to re-establish the ice pile in the later portion of February and the first week in March were unsuccessful because the water in the Cahn pond water had warmed to almost 50°F during the warm period. Reasonable amounts of ice were created on several evenings of operation but this ice was lost during the day (Table 41 and Figure 35).

3.3.2.2 FTE Demonstration Plant Performance

As discussed in previous sections, the modifications of the FTE demonstration plant design coupled with the unusually warm February at the site prevented the harvest of treated water from the ice melt. However, the operating data collected and the results of analyses of the 2/1/96 sampling can be used to determine how the demonstration would have performed, if the capability had existed to pump all the brine from the Cahn pond during the operation. At the time of sampling, 10,038 bbl of produced water had been fed to the Cahn pond. Three days prior (1/29/96) to the sampling the decision was made to transfer brine to the Schneider pond because of the high TDS concentration of the unfrozen water in the Cahn pond. The brine transferred had a TDS concentration of 56,900 ppm. However, it was not possible to transfer a substantial portion of this brine to the Schneider pond because the feed tanks were full and the brine had to be transferred using the Cahn pond transfer pump. This pump is designed for low-head applications and the pressure drop in the 2500 ft line from the Cahn pond to the Schneider pond plus the 20 to 30 foot elevation increase resulted in the ability to pump only at a 20 gpm rate. For these reasons, it was possible to transfer only 341 bbl of the approximately 2000 bbl of brine in the pond at that time, making it impossible to harvest the ice melt. Since February 1996 was the warmest February recorded since 1968, it was not possible to re-concentrate the water in the Cahn pond.

However, a TDS balance for the time period of 12/9/95 to 2/1/96 allows the demonstration performance to be estimated with reasonable accuracy. The assumption that evaporation occurring during this time period was negligible is required. This assumption is reasonable since the pond was covered with ice during most of that time period. The results of the TDS balance examination indicate that approximately 8100 bbl of treated water could have been produced from the ice melt and 1900 bbl of brine would have required disposal. The reduction in the required disposal volume is 81% and a treated water to brine yield is approximately 4-to-1. This yield is more favorable than that obtained in Simulation # 3-1 because half of the produced water feed in the simulation was evaporated prior to freezing. Interestingly, the disposal volume reduction achieved in the demonstration is similar to the reduction in the simulation: 81% versus 78%, respectively. The controlling factors in the FTE effectiveness and economics are the contaminant concentration and volume of brine removed. The greater the mass of contaminants in the brine and the higher the contaminant concentration of the brine removed during freezing and the initial ice melt, the greater the reduction in disposal volume and hence, the more economic the process. The chemistry of the brine controls the contaminant concentration at saturation and it is probably the second most important factor in the economics of the FTE process (Table 42).

Table 42. FTE Demonstration TDS Balance Results Summary

	Produced Water Feed	Brine	Ice
TDS, ppm	11,600	56,900	940
Volume, bbl	10,038	1,912	8,126

It is also worth mentioning again in this section that, based upon the detailed chemical analyses of the ice, the ice melt is suitable for beneficial use in this arid region. Realizing that the modifications required to operate the FTE demonstration during the winter of 1995-96 negated most of the advantages of the FTE process over the historical natural freeze-crystallization process, and that the exceptionally warm winter compounded the operating difficulties, the organizations funding the demonstration were encouraged by these limited results and have agreed to fund another year of FTE demonstration plant operation. In addition, a new, more economic, and environmentally safe evaporation pond design will also be tested this year. This design will significantly reduce the initial capital requirements necessary to conduct the FTE process. In summary, the FTE demonstration was a limited success.

3.3.2.3 Economic Evaluation of the FTE Demonstration

The FTE model developed in Task 1 was used to estimate the commercial-scale economics of an FTE plant treating coal bed methane waters in the San Juan Basin of New Mexico. Two operating scenarios were considered in this re-evaluation of FTE economics. The first scenario considered was of an operation similar to the base case but treating coal bed methane produced water in Northwestern New Mexico and achieving treated water and brine TDS concentrations similar to those indicated in the 2/1/96 demonstration sampling. This scenario is for comparison to other economic data in this report. The second scenario considers the economics of modifying the existing Cahn/Schneider evaporation facility to utilize the FTE process to treat coal bed methane water at the maximum capacity of the facility based upon the sizes of the existing ponds.

The results of the first scenario are summarized in Table 43. The cost of treated water produced is $0.24/bbl which is the same price same as determined from the economic analysis of Laboratory-scale Simulation # 3-1 which tested coal bed methane produced water under climatic conditions similar to northwestern New Mexico. The cost of water disposed of by treatment or evaporation is $0.16/bbl. This reduction is due to the significant evaporation rates in the region (Table 43).

Table 43. Economic and Design Summary for a Commercial-Scale FTE Plant Operating in the San Juan Basin of New Mexico - based on Demonstration Plant Performance and Base Case Design Parameters

Plant Performance:	bbl/day	bbl/yr
Produced Water Feed Rate	1000	365000
Avg. Treated Water Discharge Rate	539	196797
Avg. Net Evaporation Rate	266	97043
Avg. Brine Production Rate	195	71160
Produced Water Holding Pond	1.3 acres - 20 ft deep	
Freezing Pad	1.0 acres - 4 ft deep	
Transfer/Circulation Pump	247 gpm - 15 HP	
Freezing Pad Piping	2" dia	
Other Piping	5" dia	
Total Installed Capital Cost		$153,759
Required Annual Revenues (including return on capital)		$ 47,553
Water Treatment Cost:		
Cost/bbl of treated water produced		$ 0.24/bbl
Cost/bbl of produced water disposed of		$ 0.16/bbl

The results of the second scenario considers the economics of modifying the existing Cahn/Schneider evaporation facility to treat coal bed methane water at the maximum capacity of the facility based upon the sizes of the existing pits (Table 44). The water treatment cost for this case is $0.22/bbl. The reduction in the treatment cost is due to the savings that result from not having to construct a produced water holding pond or freezing pad. This saving is not as great as one would expect,

Table 44. Economic and Design Summary for a Commercial-Scale FTE Plant Operating at the Cahn/Schneider Evaporation Facility in New Mexico - based on Demonstration Plant Performance

Plant Performance:	bbl/day	bbl/yr
Produced Water Feed Rate	1000	365000
Avg. Treated Water Discharge Rate	291	106256
Avg. Net Evaporation Rate	510	186088
Avg. Brine Production Rate	199	72656

Produced Water Holding Pond	2.0 acres - 4 ft deep
Freezing Pad	0.6 acres - 4 ft deep
Transfer/Circulation Pump	165 gpm - 10 HP
Freezing Pad Piping	2" dia
Other Piping	4" dia

Total Installed Capital Cost	$ 70,077
Required Annual Revenues (including return on capital)	$ 23,098

Water Treatment Cost:	
Cost/bbl of treated water produced	$ 0.22/bbl
Cost/bbl of produced water disposed of	$ 0.08/bbl

when considering only the cost per barrel of treated water. This is because evaporation is approximately twice the rate as in the base case scenario which has a smaller and deeper pond. Therefore, the quantity of the treated water produced is approximately half that of the base case scenario. However, when evaporation is considered, the cost of water disposed of by treatment or evaporation is reduced to $0.08/bbl. This reduction is primarily due to the significant evaporation rates in the region and the design of the Schneider pond which is shallow and has a large surface area which facilitates evaporation. Interestingly, the Schneider pond is properly sized to be the produced water holding pond for a 1,000 bbl/day facility and the Cahn pond is oversized by approximately 60% (Table 44).

The economic analyses of the FTE process continues to indicate favorable commercial-scale economics. However, personal communication with oil and gas industry personnel suggest that the cost of transportation of produced water to the FTE facility continues to be very expensive and would limit the use of the Cahn/Schneider facility to a reduced capacity. As a part of next year's FTE demonstration project research, the feasibility of one operator running multiple smaller FTE facilities at the wellhead is to be investigated in depth. If feasible, the FTE process could be utilized in the San Juan Basin to completely eliminate or dramatically reduce produced water transportation costs which are currently greater than the disposal cost in this and many other areas.

3.3.2.4 Evaluation of TDS Concentration, Ec Readings, and Laboratory Results

As previously discussed, modifications to the ASTM 2540 procedure were necessary in order for an operator to conduct on-site gravimetric TDS analyses while operating the demonstration plant. When possible, the results of the on-site gravimetric TDS analyses were compared to analytical laboratory gravimetric TDS results to qualify the accuracy of the on-site procedure. Two differing ice samples, brine samples, and recycle water samples and two similar feed water samples were compared. Figure 36 illustrates the results of this comparison.

A linear regression analysis of these data yields an r^2 of 0.99 and a slope of 0.97 which statistically supports the validity of the on-site gravimetric TDS method used.

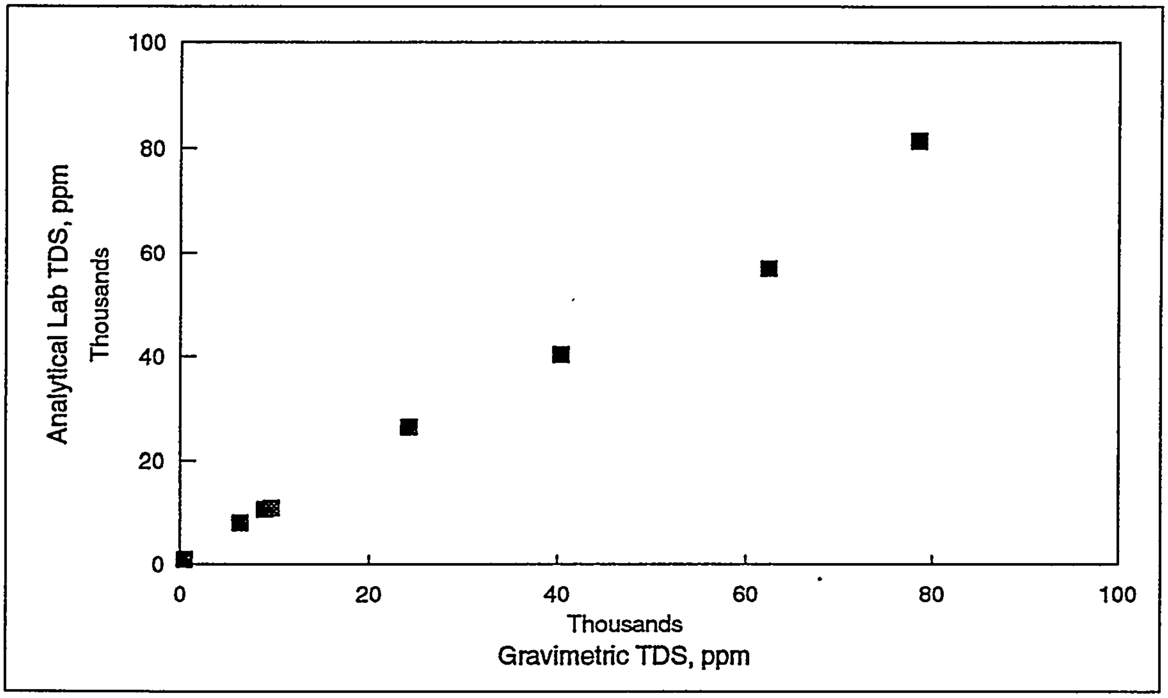


Figure 36. Analytical Laboratory versus On-site Gravimetric TDS Results

In addition to the on-site, gravimetric TDS analyses, Ec measurements of process streams were taken regularly by FTE demonstration operators. The results of the on-site gravimetric TDS analyses and the Ec readings were compared to determine the correlation between the two parameters. Figure 37 illustrates the results of this comparison.

A linear regression analysis of these data yielded an r^2 of 0.98 and a slope of 0.919. Development of this correlation was necessary to quickly and qualitatively estimate TDS concentrations from Ec measurements because the relationship of TDS concentration to Ec differs with each differing water chemistry. Rapid and economic estimation of TDS in the process streams is needed to properly and economically evaluate the FTE facility operation. The time and cost savings to an operating FTE facility represented by the use of these data or similar is significant. Similar data should be generated at each operating FTE facility to determine this relationship for the specific chemistry of the water being treated at the facility.

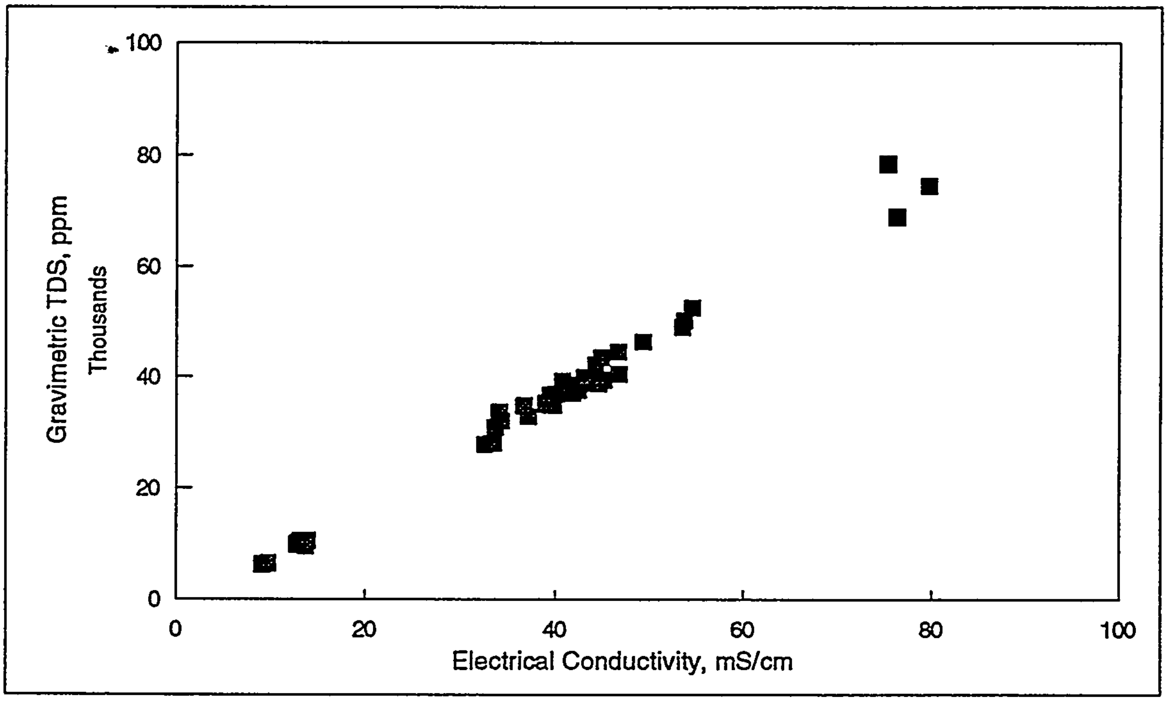


Figure 37. On-site Gravimetric TDS Results versus Electrical Conductivity Measurements

3.4 Summary of Achievements

The project achievements are as follows:

- Related literature has been reviewed. The results of previous research indicates the process is applicable to the removal of the types of constituents typically associated with produced waters. Process constraints related to saturation of constituents solubility in the waters treated may limit the produced waters to which the process is applicable.
- Meteorological data for locations depicting mild, moderate, and severe conditions for application of the process in states with significant oil and gas production and climates suitable for the FTE process have been compiled and reduced to monthly averages.
- Evaluation of environmental regulatory requirements for large-scale process application and an evaluation of process and environmental constraints were completed.
- The conceptual process design was completed.
- The preliminary economic feasibility and sensitivity analyses were completed.
- The Task 1 objectives to develop an economic model and determine the commercial viability, economically significant parameters, and research issues of the FTE process have been achieved.
- All specific objectives for Subtasks 1.1 through 1.5 have been successfully achieved with one exception: a literature survey to provide data depicting the behavior of organics and heavy metals in a natural freezing water purification process was not possible. The natural freezing process data located related only to salts. However, data in the literature related to artificial freezing processes confirm that organic and heavy metal compounds can be successfully and efficiently removed from contaminated water by freezing processes.
- A laboratory-scale FTE process simulator was designed and constructed.
- Twenty-one laboratory-scale FTE process simulations were completed. Nine process simulations were conducted to determine the optimum design of the freezing pad and holding pond required for the FTE process (Series 1). Twelve additional simulations were conducted to determine the impact of climate and produced water quality on the effectiveness of the FTE process (Series 2, 3, 4, and 5).

Three different produced waters were tested in each series. Produced waters tested were from an oil and gas producing well, a natural gas producing well, and a coal bed methane well. Atmospheric conditions simulated were northeastern Colorado (Series 2), northwestern New Mexico (Series #3) and central Wyoming (Series 4 and 5).

- Detailed chemical analyses (Table 2) were conducted on experimental products from Simulation Series 5. The treated waters generated in Series 5 were all of a quality suitable for beneficial use without further treatment. With a minor polishing process, such as activated carbon filtration, all of the treated waters would be suitable for municipal use. Such polishing steps are economic due to the low concentrations of analytes in the treated waters.
- The data from Series 5 confirms the FTE process is capable of simultaneously removing dissolved solids, organics, and heavy metals (including NORM) from the produced waters.
- Task 2 results confirm the technical feasibility of the FTE process and confirm Task 1 economic results.
- An FTE field demonstration was conducted at an operating produced water disposal facility in the San Juan Basin of New Mexico during the winter of 1995-96.
- In spite of the elemental TDS concentration of water in the produced water holding pond that necessitated undesired modifications to the demonstration plant design, and in spite of one of the warmest winters on record in the area of the demonstration, an ice pile containing approximately 8100 bbl of purified produced water was created.
- Detailed chemical analyses (Table 2) were conducted on experimental products from the FTE demonstration plant and confirm that the ice produced by the process would be suitable for beneficial uses. In addition, based upon organic data only, the ice produced would be suitable for domestic uses.
- The data from the demonstration plant process streams confirms the FTE process is capable of simultaneously removing dissolved solids, organics, and heavy metals (including NORM) from produced waters.
- The data from solids produced from the demonstration plant indicate that sediment remaining after evaporation may have commercial economic value.

- A modified technique for TDS determination was shown to be reliable under field conditions and Ec measurements were strongly correlated to the results of the TDS determinations. This provided a quick and inexpensive qualitative means for evaluating plant operations.
- The results of the FTE demonstration during the winter of 1995-96 were encouraging enough for the sponsors of the demonstration to agree to support continuation of the demonstration through 1997.

3.5 Technical Problems Encountered

The following technical problems were encountered during this research project:

- Multiple power outages induced by lightning during operation of the simulator.
- One failure of the refrigeration unit during the simulator operation.
- Introduction of organic compounds from external sources during the simulator operation and during the analyses of experimental products from the simulations and the demonstration.
- Cross-contamination by organic compounds during the simulations.
- Significant microbiological activity during the simulations.
- Precipitation of insoluble materials or slightly soluble materials during the simulations adversely affected material balance closures for certain chemical species.
- Precipitated salts from produced waters previously stored in the FTE demonstration's produced water holding pond made it unusable and severely limited the operation of the demonstration.
- One of the warmest winters on record in the San Juan Basin of New Mexico coupled with contamination of the produced water holding pond made it impossible to collect the clean ice melt.
- The transfer pump at the Cahn pond was inadequately sized for the transfer of brine to the Schneider pond.
- Limited levels of organic compounds (predominantly solvents and plasticisers) were detected on some demonstration samples. Their introduction probably occurred during sampling or sample analyses.
- One break in at the demonstration site.
- Unauthorized introduction of fluids in the Cahn pond prior to the demonstration and suspected introduction near the end of the demonstration.

4.0 Summary

The following conclusions regarding the technical and economic feasibility of the FTE process are drawn based upon the results of the research conducted:

- The FTE process is capable of economically providing significant quantities of water of a quality suitable for beneficial use from oil and gas produced waters. Treated waters with TDS concentrations in the range of 200 to 1500 mg/l can be readily produced using the FTE process. Results of sample analyses indicate that organics and metals are also significantly removed.
- This research and previous research confirm the FTE process is commercially feasible in the Rocky Mountain and Great Plains Regions treating 500 bbl/day or more of produced water. For a 1,000 bbl/day produced water treatment facility operating in these regions, the cost for produced water treatment/disposal is approximately $0.25/bbl.
- This research and previous research confirms freeze-crystallization is effective in removing a wide variety of constituents from water. This process is capable of simultaneously removing salts, organics, and heavy metals (including NORM) from produced waters.
- Regulatory and permitting requirements for an FTE facility are similar to those of conventional evaporative disposal methods for produced waters. Two benefits of the FTE process that make it more environmentally acceptable are: 1) the treated water may be beneficially used and 2) the volume of brine disposal is small compared to disposal of the produced water by conventional methods.
- The sensitivity of base case water treatment costs to the economic parameters investigated does not impact the commercial feasibility of the FTE process.
- The FTE process is applicable, in regions where sub-freezing temperatures seasonally occur, to treat most waste waters containing mixtures of salts, organics, and/or heavy metals in concentrations below eutectic compositions. Potential applications of the process are: oil and gas produced waters, drilling fluids, refinery and gas treatment plant waste waters, groundwater decontamination, groundwater desalinization, industrial waste waters, municipal waste waters, and contaminated waters associated with defense plants.

- An on-site field demonstration of the FTE process was completed in the San Juan Basin of New Mexico treating produced water from numerous coal bed methane wells.

In closing, commercial impact from this project research is expected in 1997 as a result of the continuing demonstration project. The potential impact of this research is:

- Increased production from depleted and/or marginally economic oil and gas reserves.
- Reduced operating expenses for reserves that are currently economic.
- Development of new coal bed methane reserves.
- Reduced costs for groundwater cleanup by pump and treat.
- Reduced costs for treatment of industrial waste waters.
- Increased municipal and agricultural development in the arid western United States.
- Reduced costs for decommissioning defense plants and bases.

5.0 Recommendations

The results of this research confirm the FTE process has very significant commercial economic potential and is technically feasible. Research related to the development of the process should continue to investigate the FTE process in the vast number of potential applications identified. Field demonstration of the FTE process in a variety of differing climates treating a variety of contaminated waters with differing chemistry should be conducted as soon as possible to better understand the technical aspects of the process and to confirm the numerous potential applications of the process to provide water for beneficial uses.

6.0 Acknowledgements

The author wishes to express appreciation to Mr. Buddy Shaw of Amoco Production Company; Mr. Thomas Hayes and Mr. David Linz of GRI; Mr. Alonzo Lawrence of Remediation Technologies Inc.; and Mr. David Alleman and Mr. Eugene Pauling of the United States Department of Energy for sponsoring this research. Also, special thanks are offered to Dr. Donald Stinson for openly sharing his expertise and research data regarding the water purification by the natural freezing process. In closing, the author would like to thank Mr. Bill Hall (Silverado Oil), Mr. Doug Bessert (Thorofare Oil), and Ms. Betsy Wagner (Chevron) for their interest in the project.

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8.0 INDEX

APPENDIX A

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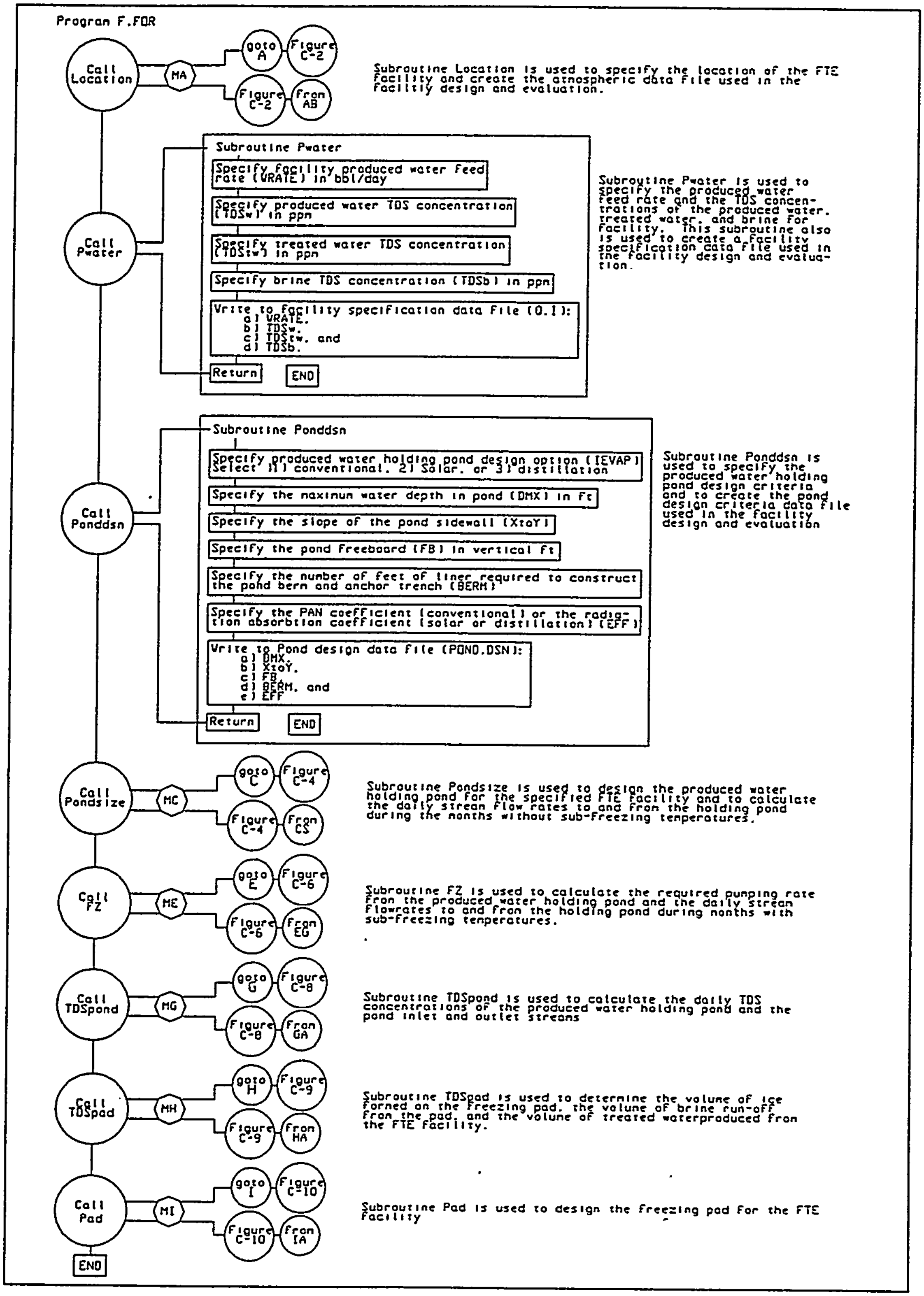
APPENDIX B

THE PROCESS MODEL

THE PROCESS MODEL

The process model source code for the main program and its subroutines are described in detail in the ten flow charts contained in this Appendix. Model calculations, equations, nomenclature, and units for each parameter are described in these flow charts.



Subroutine Location is used to specify the location of the FTE facility and create the atmospheric data file used in the facitity design and evaluation.

Subroutine Pwater is used to specify the produced water feed rate and the TDS concentrations of the produced water. treated water. and brine for facility. This subroutine also is used to create a facility specification data file used in the facility design and evaluation.

Subroutine Ponddsn is used to specify the produced water holding pond design criteria and to create the pond design criteria data file used in the facility design and evaluation

Subroutine Pondsize is used to design the produced water holding pond for the specified FTE facility and to calculate the daily stream flow rates to and from the holding pond during the months without sub-freezing temperatures.

Subroutine FZ is used to calculate the required pumping rate from the produced water holding pond and the daily stream flowrates to and from the holding pond during months with sub-freezing temperatures.

Subroutine TDSpond is used to calculate the daily TDS concentrations of the produced water holding pond and the pond inlet and outlet streams

Subroutine TDSpad is used to determine the volume of ice formed on the freezing pad. the volume of brine run-off from the pad. and the volume of treated waterproduced from the FTE facility.

Subroutine Pad is used to design the freezing pad for the FTE facility

Figure B-1. Program F.FOR (Main Program)

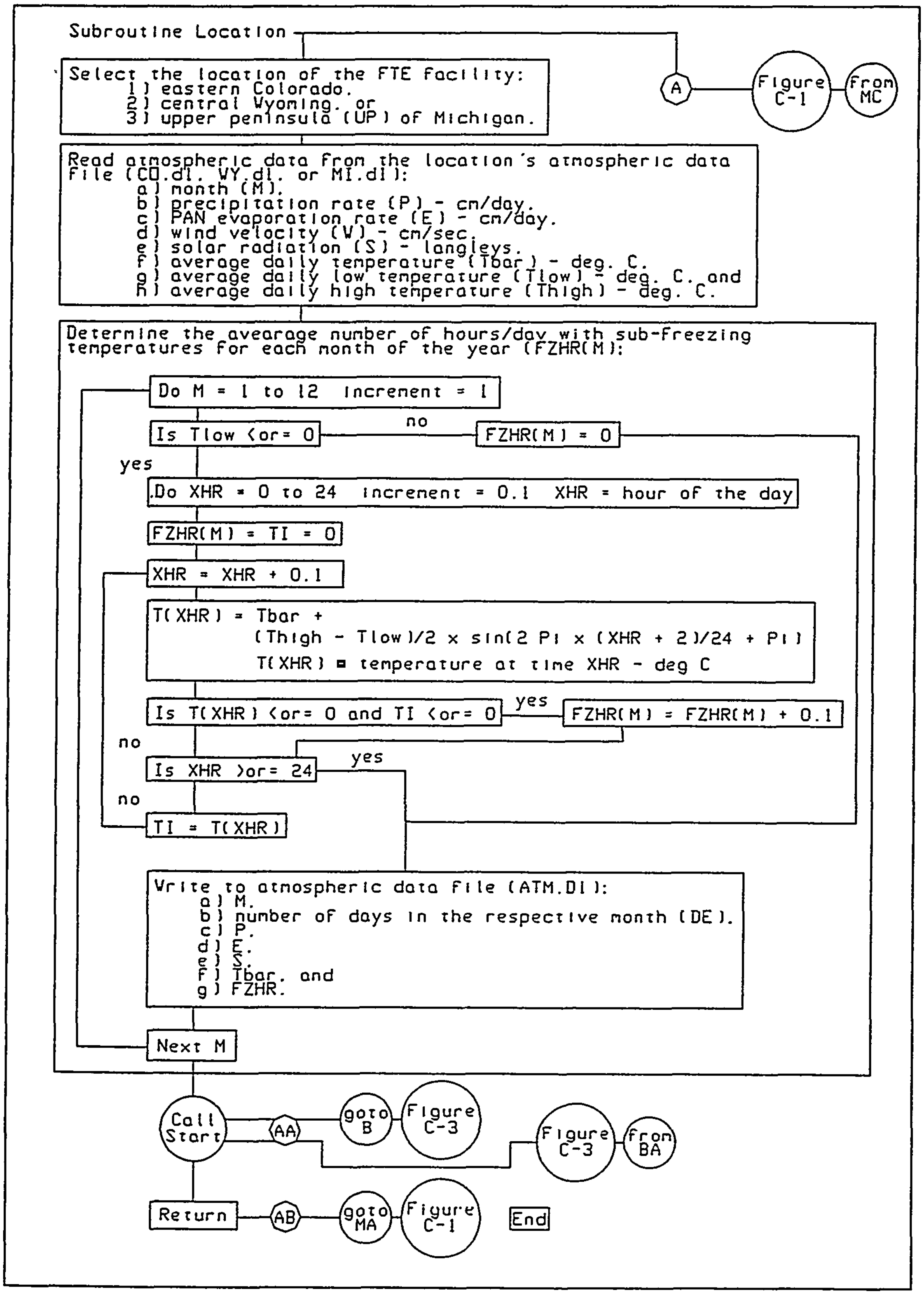


Figure B-2. Subroutine Location

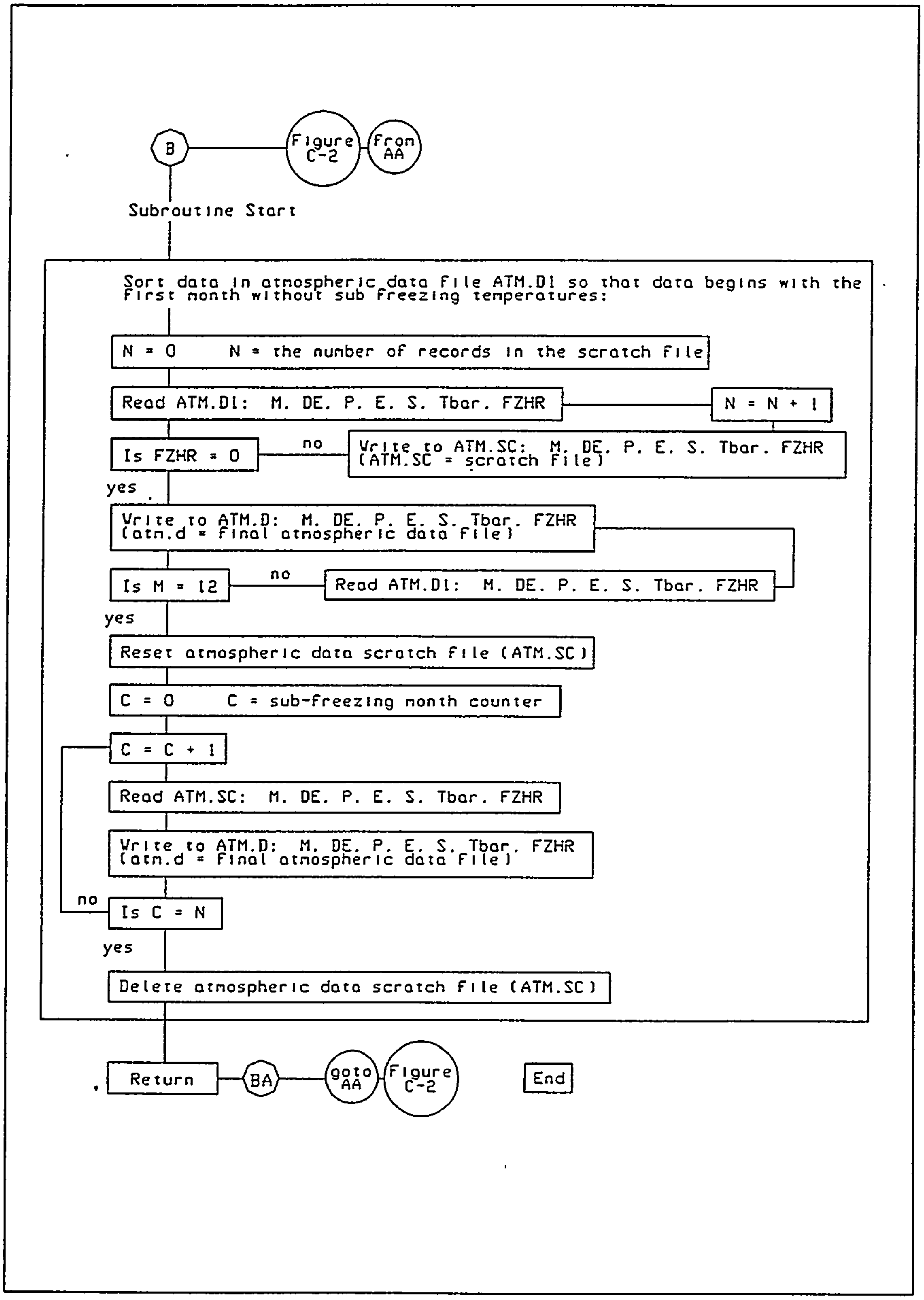


Figure B-3. Subroutine Start

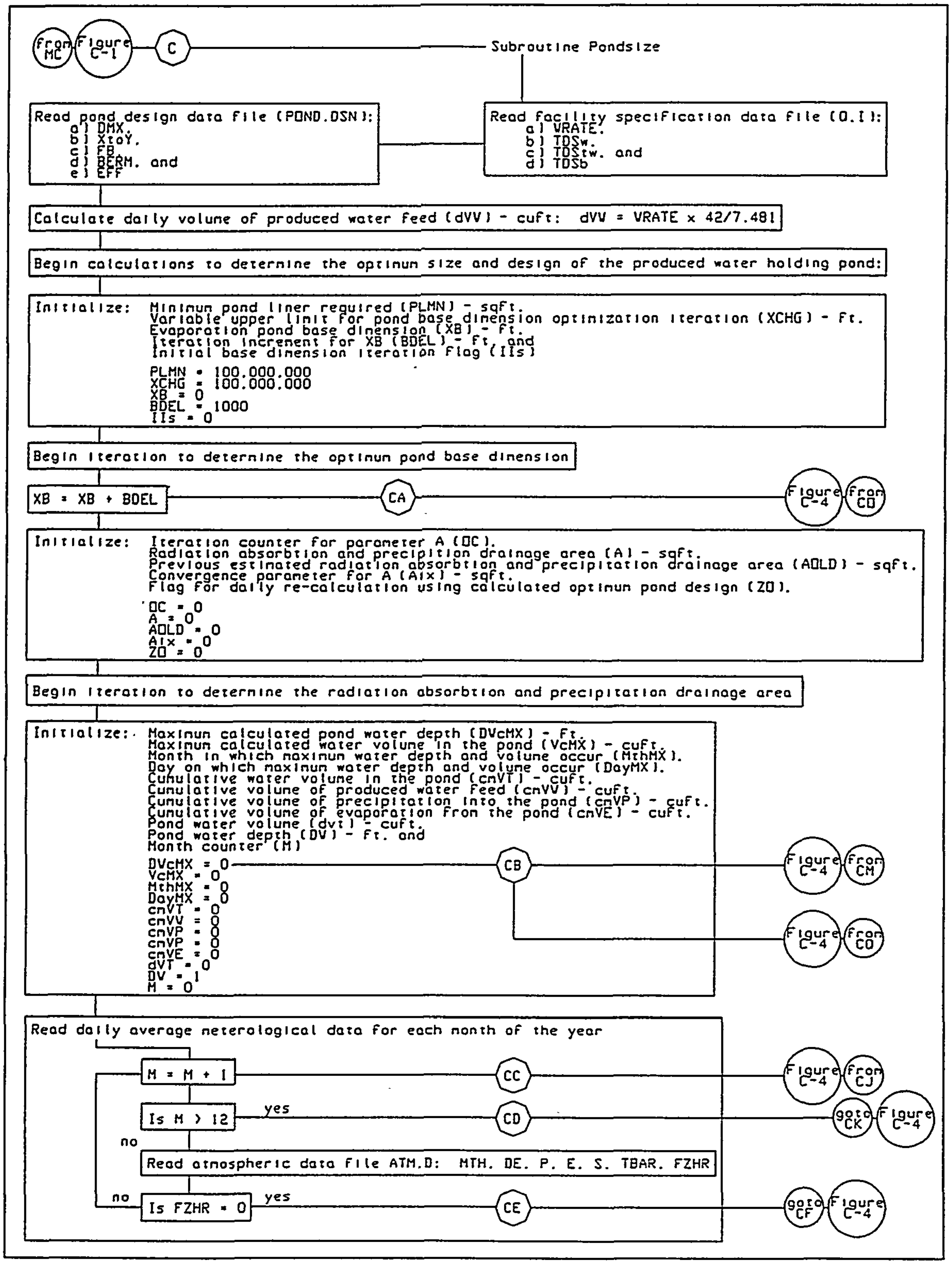


Figure B-4. Subroutine Pondsize

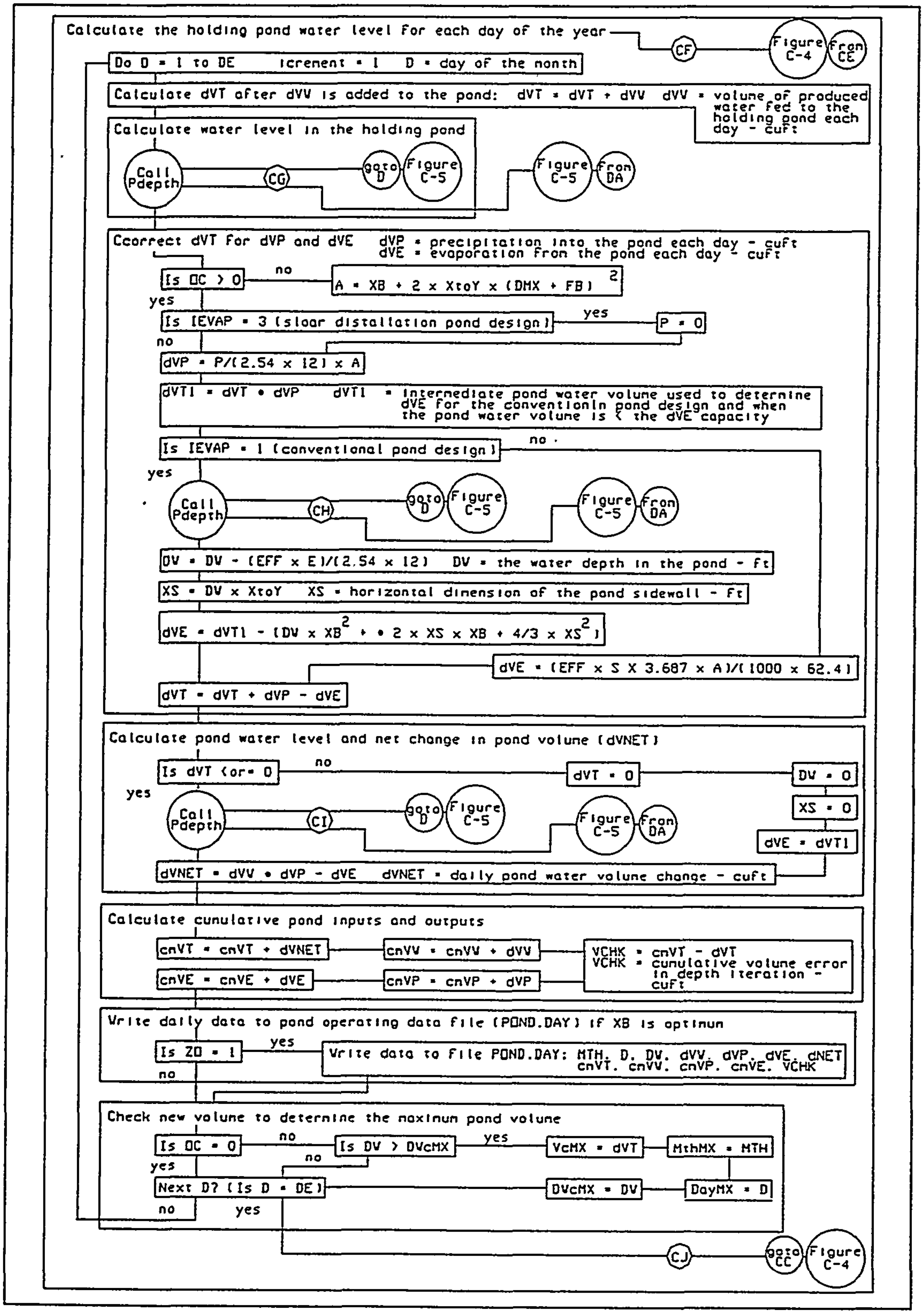


Figure B-4. Subroutine Pondsize (continued)

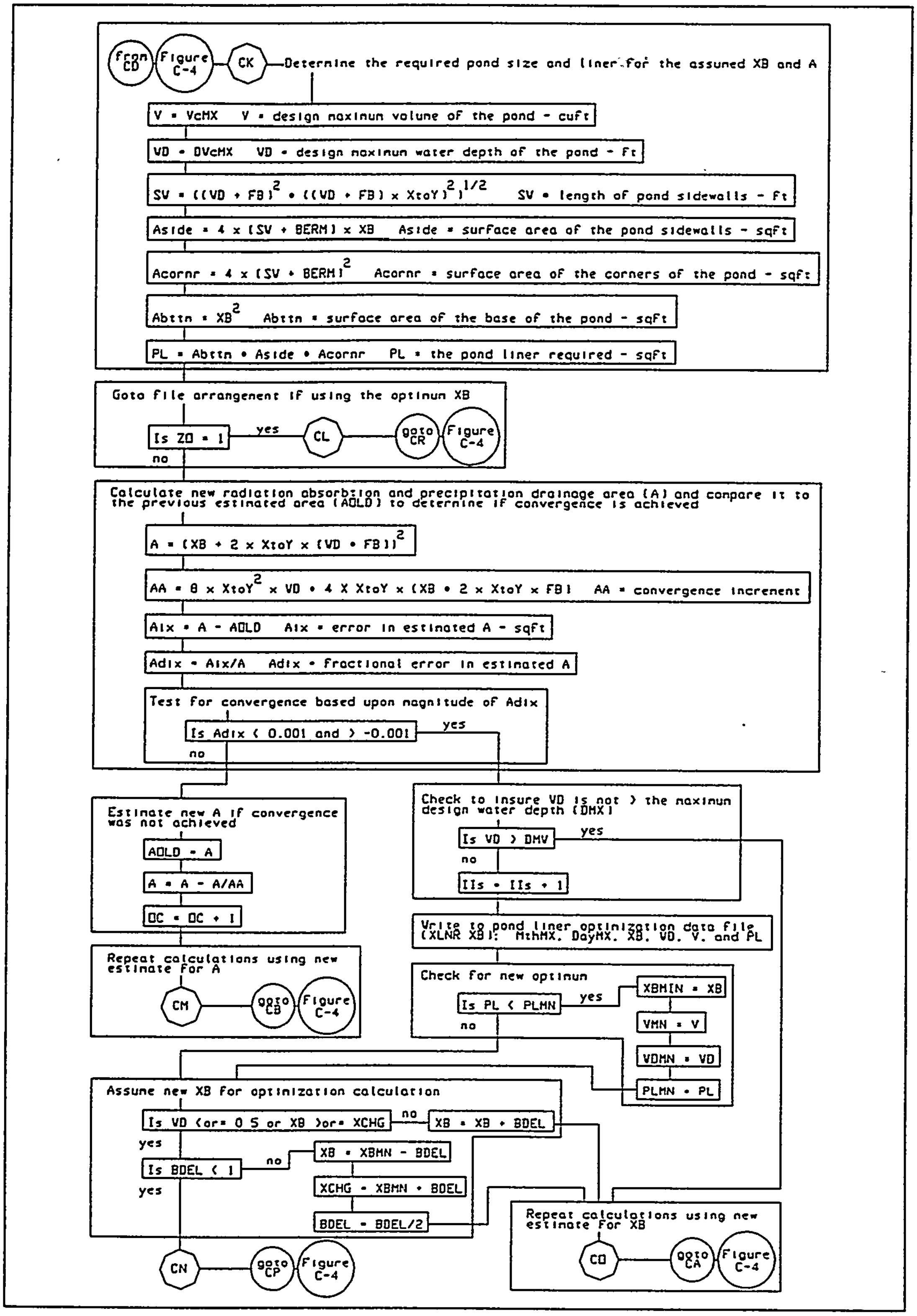


Figure B-4. Subroutine Pondsize (continued)

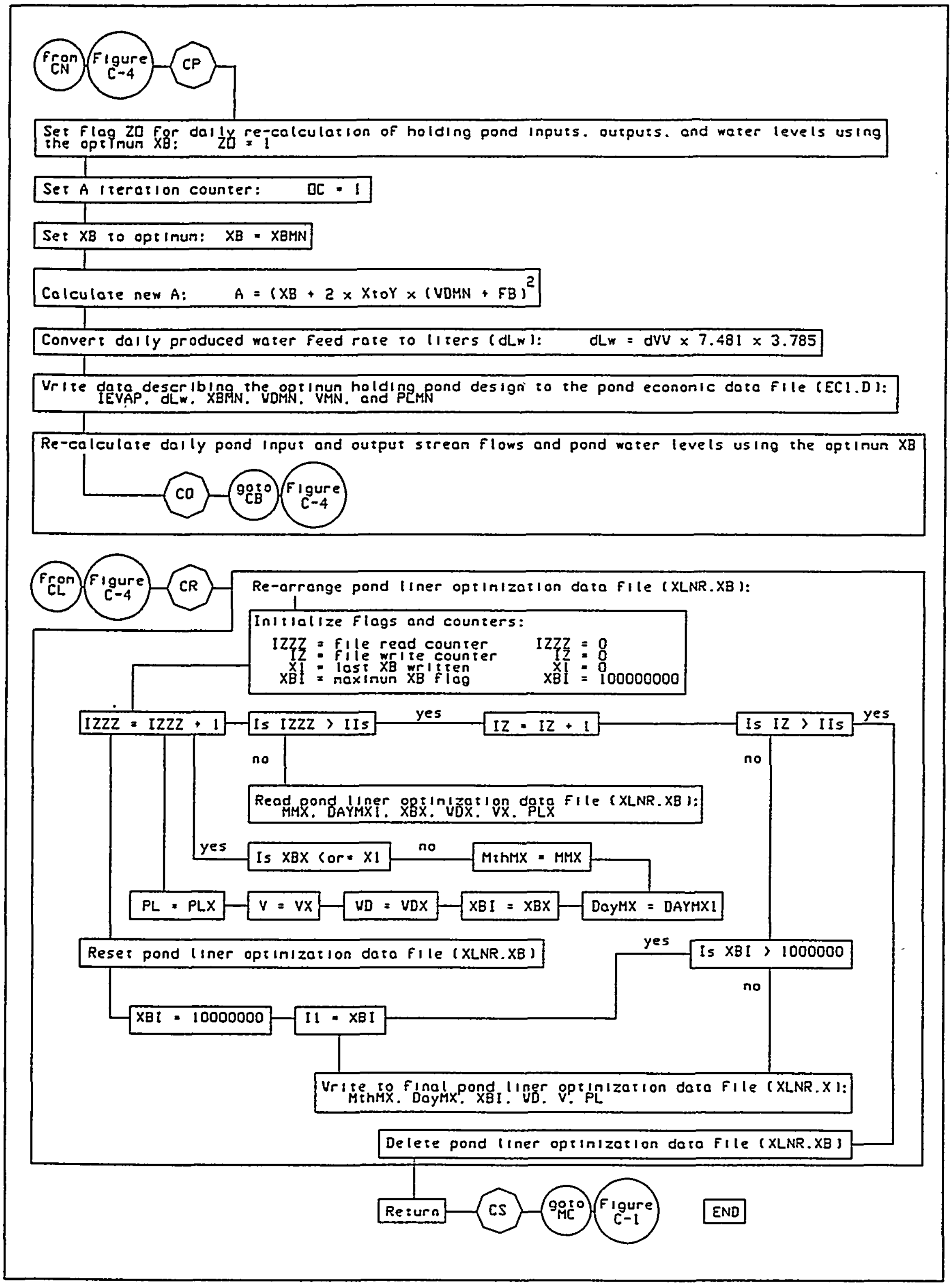


Figure B-4. Subroutine Pondsize (continued)

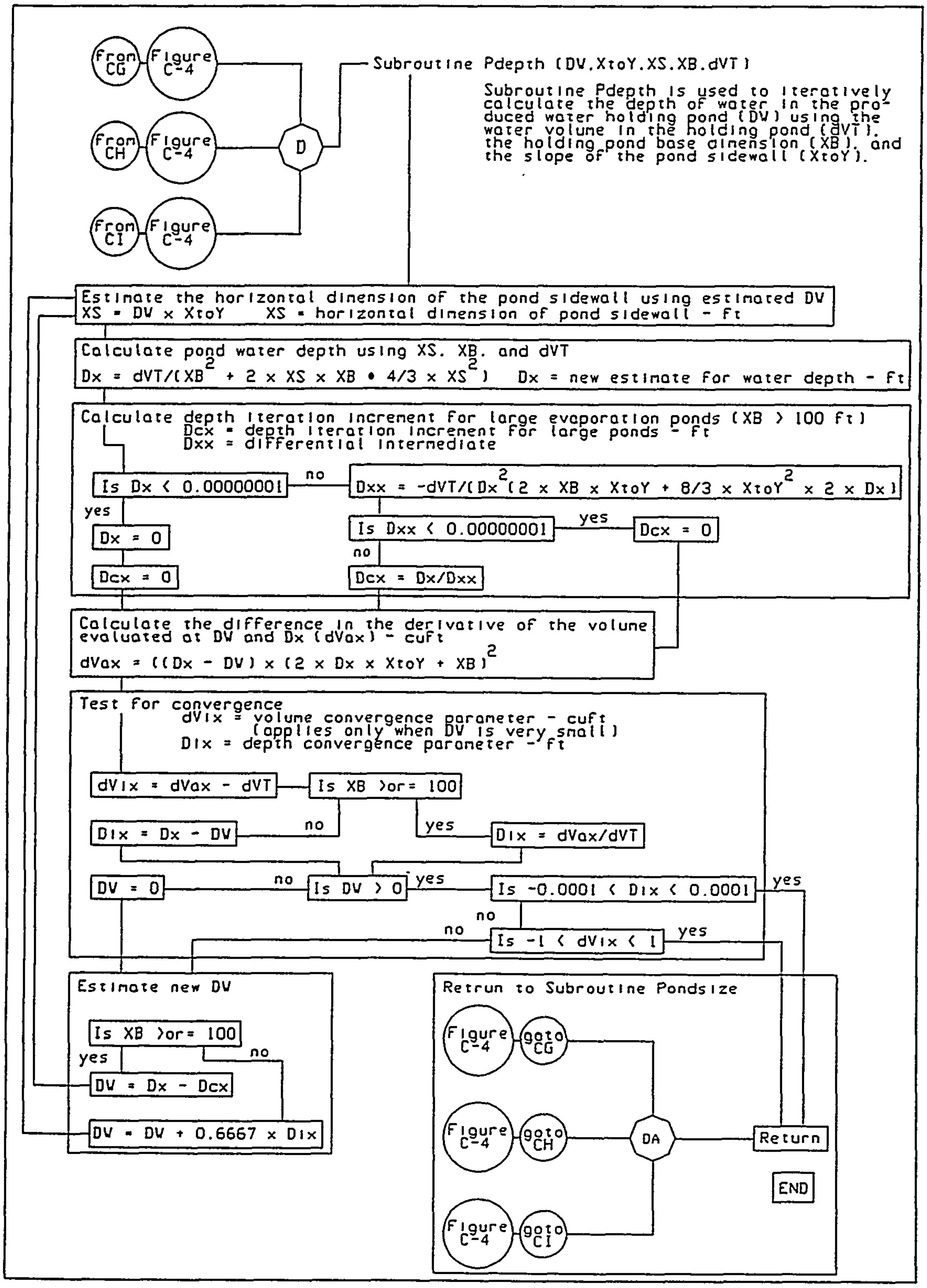


Figure B-5. Subroutine Pdepth

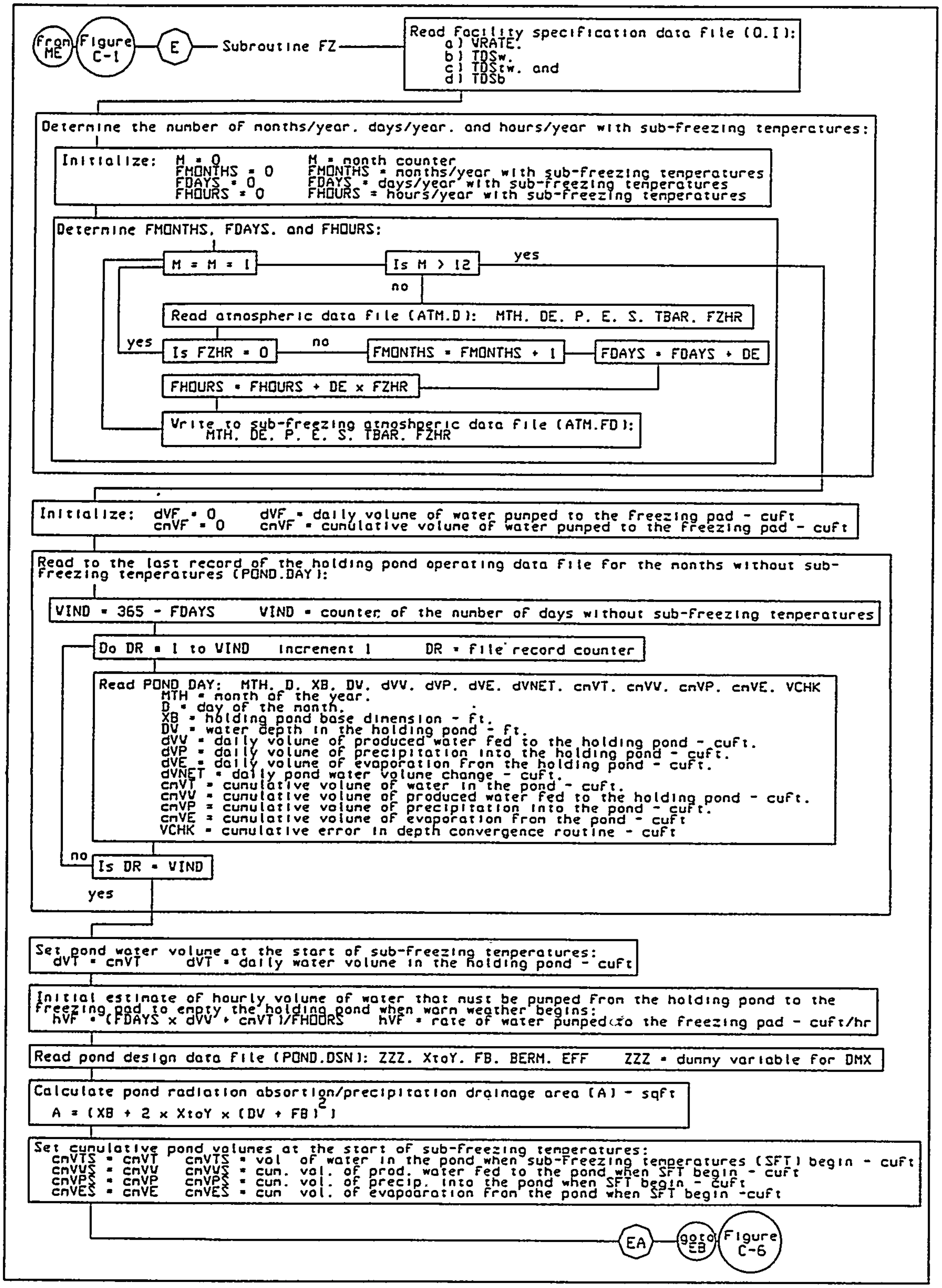


Figure B-6. Subroutine FZ

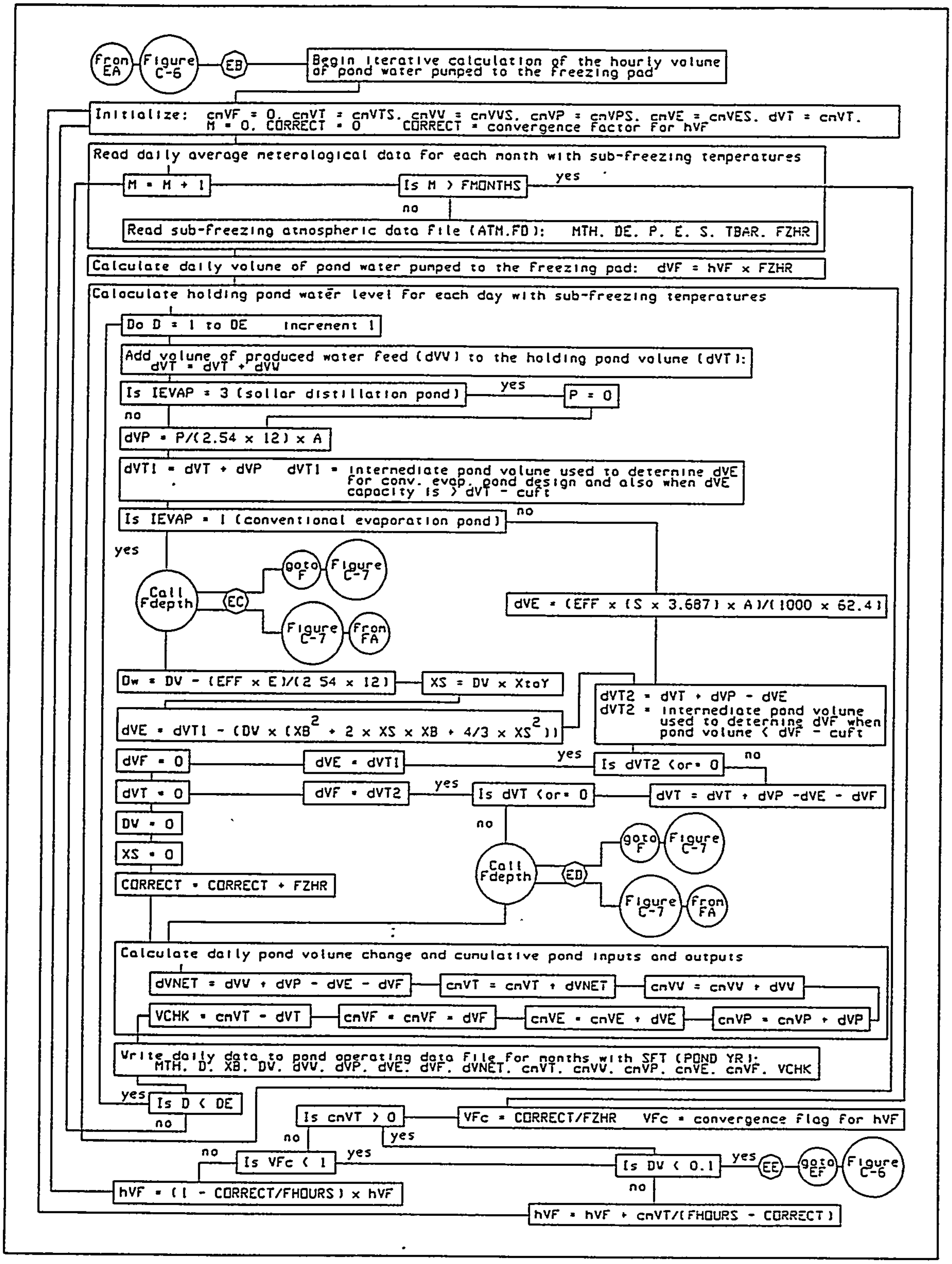


Figure B-6. Subroutine FZ (continued)

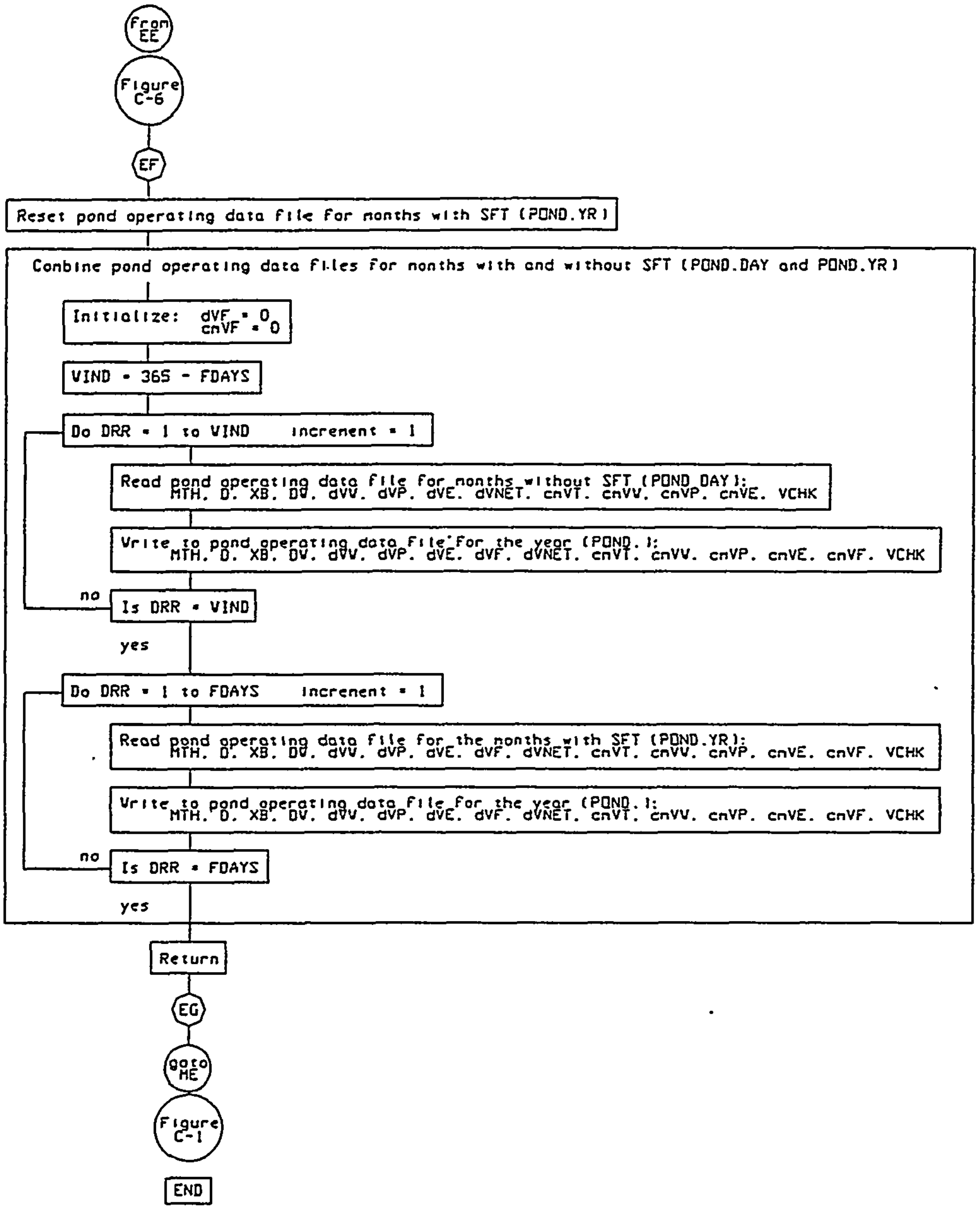


Figure B-6. Subroutine FZ (continued)

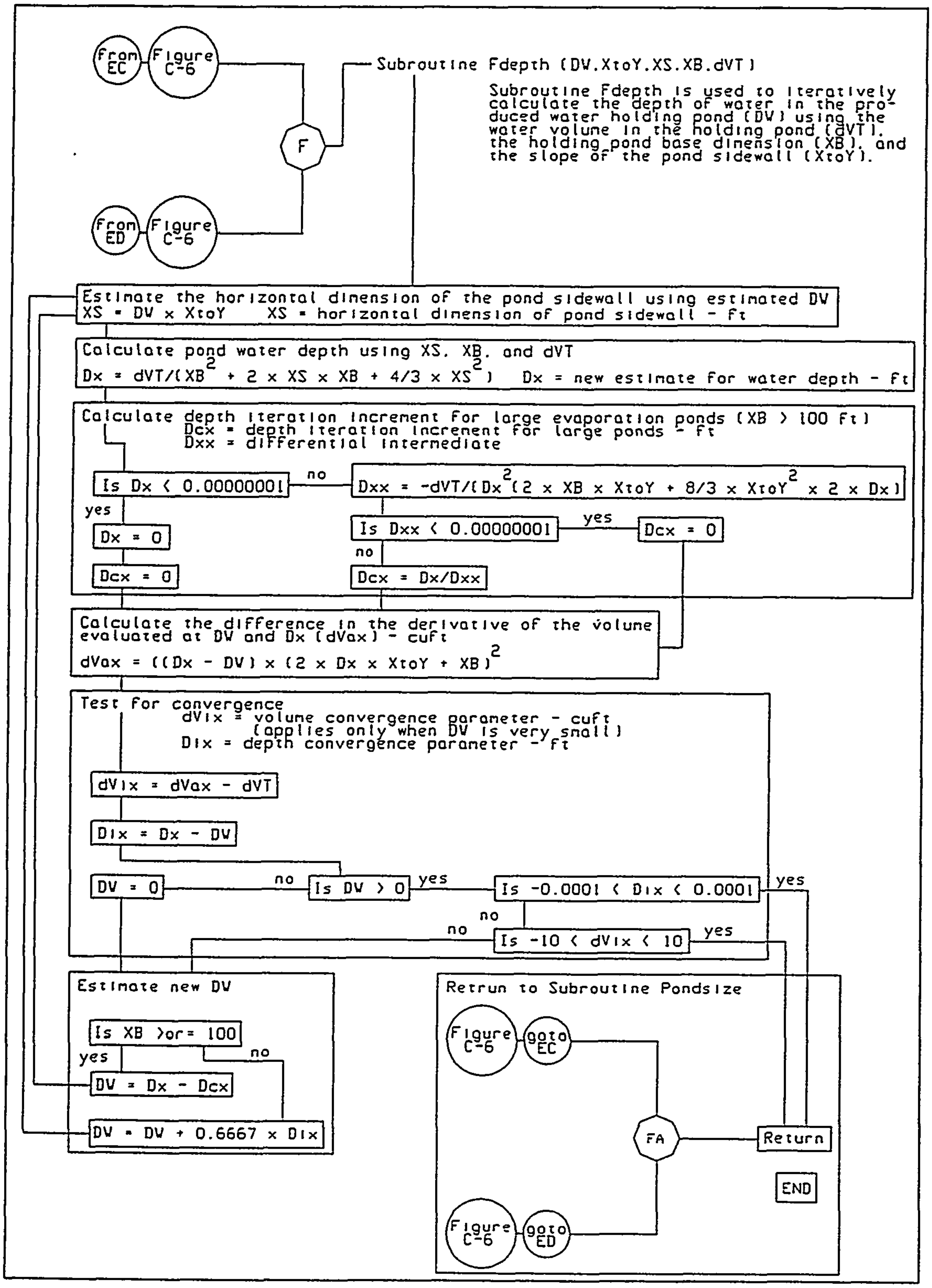


Figure B-7. Subroutine Fdepth

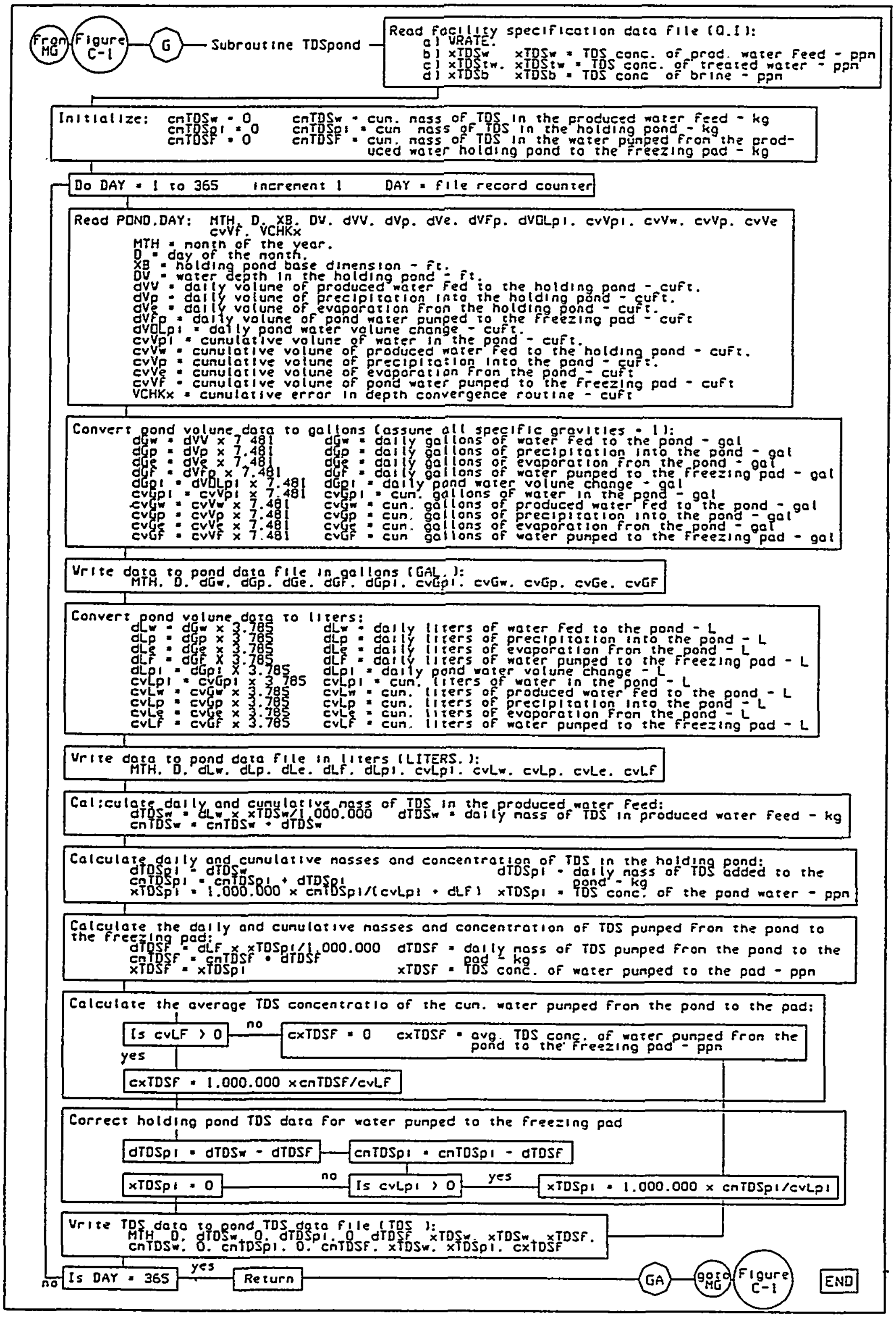


Figure B-8. Subroutine TDSpond

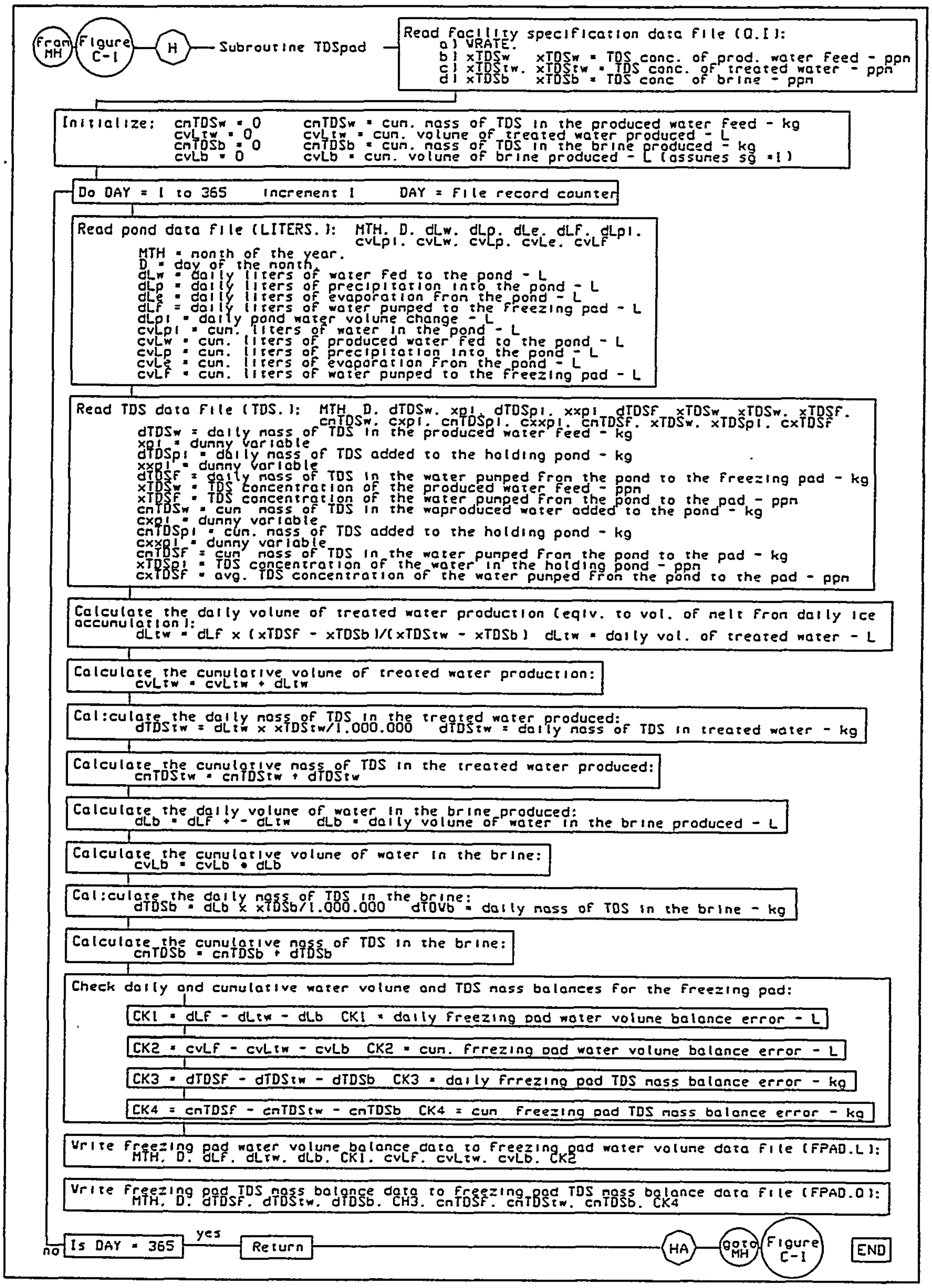


Figure B-9. Subroutine TDSpad

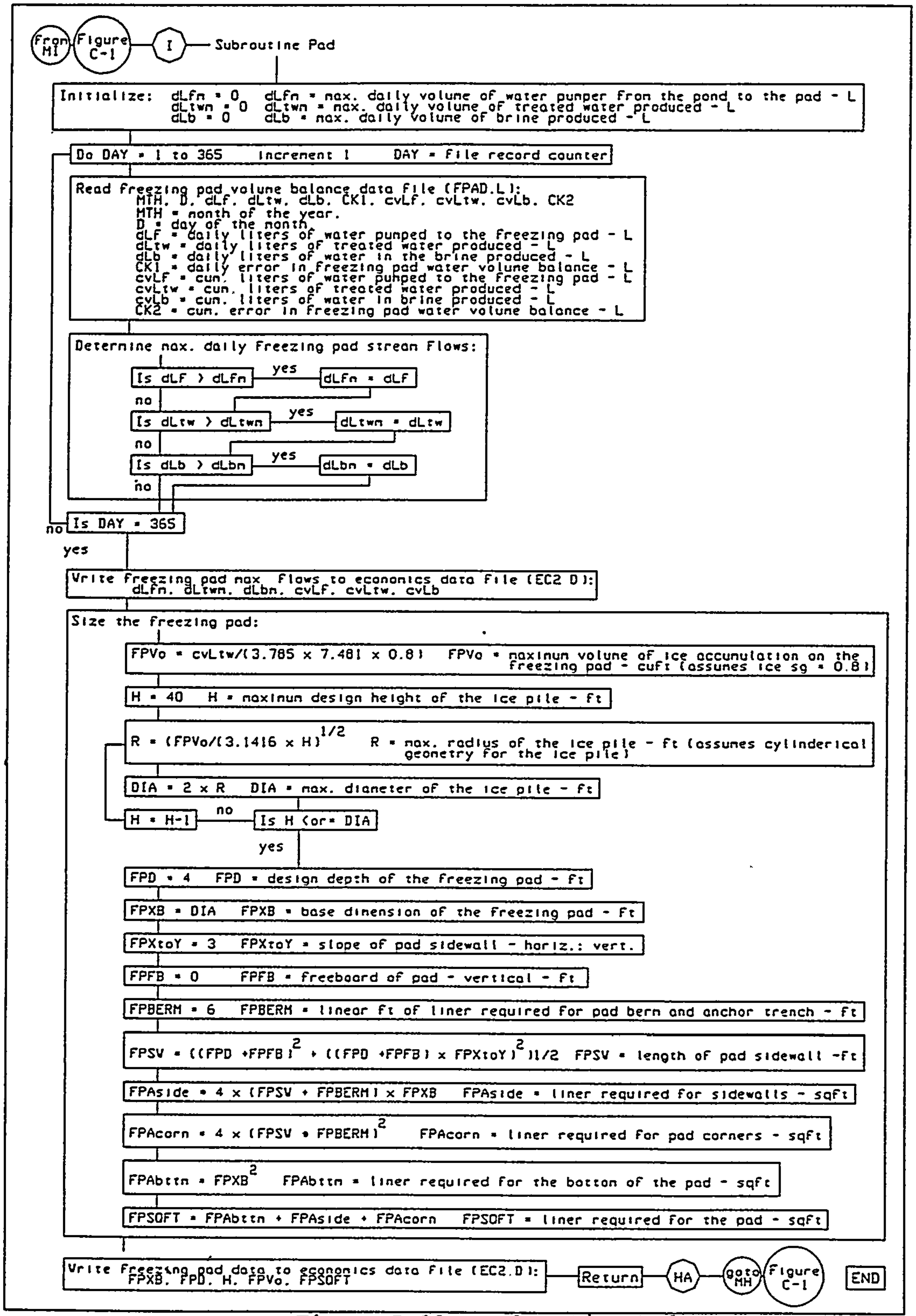


Figure B-10. Subroutine Pad

APPENDIX C

THE ECONOMIC MODEL

THE ECONOMIC MODEL

The economic model source code is described in detail in the flow chart contained in this Appendix. Model calculations, equations, nomenclature, and units for each parameter are described in this flow chart.

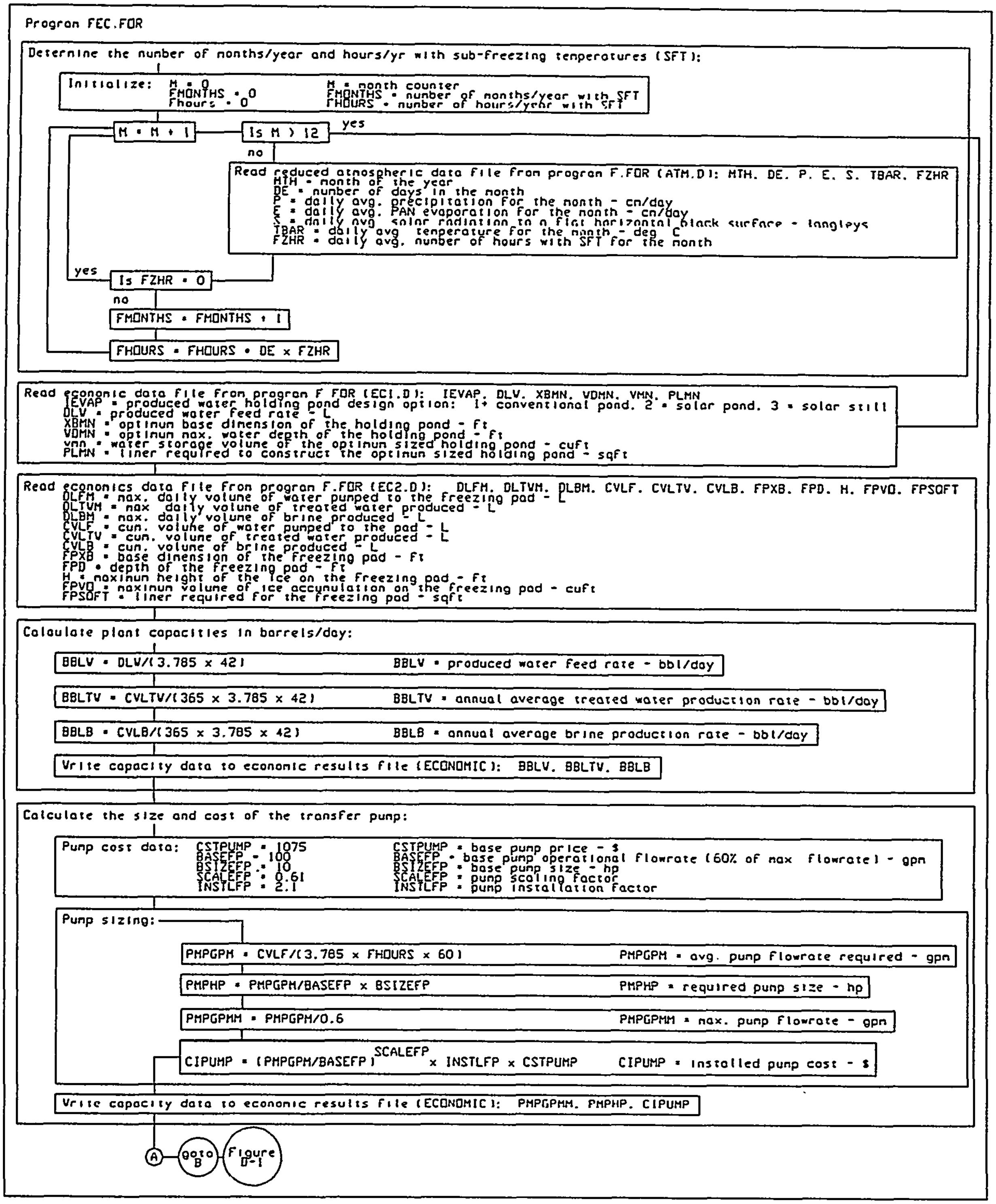


Figure C-1. Program FEC.FOR (Main Program)

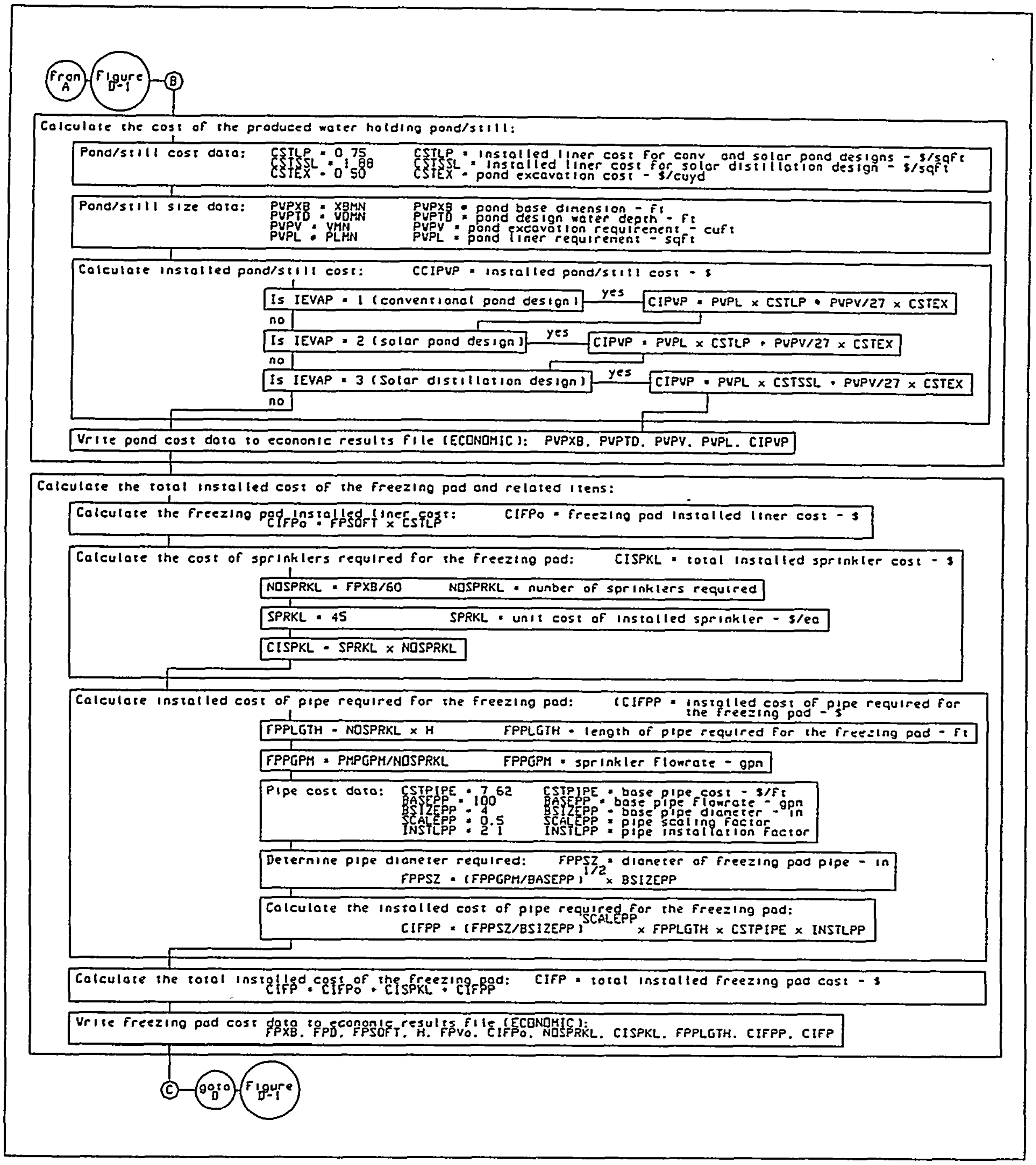


Figure C-1. Program FEC.FOR (Main Program) - (continued)

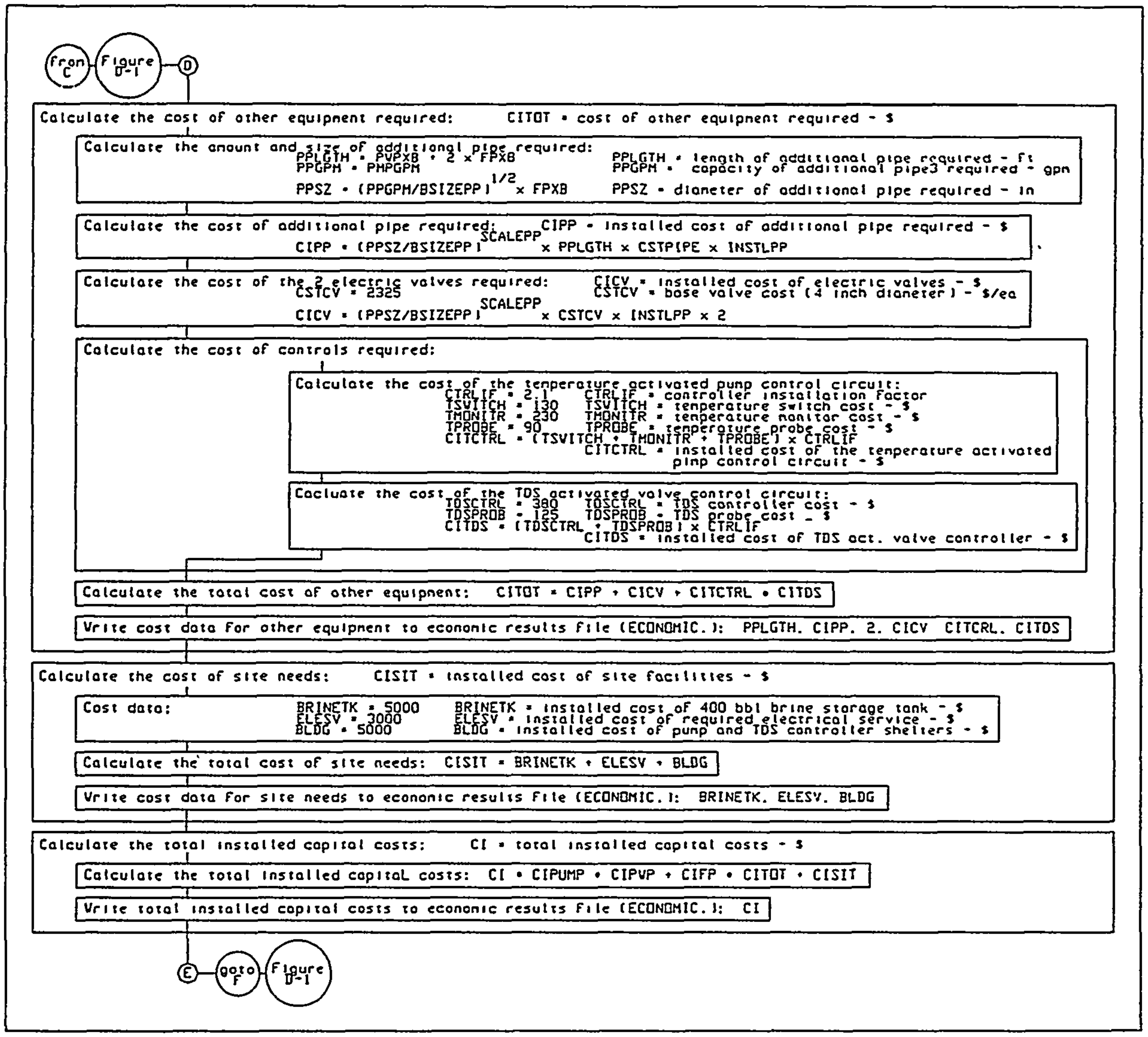


Figure C-1. Program FEC.FOR (Main Program) - (continued)

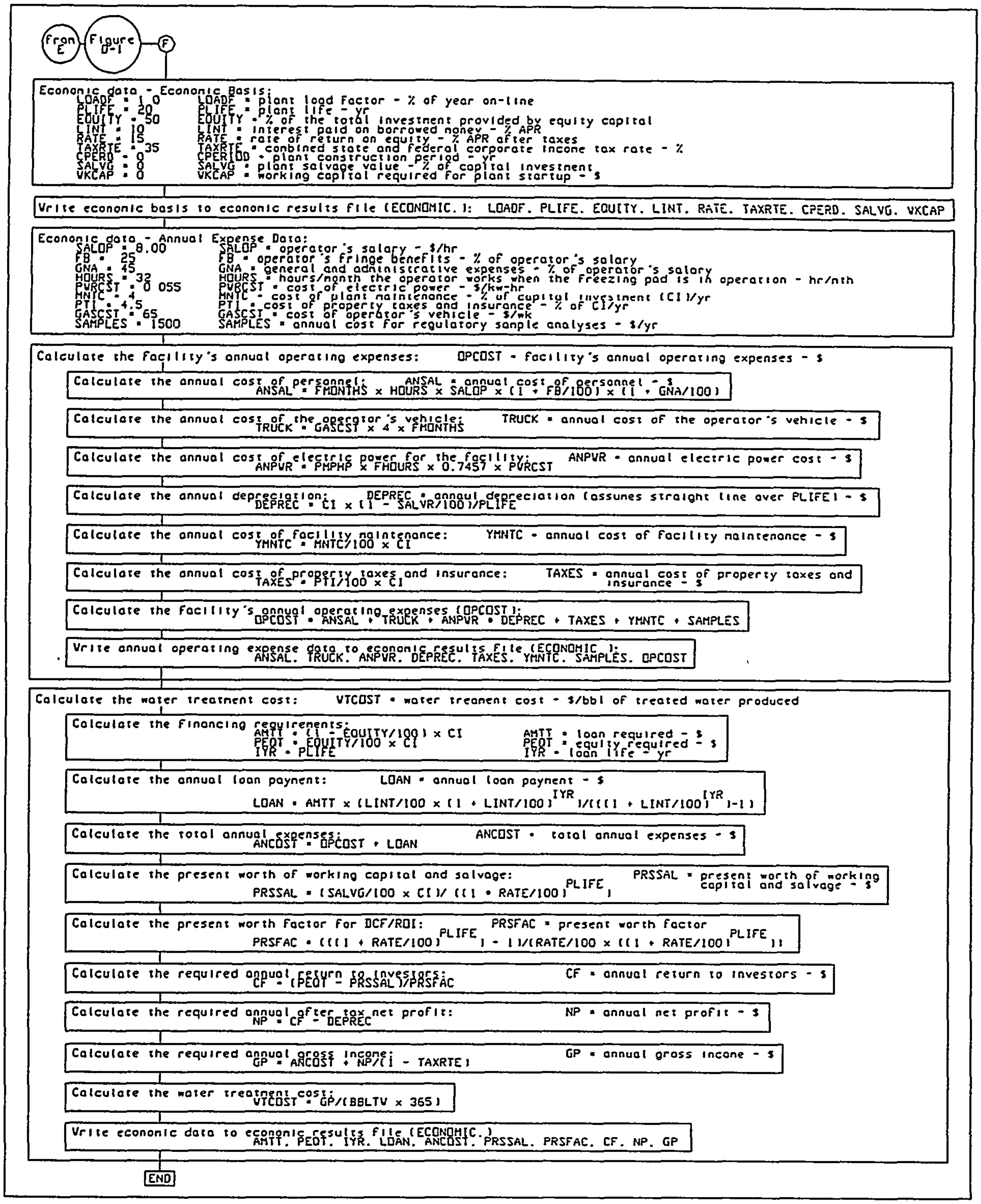


Figure C-1. Program FEC.FOR (Main Program) - (continued)

APPENDIX D-1

SIMULATION SERIES #1 RESULTS

FTE Simulation # 1-1.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #1	- Enhanced Evaporation Pond Design - Water Column Freezing Pad Design

Table D-1-1. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-1.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9722		115.7		2.4		0.102	
Out::								
Treated Water	3737	38.4%	2.9	2.5%	0.0	0.0%	0.003	3.0%
Brine	1752	18.0%	96.9	83.7%	1.7	71.4%	0.090	88.4%
Final Pond Inventory	576	5.9%	10.8	9.3%				
Evaporation	3657	37.6%						
Losses			5.1	4.4%	0.7	28.6%	0.009	8.6%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7590.0		90.3	
Out::				
Evaporation	4280.0	56.4%	-	
Final Pond Inventory	3058.0	40.3%	79.5	88.0%
Losses	252.0	3.3%	10.8	12.0%

Table D-1-2. Produced Water Feed for FTE Simulation #1-1.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9722
06/06/94	3:00 p	Evap. Test Charge	7590
		Total	17312

Table D-1-3. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-1 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	780	0	0.82
Brine	55300	990	51.5

Table D-1-4. TDS Concentrations of Pond Inventories for FTE Simulation #1-1 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	18700
Final Pond Inventory - Evaporation Test	26000

FTE Simulation # 1-1.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #1	- Enhanced Evaporation Pond Design - Water Column Freezing Pad Design

Table D-1-5. Produced Water Holding Pond Level Data for FTE Simulation 1-1.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	133	0
06/08/94	3:20 p		127	6
06/09/94	4:30 p		124	3
06/13/94	4:00 p		101	23
06/14/94	4:30 p		95	6
06/15/94	4:30 p		89	6
06/16/94	4:30 p		82	7
06/17/94	4:30 p		74	8
06/18/94	4:30 p		67	7
06/19/94	4:30 p		62	5
06/20/94	4:45 p		58	4

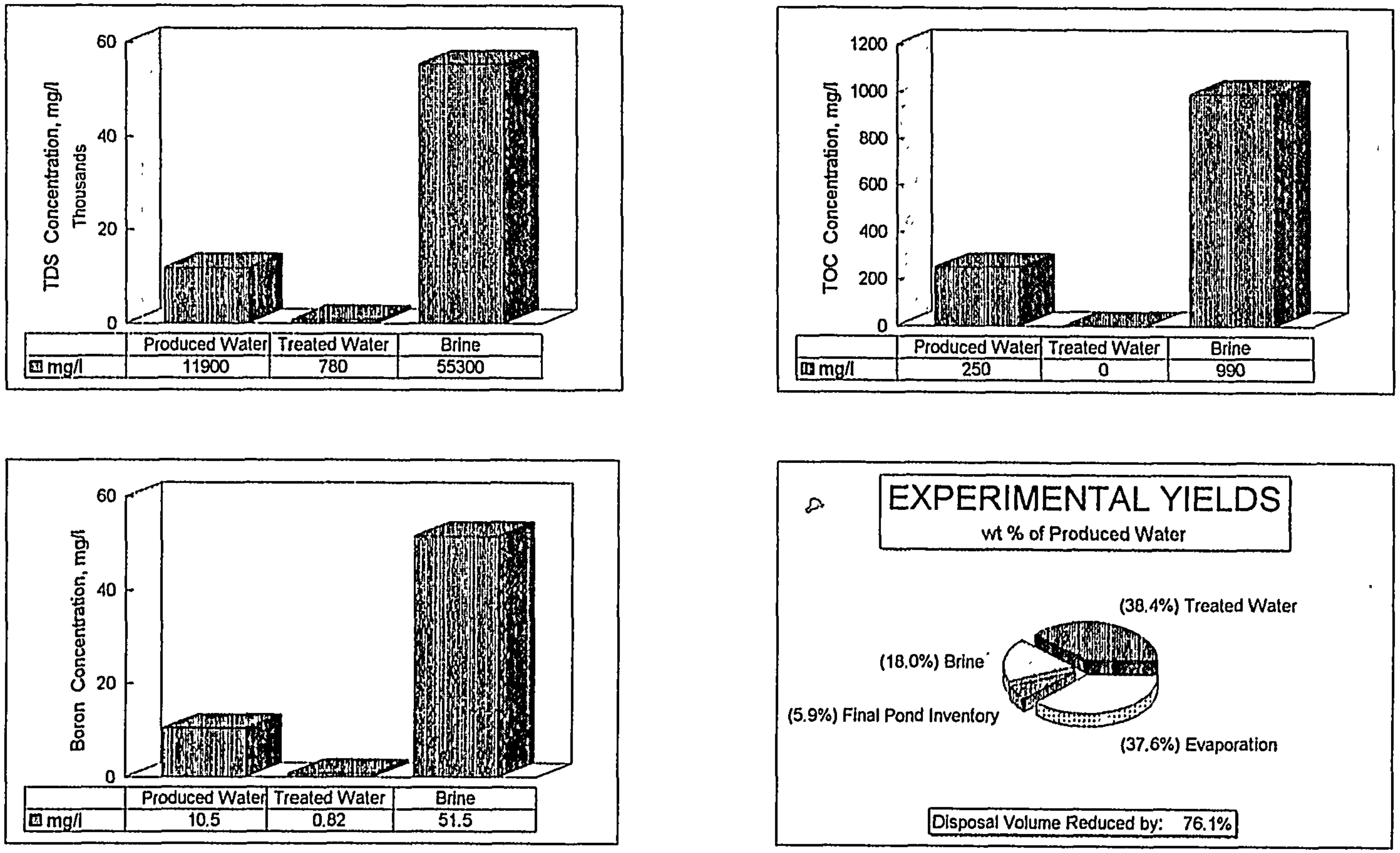
Table D-1-6. Evaporation Rates Achieved for FTE Simulation 1-1.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	138%	104%
06/08/94	06/09/94	April	4.34	69%	
06/14/94	06/15/94	July	7.16	84%	84%
06/15/94	06/16/94	August	6.16	114%	119%
06/16/94	06/17/94	August	6.16	130%	
06/17/94	06/18/94	August	6.16	114%	
06/18/94	06/19/94	June	6.92	72%	65%
06/19/94	06/20/94	June	6.92	58%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					93%

FIGURE D-1-1. FTE SIMULATION # 1-1 EXPERIMENTAL RESULTS
Simulation Series #1: Equipment Optimization

FTE Simulation # 1-1.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

Simulator #1
- Enhanced Evaporation Pond Design
- Water Column Freezing Pad Design



	Produced Water	Treated Water	Brine
▥ mg/l	11900	780	55300

	Produced Water	Treated Water	Brine
▥ mg/l	250	0	990

	Produced Water	Treated Water	Brine
▥ mg/l	10.5	0.82	51.5

Disposal Volume Reduced by: 76.1%

FTE Simulation # 1-2.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #2	- Solar Distillation Pond Design - Water Spray Freezing Pad Design

Table D-1-7. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-2.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9718		115.6		2.4		0.102	
Out::								
Treated Water	2416	24.9%	1.7	1.5%	0.0	0.0%	0.002	1.8%
Brine	3312	34.1%	102.7	88.8%	2.2	88.6%	0.106	103.9%
Final Pond Inventory	374	3.8%	8.8	7.6%				
Evaporation	3616	37.2%						
Losses			2.5	2.1%	0.3	11.4%	-0.006	-5.7%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7510.0		89.4	
Out::				
Evaporation	1073.0	14.3%		
Final Pond Inventory	5820.0	77.5%	75.7	84.7%
Losses	617.0	8.2%	13.7	15.3%

Table D-1-8. Produced Water Feed for FTE Simulation #1-2.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9718
06/06/94	3:00 p	Evap. Test Charge	7510
		Total	17228

Table D-1-9. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-2 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	710	0	0.76
Brine	31000	650	32.0

Table D-1-10. TDS Concentrations of Pond Inventories for FTE Simulation #1-2 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	23500
Final Pond Inventory - Evaporation Test	13000

FTE Simulation # 1-2.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #2	- Solar Distillation Pond Design - Water Spray Freezing Pad Design

Table D-1-11. Produced Water Holding Pond Level Data for FTE Simulation #1-2.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	133	0
06/08/94	3:20 p		131	2
06/09/94	4:30 p		130	1
06/13/94	4:00 p		125	5
06/14/94	4:30 p		123	2
06/15/94	4:30 p		121	2
06/16/94	4:30 p		119	2
06/17/94	4:30 p		117	2
06/18/94	4:30 p		116	1
06/19/94	4:30 p		115	1
06/20/94	4:45 p		114	1

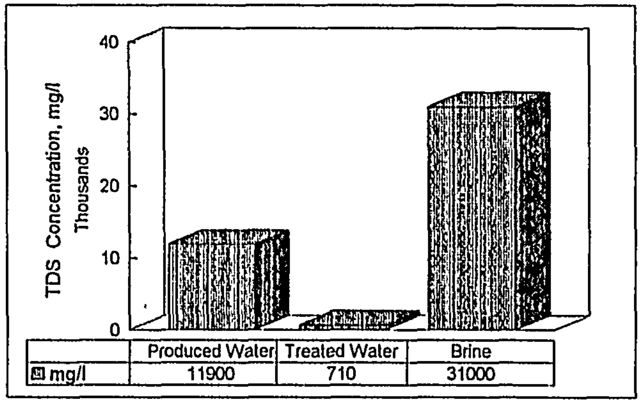
Table D-1-12. Evaporation Rates Achieved for FTE Simulation #1-2.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	46%	35%
06/08/94	06/09/94	April	4.34	23%	
06/14/94	06/15/94	July	7.16	28%	28%
06/15/94	06/16/94	August	6.16	32%	27%
06/16/94	06/17/94	August	6.16	32%	
06/17/94	06/18/94	August	6.16	16%	
06/18/94	06/19/94	June	6.92	14%	14%
06/19/94	06/20/94	June	6.92	14%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					26%

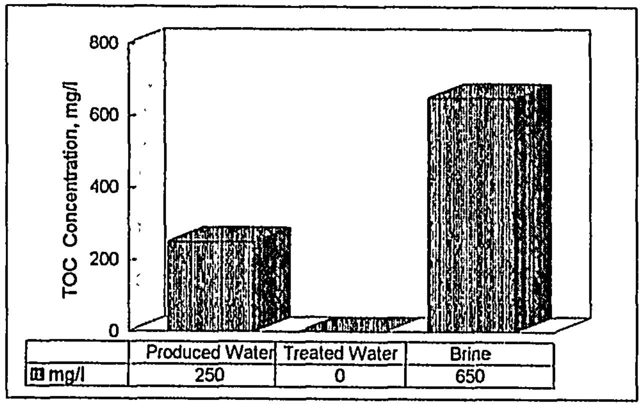
FIGURE D-1-2. FTE SIMULATION # 1 - 2 EXPERIMENTAL RESULTS
Simulation Series #1: Equipment Optimization

FTE Simulation # 1-2.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

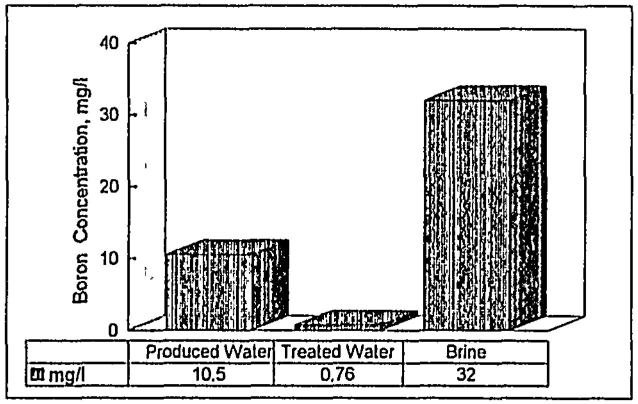
Simulator #2
- Solar Distillation Pond Design
- Water Spray Freezing Pad Design



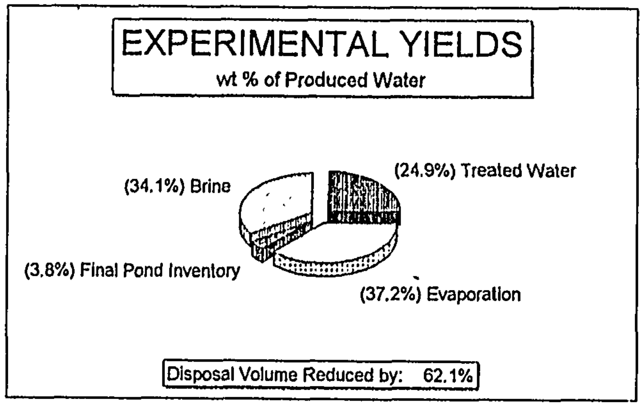
	Produced Water	Treated Water	Brine
▩ mg/l	11900	710	31000



	Produced Water	Treated Water	Brine
▩ mg/l	250	0	650



	Produced Water	Treated Water	Brine
▩ mg/l	10.5	0.76	32



FTE Simulation # 1-3.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

Simulator #3
- Enhanced Evaporation Pond Design
- Water Spray Freezing Pad Design

Table D-1-13. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-3.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9882		117.6		2.5		0.104	
Out::								
Treated Water	3418	34.6%	5.4	4.6%	0.0	0.0%	0.005	4.9%
Brine	2274	23.0%	95.5	81.2%	1.4	56.1%	0.088	84.8%
Final Pond Inventory	302	3.1%	9.4	8.0%				
Evaporation	3888	39.3%						
Losses			7.3	6.2%	1.1	43.9%	0.011	10.3%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7532.0		89.6	
Out::				
Evaporation	4082.0	54.2%		
Final Pond Inventory	3185.0	42.3%	76.4	85.3%
Losses	265.0	3.5%	13.2	14.7%

Table D-1-14. Produced Water Feed for FTE Simulation 1-3.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9882
06/06/94	3:00 p	Evap. Test Charge	7532
		Total	17414

Table D-1-15. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-3 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	1580	0	1.48
Brine	42000	610	38.7

Table D-1-16. TDS Concentrations of Pond Inventories for FTE Simulation #1-3 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	31000
Final Pond Inventory - Evaporation Test	24000

FTE Simulation # 1-3.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #3	- Enhanced Evaporation Pond Design - Water Spray Freezing Pad Design

Table D-1-17. Produced Water Holding Pond Level Data for FTE Simulation #1-3.

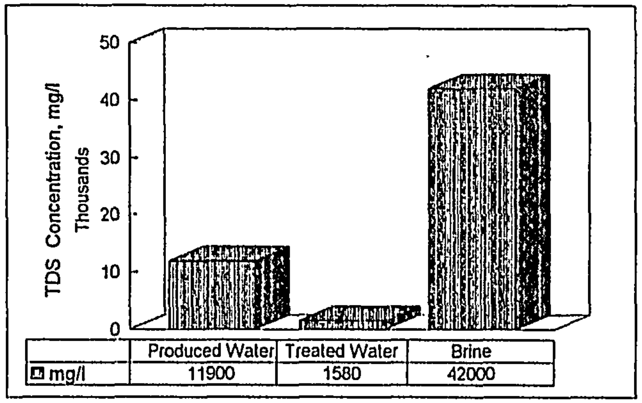
Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	131	0
06/08/94	3:20 p		124	7
06/09/94	4:30 p		117	7
06/13/94	4:00 p		100	17
06/14/94	4:30 p		94	6
06/15/94	4:30 p		88	6
06/16/94	4:30 p		80	8
06/17/94	4:30 p		73	7
06/18/94	4:30 p		67	6
06/19/94	4:30 p		63	4
06/20/94	4:45 p		60	3

Table D-1-18. Evaporation Rates Achieved for FTE Simulation #1-3.

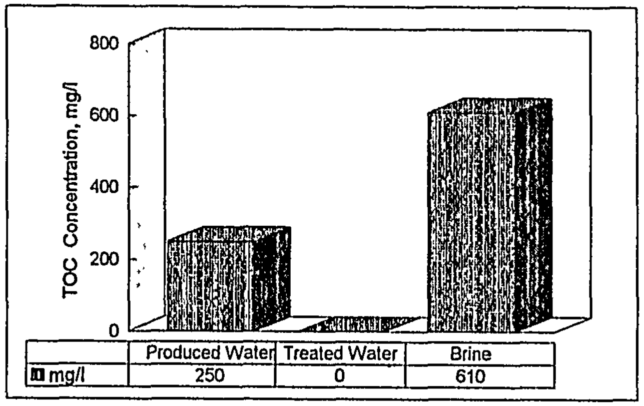
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	161%	161%
06/08/94	06/09/94	April	4.34	161%	
06/14/94	06/15/94	July	7.16	84%	84%
06/15/94	06/16/94	August	6.16	130%	114%
06/16/94	06/17/94	August	6.16	114%	
06/17/94	06/18/94	August	6.16	97%	
06/18/94	06/19/94	June	6.92	58%	51%
06/19/94	06/20/94	June	6.92	43%	
		Average PAN Evaporation Efficiency Achieved (% of PAN)			102%

FIGURE D-1-3. FTE SIMULATION # 1-3 EXPERIMENTAL RESULTS
Simulation Series #1: Equipment Optimization

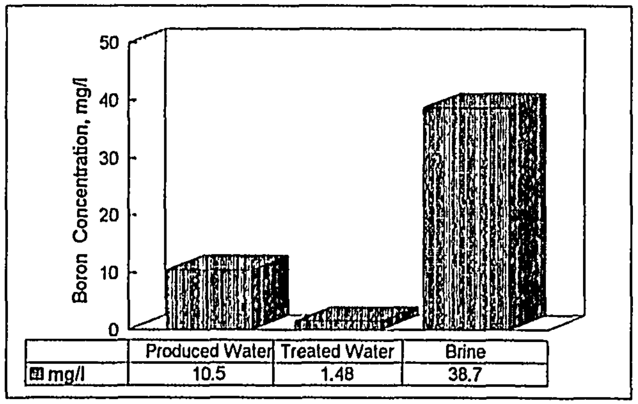
FTE Simulation # 1-3.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #3	- Enhanced Evaporation Pond Design - Water Spray Freezing Pad Design



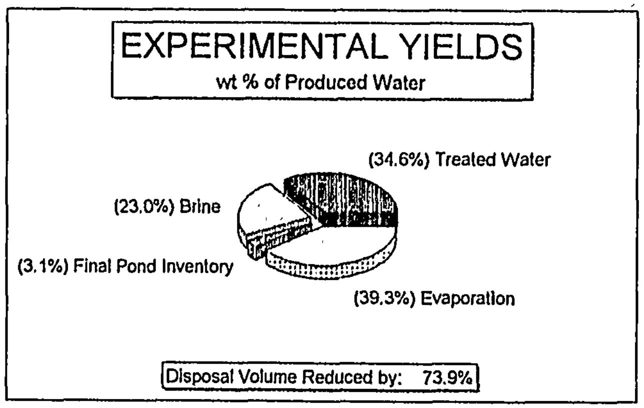
	Produced Water	Treated Water	Brine
▨ mg/l	11900	1580	42000



	Produced Water	Treated Water	Brine
▨ mg/l	250	0	610



	Produced Water	Treated Water	Brine
▨ mg/l	10.5	1.48	38.7



FTE Simulation # 1-4.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #4	- Enhanced Evaporation Pond Design - Atomizing Spray Freezing Pad Design

Table D-1-19. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-4.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	10078		119.9		2.5		0.106	
Out::								
Treated Water	2700	26.8%	1.6	1.3%	0.0	0.0%	0.002	1.6%
Brine	2036	20.2%	89.6	74.7%	1.3	53.3%	0.078	73.3%
Final Pond Inventory	1272	12.6%	24.2	20.2%				
Evaporation	4070	40.4%						
Losses			4.6	3.8%	1.2	46.7%	0.027	25.1%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7533.0		89.6	
Out::				
Evaporation	4099.0	54.4%		
Final Pond Inventory	3052.0	40.5%	73.2	81.7%
Losses	382.0	5.1%	16.4	18.3%

Table D-1-20. Produced Water Feed for FTE Simulation 1-4.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	10078
06/06/94	3:00 p	Evap. Test Charge	7533
		Total	17611

Table D-1-21. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-4 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	580	0	0.61
Brine	44000	660	38.1

Table D-1-22. TDS Concentrations of Pond Inventories for FTE Simulation #1-4 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	19000
Final Pond Inventory - Evaporation Test	24000

FTE Simulation # 1-4.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #4	- Enhanced Evaporation Pond Design - Atomizing Spray Freezing Pad Design

Table D-1-23. Produced Water Holding Pond Level Data for FTE Simulation #1-4.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	136	0
06/08/94	3:20 p		131	5
06/09/94	4:30 p		128	3
06/13/94	4:00 p		103	25
06/14/94	4:30 p		97	6
06/15/94	4:30 p		91	6
06/16/94	4:30 p		83	8
06/17/94	4:30 p		76	7
06/18/94	4:30 p		70	6
06/19/94	4:30 p		66	4
06/20/94	4:45 p		62	4

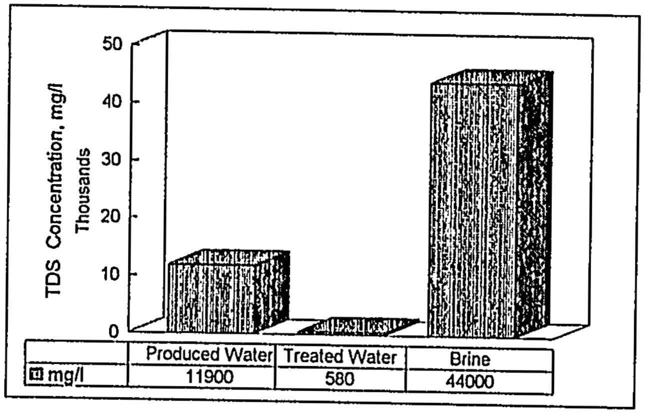
Table D-1-24. Evaporation Rates Achieved for FTE Simulation #1-4.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	115%	92%
06/08/94	06/09/94	April	4.34	69%	
06/14/94	06/15/94	July	7.16	84%	84%
06/15/94	06/16/94	August	6.16	130%	114%
06/16/94	06/17/94	August	6.16	114%	
06/17/94	06/18/94	August	6.16	97%	
06/18/94	06/19/94	June	6.92	58%	58%
06/19/94	06/20/94	June	6.92	58%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					87%

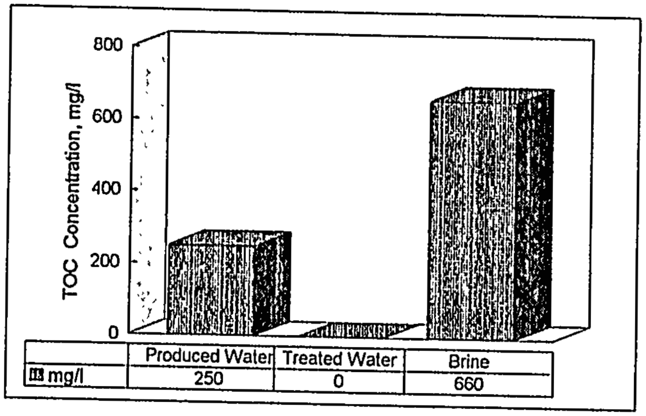
FIGURE D-1-4. FTE SIMULATION # 1 - 4 EXPERIMENTAL RESULTS

Simulation Series #1: Equipment Optimization

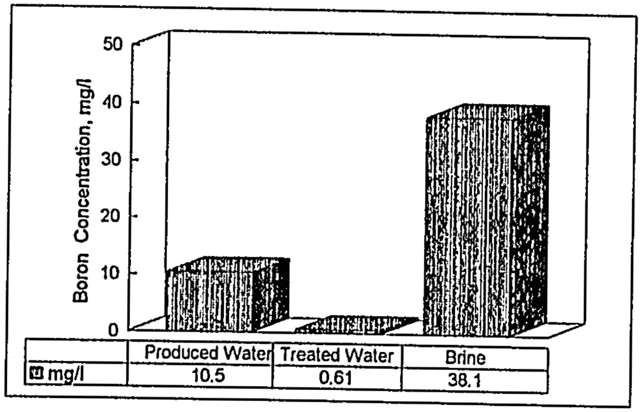
FTE Simulation # 1-4.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #4	- Enhanced Evaporation Pond Design - Atomizing Spray Freezing Pad Design



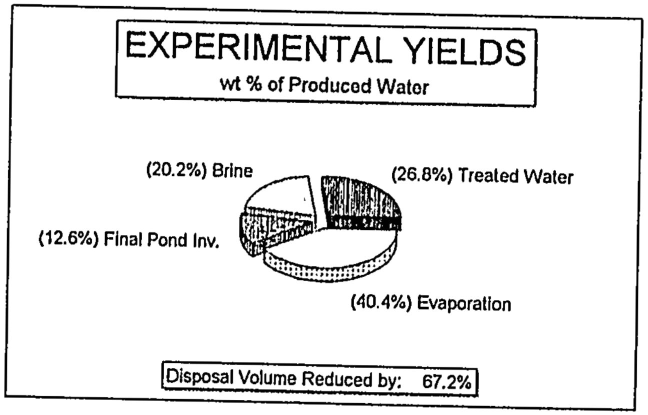
	Produced Water	Treated Water	Brine
▥ mg/l	11900	580	44000



	Produced Water	Treated Water	Brine
▥ mg/l	250	0	660



	Produced Water	Treated Water	Brine
▥ mg/l	10.5	0.61	38.1


EXPERIMENTAL YIELDS

wt % of Produced Water

Disposal Volume Reduced by: 67.2%

FTE Simulation # 1-5.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #5	- Solar Distillation Pond Design - Water Column Freezing Pad Design

Table D-1-25. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-5.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9156		109.0		2.3		0.096	
Out::								
Treated Water	2016	22.0%	1.2	1.1%	0.0	0.0%	0.001	1.3%
Brine	3224	35.2%	81.9	75.2%	1.4	60.6%	0.072	74.8%
Final Pond Inventory	612	6.7%	14.1	12.9%				
Evaporation	3304	36.1%						
Losses			11.7	10.8%	0.9	39.4%	0.023	23.9%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7648.0		91.0	
Out::				
Evaporation	1323.0	17.3%		
Final Pond Inventory	5912.0	77.3%	76.9	84.4%
Losses	413.0	5.4%	14.2	15.6%

Table D-1-26. Produced Water Feed for FTE Simulation 1-5.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9156
06/06/94	3:00 p	Evap. Test Charge	7648
		Total	16804

Table D-1-27. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-5 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	620	0	0.62
Brine	25400	430	22.3

Table D-1-28. TDS Concentrations of Pond Inventories for FTE Simulation #1-5 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	23000
Final Pond Inventory - Evaporation Test	13000

FTE Simulation # 1-5.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #5	- Solar Distillation Pond Design - Water Column Freezing Pad Design

Table D-1-29. Produced Water Holding Pond Level Data for FTE Simulation #1-5.

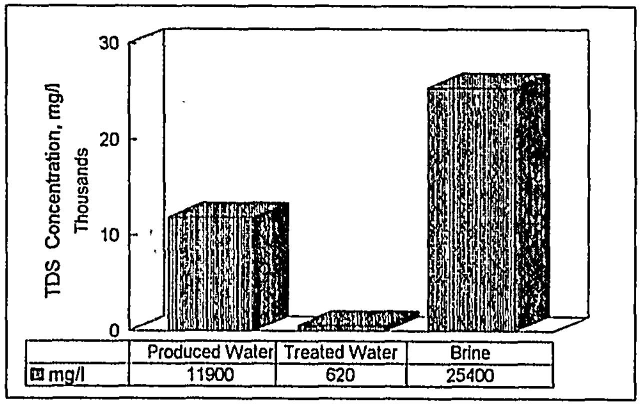
Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	133	0
06/08/94	3:20 p		131	2
06/09/94	4:30 p		130	1
06/13/94	4:00 p		124	6
06/14/94	4:30 p		122	2
06/15/94	4:30 p		120	2
06/16/94	4:30 p		117	3
06/17/94	4:30 p		115	2
06/18/94	4:30 p		113	2
06/19/94	4:30 p		112	1
06/20/94	4:45 p		110	2

Table D-1-30. Evaporation Rates Achieved for FTE Simulation #1-5.

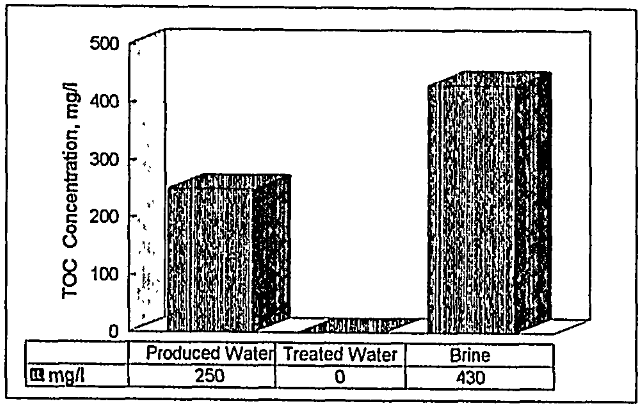
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	46%	35%
06/08/94	06/09/94	April	4.34	23%	
06/14/94	06/15/94	July	7.16	28%	28%
06/15/94	06/16/94	August	6.16	49%	38%
06/16/94	06/17/94	August	6.16	32%	
06/17/94	06/18/94	August	6.16	32%	
06/18/94	06/19/94	June	6.92	14%	22%
06/19/94	06/20/94	June	6.92	29%	
		Average PAN Evaporation Efficiency Achieved (% of PAN)			31%

FIGURE D-1-5. FTE SIMULATION # 1 - 5 EXPERIMENTAL RESULTS
Simulation Series #1: Equipment Optimization

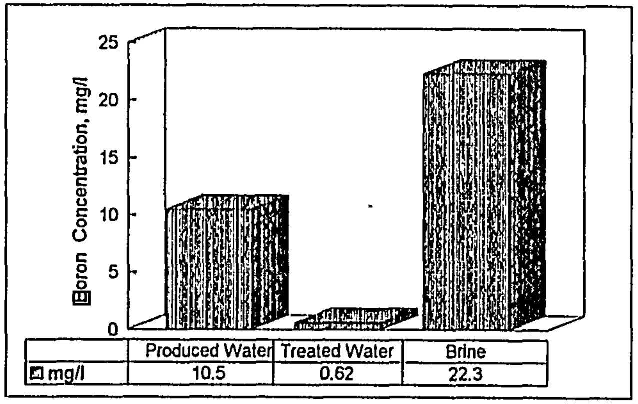
FTE Simulation # 1-5.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #5	- Solar Distillation Pond Design - Water Column Freezing Pad Design



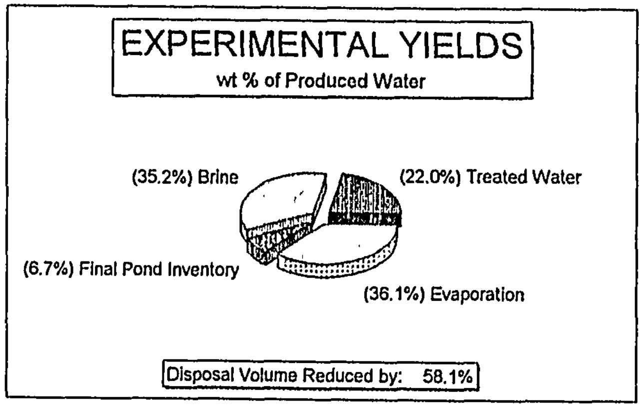
	Produced Water	Treated Water	Brine
▣ mg/l	11900	620	25400



	Produced Water	Treated Water	Brine
▣ mg/l	250	0	430



	Produced Water	Treated Water	Brine
▣ mg/l	10.5	0.62	22.3



FTE Simulation # 1-6.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #6	- Conventional Evaporation Pond Design - Atomizing Spray Freezing Pad Design

Table D-1-31. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-6.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9714		115.6		2.4		0.102	
Out::								
Treated Water	3156	32.5%	2.9	2.5%	0.0	0.0%	0.003	2.8%
Brine	2394	24.6%	77.3	66.9%	1.3	52.2%	0.068	66.7%
Final Pond Inventory	676	7.0%	16.2	14.0%				
Evaporation	3488	35.9%						
Losses			19.1	16.5%	1.2	47.8%	0.031	30.6%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7502		89.3	
Out::				
Evaporation	2924	39.0%		
Final Pond Inventory	4464	59.5%	78.1	87.5%
Losses	114	1.5%	11.2	12.5%

Table D-1-32. Produced Water Feed for FTE Simulation 1-6.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9714
06/06/94	3:00 p	Evap. Test Charge	7502
		Total	17216

Table D-1-33. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-6 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	930	0	0.89
Brine	32300	530	28.4

Table D-1-34. TDS Concentrations of Pond Inventories for FTE Simulation #1-6 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	24000
Final Pond Inventory - Evaporation Test	17500

FTE Simulation # 1-6.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

Simulator #6
- Conventional Evaporation Pond Design
- Atomizing Spray Freezing Pad Design

Table D-1-35. Produced Water Holding Pond Level Data for FTE Simulation #1-6.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	136	0
06/08/94	3:20 p		132	4
06/09/94	4:30 p		129	3
06/13/94	4:00 p		104	25
06/14/94	4:30 p		100	4
06/15/94	4:30 p		97	3
06/16/94	4:30 p		93	4
06/17/94	4:30 p		90	3
06/18/94	4:30 p		87	3
06/19/94	4:30 p		85	2
06/20/94	4:45 p		83	2

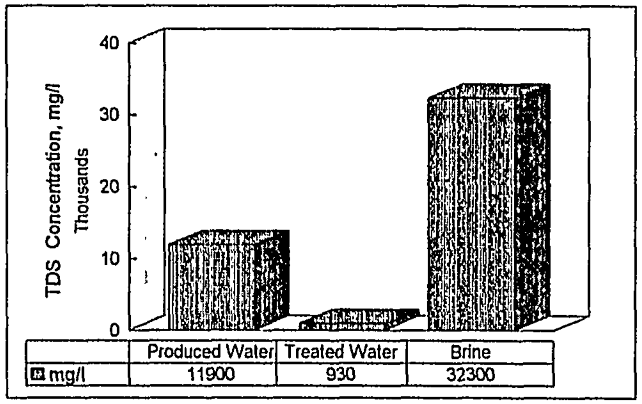
Table D-1-36. Evaporation Rates Achieved for FTE Simulation #1-6.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	92%	81%
06/08/94	06/09/94	April	4.34	69%	
06/14/94	06/15/94	July	7.16	42%	42%
06/15/94	06/16/94	August	6.16	65%	54%
06/16/94	06/17/94	August	6.16	49%	
06/17/94	06/18/94	August	6.16	49%	
06/18/94	06/19/94	June	6.92	29%	29%
06/19/94	06/20/94	June	6.92	29%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					51%

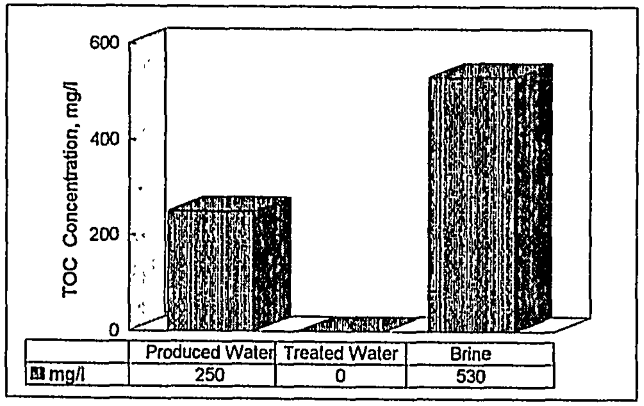
FIGURE D-1-6. FTE SIMULATION # 1 - 6 EXPERIMENTAL RESULTS

Simulation Series #1: Equipment Optimization

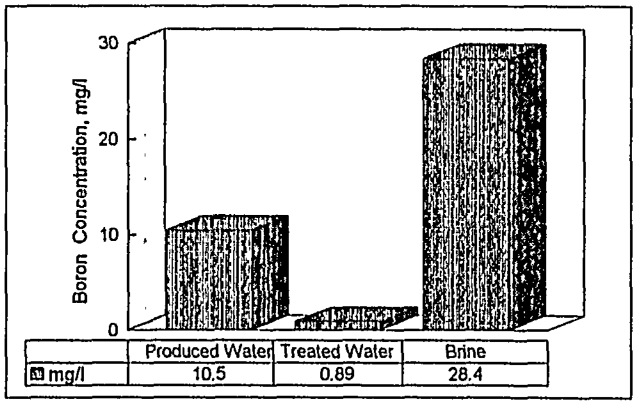
FTE Simulation # 1-6.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #6	- Conventional Evaporation Pond Design - Atomizing Spray Freezing Pad Design



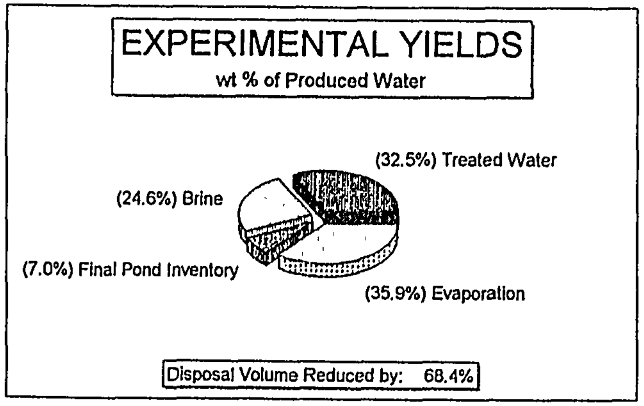
	Produced Water	Treated Water	Brine
▣ mg/l	11900	930	32300



	Produced Water	Treated Water	Brine
▣ mg/l	250	0	530



	Produced Water	Treated Water	Brine
▣ mg/l	10.5	0.89	28.4



FTE Simulation # 1-7.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #7	- Conventional Evaporation Pond Design - Water Spray Freezing Pad Design

Table D-1-37. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-7.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9902		117.8		2.5		0.104	
Out::								
Treated Water	2958	29.9%	2.5	2.1%	0.0	0.0%	0.002	2.3%
Brine	2302	23.2%	76.0	64.5%	1.2	50.2%	0.067	64.9%
Final Pond Inventory	980	9.9%	24.3	20.6%				
Evaporation	3662	37.0%						
Losses			15.1	12.8%	1.2	49.8%	0.034	32.8%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7536		89.7	
Out::				
Evaporation	2776	36.8%		
Final Pond Inventory	4684	62.2%	77.3	86.2%
Losses	76	1.0%	12.4	13.8%

Table D-1-38. Produced Water Feed for FTE Simulation 1-7.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9902
06/06/94	3:00 p	Evap. Test Charge	7536
		Total	17438

Table D-1-39. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-7 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	830	0	0.81
Brine	33000	540	29.3

Table D-1-40. TDS Concentrations of Pond Inventories for FTE Simulation #1-7 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	24800
Final Pond Inventory - Evaporation Test	16500

FTE Simulation # 1-7.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #7	- Conventional Evaporation Pond Design - Water Spray Freezing Pad Design

Table D-1-41. Produced Water Holding Pond Level Data for FTE Simulation #1-7.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	133	0
06/08/94	3:20 p		130	3
06/09/94	4:30 p		128	2
06/13/94	4:00 p		102	26
06/14/94	4:30 p		99	3
06/15/94	4:30 p		96	3
06/16/94	4:30 p		93	3
06/17/94	4:30 p		91	2
06/18/94	4:30 p		88	3
06/19/94	4:30 p		86	2
06/20/94	4:45 p		84	2

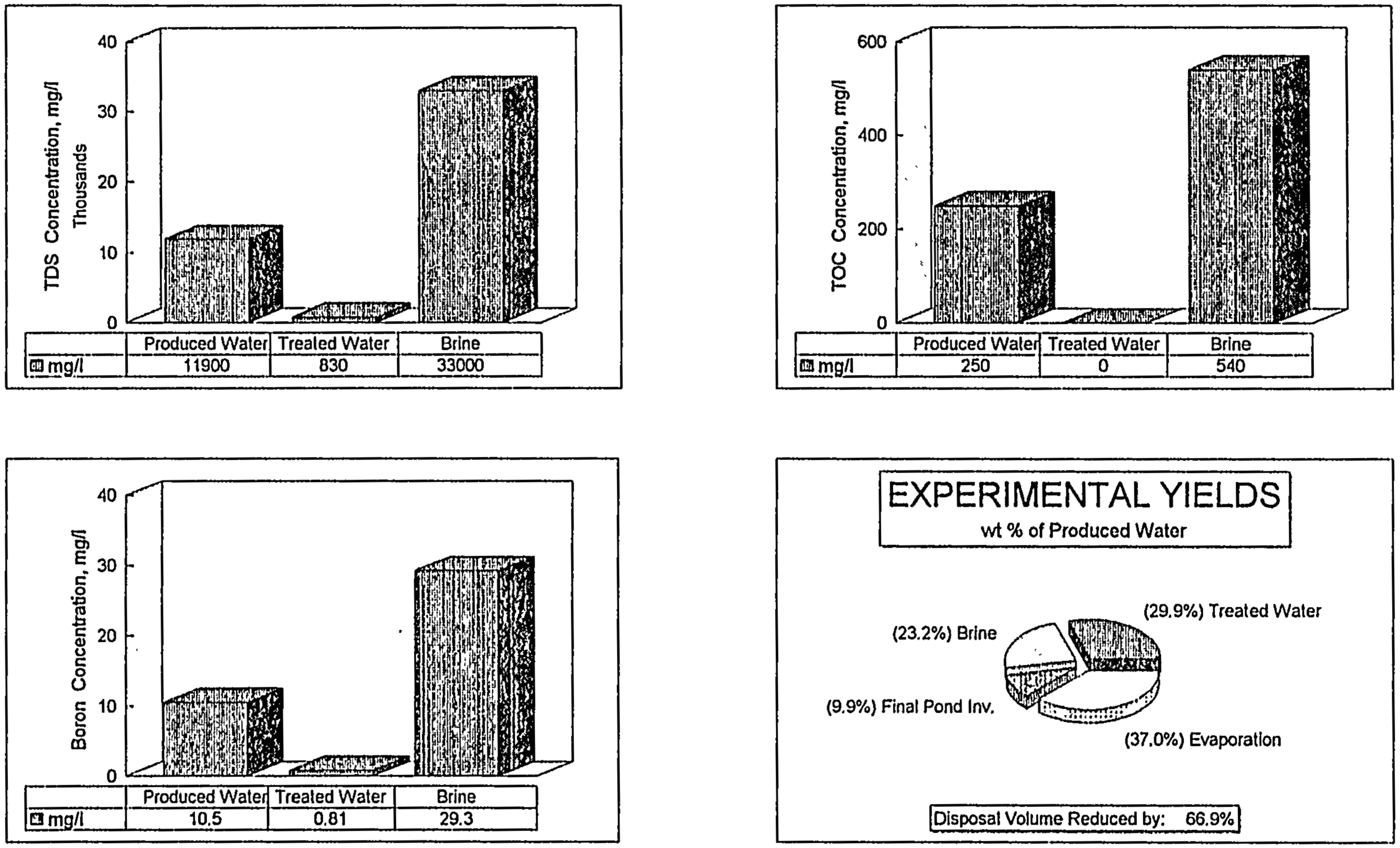
Table D-1-42. Evaporation Rates Achieved for FTE Simulation #1-7.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN 24 hr.	Simulator Evaporation Rate Achieved % of PAN Month Average
06/07/94	06/08/94	April	4.34	69%	58%
06/08/94	06/09/94	April	4.34	46%	
06/14/94	06/15/94	July	7.16	42%	42%
06/15/94	06/16/94	August	6.16	49%	43%
06/16/94	06/17/94	August	6.16	32%	
06/17/94	06/18/94	August	6.16	49%	
06/18/94	06/19/94	June	6.92	29%	29%
06/19/94	06/20/94	June	6.92	29%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					43%

FIGURE D-1-7. FTE SIMULATION # 1-7 EXPERIMENTAL RESULTS
Simulation Series #1: Equipment Optimization

FTE Simulation # 1-7.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

Simulator #7
- Conventional Evaporation Pond Design
- Water Spray Freezing Pad Design



FTE Simulation # 1-8.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #8	- Solar Distillation Pond Design - Atomizing Spray Freezing Pad Design

Table D-1-43. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-8.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	9776		116.3		2.4		0.103	
Out::								
Treated Water	2853	29.2%	3.3	2.8%	0.0	0.0%	0.003	3.0%
Brine	1958	20.0%	82.8	71.2%	1.1	44.1%	0.055	53.8%
Final Pond Inventory	772	7.9%	19.3	16.6%				
Evaporation	4193	42.9%						
Losses			11.0	9.4%	1.4	55.9%	0.044	43.2%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7534		89.7	
Out::				
Evaporation	1495	19.8%		
Final Pond Inventory	5340	70.9%	72.1	80.4%
Losses	699	9.3%	17.6	19.6%

Table D-1-44. Produced Water Feed for FTE Simulation 1-8.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	9776
06/06/94	3:00 p	Evap. Test Charge	7534
		Total	17310

Table D-1-45. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-8 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	1140	0	1.09
Brine	42300	550	28.2

Table D-1-46. TDS Concentrations of Pond Inventories for FTE Simulation #1-8 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	25000
Final Pond Inventory - Evaporation Test	13500

FTE Simulation # 1-8.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #8	- Solar Distillation Pond Design - Atomizing Spray Freezing Pad Design

Table D-1-47. Produced Water Holding Pond Level Data for FTE Simulation #1-8.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	131	0
06/08/94	3:20 p		129	2
06/09/94	4:30 p		127	2
06/13/94	4:00 p		120	7
06/14/94	4:30 p		118	2
06/15/94	4:30 p		116	2
06/16/94	4:30 p		113	3
06/17/94	4:30 p		110	3
06/18/94	4:30 p		108	2
06/19/94	4:30 p		107	1
06/20/94	4:45 p		105	2

Table D-1-48. Evaporation Rates Achieved for FTE Simulation #1-8.

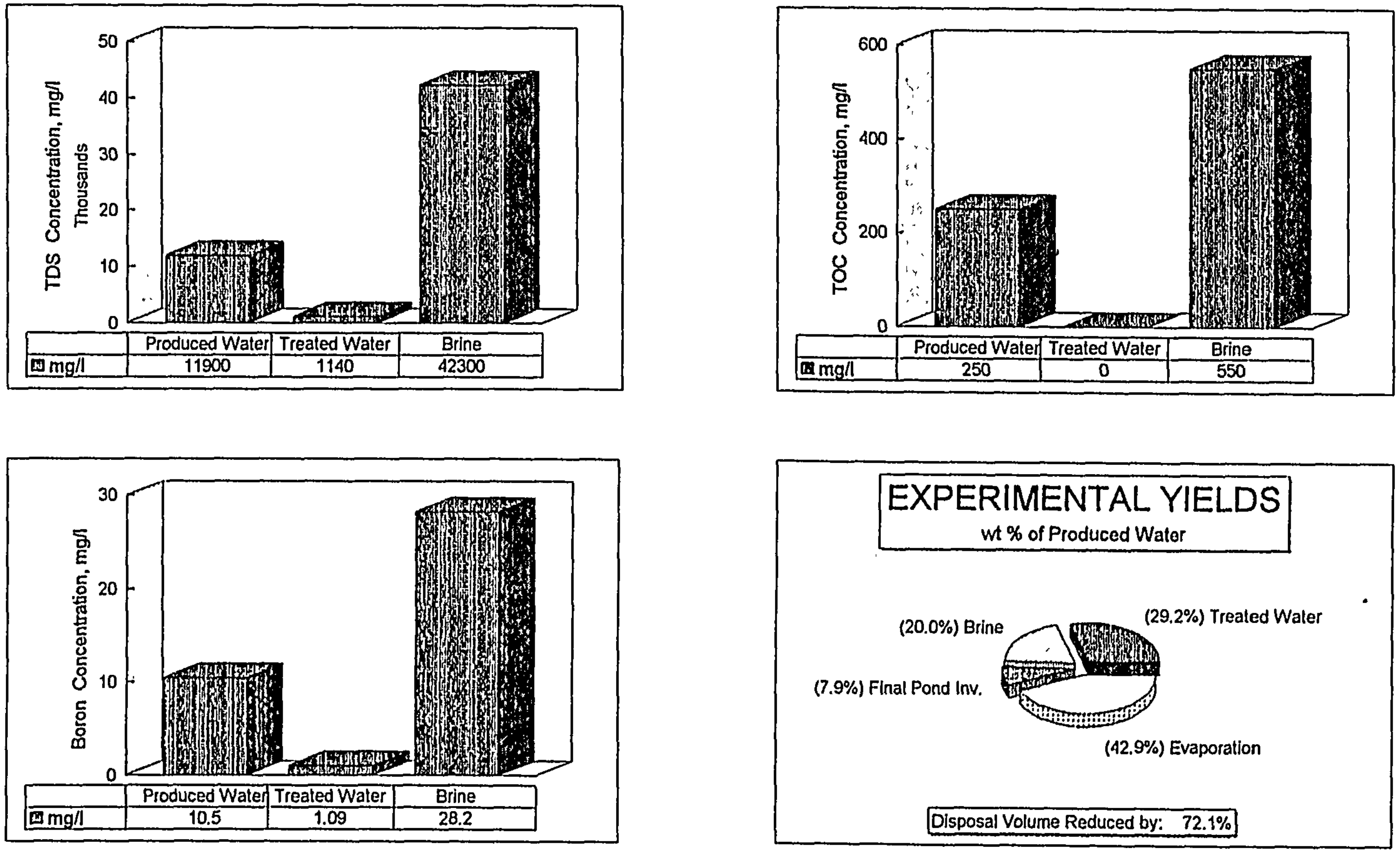
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	46%	46%
06/08/94	06/09/94	April	4.34	46%	
06/14/94	06/15/94	July	7.16	28%	28%
06/15/94	06/16/94	August	6.16	49%	43%
06/16/94	06/17/94	August	6.16	49%	
06/17/94	06/18/94	August	6.16	32%	
06/18/94	06/19/94	June	6.92	14%	22%
06/19/94	06/20/94	June	6.92	29%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					35%

FIGURE D-1-8. FTE SIMULATION # 1-8 EXPERIMENTAL RESULTS

Simulation Series #1: Equipment Optimization

FTE Simulation # 1-8.
- Equipment Optimization - Produced Water from an Oil and Gas Producing Well
- 168.5 hour of sub-freezing temperatures
- Evaporation test using climatic conditions similar to warm months in Northeastern Colorado

Simulator #8
- Solar Distillation Pond Design
- Atomizing Spray Freezing Pad Design



	Produced Water	Treated Water	Brine
▨ mg/l	11900	1140	42300

	Produced Water	Treated Water	Brine
▨ mg/l	250	0	550

	Produced Water	Treated Water	Brine
▨ mg/l	10.5	1.09	28.2

FTE Simulation # 1-9.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #9	- Conventional Evaporation Pond Design - Water Column Freezing Pad Design

Table D-1-49. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 1-9.

Freezing Test	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	10032		119.4		2.5		0.105	
Out::								
Treated Water	4374	43.6%	4.5	3.8%	0.0	0.0%	0.004	4.1%
Brine	1386	13.8%	73.9	61.9%	1.0	39.8%	0.054	51.4%
Final Pond Inventory	625	6.2%	19.1	16.0%				
Evaporation	3647	36.4%						
Losses			21.9	18.3%	1.5	60.2%	0.047	44.5%

Evaporation Test	Overall Mass Balance		TDS Balance	
Process Stream:	mass (g)	% of Mass Input	TDS (g)	% of TDS Input
In:				
Produced Water Charge	7602		90.5	
Out::				
Evaporation	3372	44.4%		
Final Pond Inventory	4084	53.7%	83.7	92.5%
Losses	146	1.9%	6.7	7.5%

Table D-1-50. Produced Water Feed for FTE Simulation 1-9.

Date:	Time:	Description	Mass Added (g)
05/24/94	8:00 a	Freezing Test Charge	10032
06/06/94	3:00 p	Evap. Test Charge	7602
		Total	17634

Table D-1-51. TDS, TOC, and Boron Concentrations of Process Streams for FTE Simulation #1-9 (From Chemical Analyses).

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	11900	250	10.5
Treated Water	1040	0	0.98
Brine	53300	720	39.1

Table D-1-52. TDS Concentrations of Pond Inventories for FTE Simulation #1-9 (from Conductivity Meter).

Process Stream	TDS mg/l
Final Pond Inventory - Freezing Test	30500
Final Pond Inventory - Evaporation Test	20500

FTE Simulation # 1-9.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #9	- Conventional Evaporation Pond Design - Water Column Freezing Pad Design

Table D-1-53. Produced Water Holding Pond Level Data for FTE Simulation #1-9.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/07/94	3:00 p	Evaporation Test Charge	133	0
06/08/94	3:20 p		127	6
06/09/94	4:30 p		124	3
06/13/94	4:00 p		98	26
06/14/94	4:30 p		94	4
06/15/94	4:30 p		90	4
06/16/94	4:30 p		84	6
06/17/94	4:30 p		81	3
06/18/94	4:30 p		78	3
06/19/94	4:30 p		76	2
06/20/94	4:45 p		74	2

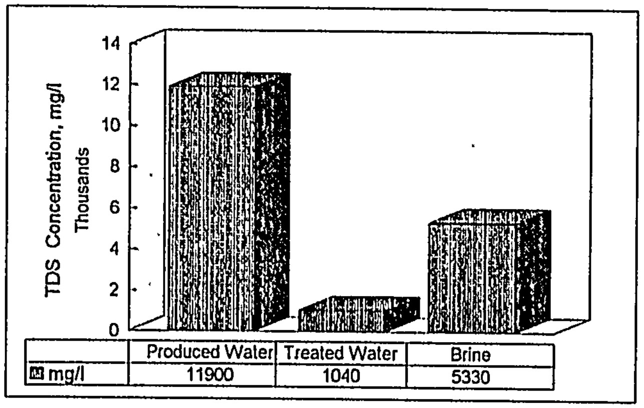
Table D-1-54. Evaporation Rates Achieved for FTE Simulation #1-9.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/07/94	06/08/94	April	4.34	138%	104%
06/08/94	06/09/94	April	4.34	69%	
06/14/94	06/15/94	July	7.16	56%	56%
06/15/94	06/16/94	August	6.16	97%	65%
06/16/94	06/17/94	August	6.16	49%	
06/17/94	06/18/94	August	6.16	49%	
06/18/94	06/19/94	June	6.92	29%	29%
06/19/94	06/20/94	June	6.92	29%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					63%

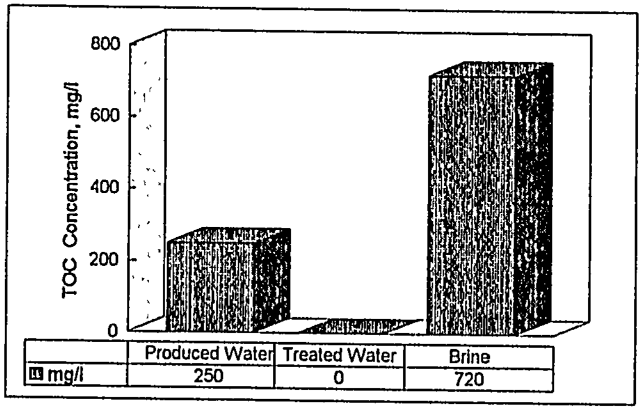
FIGURE D-1-9. FTE SIMULATION # 1-9 EXPERIMENTAL RESULTS

Simulation Series #1: Equipment Optimization

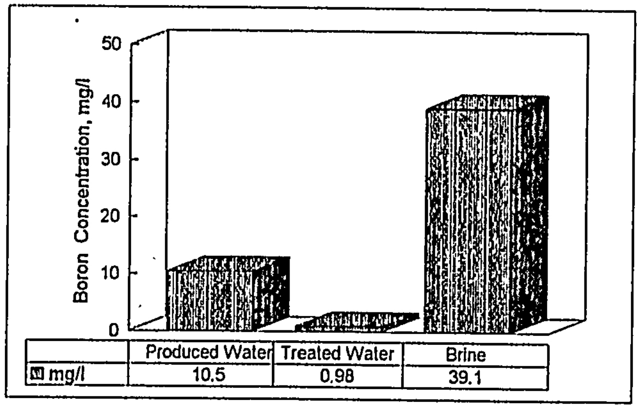
FTE Simulation # 1-9.	- Equipment Optimization - Produced Water from an Oil and Gas Producing Well - 168.5 hour of sub-freezing temperatures - Evaporation test using climatic conditions similar to warm months in Northeastern Colorado
Simulator #9	- Conventional Evaporation Pond Design - Water Column Freezing Pad Design



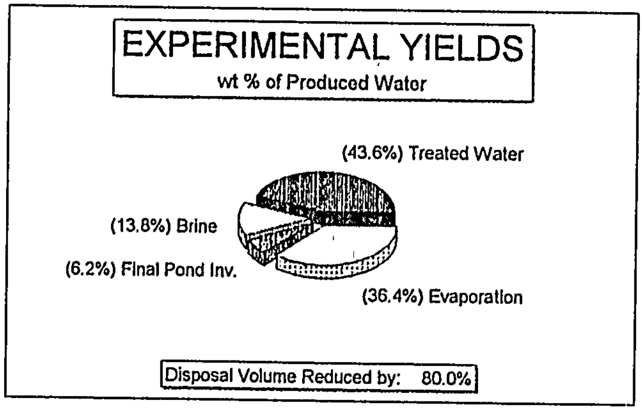
	Produced Water	Treated Water	Brine
▩ mg/l	11900	1040	5330



	Produced Water	Treated Water	Brine
▩ mg/l	250	0	720



	Produced Water	Treated Water	Brine
▩ mg/l	10.5	0.98	39.1



Disposal Volume Reduced by: 80.0%

APPENDIX D-2

SIMULATION SERIES #2 RESULTS

FTE Simulation # 2-1. - Northeastern Colorado climate - 103 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-2-1. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 2-1.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	20268		218.9		2.8		0.061	
Out::								
Treated Water	5090	25.1%	2.0	0.9%	0.0	0.0%	0.001	1.0%
Brine	3870	19.1%	210.1	96.0%	27.2	960.2%	0.042	69.6%
Evaporation	10841	53.5%	0	0.0%	0	0.0%	0.000	0.0%
Losses	467	2.3%	6.8	3.1%	-24.4	-860.2%	0.018	29.4%

Table D-2-2. Produced Water Feed for FTE Simulation #2-1.

Date:	Time:	Description	Mass Added (g)
06/23/94	2:00 p	Iniaital Charge	9427
06/25/94	4:20 p	April Evaporation	1248
06/27/94	4:30 p	May Evaporation	1314
06/29/94	4:30 p	June Evaporation	1511
07/01/94	4:00 p	July Evaporation	2299
07/03/94	5:00 p	Aug. Evaporation	2037
07/05/94	4:30 p	Sept. Evaporation	1380
07/07/94	4:30 p	Oct. Evaporation	1052
		Total	20268

Table D-2-3. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #2-1.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	10800	140	2.99
Treated Water	386	0	0.114
Brine	54300	7040	10.9

FTE Simulation # 2-1.	- Northeastern Colorado Climate - 103 hours of sub-freezing temperatures
Simulator #1	- Produced Water From a Coal Bed Methane Well

Table D-2-4. Produced Water Holding Pond Level Data for FTE Simulation #2-1.

Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/23/94	5:00 p	Initial Charge	155	
06/24/94	4:30 p		147	8
06/25/94	4:20 p	Before Water Addition	140	7
06/25/94	4:20 p	After Water Addition	155	
06/26/94	4:10 p		149	6
06/27/94	4:30 p	Before Water Addition	140	9
06/27/94	4:30 p	After Water Addition	155	
06/28/94	3:20 p		147	8
06/29/94	4:30 p	Before Water Addition	138	9
06/29/94	4:30 p	After Water Addition	155	
06/30/94	4:30 p		140	15
07/01/94	4:00 p	Before Water Addition	129	11
07/01/94	4:00 p	After Water Addition	155	
07/02/94	4:00 p		142	13
07/03/94	5:00 p	Before Water Addition	131	11
07/03/94	5:00 p	After Water Addition	155	
07/04/94	5:00 p		146	9
07/05/94	4:30 p	Before Water Addition	139	7
07/05/94	4:30 p	After Water Addition	155	
07/06/94	4:30 p		148	7
07/07/94	4:30 p	Before Water Addition	143	5
07/07/94	4:30 p	After Water Addition	155	

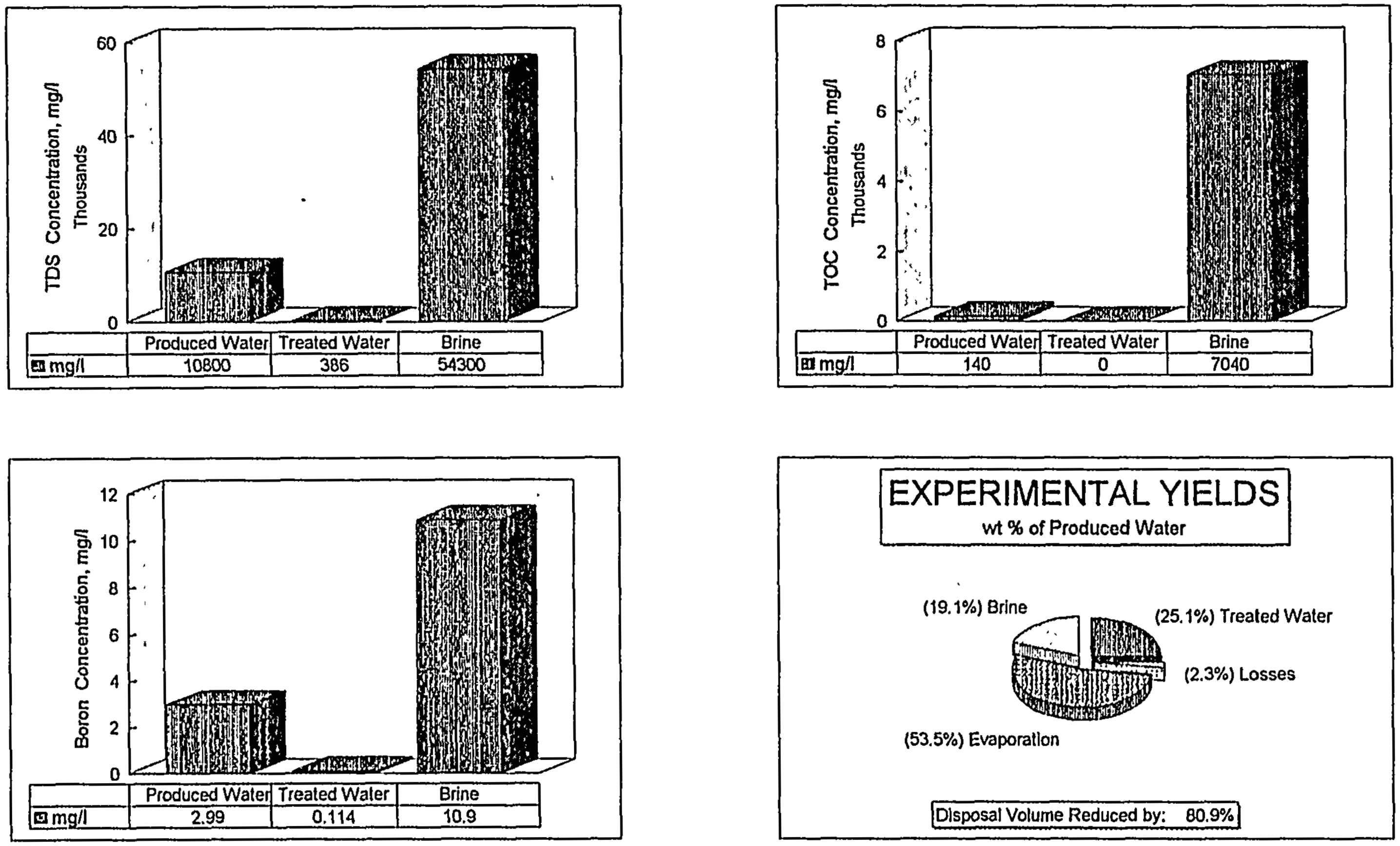
Table D-2-5. Evaporation Rates Achieved for FTE Simulation #2-1.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/23/94	06/24/94	April	4.34	184%	173%
06/24/94	06/25/94	April	4.34	161%	
06/25/94	06/26/94	May	5.18	116%	145%
06/26/94	06/27/94	May	5.18	174%	
06/27/94	06/28/94	June	6.92	116%	123%
06/28/94	06/29/94	June	6.92	130%	
06/29/94	06/30/94	July	7.16	209%	182%
06/30/94	07/01/94	July	7.16	154%	
07/01/94	07/02/94	August	6.16	211%	195%
07/02/94	07/03/94	August	6.16	179%	
07/03/94	07/04/94	September	4.82	187%	166%
07/04/94	07/05/94	September	4.82	145%	
07/05/94	07/06/94	October	3.2	219%	188%
07/06/94	07/07/94	October	3.2	156%	
		Average PAN Evaporation Efficiency Achieved (% of PAN)			167%

FIGURE D-2-1. FTE SIMULATION # 2-1 EXPERIMENTAL RESULTS

Simulation Series #2: Northeastern Colorado Climate

FTE Simulation # 2-1.	- Northeastern Colorado Climate - 103 hours of sub-freezing temperatures
Simulator #1	- Produced Water from a Coal Bed Methane Well



	Produced Water	Treated Water	Brine
▣ mg/l	10800	386	54300

	Produced Water	Treated Water	Brine
▣ mg/l	140	0	7040

	Produced Water	Treated Water	Brine
▣ mg/l	2.99	0.114	10.9

Disposal Volume Reduced by: 80.9%

FTE Simulation # 2-2. - Northeastern Colorado climate - 103 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-2-6. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 2-2.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	19893		169.7		52.5		0.209	
Out::								
Treated Water	4284	21.5%	2.1	1.2%	0.9	1.8%	0.005	2.3%
Brine	3180	16.0%	161.2	95.0%	102.7	195.6%	0.169	81.0%
Evaporation	11106	55.8%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1323	6.7%	6.4	3.8%	-51.1	-97.4%	0.035	16.7%

Table D-2-7. Produced Water Feed for FTE Simulation #2-2.

Date:	Time:	Description	Mass Added (g)
06/23/94	2:00 p	Iniaital Charge	8787
06/25/94	4:20 p	April Evaporation	1356
06/27/94	4:30 p	May Evaporation	1441
06/29/94	4:30 p	June Evaporation	1696
07/01/94	4:00 p	July Evaporation	1865
07/03/94	5:00 p	Aug. Evaporation	1865
07/05/94	4:30 p	Sept. Evaporation	1441
07/07/94	4:30 p	Oct. Evaporation	1442
		Total	19893

Table D-2-8. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #2-2.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	8530	2640	10.5
Treated Water	484	220	1.14
Brine	50700	32300	53.2

FTE Simulation # 2-2.	- Northeastern Colorado Climate - 103 hours of sub-freezing temperatures
Simulator #2	- Produced Water From an Oil and Gas Producing Well

Table D-2-9. Produced Water Holding Pond Level Data for FTE Simulation #2-2.

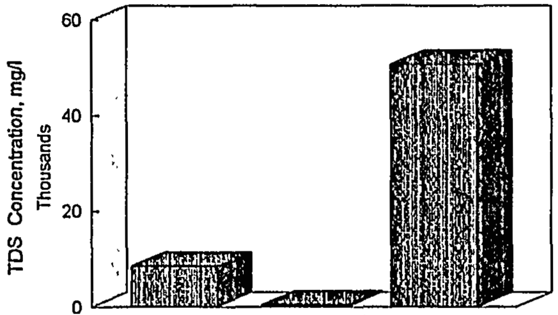
Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/23/94	5:00 p	Initial Charge	148	
06/24/94	4:30 p		140	8
06/25/94	4:20 p	Before Water Addition	133	7
06/25/94	4:20 p	After Water Addition	148	
06/26/94	4:10 p		138	10
06/27/94	4:30 p	Before Water Addition	132	6
06/27/94	4:30 p	After Water Addition	148	
06/28/94	3:20 p		138	10
06/29/94	4:30 p	Before Water Addition	129	9
06/29/94	4:30 p	After Water Addition	148	
06/30/94	4:30 p		136	12
07/01/94	4:00 p	Before Water Addition	127	9
07/01/94	4:00 p	After Water Addition	148	
07/02/94	4:00 p		137	11
07/03/94	5:00 p	Before Water Addition	128	9
07/03/94	5:00 p	After Water Addition	148	
07/04/94	5:00 p		140	8
07/05/94	4:30 p	Before Water Addition	132	8
07/05/94	4:30 p	After Water Addition	148	
07/06/94	4:30 p		141	7
07/07/94	4:30 p	Before Water Addition	132	9
07/07/94	4:30 p	After Water Addition	148	

Table D-2-10. Evaporation Rates Achieved for FTE Simulation #2-2.

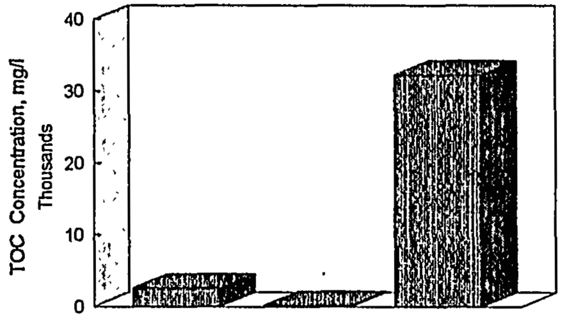
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/23/94	06/24/94	April	4.34	184%	173%
06/24/94	06/25/94	April	4.34	161%	
06/25/94	06/26/94	May	5.18	193%	154%
06/26/94	06/27/94	May	5.18	116%	
06/27/94	06/28/94	June	6.92	145%	137%
06/28/94	06/29/94	June	6.92	130%	
06/29/94	06/30/94	July	7.16	168%	147%
06/30/94	07/01/94	July	7.16	126%	
07/01/94	07/02/94	August	6.16	179%	162%
07/02/94	07/03/94	August	6.16	146%	
07/03/94	07/04/94	September	4.82	166%	166%
07/04/94	07/05/94	September	4.82	166%	
07/05/94	07/06/94	October	3.2	219%	250%
07/06/94	07/07/94	October	3.2	281%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					170%

FIGURE D-2-2. FTE SIMULATION # 2-2 EXPERIMENTAL RESULTS
Simulation Series #2: Northeastern Colorado Climate

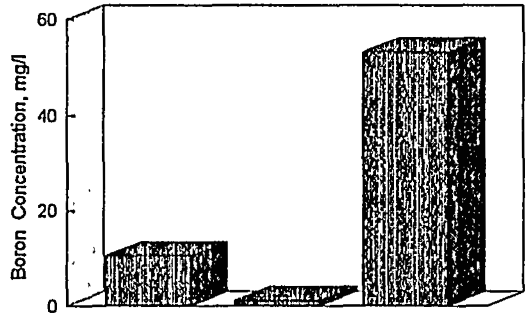
FTE Simulation # 2-2.	- Northeastern Colorado Climate - 103 hours of sub-freezing temperatures
Simulator #2	- Produced Water from an Oil and Gas Producing Well



	Produced Water	Treated Water	Brine
▨ mg/l	8530	484	50700



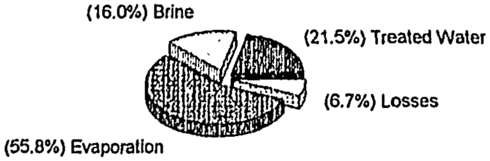
	Produced Water	Treated Water	Brine
▨ mg/l	2640	220	32300



	Produced Water	Treated Water	Brine
▨ mg/l	10.5	1.14	53.2

EXPERIMENTAL YIELDS

wt % of Produced Water



Disposal Volume Reduced by: 84.0%

FTE Simulation # 2-3. - Northeastern Colorado climate - 103 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-2-11. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 2-3.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	23478		62.9		2.3		0.086	
Out::								
Treated Water	8176	34.8%	2.5	4.0%	0.0	0.0%	0.007	7.9%
Brine	1280	5.5%	54.1	86.1%	1.9	79.6%	0.065	75.8%
Evaporation	13843	59.0%	0	0.0%	0	0.0%	0.000	0.0%
Losses	179	0.8%	6.3	9.9%	0.5	20.4%	0.014	16.3%

Table D-2-12. Produced Water Feed for FTE Simulation #2-3.

Date:	Time:	Description	Mass Added (g)
06/23/94	2:00 p	Iniaital Charge	9635
06/25/94	4:20 p	April Evaporation	1690
06/27/94	4:30 p	May Evaporation	1690
06/29/94	4:30 p	June Evaporation	2012
07/01/94	4:00 p	July Evaporation	2737
07/03/94	5:00 p	Aug. Evaporation	2576
07/05/94	4:30 p	Sept. Evaporation	1690
07/07/94	4:30 p	Oct. Evaporation	1448
		Total	23478

Table D-2-13. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #2-3.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	2680	100	3.67
Treated Water	308	0	0.833
Brine	42300	1460	51.0

FTE Simulation # 2-3.	**- Northeastern Colorado Climate** **- 103 hours of sub-freezing temperatures**
Simulator #1	**- Produced Water From a Natural Gas Producing Well**

Table D-2-14. Produced Water Holding Pond Level Data for FTE Simulation #2-3.

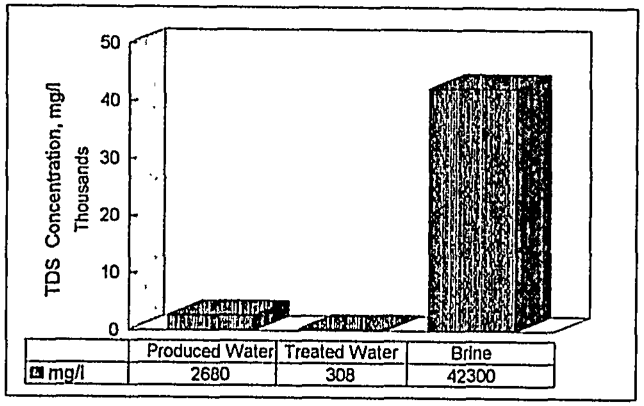
Date	Time	Remarks	Pond Level (mm)	Evaporation Rate Achieved (mm)
06/23/94	5:00 p	Initial Charge	157	
06/24/94	4:30 p		148	9
06/25/94	4:20 p	Before Water Addition	139	9
06/25/94	4:20 p	After Water Addition	157	
06/26/94	4:10 p		146	11
06/27/94	4:30 p	Before Water Addition	139	7
06/27/94	4:30 p	After Water Addition	157	
06/28/94	3:20 p		145	12
06/29/94	4:30 p	Before Water Addition	135	10
06/29/94	4:30 p	After Water Addition	157	
06/30/94	4:30 p		142	15
07/01/94	4:00 p	Before Water Addition	128	14
07/01/94	4:00 p	After Water Addition	157	
07/02/94	4:00 p		144	13
07/03/94	5:00 p	Before Water Addition	130	14
07/03/94	5:00 p	After Water Addition	157	
07/04/94	5:00 p		147	10
07/05/94	4:30 p	Before Water Addition	139	8
07/05/94	4:30 p	After Water Addition	157	
07/06/94	4:30 p		150	7
07/07/94	4:30 p	Before Water Addition	142	8
07/07/94	4:30 p	After Water Addition	157	

Table D-2-15. Evaporation Rates Achieved for FTE Simulation #2-3.

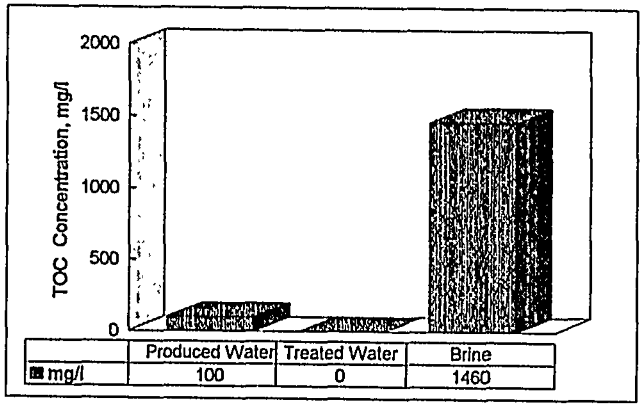
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
06/23/94	06/24/94	April	4.34	207%	207%
06/24/94	06/25/94	April	4.34	207%	
06/25/94	06/26/94	May	5.18	212%	174%
06/26/94	06/27/94	May	5.18	135%	
06/27/94	06/28/94	June	6.92	173%	159%
06/28/94	06/29/94	June	6.92	145%	
06/29/94	06/30/94	July	7.16	209%	203%
06/30/94	07/01/94	July	7.16	196%	
07/01/94	07/02/94	August	6.16	211%	219%
07/02/94	07/03/94	August	6.16	227%	
07/03/94	07/04/94	September	4.82	207%	187%
07/04/94	07/05/94	September	4.82	166%	
07/05/94	07/06/94	October	3.2	219%	234%
07/06/94	07/07/94	October	3.2	250%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					198%

FIGURE D-2-3. FTE SIMULATION # 2-3 EXPERIMENTAL RESULTS
Simulation Series #2: Northeastern Colorado Climate

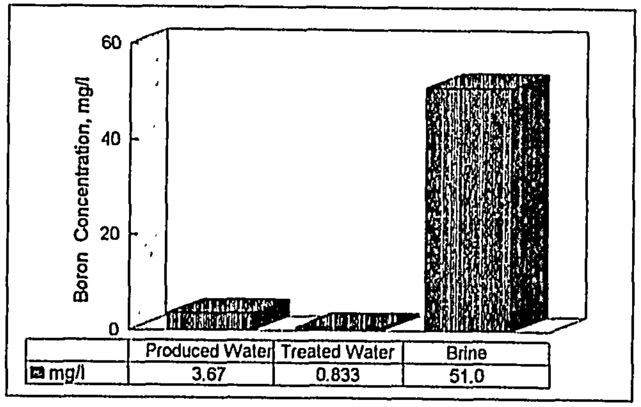
FTE Simulation # 2-3.	- Northeastern Colorado Climate - 103 hours of sub-freezing temperatures
Simulator #3	- Produced Water from a Natural Gas Producing Well



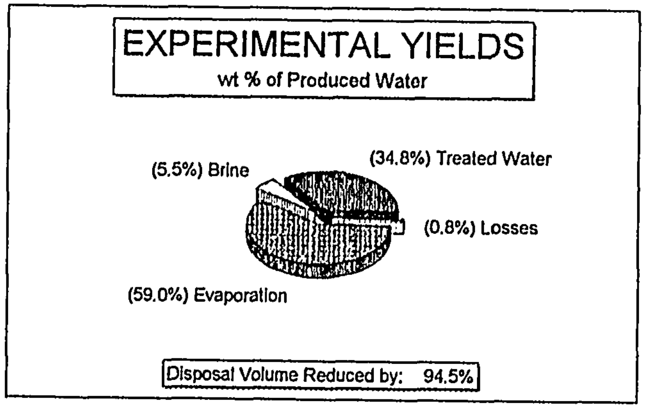
	Produced Water	Treated Water	Brine
▨ mg/l	2680	308	42300



	Produced Water	Treated Water	Brine
▨ mg/l	100	0	1460



	Produced Water	Treated Water	Brine
▨ mg/l	3.67	0.833	51.0



Disposal Volume Reduced by: 94.5%

APPENDIX D-3

SIMULATION SERIES #3 RESULTS

FTE Simulation # 3-1. - Northwestern New Mexico climate - 94 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-3-1. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 3-1.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	25082		259.3		3.3		0.054	
Out::								
Treated Water	5912	23.6%	8.2	3.1%	0.7	19.9%	0.004	6.7%
Brine	5488	21.9%	226.1	87.2%	2.0	62.3%	0.044	81.0%
Evaporation	13578	54.1%	0	0.0%	0	0.0%	0.000	0.0%
Losses	104	0.4%	25.1	9.7%	0.6	17.8%	0.007	12.3%

Table D-3-2. Produced Water Feed for FTE Simulation #3-1.

Date:	Time:	Description	Mass Added (g)
07/26/94	5:00 p	Iniaital Charge	11504
07/28/94	4:30 p	April Evaporation	1044
07/30/94	3:00 p	May Evaporation	1322
08/01/94	4:30 p	June Evaporation	1846
08/03/94	4:30 p	July Evaporation	2736
08/05/94	4:30 p	Aug. Evaporation	2648
08/07/94	4:30 p	Sept. Evaporation	1248
08/09/94	4:00 p	Oct. Evaporation	994
08/15/94	5:00 p	Downtime Evaporation	780
08/17/94	5:00 p	Nov. Evaporation	960
		Total	25082

Table D-3-3. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #3-1.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	10340	130	2.16
Treated Water	1380	110	0.612
Brine	41200	370	8

FTE Simulation # 3-1.	- Northwestern New Mexico Climate - 94 hours of sub-freezing temperatures
Simulator #1	- Produced Water From a Coal Bed Methane Well

Table D-3-4. Produced Water Holding Pond Level Data for FTE Simulation #3-1.

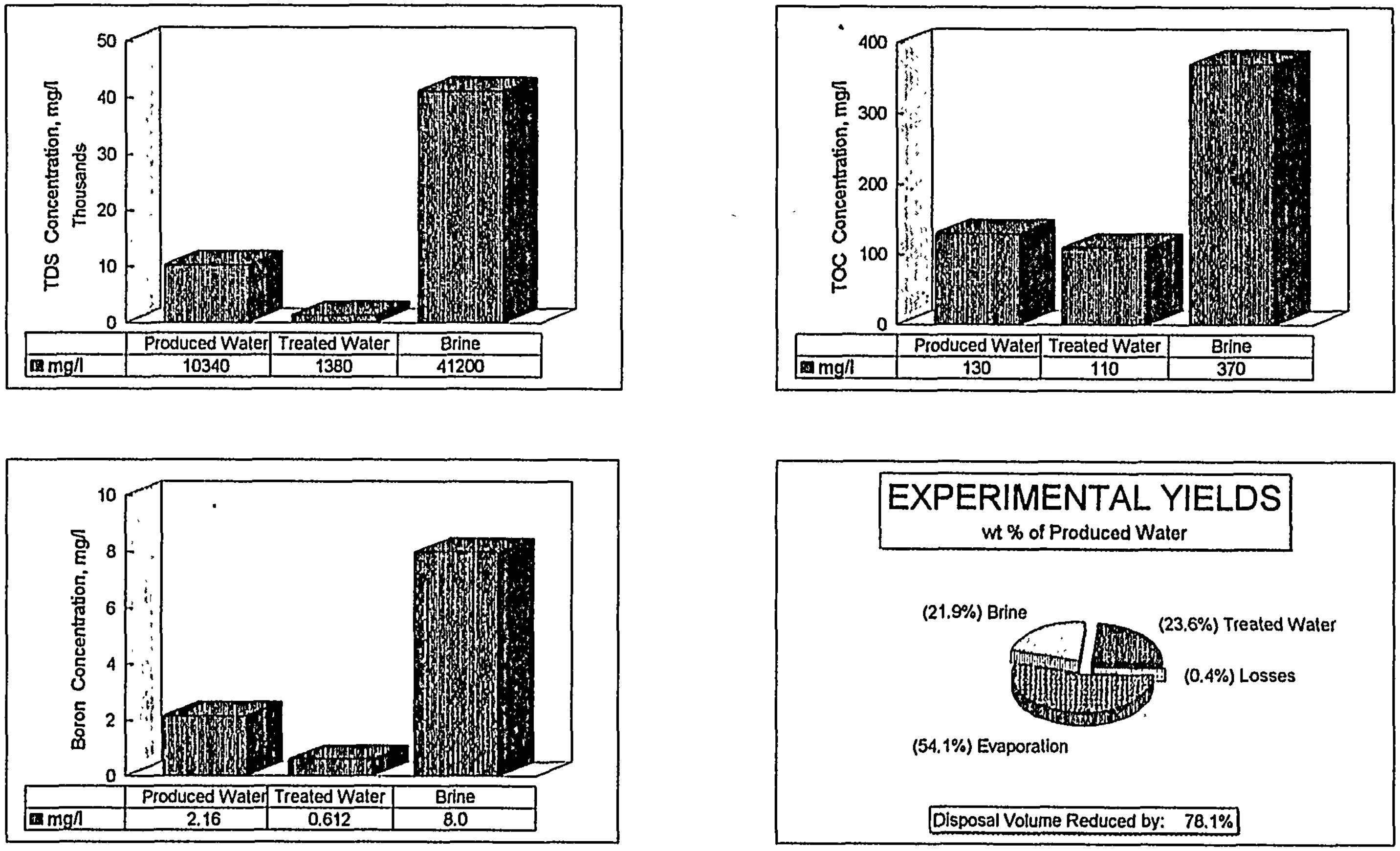
Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
07/26/94	5:00 p	Initial Charge	54		
07/27/94	4:30 p		52	418	4
07/28/94	4:30 p	Before Water Addition	49	626	7
07/28/94	4:30 p	After Water Addition	54		
07/29/94	4:30 p		52	441	5
07/30/94	3:00 p	Before Water Addition	48	881	9
07/30/94	3:00 p	After Water Addition	54		
07/31/94	4:30 p		50	820	9
08/01/94	4:30 p	Before Water Addition	45	1026	11
08/01/94	4:30 p	After Water Addition	54		
08/02/94	4:30 p		49	1052	11
08/03/94	4:30 p	Before Water Addition	41	1684	18
08/03/94	4:30 p	After Water Addition	54		
08/04/94	4:30 p		47	1426	15
08/05/94	4:30 p	Before Water Addition	41	1222	13
08/05/94	4:30 p	After Water Addition	54		
08/06/94	4:30 p		51	624	7
08/07/94	4:30 p	Before Water Addition	48	624	7
08/07/94	4:30 p	After Water Addition	54		
08/08/94	4:30 p		52	398	4
08/09/94	4:00 p	Before Water Addition	49	596	6
08/09/94	4:00 p	After Water Addition	54		
08/15/94	5:00 p	Before Water Addition	50	780	
08/15/94	5:00 p	After Water Addition	54		
08/16/94	5:00 p		52	384	4
08/17/94	5:00 p	Before Water Addition	49	576	6
08/17/94	5:00 p	After Water Addition	54		

Table D-3-5. Evaporation Rates Achieved for FTE Simulation #3-1.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
07/26/94	07/27/94	April	6.55	69%	86%
07/27/94	07/28/94	April	6.55	103%	
07/28/94	07/29/94	May	8.48	56%	84%
07/29/94	07/30/94	May	8.48	112%	
07/30/94	07/31/94	June	10.82	82%	92%
07/31/94	08/01/94	June	10.82	102%	
08/01/94	08/02/94	July	10.39	109%	142%
08/02/94	08/03/94	July	10.39	174%	
08/03/94	08/04/94	August	9.37	164%	152%
08/04/94	08/05/94	August	9.37	140%	
08/05/94	08/06/94	September	7.11	94%	94%
08/06/94	08/07/94	September	7.11	94%	
08/07/94	08/08/94	October	4.95	86%	108%
08/08/94	08/09/94	October	4.95	130%	
08/15/94	08/16/94	November	3.91	106%	132%
08/16/94	08/17/94	November	3.91	159%	
					111%

FIGURE D-3-1. FTE SIMULATION # 3 - 1 EXPERIMENTAL RESULTS
Simulation Series #3: Northwestern New Mexico Climate

FTE Simulation # 3-1.	- Northwestern New Mexico Climate - 94 hours of sub-freezing temperatures
Simulator #1	- Produced Water from a Coal Bed Methane Well



FTE Simulation # 3-2. - Northwestern New Mexico climate - 94 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-3-6. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 3-2.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	21873		178.9		175.0		0.216	
Out::								
Treated Water	4422	20.2%	3.8	2.1%	2.7	1.6%	0.006	2.6%
Brine	5845	26.7%	163.1	91.1%	81.8	46.8%	0.168	77.9%
Evaporation	10805	49.4%	0	0.0%	0	0.0%	0.000	0.0%
Losses	801	3.7%	12.0	6.7%	90.4	51.7%	0.042	19.5%

Table D-3-7. Produced Water Feed for FTE Simulation #3-2.

Date:	Time:	Description	Mass Added (g)
07/26/94	5:00 p	Iniaital Charge	11068
07/28/94	4:30 p	April Evaporation	1018
07/30/94	3:00 p	May Evaporation	1078
08/01/94	4:30 p	June Evaporation	1338
08/03/94	4:30 p	July Evaporation	1990
08/05/94	4:30 p	Aug. Evaporation	1746
08/07/94	4:30 p	Sept. Evaporation	1042
08/09/94	4:00 p	Oct. Evaporation	1020
08/15/94	5:00 p	Downtime Evaporation	633
08/17/94	5:00 p	Nov. Evaporation	940
		Total	21873

Table D-3-8. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #3-2.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	8180	8000	9.88
Treated Water	866	620	1.27
Brine	27900	14000	28.8

FTE Simulation # 3-2.	- Northwestern New Mexico Climate - 94 hours of sub-freezing temperatures
Simulator #2	- Produced Water From an Oil and Gas Producing Well

Table D-3-9. Produced Water Holding Pond Level Data for FTE Simulation #3-2.

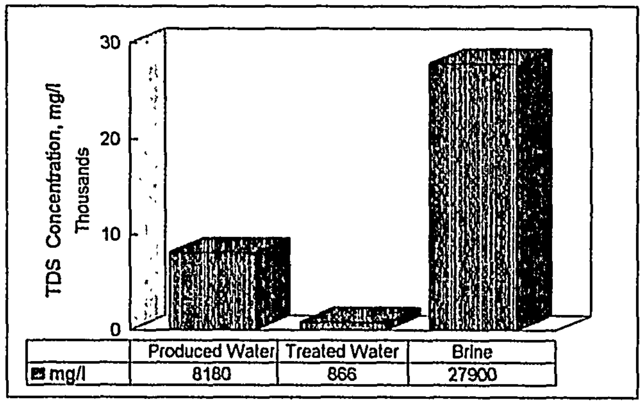
Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
07/26/94	5:00 p	Initial Charge	52		
07/27/94	4:30 p		50	407	4
07/28/94	4:30 p	Before Water Addition	47	611	7
07/28/94	4:30 p	After Water Addition	52		
07/29/94	4:30 p		50	431	5
07/30/94	3:00 p	Before Water Addition	47	647	7
07/30/94	3:00 p	After Water Addition	52		
07/31/94	4:30 p		49	669	7
08/01/94	4:30 p	Before Water Addition	46	669	7
08/01/94	4:30 p	After Water Addition	52		
08/02/94	4:30 p		48	884	10
08/03/94	4:30 p	Before Water Addition	43	1106	12
08/03/94	4:30 p	After Water Addition	52		
08/04/94	4:30 p		48	873	9
08/05/94	4:30 p	Before Water Addition	44	873	9
08/05/94	4:30 p	After Water Addition	52		
08/06/94	4:30 p		49	625	7
08/07/94	4:30 p	Before Water Addition	47	417	5
08/07/94	4:30 p	After Water Addition	52		
08/08/94	4:30 p		50	510	6
08/09/94	4:00 p	Before Water Addition	48	510	6
08/09/94	4:00 p	After Water Addition	52		
08/15/94	5:00 p	Before Water Addition	49	633	
08/15/94	5:00 p	After Water Addition	52		
08/16/94	5:00 p		50	470	5
08/17/94	5:00 p	Before Water Addition	48	470	5
08/17/94	5:00 p	After Water Addition	52		

Table D-3-10. Evaporation Rates Achieved for FTE Simulation #3-2.

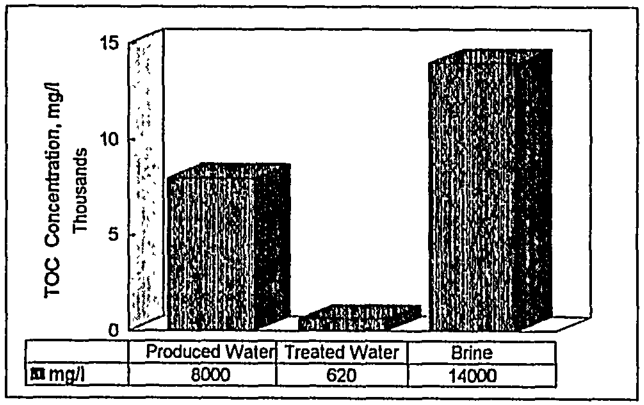
Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
07/26/94	07/27/94	April	6.55	67%	84%
07/27/94	07/28/94	April	6.55	101%	
07/28/94	07/29/94	May	8.48	55%	69%
07/29/94	07/30/94	May	8.48	82%	
07/30/94	07/31/94	June	10.82	67%	67%
07/31/94	08/01/94	June	10.82	67%	
08/01/94	08/02/94	July	10.39	92%	104%
08/02/94	08/03/94	July	10.39	115%	
08/03/94	08/04/94	August	9.37	101%	101%
08/04/94	08/05/94	August	9.37	101%	
08/05/94	08/06/94	September	7.11	95%	79%
08/06/94	08/07/94	September	7.11	63%	
08/07/94	08/08/94	October	4.95	111%	111%
08/08/94	08/09/94	October	4.95	111%	
08/15/94	08/16/94	November	3.91	129%	129%
08/16/94	08/17/94	November	3.91	129%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					93%

FIGURE D-3-2. FTE SIMULATION # 3-2 EXPERIMENTAL RESULTS
Simulation Series #3: Northwestern New Mexico Climate

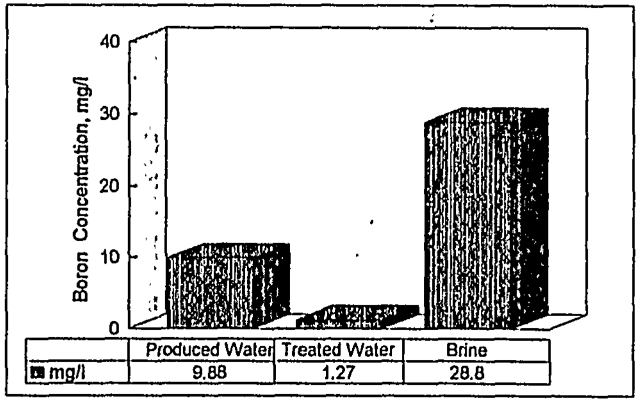
FTE Simulation # 3-2.	- Northwestern New Mexico Climate - 94 hours of sub-freezing temperatures
Simulator #2	- Produced Water from an Oil and Gas Producing Well



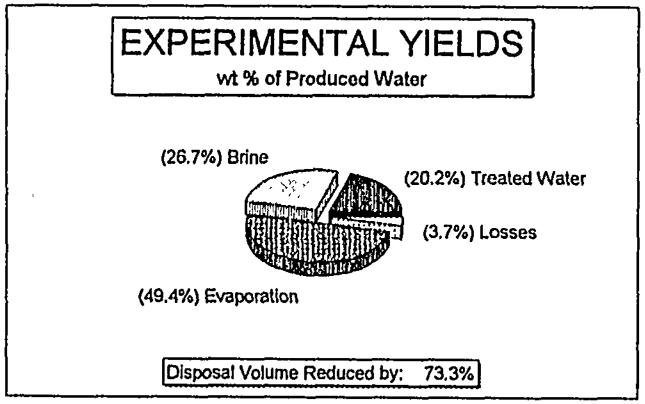
	Produced Water	Treated Water	Brine
▨ mg/l	8180	866	27900



	Produced Water	Treated Water	Brine
▨ mg/l	8000	620	14000



	Produced Water	Treated Water	Brine
▨ mg/l	9.88	1.27	28.8



Disposal Volume Reduced by: 73.3%

FTE Simulation # 3-3. - Northwestern New Mexico climate - 94 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-3-11. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 3-3.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	35660		92.7		3.6		0.126	
Out::								
Treated Water	9152	25.7%	2.2	2.4%	1.1	30.8%	0.006	5.0%
Brine	2972	8.3%	37.2	40.1%	1.1	31.7%	0.046	36.5%
Evaporation	11996	33.6%	0	0.0%	0	0.0%	0.000	0.0%
Losses occurring 8/7-8/8/94 (See Note 1.)	11110	31.2%	54.9	59.2%	2.1	59.2%	0.075	59.2%
Other Losses	430	1.2%	-1.5	-1.6%	-0.8	-21.6%	-0.001	-0.7%

Table D-3-12. Produced Water Feed for FTE Simulation #3-3.

Date:	Time:	Description	Mass Added (g)
07/26/94	5:00 p	Inialtal Charge	11110
07/28/94	4:30 p	April Evaporation	1103
07/30/94	3:00 p	May Evaporation	1268
08/01/94	4:30 p	June Evaporation	1770
08/03/94	4:30 p	July Evaporation	2298
08/05/94	4:30 p	Aug. Evaporation	2282
08/07/94	4:30 p	Sept. Evaporation	1266
08/08/94	8:00a	See Note 1.	12554
08/09/94	4:00 p	Oct. Evaporation	746
08/15/94	5:00 p	Downtime Evaporation	633
08/17/94	5:00 p	Nov. Evaporation	630
		Total	35660

Table D-3-13. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #3-3.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	2600	100	3.54
Treated Water	240	120	0.694
Brine	12500	380	15.5

Note 1. On the evening of 8/7-8/8/94 the produced water holding pond spray plugged from a microbiological precipitate growing in the pond. When the spray nozzle partially plugged, the entire pond water volume was sprayed outside the pond and lost. The mass of produced water considered lost in this incident was an amount equal to the initial pond water charge. The grams of TDS, TOC, and Boron considered lost in this incident were considered to be equal to the the respective grams of each species introduced into the pond at the time of the spill.

FTE Simulation # 3-3. - Northwestern New Mexico Climate
- 94 hours of sub-freezing temperatures

Simulator #3 - Produced Water From a Natural Gas Producing Well

Table D-3-14. Produced Water Holding Pond Level Data for FTE Simulation #3-3.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
07/26/94	5:00 p	Initial Charge	53		
07/27/94	4:30 p		51	441	5
07/28/94	4:30 p	Before Water Addition	48	662	7
07/28/94	4:30 p	After Water Addition	53		
07/29/94	4:30 p		50	634	7
07/30/94	3:00 p	Before Water Addition	47	634	7
07/30/94	3:00 p	After Water Addition	53		
07/31/94	4:30 p		49	885	10
08/01/94	4:30 p	Before Water Addition	45	885	10
08/01/94	4:30 p	After Water Addition	53		
08/02/94	4:30 p		48	1045	11
08/03/94	4:30 p	Before Water Addition	42	1253	14
08/03/94	4:30 p	After Water Addition	53		
08/04/94	4:30 p		48	1141	12
08/05/94	4:30 p	Before Water Addition	43	1141	12
08/05/94	4:30 p	After Water Addition	53		
08/06/94	4:30 p		49	844	9
08/07/94	4:30 p	Before Water Addition	47	422	5
08/07/94	4:30 p	After Water Addition	53		
08/08/94	8:00 a	After Water Addition	60		
08/08/94	4:30 p		59	249	
08/09/94	4:00 p	Before Water Addition	57	497	5
08/09/94	4:00 p	After Water Addition	60		
08/15/94	5:00 p	Before Water Addition	58	633	
08/15/94	5:00 p	After Water Addition	60		
08/16/94	5:00 p		58	420	5
08/17/94	5:00 p	Before Water Addition	57	210	2
08/17/94	5:00 p	After Water Addition	60		

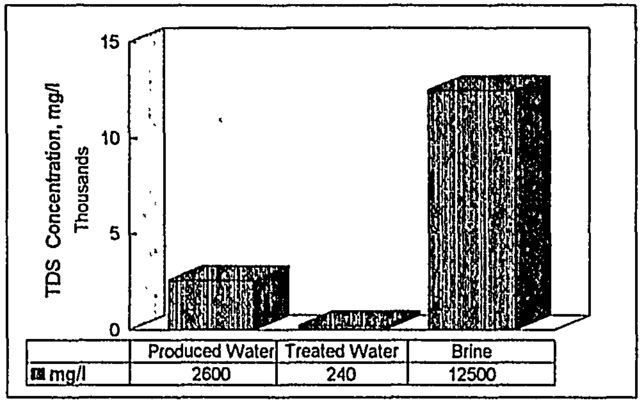
Table D-3-15. Evaporation Rates Achieved for FTE Simulation #3-3.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN 24 hr.	Simulator Evaporation Rate Achieved % of PAN Month Average
07/26/94	07/27/94	April	6.55	73%	92%
07/27/94	07/28/94	April	6.55	110%	
07/28/94	07/29/94	May	8.48	81%	81%
07/29/94	07/30/94	May	8.48	81%	
07/30/94	07/31/94	June	10.82	89%	89%
07/31/94	08/01/94	June	10.82	89%	
08/01/94	08/02/94	July	10.39	109%	120%
08/02/94	08/03/94	July	10.39	131%	
08/03/94	08/04/94	August	9.37	133%	133%
08/04/94	08/05/94	August	9.37	133%	
08/05/94	08/06/94	September	7.11	129%	97%
08/06/94	08/07/94	September	7.11	65%	
08/07/94	08/08/94	October	4.95		109%
08/08/94	08/09/94	October	4.95	109%	
08/15/94	08/16/94	November	3.91	117%	88%
08/16/94	08/17/94	November	3.91	58%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					101%

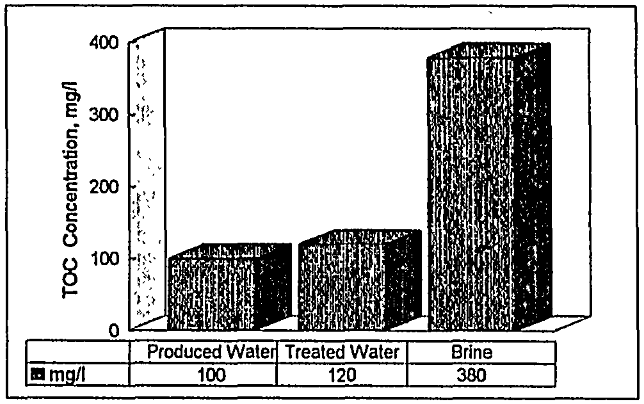
FIGURE D-3-3. FTE SIMULATION # 3-3 EXPERIMENTAL RESULTS

Simulation Series #3: Northwestern New Mexico Climate

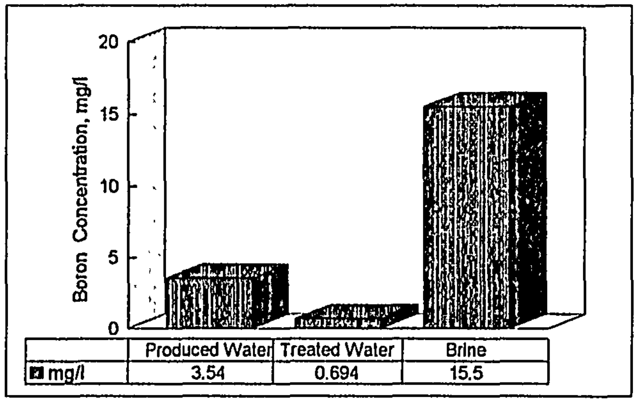
FTE Simulation # 3-3.	- Northwestern New Mexico Climate - 94 hours of sub-freezing temperatures
Simulator #3	- Produced Water from a Natural Gas Producing Well - Data Corrected for a Spill Occurring 8/7 - 8/8/94



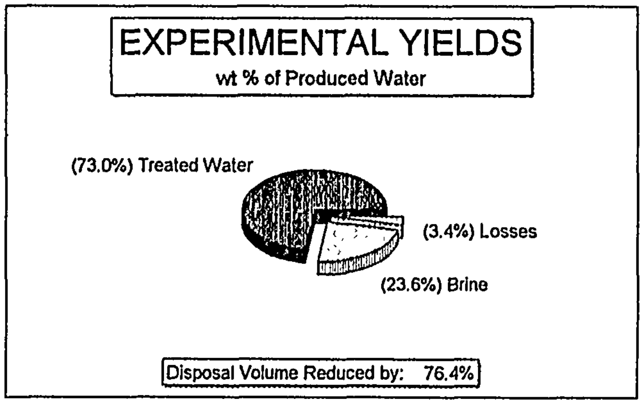
	Produced Water	Treated Water	Brine
▩ mg/l	2600	240	12500



	Produced Water	Treated Water	Brine
▩ mg/l	100	120	380



	Produced Water	Treated Water	Brine
▩ mg/l	3.54	0.694	15.5



Disposal Volume Reduced by: 76.4%

APPENDIX D-4

SIMULATION SERIES #4 RESULTS

FTE Simulation # 4-1. - Central Wyoming - 169 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Goal Bed Methane Well

Table D-4-1. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 4-1.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	19122		204.6		6.9		0.041	
Out::								
Treated Water	7338	38.4%	3.2	1.5%	0.0	0.0%	0.000	0.0%
Brine	2826	14.8%	196.4	96.0%	3.3	48.0%	0.029	69.1%
Evaporation	7892	41.3%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1066	5.6%	5.0	2.5%	3.6	52.0%	0.013	30.9%

Table D-4-2. Produced Water Feed for FTE Simulation #4-1.

Date:	Time:	Description	Mass Added (g)
08/30/94	5:00 p	Iniaital Charge	11230
09/03/94	4:00 p	May and June Evap.	2424
09/05/94	3:30 p	July Evaporation	1424
09/07/94	4:30 p	Aug. Evaporation	1436
09/09/94	4:30 p	Sept. Evaporation	1184
09/11/94	4:30 p	Oct. Evaporation	1424
		Total	19122

Table D-4-3. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #4-1.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	10700	360	2.16
Treated Water	430	<100	<0.2
Brine	69500	1170	10.1

FTE Simulation # 4-1.	- Central Wyoming Climate - 169 hours of sub-freezing temperatures
Simulator #1	- Produced Water From a Coal Bed Methane Well

Table D-4-4. Produced Water Holding Pond Level Data for FTE Simulation #4-1.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
08/30/94	5:00 p	Initial Charge	53		
08/31/94	4:30 p		51	404	4
09/01/94	4:30 p		48	606	7
09/02/94	4:30 p		44	808	9
09/03/94	4:00 p	Before Water Addition	41	606	7
09/03/94	4:00 p	After Water Addition	53		
09/04/94	4:30 p		50	610	7
09/05/94	3:30 p	Before Water Addition	46	814	9
09/05/94	3:30 p	After Water Addition	53		
09/06/94	4:30 p		49	821	9
09/07/94	4:30 p	Before Water Addition	46	615	7
09/07/94	4:30 p	After Water Addition	53		
09/08/94	4:30 p		50	592	6
09/09/94	4:30 p	Before Water Addition	47	592	6
09/09/94	4:30 p	After Water Addition	53		
09/10/94	4:30 p		50	610	7
09/11/94	4:30 p	Before Water Addition	46	814	9
09/11/94	4:30 p	After Water Addition	53		

Table D-4-5. Evaporation Rates Achieved for FTE Simulation #4-1.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
08/30/94	08/31/94	May	4.58	95%	119%
08/31/94	09/01/94	May	4.58	142%	
09/01/94	09/02/94	June	6.54	133%	116%
09/02/94	09/03/94	June	6.54	100%	
09/03/94	09/04/94	July	7.53	87%	102%
09/04/94	09/05/94	July	7.53	116%	
09/05/94	09/06/94	August	6.46	137%	120%
09/06/94	09/07/94	August	6.46	103%	
09/07/94	09/08/94	September	4.58	139%	139%
09/08/94	09/09/94	September	4.58	139%	
09/09/94	09/10/94	October	2.88	228%	266%
09/10/94	09/11/94	October	2.88	304%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					144%

FTE Simulation # 4-2. - Central Wyoming - 169 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-4-6. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 4-2.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	19296		167.7		173.7		0.152	
Out::								
Treated Water	6866	35.6%	2.8	1.7%	1.2	0.7%	0.002	1.6%
Brine	2882	14.9%	138.0	82.3%	51.2	29.5%	0.078	51.1%
Evaporation	8258	42.8%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1290	6.7%	26.8	16.0%	121.3	69.8%	0.072	47.3%

Table D-4-7. Produced Water Feed for FTE Simulation #4-2.

Date:	Time:	Description	Mass Added (g)
08/30/94	5:00 p	Iniaital Charge	11038
09/03/94	4:00 p	May and June Evap.	2634
09/05/94	3:30 p	July Evaporation	1516
09/07/94	4:30 p	Aug. Evaporation	1508
09/09/94	4:30 p	Sept. Evaporation	1252
09/11/94	4:30 p	Oct. Evaporation	1348
		Total	19296

Table D-4-8. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #4-2.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	8690	9000	7.87
Treated Water	410	180	0.35
Brine	47900	17750	26.95

FTE Simulation # 4-2.
- Central Wyoming Climate
- 169 hours of sub-freezing temperatures

Simulator #2
- Produced Water From an Oil and Gas Producing Well

Table D-4-9. Produced Water Holding Pond Level Data for FTE Simulation #4-2.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
08/30/94	5:00 p	Initial Charge	53		
08/31/94	4:30 p		51	405	4
09/01/94	4:30 p		48	608	7
09/02/94	4:30 p		44	810	9
09/03/94	4:00 p	Before Water Addition	40	810	9
09/03/94	4:00 p	After Water Addition	53		
09/04/94	4:30 p		50	569	6
09/05/94	3:30 p	Before Water Addition	45	948	10
09/05/94	3:30 p	After Water Addition	53		
09/06/94	4:30 p		49	754	8
09/07/94	4:30 p	Before Water Addition	45	754	8
09/07/94	4:30 p	After Water Addition	53		
09/08/94	4:30 p		50	537	6
09/09/94	4:30 p	Before Water Addition	46	715	8
09/09/94	4:30 p	After Water Addition	53		
09/10/94	4:30 p		50	578	6
09/11/94	4:30 p	Before Water Addition	46	770	8
09/11/94	4:30 p	After Water Addition	53		

Table D-4-10. Evaporation Rates Achieved for FTE Simulation #4-2.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
08/30/94	08/31/94	May	4.58	96%	120%
08/31/94	09/01/94	May	4.58	143%	
09/01/94	09/02/94	June	6.54	134%	134%
09/02/94	09/03/94	June	6.54	134%	
09/03/94	09/04/94	July	7.53	82%	109%
09/04/94	09/05/94	July	7.53	136%	
09/05/94	09/06/94	August	6.46	126%	126%
09/06/94	09/07/94	August	6.46	126%	
09/07/94	09/08/94	September	4.58	127%	148%
09/08/94	09/09/94	September	4.58	169%	
09/09/94	09/10/94	October	2.88	217%	253%
09/10/94	09/11/94	October	2.88	289%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					148%

FTE Simulation # 4-3. - Central Wyoming - 169 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-4-11. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 4-3.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	20138		54.5		0.0		0.068	
Out::								
Treated Water	8076	40.1%	1.9	3.6%	0.0		0.002	3.3%
Brine	1322	6.6%	50.0	91.7%	0.9		0.044	64.5%
Evaporation	8808	43.7%	0	0.0%	0		0.000	0.0%
Losses	1932	9.6%	2.6	4.7%	-0.9		0.022	32.2%

Table D-4-12. Produced Water Feed for FTE Simulation #4-3.

Date:	Time:	Description	Mass Added (g)
08/30/94	5:00 p	Inialtal Charge	11330
09/03/94	4:00 p	May and June Evap.	3032
09/05/94	3:30 p	July Evaporation	1630
09/07/94	4:30 p	Aug. Evaporation	1554
09/09/94	4:30 p	Sept. Evaporation	1288
09/11/94	4:30 p	Oct. Evaporation	1304
		Total	20138

Table D-4-13. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #4-3.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	B
Produced Water	2705	<100	3.40
Treated Water	240	<100	0.28
Brine	37800	680	33.4

FTE Simulation # 4-3.	- Central Wyoming Climate - 169 hours of sub-freezing temperatures
Simulator #3	- Produced Water From a Natural Gas Producing Well

Table D-4-14. Produced Water Holding Pond Level Data for FTE Simulation #4-3.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
08/30/94	5:00 p	Initial Charge	54		
08/31/94	4:30 p		50	866	9
09/01/94	4:30 p		47	650	7
09/02/94	4:30 p		44	650	7
09/03/94	4:00 p	Before Water Addition	40	866	9
09/03/94	4:00 p	After Water Addition	54		
09/04/94	4:30 p		50	815	9
09/05/94	3:30 p	Before Water Addition	46	815	9
09/05/94	3:30 p	After Water Addition	54		
09/06/94	4:30 p		50	888	10
09/07/94	4:30 p	Before Water Addition	47	666	7
09/07/94	4:30 p	After Water Addition	54		
09/08/94	4:30 p		51	644	7
09/09/94	4:30 p	Before Water Addition	48	644	7
09/09/94	4:30 p	After Water Addition	54		
09/10/94	4:30 p		50	745	8
09/11/94	4:30 p	Before Water Addition	47	559	6
09/11/94	4:30 p	After Water Addition	54		

Table D-4-15. Evaporation Rates Achieved for FTE Simulation #4-3.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
08/30/94	08/31/94	May	4.58	206%	180%
08/31/94	09/01/94	May	4.58	154%	
09/01/94	09/02/94	June	6.54	108%	126%
09/02/94	09/03/94	June	6.54	144%	
09/03/94	09/04/94	July	7.53	118%	118%
09/04/94	09/05/94	July	7.53	118%	
09/05/94	09/06/94	August	6.46	150%	131%
09/06/94	09/07/94	August	6.46	112%	
09/07/94	09/08/94	September	4.58	153%	153%
09/08/94	09/09/94	September	4.58	153%	
09/09/94	09/10/94	October	2.88	282%	246%
09/10/94	09/11/94	October	2.88	211%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					159%

APPENDIX D-5

SIMULATION SERIES #5 RESULTS

FTE Simulation # 5-1. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-5-1. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 5-1.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	19716		214.9		27.6		0.042	
Out::								
Treated Water	7703	39.1%	2.2	1.0%	0.0	0.0%	0.000	0.0%
Brine	2578	13.1%	197.0	91.7%	22.7	82.1%	0.033	77.7%
Evaporation	8290	42.0%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1145	5.8%	15.7	7.3%	5.0	17.9%	0.009	22.3%

Table D-5-2. Produced Water Feed for FTE Simulation #5-1.

Date:	Time:	Description	Mass Added (g)
10/05/94	5:00 p	Iniaital Charge	11426
10/07/94	5:00 p	May Evaporation	1258
10/09/94	3:00 p	June Evaporation	1326
10/11/94	4:30 p	July Evaporation	1486
10/13/94	5:00 p	Aug. Evaporation	1448
10/15/94	4:30 p	Sept. Evaporation	1266
10/18/94	4:30 p	Oct. Evaporation	1506
		Total	19716

Table D-5-3. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #5-1.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	Boron
Produced Water	10900	1400	2.14
Treated Water	286	0	0.00
Brine	76417	8786	12.72

FTE Simulation # 5-1. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-5-4. Summary of Experimental Mass, Ammonia, Fe, and Cl Balances from FTE Simulation # 5-1.

Process Stream:	Overall Mass Balance		Ammonia Balance		Fe Balance		Cl Balance	
	mass (g)	% of Mass Input	Ammonia (g)	% of Ammonia In	Fe (g)	% of Fe In	Cl (g)	% of Cl In
In:								
Produced Water Charge	19716		0.018		0.005		21.7	
Out::								
Treated Water	7703	39.1%	0.004	21.1%	0.000	0.0%	0.2	0.8%
Brine	2578	13.1%	0.014	77.3%	0.002	45.1%	15.7	72.4%
Evaporation	8290	42.0%	0.000	0.0%	0.000	0.0%	0.0	0.0%
Losses	1145	5.8%	0.0	1.7%	0.003	54.9%	5.8	26.8%

Table D-5-5. Ammonia, Fe, and Cl Conecntrations of Process Streams for FTE Simulation #5-1.

Process Stream	Analyte Concentration, mg/l		
	Ammonia	Fe	Cl
Produced Water	0.89	0.26	1100.0
Treated Water	0.48	0.00	22.5
Brine	5.26	0.90	6094.8

FTE Simulation # 5-1. - Central Wyoming Climate - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-5-6. Summary of Experimental Mass, Br, Ba, and Sr Balances from FTE Simulation # 5-1.

Process Stream:	Overall Mass Balance		Br Balance		Ba Balance		Sr Balance	
	mass (g)	% of Mass Input	Br (g)	% of Br In	Ba (g)	% of Ba In	Sr (g)	% of Sr In
In:								
Produced Water Charge	19716		0.103		0.550		0.296	
Out::								
Treated Water	7703	39.1%	0.000	0.0%	0.007	1.2%	0.003	1.0%
Brine	2578	13.1%	0.102	99.6%	0.058	10.6%	0.041	14.0%
Evaporation	8290	42.0%	0.000	0.0%	0.000	0.0%	0.000	0.0%
Losses	1145	5.8%	0.000	0.4%	0.485	88.2%	0.251	85.0%

Table D-5-7. Br, Ba, and Sr Conecntrations of Process Streams for FTE Simulation #5-1.

Process Stream	Analyte Concentration, mg/l		
	Br	Ba	Sr
Produced Water	5.20	27.90	15.00
Treated Water	0.00	0.86	0.39
Brine	39.60	22.52	16.09

FTE Simulation # 5-1.	- Central Wyoming Climate - 182.5 hours of sub-freezing temperatures
Simulator #1	- Produced Water From a Coal Bed Methane Well

Table D-5-8. Produced Water Holding Pond Level Data for FTE Simulation #5-1.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
10/05/94	5:00 p	Initial Charge	54		
10/06/94	5:00 p		51	629	7
10/07/94	5:00 p	Before Water Addition	48	629	7
10/07/94	5:00 p	After Water Addition	54		
10/08/94	4:30 p		51	663	7
10/09/94	3:00 p	Before Water Addition	48	663	7
10/09/94	3:00 p	After Water Addition	54		
10/10/94	4:30 p		50	849	9
10/11/94	4:30 p	Before Water Addition	47	637	7
10/11/94	4:30 p	After Water Addition	54		
10/12/94	4:30 p		50	827	9
10/13/94	5:00 p	Before Water Addition	47	621	7
10/13/94	5:00 p	After Water Addition	54		
10/14/94	4:30 p		51	633	7
10/15/94	4:30 p	Before Water Addition	48	633	7
10/15/94	4:30 p	After Water Addition	54		
10/16/94	4:30 p		51	645	7
10/17/94	4:30 p	Before Water Addition	47	861	9
10/17/94	4:30 p	After Water Addition	54		

Table D-5-9. Evaporation Rates Achieved for FTE Simulation #5-1.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
10/05/94	10/06/94	May	4.58	148%	148%
10/06/94	10/07/94	May	4.58	148%	
10/07/94	10/08/94	June	6.54	109%	109%
10/08/94	10/09/94	June	6.54	109%	
10/09/94	10/10/94	July	7.53	121%	106%
10/10/94	10/11/94	July	7.53	91%	
10/11/94	10/12/94	August	6.46	138%	121%
10/12/94	10/13/94	August	6.46	103%	
10/13/94	10/14/94	September	4.58	149%	149%
10/14/94	10/15/94	September	4.58	149%	
10/15/94	10/16/94	October	2.88	241%	281%
10/16/94	10/17/94	October	2.88	322%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					152%

FTE Simulation # 5-1. - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-5-10. Results of Chemical Analyses of Process Streams for Simulation # 5-1.

Process Stream: Analyte	Produced Water Feed (mg/L)	Est. Pond Water prior to Freezing (mg/L)	Treated Water (mg/L)	Brine (mg/L)
TDS	10900	18808	286	76570
Alkalinity	8500	14667	188	38750
Ammonia	0.89	1.54	0.48	5.27
Cyanide	<0.1	<0.1	<0.1	<0.3
H2S	<0.05	<0.05	<0.05	<0.16
TOC	1400	2416	<100	8804
Total Phenolics	<0.01	<0.01	<0.01	0.84
Na	3750	6471	111	26288
Ca	6.3	10.9	2.0	12.4
Mg	23.5	40.6	0.84	163.7
Fe	0.26	0.45	<0.1	0.90
SO4	1.5	2.6	1.5	19.2
NO3	42.4	73.2	<1	163.7
NO2	<1		<1	<3
Cl	1100	1898	22.5	6107
F	<1		<1	28.5
Br	5.2	9.0	<1	39.7
Al	<1		<1	<3
As	<0.05		<0.05	<0.16
Ba	27.9	48.1	0.86	22.6
Be	<0.05		<0.05	<0.16
B	2.14	3.69	<0.2	12.74
Cd	<0.01		<0.01	0.05
Cr	<0.05		<0.05	<0.16
Co	<0.01		<0.01	<0.03
Cu	<0.1		<0.1	<0.3
Pb	<0.01		<0.01	0.124
Li	<1		<1	4
Mn	0.017	0.029	<0.01	<0.03
Hg	<0.0001		<0.0001	0.0015
Ni	<0.1		<0.1	<0.3
Ra 226 (a)	2.8(+/- 1.8)	4.8(+/-3.1)	<0.3	11.8 (+/- 6.5)
Ra 228 (a)	(b)		(b)	17.1 (+/- 6.5)
Se	<0.01		<0.01	<0.03
Sr	15	25.9	0.39	16
Ag	<0.01		<0.01	<0.03
U	<0.1		<0.1	<0.3
V	<0.1		<0.1	<0.3
Zn	<0.05		<0.05	<0.16

(a) - Concentration in pCi/l.
(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

FTE Simulation # 5-1. - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-5-11. Chemical Component Balances and Closures for Simulation #5-1.

Process Stream:	Produced Water Feed	Treated Water		Brine		Losses	
Analyte	Mass (g)	Mass (g)	% of Input	Mass (g)	% of Input	Mass (g)	% of Input
TDS	215	2	1.0%	197	91.9%	15	7.1%
Alkalinity	167.6	1.4	0.9%	99.9	59.6%	66.2	39.5%
Ammonia	0.018	0.004	21.1%	0.014	77.4%	0.000	1.5%
Cyanide	(a)	(a)		(a)			
H2S	(a)	(a)		(a)			
TOC	27.6	(a)	0.0%	22.7	82.2%	4.9	17.8%
Total Phenolics	(a)	(a)		0.002			
Na	73.9	0.9	1.2%	67.8	91.7%	5.3	7.2%
Ca	0.124	0.015	12.4%	0.032	25.7%	0.077	61.9%
Mg	0.463	0.006	1.4%	0.422	91.1%	0.035	7.5%
Fe	0.005	(a)	0.0%	0.002	45.2%	0.003	54.8%
SO4	0.030	0.012	39.1%	0.050	167.5%	-0.032	-106.6%
NO3	0.836	(a)	0.0%	0.422	50.5%	0.414	49.5%
NO2	(a)	(a)		(a)			
Cl	21.7	0.2	0.8%	15.7	72.6%	5.8	26.6%
F	(a)	(a)		0.074			
Br	0.103	(a)	0.0%	0.102	99.8%	0.000	0.2%
Trace Metals	(mg)	(mg)		(mg)		(mg)	
Al	(a)	(a)		(a)			
As	(a)	(a)		(a)			
Ba	550	7	1.2%	58	10.6%	485	88.2%
Be	(a)	(a)		(a)			
B	42	(a)	0.0%	33	77.8%	9	22.2%
Cd	(a)	(a)		0.128			
Cr	(a)	(a)		(a)			
Co	(a)	(a)		(a)			
Cu	(a)	(a)		(a)			
Pb	(a)	(a)		0.320			
Li	(a)	(a)		11.189			
Mn	0.335	(a)	0.0%	(a)	0.0%	0.335	100.0%
Hg	(a)	(a)		0.004			
Ni	(a)	(a)		(a)			
Ra 226	(b)	(a)		(b)			
Ra 228	(b)	(b)		(b)			
Se	(a)	(a)		(a)			
Sr	296	3	1.0%	42	14.1%	251	84.9%
Ag	(a)	(a)		(a)			
U	(a)	(a)		(a)			
V	(a)	(a)		(a)			
Zn	(a)	(a)		(a)			

(a) - Concentration of analyte in process stream below detection limit for analytical procedure.
(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

FTE Simulation # 5-2. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-5-12. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 5-2.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In:								
Produced Water Charge	19770		165.3		119.6		0.174	
Out::								
Treated Water	7152	36.2%	1.5	0.9%	0.7	0.6%	0.000	0.0%
Brine	2456	12.4%	112.7	68.2%	67.0	56.1%	0.096	55.1%
Evaporation	8698	44.0%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1464	7.4%	51.1	30.9%	51.8	43.3%	0.078	44.9%

Table D-5-13. Produced Water Feed for FTE Simulation #5-2.

Date:	Time:	Description	Mass Added (g)
10/05/94	5:00 p	Inialtal Charge	11072
10/07/94	5:00 p	May Evaporation	1376
10/09/94	3:00 p	June Evaporation	1440
10/11/94	4:30 p	July Evaporation	1646
10/13/94	5:00 p	Aug. Evaporation	1514
10/15/94	4:30 p	Sept. Evaporation	1280
10/18/94	4:30 p	Oct. Evaporation	1442
		Total	19770

Table D-5-14. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #5-2.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	Boron
Produced Water	8360	6050	8.80
Treated Water	206	100	0.00
Brine	45900	27300	39.00

FTE Simulation # 5-2. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-5-15. Summary of Experimental Mass, Alkalinity, Sulfate, and Ammonia Balances from FTE Simulation # 5-2.

Process Stream:	Overall Mass Balance		Alkalinity Balance		Sulfate Balance		Ammonia Balance	
	mass (g)	% of Mass Input	Alkalinity (g)	% of Alkalinity In	Sulfate (g)	% of Sulfate In	Ammonia (g)	% of Ammonia In
In:								
Produced Water Charge	19770		20.6		1.7		0.151	
Out::								
Treated Water	7452	37.7%	0.3	1.4%	0.0	1.3%	0.028	18.8%
Brine	3326	16.8%	20.9	101.4%	2.1	119.9%	0.221	146.2%
Evaporation	8698	44.0%	0	0.0%	0	0.0%	0.000	0.0%
Losses	294	1.5%	-0.6	-2.8%	-0.4	-21.2%	-0.098	-65.0%

Table D-5-16. Alkalinity, Sulfate, and Ammonia Conecntrations of Process Streams for FTE Simulation #5-2.

Process Stream	Analyte Concentration, mg/l		
	Alkalinity	Sulfate	Ammonia
Produced Water	1040	87.1	7.6
Treated Water	39	3.0	3.8
Brine	6270	621.0	66.3

FTE Simulation # 5-2. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil and Gas Producing Well

Table D-5-17. Summary of Experimental Mass, Alkalinity, Sulfate, and Ammonia Balances from FTE Simulation # 5-2.

Process Stream:	Overall Mass Balance		Alkalinity Balance		Sulfate Balance		Ammonia Balance	
	mass (g)	% of Mass Input	Alkalinity (g)	% of Alkalinity In	Sulfate (g)	% of Sulfate In	Ammonia (g)	% of Ammonia In
In:								
Produced Water Charge	19770		20.6		1.7		0.151	
Out::								
Treated Water	7452	37.7%	0.3	1.4%	0.0	1.3%	0.028	18.8%
Brine	3326	16.8%	20.9	101.4%	2.1	119.9%	0.221	146.2%
Evaporation	8698	44.0%	0	0.0%	0	0.0%	0.000	0.0%
Losses	294	1.5%	-0.6	-2.8%	-0.4	-21.2%	-0.098	-65.0%

Table D-5-18. Alkalinity, Sulfate, and Ammonia Conecntrations of Process Streams for FTE Simulation #5-2.

Process Stream	Analyte Concentration, mg/l		
	Alkalinity	Sulfate	Ammonia
Produced Water	1040	87.1	7.6
Treated Water	39	3.0	3.8
Brine	6270	621.0	66.3

FTE Simulation # 5-2.	- Central Wyoming Climate - 182.5 hours of sub-freezing temperatures
Simulator #2	- Produced Water From an Oil and Gas Porducing Well

Table D-5-19. Produced Water Holding Pond Level Data for FTE Simulation #5-2.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
10/05/94	5:00 p	Initial Charge	52		
10/06/94	5:00 p		49	688	7
10/07/94	5:00 p	Before Water Addition	46	688	7
10/07/94	5:00 p	After Water Addition	52		
10/08/94	4:30 p		48	823	9
10/09/94	3:00 p	Before Water Addition	45	617	7
10/09/94	3:00 p	After Water Addition	52		
10/10/94	4:30 p		48	941	10
10/11/94	4:30 p	Before Water Addition	45	705	8
10/11/94	4:30 p	After Water Addition	52		
10/12/94	4:30 p		48	865	9
10/13/94	5:00 p	Before Water Addition	45	649	7
10/13/94	5:00 p	After Water Addition	52		
10/14/94	4:30 p		49	640	7
10/15/94	4:30 p	Before Water Addition	46	640	7
10/15/94	4:30 p	After Water Addition	52		
10/16/94	4:30 p		49	721	8
10/17/94	4:30 p	Before Water Addition	46	721	8
10/17/94	4:30 p	After Water Addition	52		

Table D-5-20. Evaporation Rates Achieved for FTE Simulation #5-2.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN	
				24 hr.	Month Average
10/05/94	10/06/94	May	4.58	162%	162%
10/06/94	10/07/94	May	4.58	162%	
10/07/94	10/08/94	June	6.54	136%	119%
10/08/94	10/09/94	June	6.54	102%	
10/09/94	10/10/94	July	7.53	135%	118%
10/10/94	10/11/94	July	7.53	101%	
10/11/94	10/12/94	August	6.46	145%	127%
10/12/94	10/13/94	August	6.46	109%	
10/13/94	10/14/94	September	4.58	151%	151%
10/14/94	10/15/94	September	4.58	151%	
10/15/94	10/16/94	October	2.88	271%	271%
10/16/94	10/17/94	October	2.88	271%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					158%

Table D-5-21. Results of Chemical Analyses of Process Streams for Simulation #5-2.

Process Stream:	Produced Water Feed	Est. Pond Water prior to Freezing	Treated Water	Brine
Analyte	(mg/L)	(mg/L)	(mg/L)	(mg/L)
TDS	8360	14927	206	45900
Alkalinity	1040	1857	39	6270
Ammonia	7.63	13.62	3.80	66.3
Cyanide	2.5	4.5	<0.1	9.6
H2S	<0.05		<0.05	<0.15
TOC	6050	10803	100	27300
Total Phenolics	1.51	2.70	<0.01	9.51
Na	2240	4000	51.4	17040
Ca	66.6	118.9	12.4	126.6
Mg	12.0	21.4	<0.5	95.1
Fe	1.41	2.52	<0.1	47.4
SO4	87.1	155.5	3.0	621
NO3	<1		<1	<3
NO2	<1		<1	<3
Cl	4020	7178	83.0	29970
F	45.6	81.4	1.3	247.8
Br	26.3	47.0	<1	188.1
Al	<1		<1	4.2
As	<0.05		<0.05	<0.15
Ba	0.22	0.39	<0.1	122.1
Be	<0.05		<0.05	<0.15
B	8.80	15.71	<0.2	39.0
Cd	<0.01		<0.01	0.075
Cr	<0.05		<0.05	<0.15
Co	<0.01		<0.01	<0.03
Cu	<0.1		<0.1	<0.3
Pb	<0.01		<0.01	0.069
Li	1.1	2.0	<1	6.6
Mn	0.43	0.77	0.013	2.61
Hg	0.0002	0.0004	<0.0001	<0.0015
Ni	<0.1		<0.1	<0.3
Ra 226 (a)	2.5(+/- 1.2)	4.5(+/- 2.1)	(b)	5.7 (+/- 3.3)
Ra 228 (a)	4.2(+/- 1.7)	7.5(+/- 3.0)	(b)	(b)
Se	<0.01		<0.01	0.036
Sr	5.7	10.2	0.55	29
Ag	<0.01		<0.01	<0.01
U	<0.1		<0.1	<0.1
V	<0.1		<0.1	<0.1
Zn	<0.05		<0.05	<0.05

(a) - Concentration in pCi/l.
(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

FTE Simulation # 5-2. - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil & Gas Producing Well

Table D-5-22. Chemical Component Balances and Closures for Simulation #5-2.

Process Stream:	Produced Water Feed	Treated Water		Brine		Losses	
Analyte	Mass (g)	Mass (g)	% of Input	Mass (g)	% of Input	Mass (g)	% of Input
TDS	165	1	0.9%	113	68.2%	51	30.9%
Alkalinity	20.6	0.3	1.4%	15.4	74.9%	4.88	23.7%
Ammonia	0.151	0.027	18.0%	0.163	107.9%	-0.039	-26.0%
Cyanide	0.049	(a)	0.0%	0.024	47.7%	0.026	52.3%
H2S	(a)	(a)		(a)			
TOC	119.6	0.7	0.6%	67.0	56.1%	51.84	43.3%
Total Phenolics	0.030	(a)	0.0%	0.023	78.2%	0.006	21.8%
Na	44.3	0.4	0.8%	41.9	94.5%	2.07	4.7%
Ca	1.317	0.089	6.7%	0.311	23.6%	0.917	69.6%
Mg	0.237	(a)	0.0%	0.234	98.5%	0.004	1.5%
Fe	0.028	(a)	0.0%	0.116	417.6%	-0.089	-317.6%
SO4	1.722	0.021	1.2%	1.525	88.6%	0.175	10.2%
NO3	(a)	(a)		(a)			
NO2	(a)	(a)		(a)			
Cl	79.5	0.6	0.7%	73.6	92.6%	5.3	6.6%
F	0.902	0.009	1.0%	0.609	67.5%	0.284	31.5%
Br	0.520	(a)	0.0%	0.462	88.8%	0.058	11.2%
Trace Metals	(mg)	(mg)		(mg)		(mg)	
Al	(a)	(a)		10			
As	(a)	(a)		(a)			
Ba	4	(a)	0.0%	300	6894.7%	-296	-6794.7%
Be	(a)	(a)		(a)			
B	174	(a)	0.0%	96	55.1%	78	44.9%
Cd	(a)	(a)		0.184			
Cr	(a)	(a)		(a)			
Co	(a)	(a)		(a)			
Cu	(a)	(a)		(a)			
Pb	(a)	(a)		0.169			
Li	(a)	(a)		16			
Mn	8.501	0.093	1.1%	6.410	75.4%	1.998	23.5%
Hg	0.004	(a)		(a)		0.004	100.0%
Ni	(a)	(a)		(a)			
Ra 226	(b)	(b)		(b)			
Ra 228	(b)	(b)		(b)			
Se	(a)	(a)		0.088			
Sr	113	4	3.5%	71	63.4%	37	33.1%
Ag	(a)	(a)		(a)			
U	(a)	(a)		(a)			
V	(a)	(a)		(a)			
Zn	(a)	(a)		(a)			

(a) - Concentration of analyte in process stream below detection limit for analytical procedure.
(b) - Detected concentration but perscision in laboratory analyses prevents quantification.

FTE Simulation # 5-3. - Central Wyoming climate - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from an Natural Gas Producing Well

Table D-5-23. Summary of Experimental Mass, TDS, TOC, and Boron Balances from FTE Simulation # 5-3.

Process Stream:	Overall Mass Balance		TDS Balance		TOC Balance		Boron Balance	
	mass (g)	% of Mass Input	TDS (g)	% of TDS Input	TOC (g)	% of TOC Input	Boron (g)	% of Boron Input
In: Produced Water Charge	20916		55.2		2.0		0.064	
Out:: Treated Water	8834	42.2%	1.8	3.2%	0.0	0.0%	0.002	3.9%
Brine	1054	5.0%	49.1	89.0%	1.8	89.1%	0.049	77.5%
Evaporation	9562	45.7%	0	0.0%	0	0.0%	0.000	0.0%
Losses	1466	7.0%	4.3	7.8%	0.2	10.9%	0.012	18.6%

Table D-5-24. Produced Water Feed for FTE Simulation #5-3.

Date:	Time:	Description	Mass Added (g)
10/05/94	5:00 p	Inlaital Charge	.11354
10/07/94	5:00 p	May Evaporation	1532
10/09/94	3:00 p	June Evaporation	1550
10/11/94	4:30 p	July Evaporation	1792
10/13/94	5:00 p	Aug. Evaporation	1628
10/15/94	4:30 p	Sept. Evaporation	1478
10/18/94	4:30 p	Oct. Evaporation	1582
		Total	20916

Table D-5-25. TDS, TOC, and Boron Conecntrations of Process Streams for FTE Simulation #5-3.

Process Stream	Analyte Concentration, mg/l		
	TDS	TOC	Boron
Produced Water	2640	95	3.05
Treated Water	200	0	0.28
Brine	46620	1680	46.90

FTE Simulation # 5-3.	- Central Wyoming Climate - 182.5 hours of sub-freezing temperatures
Simulator #3	- Produced Water From a Natural Gas Producing Well

Table D-5-26. Produced Water Holding Pond Level Data for FTE Simulation #5-3.

Date	Time	Remarks	Pond Level (mm)	Mass of Water Evaporated (grams)	Eff. Evap. Rate Achieved (mm)
10/05/94	5:00 p	Initial Charge	54		
10/06/94	5:00 p		51	766	8
10/07/94	5:00 p	Before Water Addition	48	766	8
10/07/94	5:00 p	After Water Addition	54		
10/08/94	4:30 p		51	664	7
10/09/94	3:00 p	Before Water Addition	47	886	10
10/09/94	3:00 p	After Water Addition	54		
10/10/94	4:30 p		51	896	10
10/11/94	4:30 p	Before Water Addition	48	896	10
10/11/94	4:30 p	After Water Addition	54		
10/12/94	4:30 p		50	814	9
10/13/94	5:00 p	Before Water Addition	46	814	9
10/13/94	5:00 p	After Water Addition	54		
10/14/94	4:30 p		50	845	9
10/15/94	4:30 p	Before Water Addition	47	633	7
10/15/94	4:30 p	After Water Addition	54		
10/16/94	4:30 p		50	904	10
10/17/94	4:30 p	Before Water Addition	47	678	7
10/17/94	4:30 p	After Water Addition	54		

Table D-5-27. Evaporation Rates Achieved for FTE Simulation #5-3.

Starting Date	Ending Date	Month Simulated	Climate's Monthly PAN Evaporation Rate (mm/day)	Simulator Evaporation Rate Achieved % of PAN 24 hr.	Simulator Evaporation Rate Achieved % of PAN Month Average
10/05/94	10/06/94	May	4.58	182%	182%
10/06/94	10/07/94	May	4.58	182%	
10/07/94	10/08/94	June	6.54	110%	129%
10/08/94	10/09/94	June	6.54	147%	
10/09/94	10/10/94	July	7.53	129%	129%
10/10/94	10/11/94	July	7.53	129%	
10/11/94	10/12/94	August	6.46	137%	137%
10/12/94	10/13/94	August	6.46	137%	
10/13/94	10/14/94	September	4.58	200%	175%
10/14/94	10/15/94	September	4.58	150%	
10/15/94	10/16/94	October	2.88	341%	299%
10/16/94	10/17/94	October	2.88	256%	
Average PAN Evaporation Efficiency Achieved (% of PAN)					175%

FTE Simulation # 5-3. - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-5-28. Results of Chemical Analyses of Process Streams for Simulation #5-3.

Process Stream: Analyte	Produced Water Feed (mg/L)	Est. Pond Water prior to Freezing (mg/L)	Treated Water (mg/L)	Brine (mg/L)
TDS	2640	4863	200	46620
Alkalinity	225	414	17	637
Ammonia	6.81	12.55	2.20	83.3
Cyanide	0.2	0.4	<0.1	2.1
H2S	<0.05		<0.05	<0.35
TOC	<100		<100	1680
Total Phenolics	0.13	0.24	<0.01	5.67
Na	757	1395	72.6	13650
Ca	63.6	117.2	11.0	791.0
Mg	5.7	10.4	0.7	105.0
Fe	0.21	0.39	<0.1	3.5
SO4	2.6	4.8	1.3	36
NO3	<1		<1	<7
NO2	<1		<1	<7
Cl	1350	2487	125.0	22050
F	<1		<1	<7
Br	10.3	19.0	<1	284.9
Al	<1		<1	<7
As	<0.05		<0.05	<0.35
Ba	2.23	4.11	0.17	17.4
Be	<0.05		<0.05	<0.35
B	3.05	5.62	0.28	46.9
Cd	<0.01		0.013	0.175
Cr	<0.05		<0.05	<0.35
Co	<0.01		<0.01	<0.07
Cu	<0.1		<0.1	<0.7
Pb	<0.01		<0.01	<0.07
Li	<1		<1	13.3
Mn	0.11	0.20	0.018	0.48
Hg	<0.0001		<0.0001	0.0042
Ni	<0.1		<0.1	<0.7
Ra 226 (a)	3.1(+/- 1.2)	5.7(+/-2.2)	(b)	34.3 (+/- 18.2)
Ra 228 (a)	(b)		<2.0	(b)
Se	<0.01		<0.01	<0.07
Sr	8.4	15.5	0.81	133
Ag	<0.01		<0.01	<0.07
U	<0.1		<0.1	<0.07
V	<0.1		<0.1	<0.7
Zn	<0.05		<0.05	<0.05

(a) - Concentration in pCi/l.
(b) - Detectable concentration but perscision in laboratory analysis prevents quantification.

Table D-5-29. Chemical Component Balances and Closures for Simulation #5-3.

Process Stream:	Produced Water Feed	Treated Water		Brine		Losses	
Analyte	Mass (g)	Mass (g)	% of Input	Mass (g)	% of Input	Mass (g)	% of Input
TDS	55	2	3.2%	49	89.0%	4	7.8%
Alkalinity	4.7	0.2	3.2%	0.7	14.3%	3.88	82.5%
Ammonia	0.142	0.019	13.6%	0.088	61.6%	0.035	24.7%
Cyanide	0.004	(a)	0.0%	0.002	52.9%	0.002	47.1%
H2S	(a)	(a)		(a)			
TOC	(a)	(a)		1.8			
Total Phenolics	0.003	(a)		0.006	219.8%	-0.003	-119.8%
Na	15.8	0.6	4.1%	14.4	90.9%	0.80	5.1%
Ca	1.330	0.097	7.3%	0.834	62.7%	0.399	30.0%
Mg	0.118	0.006	4.9%	0.111	93.6%	0.002	1.5%
Fe	0.004	(a)		0.004	84.0%	0.001	16.0%
SO4	0.054	0.011	21.1%	0.038	70.5%	0.005	8.3%
NO3	(a)	(a)		(a)			
NO2	(a)	(a)		(a)			
Cl	28.2	1.1	3.9%	23.2	82.3%	3.9	13.8%
F	(a)	(a)		(a)			
Br	0.215	(a)		0.300	139.4%	-0.085	-39.4%
Trace Metals	(mg)	(mg)		(mg)		(mg)	
Al	(a)	(a)		(a)			
As	(a)	(a)		(a)			
Ba	47	2	3.2%	18	39.4%	27	57.4%
Be	(a)	(a)		(a)			
B	64	2	3.9%	49	77.5%	12	18.6%
Cd	(a)	0.115		0.184			
Cr	(a)	(a)		(a)			
Co	(a)	(a)		(a)			
Cu	(a)	(a)		(a)			
Pb	(a)	(a)		(a)			
Li	(a)	(a)		14			
Mn	2.301	0.159	6.9%	0.509	22.1%	1.633	71.0%
Hg	(a)	(a)		0.004			
Ni	(a)	(a)		(a)			
Ra 226	(b)	(b)		(b)			
Ra 228	(b)	(a)		(b)			
Se	(a)	(a)		(a)			
Sr	176	7	4.1%	140	79.8%	28	16.1%
Ag	(a)	(a)		(a)			
U	(a)	(a)		(a)			
V	(a)	(a)		(a)			
Zn	(a)	(a)		(a)			

(a) - Concentration of analyte in process stream below detection limit for analytical procedure.
(b) - Detectable concentration but perscision in laboratory analysis prevents quantification.

Table D-5-30. Experimental Yields for Simulation #5-1.

FTE Simulation # 5-1. - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Process Stream:	Mass (g)	% of Mass Input
Produced Water Charge	19716	
Treated Water	7703	39.1%
Brine	2578	13.1%
Evaporation	8290	42.0%
Losses	1145	5.8%

Table D-5-31. Experimental Yields for Simulation #5-2.

FTE Simulation # 5-2. - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil & Gas Producing Well

Process Stream:	Mass (g)	% of Mass Input
Produced Water Charge	19770	
Treated Water	7152	36.2%
Brine	2456	12.4%
Evaporation	8698	44.0%
Losses	1464	7.4%

Table D-5-32. Experimental Yields for Simulation #5-3.

FTE Simulation # 5-3. - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Process Stream:	Mass (g)	% of Mass Input
Produced Water Charge	20916	
Treated Water	8834	42.2%
Brine	1054	5.0%
Evaporation	9562	45.7%
Losses	1466	7.0%

Table D-5-33. Quality of Freezing Pad Feed Water and Treated Water Produced from FTE Simulation Series #5.

	Simulation # 5-1		Simulation # 5-2		Simulation # 5-3	
Process Stream: Analyte	Freeze Crystallization Feed Water (mg/L)	Treated Water (mg/L)	Freeze Crystallization Feed Water (mg/L)	Treated Water (mg/L)	Freeze Crystallization Feed Water (mg/L)	Treated Water (mg/L)
TDS	18808	286	14927	206	4863	200
Alkalinity	14667	188	1857	39	414	17
Ammonia	1.54	0.48	13.62	3.80	12.55	2.20
Cyanide		<0.1	4.5	<0.1	0.4	<0.1
H2S		<0.05		<0.05		<0.05
TOC	2416	<100	10803	100		<100
Total Phenolics		<0.01	2.70	<0.01	0.24	<0.01
Na	6471	111	4000	51.4	1395	72.6
Ca	10.9	2.0	118.9	12.4	117.2	11.0
Mg	40.6	0.84	21.4	<0.5	10.4	0.7
Fe	0.45	<0.1	2.52	<0.1	0.39	<0.1
SO4	2.6	1.5	155.5	3.0	4.8	1.3
NO3	73.2	<1		<1		<1
NO2		<1		<1		<1
Cl	1898	22.5	7178	83.0	2487	125.0
F		<1	81.4	1.3		<1
Br	9.0	<1	47.0	<1	19.0	<1
Al		<1		<1		<1
As		<0.05		<0.05		<0.05
Ba	48.1	0.86	0.39	<0.1	4.11	0.17
Be		<0.05		<0.05		<0.05
B	3.69	<0.2	15.71	<0.2	5.62	0.28
Cd		<0.01		<0.01		0.013
Cr		<0.05		<0.05		<0.05
Co		<0.01		<0.01		<0.01
Cu		<0.1		<0.1		<0.1
Pb		<0.01		<0.01		<0.01
Li		<1	2.0	<1		<1
Mn	0.029	<0.01	0.77	0.013	0.20	0.018
Hg		<0.0001	0.0004	<0.0001		<0.0001
Ni		<0.1		<0.1		<0.1
Ra 226 (a)	4.8(+/-3.1)	<0.3	4.5(+/- 2.1)	(b)	5.7(+/-2.2)	(b)
Ra 228 (a)	(b)	(b)	7.5(+/- 3.0)	(b)	(b)	<2.0
Se		<0.01		<0.01		<0.01
Sr	25.9	0.39	10.2	0.55	15.5	0.81
Ag		<0.01		<0.01		<0.01
U		<0.1		<0.1		<0.1
V		<0.1		<0.1		<0.1
Zn		<0.05		<0.05		<0.05

(a) - Concentration in pCi/l.

(b) - Detectable concentration but precision in laboratory analysis prevents quantification.

Note: Quality of freeze crystallization feed water is based upon analyses of produced water feed to each respective FTE simulator and the mass of evaporation in that simulator during the evaporation phase of the simulation.

APPENDIX D-6

CHEMICAL SPECIES ANALYSES RESULTS

Table D-6-1. Volatile Organics Summary Data for Simulation #5-1

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	1	1
Acetone	210	3800	630
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	U	U
1,2-Dichloroethane	U	U	U
2-Butanone	U	2900	850
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	U	U	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	U	U	U
Chlorobenzene	U	U	U
Ethyl Benzene	U	U	U
Styrene	U	U	U
Total Zylenes	U	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-2. - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil & Gas Producing Well

Table D-6-2. Volatile Organics Summary Data for Simulation #5-2

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Chloromethane	U	U	U
Bromomethane	U	U	U
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	1
Acetone	43000	2800	3100
Carbon Disulfide	23	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	13	14	U
1,2-Dichloroethane	U	U	U
2-Butanone	1200	2100	U
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	1300	9	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	1
Tetrachloroethene	U	U	U
Toluene	470	12	U
Chlorobenzene	U	U	U
Ethyl Benzene	6	U	U
Styrene	U	U	U
Total Zylenes	79	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-3. - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-6-3. Volatile Organics Summary Data for Simulation #5-3

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Chloromethane	3	2	7
Bromomethane	1	U	5
Vinyl Chloride	U	U	U
Chloroethane	U	U	U
Methylene Chloride	U	U	2
Acetone	320	2100	2100
Carbon Disulfide	U	U	U
1,1-Dichloroethene	U	U	U
1,1-Dichloroethane	U	U	U
Trans-1,2-Dichloroethene	U	U	U
Cis-1,2-Dichloroethene	U	U	U
Chloroform	U	U	U
1,2-Dichloroethane	U	U	U
2-Butanone	U	1900	200
1,1,1-Trichloroethane	U	U	U
Carbon Tetrachloride	U	U	U
Bromodichloromethane	U	U	U
Vinyl Acetate	U	U	U
1,2-Dichloropropane	U	U	U
Trans-1,3-Dichloropropene	U	U	U
Trichloroethene	U	U	U
1,1,2-Trichloroethane	U	U	U
Benzene	140	2	U
Dibromochloromethane	U	U	U
Cis-1,3-Dichloropropene	U	U	U
2-Chloroethylvinyl Ether	U	U	U
Bromoform	U	U	U
4-Methyl-2-Pentanone	U	U	U
2-Hexanone	U	U	U
1,1,2,2-Tetrachloroethane	U	U	U
Tetrachloroethene	U	U	U
Toluene	64	1	1
Chlorobenzene	U	U	U
Ethyl Benzene	U	U	U
Styrene	U	U	U
Total Zylenes	29	U	U
Trichlorofluoromethane	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table D-6-4. Volatile Organics Method Blank Report for Simulation Series #5

Compound Name	Concentration ug/L
Chloromethane	U
Bromomethane	U
Vinyl Chloride	U
Chloroethane	U
Methylene Chloride	U
Acetone	11
Carbon Disulfide	U
1,1-Dichloroethene	U
1,1-Dichloroethane	U
Trans-1,2-Dichloroethene	U
Cis-1,2-Dichloroethene	U
Chloroform	2
1,2-Dichloroethane	U
2-Butanone	U
1,1,1-Trichloroethane	U
Carbon Tetrachloride	U
Bromodichloromethane	U
Vinyl Acetate	U
1,2-Dichloropropane	U
Trans-1,3-Dichloropropene	U
Trichloroethene	U
1,1,2-Trichloroethane	U
Benzene	U
Dibromochloromethane	U
Cis-1,3-Dichloropropene	U
2-Chloroethylvinyl Ether	U
Bromoform	U
4-Methyl-2-Pentanone	U
2-Hexanone	U
1,1,2,2-Tetrachloroethane	U
Tetrachloroethene	U
Toluene	U
Chlorobenzene	U
Ethyl Benzene	U
Styrene	U
Total Zylenes	U
Trichlorofluoromethane	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-1. - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-6-5. Semi- Volatile Organics Summary Data for Simulation #5-1
Base/Neutrals

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl) Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	1	U	5
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-1. - 182.5 hours of sub-freezing temperatures
Simulator # 1 - Produced Water from a Coal Bed Methane Well

Table D-6-6. Semi- Volatile Organics Summary Data for Simulation #5-1 Acids

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Phenol	U	2000	78
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	48	4
4-Methylphenol	U	45	2
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-2. - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil & Gas Producing Well

Table D-6-7. Semi- Volatile Organics Summary Data for Simulation #5-2
Base/Neutrals

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	U	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl) Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	U	U	U
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-2. - 182.5 hours of sub-freezing temperatures
Simulator # 2 - Produced Water from an Oil & Gas Producing Well

Table D-6-8. Semi- Volatile Organics Summary Data for Simulation #5-2 Acids

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Phenol	2200	1000	U
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	U	U
4-Methylphenol	U	U	U
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	U	U
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	U
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-3. - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-6-9. Semi- Volatile Organics Summary Data for Simulation #5-3
Base/Neutrals

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
bis(2-Chloroethyl)Ether	U	U	U
1,3-Dichlorobenzene	4	U	U
1,4-Dichlorobenzene	U	U	U
1,2-Dichlorobenzene	U	U	U
bis(2-chloroisopropyl) Ether	U	U	U
N-Nitroso-Di-n-Propylamine	U	U	U
Hexachloroethane	U	U	U
Nitrobenzene	U	U	U
Isophorone	U	U	U
bis(2-Chloroethoxy)Methane	U	U	U
1,2,4-Trichlorobenzene	U	U	U
Naphthalene	U	U	U
4-Chloroaniline	U	U	U
Hexachlorobutadiene	U	U	U
2-Methylnaphtalene	U	U	U
Hexachlorocyclopentadiene	U	U	U
2-Chloronaphthalene	U	U	U
2-Nitroaniline	U	U	U
Dimethylphthalate	U	U	U
2,6-Dinitrotoluene	U	U	U
Acenaphthylene	U	U	U
3-Nitroaniline	U	U	U
Acenaphthene	U	U	U
Dibenzofuran	U	U	U
2,4-Dinitrotoluene	U	U	U
Diethylphthalate	U	U	U
4-Chlorophenyl-phenylether	U	U	U
Fluorene	U	U	U
4-Nitroaniline	U	U	U
N-Nitrosodiphenylamine	U	U	U
4-Bromophenyl-phenylether	U	U	U
Hexachlorobenzene	U	U	U
Phenanthrene	U	U	U
Anthracene	U	U	U
Di-n-Butylphthalate	U	U	U
Fluoranthene	U	U	U
Pyrene	U	U	U
Butylbenzylphthalate	U	U	U
3,3'-Dichlorobenzidine	U	U	U
Benzo(a)Anthracene	U	U	U
bis(2-Ethylhexyl) Phthalate	3	U	1
Chrysene	U	U	U
Di-n-Octyl Phthalate	U	U	U
Benzo(b)Fluoranthene	U	U	U
Benzo(k)Fluoranthene	U	U	U
Benzo(a)Pyrene	U	U	U
Ideno(1,2,3-cd)Pyrene	U	U	U
Dibenz(a,h)Anthracene	U	U	U
Benzo(g,h,i)Perylene	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

FTE Simulation # 5-3. - 182.5 hours of sub-freezing temperatures
Simulator # 3 - Produced Water from a Natural Gas Producing Well

Table D-6-10. Semi- Volatile Organics Summary Data for Simulation #5-3 Acids

Compound Name	Produced Water Concentration ug/L	Brine Concentration ug/L	Treated Water Concentration ug/L
Phenol	4	2100	53
2-Chlorophenol	U	U	U
Benzylalcohol	U	U	U
2-Methylphenol	U	87	6
4-Methylphenol	U	84	5
2-Nitrophenol	U	U	U
2,4-Dimethylphenol	U	U	U
Benzoic Acid	U	300	11
2,4-Dichlorophenol	U	U	U
4-Chloro-3-Methylphenol	U	U	4
2,4,6-Tricholorophenol	U	U	U
2,4-Dinitrophenol	U	U	U
4-Nitrophenol	U	U	U
4,6-Dinitro-2-Methylphenol	U	U	U
Pentachlorophenol	U	U	U
2,4,5-Trichlorophenol	U	U	U

U: Compound analyzed for, but not detected above the reporting limits.

Table D-6-11. Semi- Volatile Organics
Method Blank Report for Simulation Series #5

Base/Neutrals

Compound Name	Concentration ug/L
bis(2-Chloroethyl)Ether	U
1,3-Dichlorobenzene	U
1,4-Dichlorobenzene	U
1,2-Dichlorobenzene	U
bis(2-chloroisopropyl) Ether	U
N-Nitroso-Di-n-Propylamine	U
Hexachloroethane	U
Nitrobenzene	U
Isophorone	U
bis(2-Chloroethoxy)Methane	U
1,2,4-Trichlorobenzene	U
Naphthalene	U
4-Chloroaniline	U
Hexachlorobutadiene	U
2-Methylnaphtalene	U
Hexachlorocyclopentadiene	U
2-Chloronaphthalene	U
2-Nitroaniline	U
Dimethylphthalate	U
2,6-Dinitrotoluene	U
Acenaphthylene	U
3-Nitroaniline	U
Acenaphthene	U
Dibenzofuran	U
2,4-Dinitrotoluene	U
Diethylphthalate	U
4-Chlorophenyl-phenylether	U
Fluorene	U
4-Nitroaniline	U
N-Nitrosodiphenylamine	U
4-Bromophenyl-phenylether	U
Hexachlorobenzene	U
Phenanthrene	U
Anthracene	U
Di-n-Butylphthalate	U
Fluoranthene	U
Pyrene	U
Butylbenzylphthalate	U
3,3'-Dichlorobenzidine	U
Benzo(a)Anthracene	U
bis(2-Ethylhexyl) Phthalate	1
Chrysene	U
Di-n-Octyl Phthalate	U
Benzo(b)Fluoranthene	U
Benzo(k)Fluoranthene	U
Benzo(a)Pyrene	U
Ideno(1,2,3-cd)Pyrene	U
Dibenz(a,h)Anthracene	U
Benzo(g,h,i)Perylene	U

U: Compound analyzed for, but not detected
above the reporting limits

Table D-6-12. Semi- Volatile Organics
Method Blank Summary Report for Simulation Series #5
Acids

Compound Name	Produced Water Concentration ug/L
Phenol	U
2-Chlorophenol	U
Benzylalcohol	U
2-Methylphenol	U
4-Methylphenol	U
2-Nitrophenol	U
2,4-Dimethylphenol	U
Benzoic Acid	U
2,4-Dichlorophenol	U
4-Chloro-3-Methylphenol	U
2,4,6-Tricholorophenol	U
2,4-Dinitrophenol	U
4-Nitrophenol	U
4,6-Dinitro-2-Methylphenol	U
Pentachlorophenol	U
2,4,5-Trichlorophenol	U

U: Compound analyzed for, but not detected above the reporting limit

APPENDIX E

REVISED ECONOMIC RESULTS

Table E-1. Base Case Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 14,700 mg/l
TDS Concentration of Treated Water is 2000 mg/l
TDS Concentration of Brine is 50,000 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.80

Table E-2. Base Case Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	672.	245308.
Avg. Net Evaporation Rate	61.	22365.
Avg. Net Evap. Rt. when temp>32F	85.	
Avg. Brine Production Rate	267.	97327.

Table E-3. Base Case Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	177.	234.
Surface Dimension	ft	269.	250.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	65836.	54798.
	acres	1.51	1.26
Max. liq. volume	cuft	947481.	54798.
	bbl	168764.	9761.
Max. Ice Volume	cuft		1721517.
Max. Ice Melt Volume	bbl		245308.
Max. Height of Ice	ft		40.
Liner required	sqft	84927.	73651.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	81241.	55238.
Total Cost for Ponds and Pads			$ 136479.

Table E-4. Base Case Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	163.gpm 10.HP	2138.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1720.
Piping for Ponds	ft	645.	4." dia.	9806.
3-way Automatic Valves	ea	3.	4." dia.	9278.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38127.

Total Installed Capital Cost = $ 174607.

Table E-5. Base Case Economic Parameters Used

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-6. Base Case Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3559.
Sample Analyses	1500.
Maintenance	6984.
Depreciation	8730.
Property Tax and Insurance	7857.
Total Annual Expenses	33215.

Table E-7. Base Case Economic Results.

Parameter		Value
Loan	$	87303.
Equity	$	87303.
Loan Life		20. yr
Loan Payment	$	10255. yr
Total Annual Expenses	$	43470./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13948./yr
Required Annual Net Profit	$	5217./yr
Required Annual Gross Revenues	$	51496./yr

Water Treatment/Disposal Cost = $ .21 per bbl

Table E-8. Simulation 1-1 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 780 mg/l
TDS Concentration of Brine is 55,300 mg/l
Enhanced Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.93

Table E-9. Simulation 1-1 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	654.	238598.
Avg. Net Evaporation Rate	141.	51351.
Avg. Net Evap. Rt. when temp>32F	194.	
Avg. Brine Production Rate	206.	75050.

Table E-10. Simulation 1-1 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	168.	231.
Surface Dimension	ft	260.	247.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	61282.	53299.
	acres	1.41	1.22
Max. liq. volume	cuft	869285.	53299.
	bbl	154836.	9494.
Max. Ice Volume	cuft		1674429.
Max. Ice Melt Volume	bbl		238598.
Max. Height of Ice	ft		40.
Liner required	sqft	79728.	71911.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	75894.	53934.
Total Cost for Ponds and Pads			$ 129828.

Table E-11. Simulation 1-1 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	150.gpm 9.HP	2025.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1683.
Piping for Ponds	ft	630.	4." dia.	9365.
3-way Automatic Valves	ea	3.	4." dia.	9075.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37334.

Total Installed Capital Cost = $ 167161.

Table E-12. Simulation 1-1 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-13. Simulation 1-1 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3258.
Sample Analyses	1500.
Maintenance	6686.
Depreciation	8358.
Property Tax and Insurance	7522.
Total Annual Expenses	31909.

Table E-14. Simulation 1-1 Economic Results.

Parameter		Value
Loan	$	83581.
Equity	$	83581.
Loan Life		20. yr
Loan Payment	$	9817. yr
Total Annual Expenses	$	41726./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13353./yr
Required Annual Net Profit	$	4995./yr
Required Annual Gross Revenues	$	49411./yr

Water Treatment/Disposal Cost = $ .21 per bbl

Table E-15. Simulation 1-2 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 710 mg/l
TDS Concentration of Brine is 31,000 mg/l
Solar Distillation Pond Design
Maximum Pond Depth is 10 ft
Slope of Pond Sidewall is 3 ft/ft
Pond Freeboard is 2 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.26

Table E-16. Simulation 1-2 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	534.	194937.
Avg. Net Evaporation Rate	96.	34958.
Avg. Net Evap. Rt. when temp>32F	132.	
Avg. Brine Production Rate	370.	135105.

Table E-17. Simulation 1-2 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	272.	209.
Surface Dimension	ft	344.	233.
Max. fluid depth	ft	10.	4.
Evaporative area	sqft	110502.	43546.
	acres	2.54	1.00
Max. liq. volume	cuft	917098.	43546.
	bbl	163353.	7756.
Max. Ice Volume	cuft		1368027.
Max. Ice Melt Volume	bbl		194937.
Max. Height of Ice	ft		40.
Liner required	sqft	129826.	60503.
Inst. Liner Cost	$/sqft	2.01	.75
Total Installed Cost	$	261056.	45377.
Total Cost for Ponds and Pads			$ 306434.

Table E-18. Simulation 1-2 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	157.gpm 10.HP	2089.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1704.
Piping for Ponds	ft	690.	4." dia.	10390.
3-way Automatic Valves	ea	3.	4." dia.	9192.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38561.

Total Installed Capital Cost = $ 344995.

Table E-19. Simulation 1-2 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-20. Simulation 1-2 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3428.
Sample Analyses	1500.
Maintenance	13800.
Depreciation	17250.
Property Tax and Insurance	15525.
Total Annual Expenses	56087.

Table E-21. Simulation 1-2 Economic Results.

Parameter		Value
Loan	$	172497.
Equity	$	172497.
Loan Life		20. yr
Loan Payment	$	20261. yr
Total Annual Expenses	$	76348./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	27558./yr
Required Annual Net Profit	$	10309./yr
Required Annual Gross Revenues	$	92208./yr

Water Treatment/Disposal Cost = $ .47 per bbl

Table E-22. Simulation 1-3 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 1580 mg/l
TDS Concentration of Brine is 42,000 mg/l
Enhanced Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.02

Table E-23. Simulation 1-3 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	584.	213320.
Avg. Net Evaporation Rate	155.	56463.
Avg. Net Evap. Rt. when temp>32F	214.	
Avg. Brine Production Rate	261.	95217.

Table E-24. Simulation 1-3 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	166.	218.
Surface Dimension	ft	258.	234.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	60310.	47652.
	acres	1.38	1.09
Max. liq. volume	cuft	852956.	47652.
	bbl	151928.	8488.
Max. Ice Volume	cuft		1497032.
Max. Ice Melt Volume	bbl		213320.
Max. Height of Ice	ft		40.
Liner required	sqft	78618.	65327.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	74759.	48995.
Total Cost for Ponds and Pads			$ 123754.

Table E-25. Simulation 1-3 Design and Installed Cost for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	147.gpm 9.HP	2005.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1676.
Piping for Ponds	ft	603.	4." dia.	8925.
3-way Automatic Valves	ea	3.	4." dia.	9038.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 36830.

Total Installed Capital Cost = $ 160584.

Table E-26. Simulation 1-3 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-27. Simulation 1-3 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3205.
Sample Analyses	1500.
Maintenance	6423.
Depreciation	8029.
Property Tax and Insurance	7226.
Total Annual Expenses	30968.

Table E-28. Simulation 1-3 Economic Results.

Parameter		Value
Loan	$	80292.
Equity	$	80292.
Loan Life		20. yr
Loan Payment	$	9431. yr
Total Annual Expenses	$	40399./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	12828./yr
Required Annual Net Profit	$	4798./yr
Required Annual Gross Revenues	$	47781./yr

Water Treatment/Disposal Cost = $ .22 per bbl

Table E-29. Simulation 1-4 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 580 mg/l
TDS Concentration of Brine is 44,000 mg/l
Enhanced Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.87

Table E-30. Simulation 1-4 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	607.	221562.
Avg. Net Evaporation Rate	131.	47810.
Avg. Net Evap. Rt. when temp>32F	181.	
Avg. Brine Production Rate	262.	95628.

Table E-31. Simulation 1-4 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	169.	222.
Surface Dimension	ft	261.	238.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	61876.	49493.
	acres	1.42	1.14
Max. liq. volume	cuft	880796.	49493.
	bbl	156887.	8816.
Max. Ice Volume	cuft		1554872.
Max. Ice Melt Volume	bbl		221562.
Max. Height of Ice	ft		40.
Liner required	sqft	80421.	67480.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	76627.	50610.
Total Cost for Ponds and Pads			$ 127236.

Table E-32. Simulation 1-4 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	151.gpm 9.HP	2039.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1687.
Piping for Ponds	ft	614.	4." dia.	9155.
3-way Automatic Valves	ea	3.	4." dia.	9101.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37168.

Total Installed Capital Cost = $ 164405.

Table E-33. Simulation 1-4 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-34. Simulation 1-4 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3295.
Sample Analyses	1500.
Maintenance	6576.
Depreciation	8220.
Property Tax and Insurance	7398.
Total Annual Expenses	31573.

Table E-35. Simulation 1-4 Economic Results.

Parameter		Value
Loan	$	82202.
Equity	$	82202.
Loan Life		20. yr
Loan Payment	$	9655. yr
Total Annual Expenses	$	41229./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13133./yr
Required Annual Net Profit	$	4913./yr
Required Annual Gross Revenues	$	48787./yr

Water Treatment/Disposal Cost = $ .22 per bbl

Table E-36. Simulation 1-5 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 620 mg/l
TDS Concentration of Brine is 25,400 mg/l
Solar Distillation Pond Design
Maximum Pond Depth is 10 ft
Slope of Pond Sidewall is 3 ft/ft
Pond Freeboard is 2 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.31

Table E-37. Simulation 1-5 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	432.	157839.
Avg. Net Evaporation Rate	111.	40695.
Avg. Net Evap. Rt. when temp>32F	154.	
Avg. Brine Production Rate	456.	166466.

Table E-38. Simulation 1-5 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	270.	188.
Surface Dimension	ft	341.	212.
Max. fluid depth	ft	10.	4.
Evaporative area	sqft	108516.	35258.
	acres	2.49	.81
Max. liq. volume	cuft	887343.	35258.
	bbl	158053.	6280.
Max. Ice Volume	cuft		1107680.
Max. Ice Melt Volume	bbl		157839.
Max. Height of Ice	ft		40.
Liner required	sqft	127666.	50657.
Inst. Liner Cost	$/sqft	2.01	.75
Total Installed Cost	$	256444.	37993.
Total Cost for Ponds and Pads			$ 294437.

Table E-39. Simulation 1-5 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	155.gpm 9.HP	2067.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1697.
Piping for Ponds	ft	645.	4." dia.	9674.
3-way Automatic Valves	ea	3.	4." dia.	9152.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37775.

Total Installed Capital Cost = $ 332211.

Table E-40. Simulation 1-5 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-41. Simulation 1-5 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3369.
Sample Analyses	1500.
Maintenance	13288.
Depreciation	16611.
Property Tax and Insurance	14950.
Total Annual Expenses	54301.

Table E-42. Simulation 1-5 Economic Results.

Parameter	Value
Loan	$ 166106.
Equity	$ 166106.
Loan Life	20. yr
Loan Payment	$ 19511. yr
Total Annual Expenses	$ 73812./yr
Pres. Worth of Rec. Cap. and Sal	$ 0.
Present Worth Factor	6.26
Required Annual Cash Flow	$ 26537./yr
Required Annual Net Profit	$ 9927./yr
Required Annual Gross Revenues	$ 89084./yr

Water Treatment/Disposal Cost = $ .56 per bbl

Table E-43. Simulation 1-6 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 930 mg/l
TDS Concentration of Brine is 32,300 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.51

Table E-44. Simulation 1-6 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	622.	226960.
Avg. Net Evaporation Rate	28.	10319.
Avg. Net Evap. Rt. when temp>32F	39.	
Avg. Brine Production Rate	350.	127721.

Table E-45. Simulation 1-6 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	182.	225.
Surface Dimension	ft	274.	241.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	68416.	50699.
	acres	1.57	1.16
Max. liq. volume	cuft	991888.	50699.
	bbl	176674.	9030.
Max. Ice Volume	cuft		1592753.
Max. Ice Melt Volume	bbl		226960.
Max. Height of Ice	ft		40.
Liner required	sqft	87863.	68886.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	84265.	51665.
Total Cost for Ponds and Pads			$ 135930.

Table E-46. Simulation 1-6 Design and Installed Cost for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	169.gpm 10.HP	2183.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1735.
Piping for Ponds	ft	632.	4." dia.	9692.
3-way Automatic Valves	ea	3.	4." dia.	9359.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38154.

Total Installed Capital Cost = $ 174085.

Table E-47. Simulation 1-6 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-48. Simulation 1-6 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3684.
Sample Analyses	1500.
Maintenance	6963.
Depreciation	8704.
Property Tax and Insurance	7834.
Total Annual Expenses	33270.

Table E-49. Simulation 1-6 Economic Results.

Parameter		Value
Loan	$	87042.
Equity	$	87042.
Loan Life		20. yr
Loan Payment	$	10224. yr
Total Annual Expenses	$	43494./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13906./yr
Required Annual Net Profit	$	5202./yr
Required Annual Gross Revenues	$	51496./yr

Water Treatment/Disposal Cost = $ .23 per bbl

Table E-50. Simulation 1-7 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 830 mg/l
TDS Concentration of Brine is 33,000 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.43

Table E-51. Simulation 1-7 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	637.	232586.
Avg. Net Evaporation Rate	19.	6859.
Avg. Net Evap. Rt. when temp>32F	26.	
Avg. Brine Production Rate	344.	125554.

Table E-52. Simulation 1-7 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	184.	228.
Surface Dimension	ft	275.	244.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	69301.	51956.
	acres	1.59	1.19
Max. liq. volume	cuft	1004595.	51956.
	bbl	178938.	9254.
Max. Ice Volume	cuft		1632240.
Max. Ice Melt Volume	bbl		232586.
Max. Height of Ice	ft		40.
Liner required	sqft	88845.	70350.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	85238.	52763.
Total Cost for Ponds and Pads			$ 138000.

Table E-53. Simulation 1-7 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	171.gpm 10.HP	2196.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1739.
Piping for Ponds	ft	639.	4." dia.	9831.
3-way Automatic Valves	ea	3.	4." dia.	9381.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38333.

Total Installed Capital Cost = $ 176333.

Table E-54. Simulation 1-7 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-55. Simulation 1-7 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3720.
Sample Analyses	1500.
Maintenance	7053.
Depreciation	8817.
Property Tax and Insurance	7935.
Total Annual Expenses	33609.

Table E-56. Simulation 1-7 Economic Results.

Parameter		Value
Loan	$	88167.
Equity	$	88167.
Loan Life		20. yr
Loan Payment	$	10356. yr
Total Annual Expenses	$	43965./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14086./yr
Required Annual Net Profit	$	5269./yr
Required Annual Gross Revenues	$	52071./yr

Water Treatment/Disposal Cost = $ .22 per bbl

Table E-57. Simulation 1-8 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 1140 mg/l
TDS Concentration of Brine is 42,300 mg/l
Solar Distillation Pond Design
Maximum Pond Depth is 10 ft
Slope of Pond Sidewall is 3 ft/ft
Pond Freeboard is 2 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.35

Table E-58. Simulation 1-8 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	612.	223358.
Avg. Net Evaporation Rate	124.	45405.
Avg. Net Evap. Rt. when temp>32F	172.	
Avg. Brine Production Rate	264.	96237.

Table E-59. Simulation 1-8 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	269.	223.
Surface Dimension	ft	340.	247.
Max. fluid depth	ft	10.	4.
Evaporative area	sqft	107495.	49894.
	acres	2.47	1.15
Max. liq. volume	cuft	871354.	49894.
	bbl	155205.	8887.
Max. Ice Volume	cuft		1567478.
Max. Ice Melt Volume	bbl		223358.
Max. Height of Ice	ft		40.
Liner required	sqft	126540.	67948.
Inst. Liner Cost	$/sqft	2.01	.75
Total Installed Cost	$	254031.	50961.
Total Cost for Ponds and Pads			$ 304992.

Table E-60. Simulation 1-8 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	152.gpm 9.HP	2049.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1690.
Piping for Ponds	ft	715.	4." dia.	10688.
3-way Automatic Valves	ea	3.	4." dia.	9118.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38731.

Total Installed Capital Cost = $ 343723.

Table E-61. Simulation 1-8 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-62. Simulation 1-8 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3320.
Sample Analyses	1500.
Maintenance	13749.
Depreciation	17186.
Property Tax and Insurance	15468.
Total Annual Expenses	55806.

Table E-63. Simulation 1-8 Economic Results.

Parameter	Value
Loan	$ 171861.
Equity	$ 171861.
Loan Life	20. yr
Loan Payment	$ 20187. yr
Total Annual Expenses	$ 75993./yr
Pres. Worth of Rec. Cap. and Sal	$ 0.
Present Worth Factor	6.26
Required Annual Cash Flow	$ 27457./yr
Required Annual Net Profit	$ 10271./yr
Required Annual Gross Revenues	$ 91794./yr

Water Treatment/Disposal Cost = $ .41 per bbl

Table E-64. Simulation 1-9 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 11,900 mg/l
TDS Concentration of Treated Water is 1040 mg/l
TDS Concentration of Brine is 53,300 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.63

Table E-65. Simulation 1-9 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	749.	273532.
Avg. Net Evaporation Rate	42.	15443.
Avg. Net Evap. Rt. when temp>32F	58.	
Avg. Brine Production Rate	208.	76025.

Table E-66. Simulation 1-9 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	180.	247.
Surface Dimension	ft	272.	263.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	67344.	61102.
	acres	1.55	1.40
Max. liq. volume	cuft	972885.	61102.
	bbl	173289.	10883.
Max. Ice Volume	cuft		1919584.
Max. Ice Melt Volume	bbl		273532.
Max. Height of Ice	ft		40.
Liner required	sqft	86639.	80933.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	82996.	60699.
Total Cost for Ponds and Pads			$ 143695.

Table E-67. Simulation 1-9 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	167.gpm 10.HP	2164.
Freezing Pad Sprinklers	ea	5.	-------	225.
Freezing Pad Piping	ft	200.	2." dia.	2044.
Piping for Ponds	ft	674.	4." dia.	10300.
3-way Automatic Valves	ea	3.	4." dia.	9325.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 39063.

Total Installed Capital Cost = $ 182758.

Table E-68. Simulation 1-9 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-69. Simulation 1-9 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3631.
Sample Analyses	1500.
Maintenance	7310.
Depreciation	9138.
Property Tax and Insurance	8224.
Total Annual Expenses	34387.

Table E-70. Simulation 1-9 Economic Results.

Parameter		Value
Loan	$	91379.
Equity	$	91379.
Loan Life		20. yr
Loan Payment	$	10733. yr
Total Annual Expenses	$	45121./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14599./yr
Required Annual Net Profit	$	5461./yr
Required Annual Gross Revenues	$	53522./yr

Water Treatment/Disposal Cost = $ .20 per bbl

Table E-71. Simulation 2-1 Input Variables.

Northeastern Colorado Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 10,800 mg/l
TDS Concentration of Treated Water is 386 mg/l
TDS Concentration of Brine is 54,300 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.67

Table E-72. Simulation 2-1 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	641.	233842.
Avg. Net Evaporation Rate	165.	60224.
Avg. Net Evap. Rt. when temp>32F	202.	
Avg. Brine Production Rate	194.	70934.

Table E-73. Simulation 2-1 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	178.	229.
Surface Dimension	ft	269.	245.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	66245.	52236.
	acres	1.52	1.20
Max. liq. volume	cuft	953007.	52236.
	bbl	169749.	9304.
Max. Ice Volume	cuft		1641049.
Max. Ice Melt Volume	bbl		233842.
Max. Height of Ice	ft		40.
Liner required	sqft	85381.	70676.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	81684.	53007.
Total Cost for Ponds and Pads			$ 134692.

Table E-74. Simulation 2-1 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	221.gpm 13.HP	2567.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1854.
Piping for Ponds	ft	635.	5." dia.	10404.
3-way Automatic Valves	ea	3.	5." dia.	10001.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 40011.

Total Installed Capital Cost = $ 174703.

Table E-75. Simulation 2-1 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-76. Simulation 2-1 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	4804.
Sample Analyses	1500.
Maintenance	6988.
Depreciation	8735.
Property Tax and Insurance	7862.
Total Annual Expenses	33709.

Table E-77. Simulation 2-1 Economic Results.

Parameter		Value
Loan	$	87352.
Equity	$	87352.
Loan Life		20. yr
Loan Payment	$	10260. yr
Total Annual Expenses	$	43970./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13955./yr
Required Annual Net Profit	$	5220./yr
Required Annual Gross Revenues	$	52001./yr

Water Treatment/Disposal Cost = $ .22 per bbl

Table E-78. Simulation 2-2 Input Variables.

Northeastern Colorado Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 8,530 mg/l
TDS Concentration of Treated Water is 484 mg/l
TDS Concentration of Brine is 50,700 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.70

Table E-79. Simulation 2-2 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	670.	244521.
Avg. Net Evaporation Rate	168.	61455.
Avg. Net Evap. Rt. when temp>32F	206.	
Avg. Brine Production Rate	162.	59024.

Table E-80. Simulation 2-2 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	177.	234.
Surface Dimension	ft	269.	250.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	65884.	54622.
	acres	1.51	1.25
Max. liq. volume	cuft	949055.	54622.
	bbl	169045.	9729.
Max. Ice Volume	cuft		1715993.
Max. Ice Melt Volume	bbl		244521.
Max. Height of Ice	ft		40.
Liner required	sqft	84989.	73447.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	81317.	55085.
Total Cost for Ponds and Pads			$ 136402.

Table E-81. Simulation 2-2 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	220.gpm 13.HP	2561.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1852.
Piping for Ponds	ft	644.	5." dia.	10546.
3-way Automatic Valves	ea	3.	5." dia.	9991.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 40136.

Total Installed Capital Cost = $ 176538.

Table E-82. Simulation 2-2 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-83. Simulation 2-2 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	4785.
Sample Analyses	1500.
Maintenance	7062.
Depreciation	8827.
Property Tax and Insurance	7944.
Total Annual Expenses	33938.

Table E-84. Simulation 2-2 Economic Results.

Parameter		Value
Loan	$	88269.
Equity	$	88269.
Loan Life		20. yr
Loan Payment	$	10368. yr
Total Annual Expenses	$	44306./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14102./yr
Required Annual Net Profit	$	5275./yr
Required Annual Gross Revenues	$	52421./yr

Water Treatment/Disposal Cost = $ .21 per bbl

Table E-85. Simulation 2-3 Input Variables.

Northeastern Colorado Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 2,680 mg/l
TDS Concentration of Treated Water is 308 mg/l
TDS Concentration of Brine is 42,300 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.98

Table E-86. Simulation 2-3 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	747.	272486.
Avg. Net Evaporation Rate	196.	71373.
Avg. Net Evap. Rt. when temp>32F	239.	
Avg. Brine Production Rate	58.	21141.

Table E-87. Simulation 2-3 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	173.	247.
Surface Dimension	ft	264.	263.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	63633.	60868.
	acres	1.46	1.40
Max. liq. volume	cuft	907289.	60868.
	bbl	161606.	10842.
Max. Ice Volume	cuft		1912244.
Max. Ice Melt Volume	bbl		272486.
Max. Height of Ice	ft		40.
Liner required	sqft	82395.	80664.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	78598.	60498.
Total Cost for Ponds and Pads			$ 139096.

Table E-88. Simulation 2-3 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	213.gpm 13.HP	2509.
Freezing Pad Sprinklers	ea	5.	-------	225.
Freezing Pad Piping	ft	200.	2." dia.	2172.
Piping for Ponds	ft	666.	5." dia.	10818.
3-way Automatic Valves	ea	3.	5." dia.	9908.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 40638.

Total Installed Capital Cost = $ 179733.

Table E-89. Simulation 2-3 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-90. Simulation 2-3 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	4629.
Sample Analyses	1500.
Maintenance	7189.
Depreciation	8987.
Property Tax and Insurance	8088.
Total Annual Expenses	34213.

Table E-91. Simulation 2-3 Economic Results.

Parameter		Value
Loan	$	89867.
Equity	$	89867.
Loan Life		20. yr
Loan Payment	$	10556. yr
Total Annual Expenses	$	44768./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14357./yr
Required Annual Net Profit	$	5371./yr
Required Annual Gross Revenues	$	53031./yr

Water Treatment/Disposal Cost = $ .19 per bbl

Table E-92. Simulation 3-1 Input Variables.

Northwestern New Mexico Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 10,340 mg/l
TDS Concentration of Treated Water is 1380 mg/l
TDS Concentration of Brine is 41,200 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.11

Table E-93. Simulation 3-1 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	604.	220518.
Avg. Net Evaporation Rate	165.	60264.
Avg. Net Evap. Rt. when temp>32F	193.	
Avg. Brine Production Rate	231.	84218.

Table E-94. Simulation 3-1 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	174.	222.
Surface Dimension	ft	266.	238.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	64356.	49260.
	acres	1.48	1.13
Max. liq. volume	cuft	922812.	49260.
	bbl	164370.	8774.
Max. Ice Volume	cuft		1547547.
Max. Ice Melt Volume	bbl		220518.
Max. Height of Ice	ft		40.
Liner required	sqft	83248.	67207.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	79525.	50406.
Total Cost for Ponds and Pads			$ 129931.

Table E-95. Simulation 3-1 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	281.gpm 17.HP	2974.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	3." dia.	1969.
Piping for Ponds	ft	618.	5." dia.	10753.
3-way Automatic Valves	ea	3.	5." dia.	10622.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 41503.

Total Installed Capital Cost = $ 171434.

Table E-96. Simulation 3-1 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-97. Simulation 3-1 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	6115.
Sample Analyses	1500.
Maintenance	6857.
Depreciation	8572.
Property Tax and Insurance	7715.
Total Annual Expenses	34578.

Table E-98. Simulation 3-1 Economic Results.

Parameter		Value
Loan	$	85717.
Equity	$	85717.
Loan Life		20. yr
Loan Payment	$	10068. yr
Total Annual Expenses	$	44646./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13694./yr
Required Annual Net Profit	$	5123./yr
Required Annual Gross Revenues	$	52527./yr

Water Treatment/Disposal Cost = $ .24 per bbl

Table E-99. Simulation 3-2 Input Variables.

Northwestern New Mexico Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 8,180 mg/l
TDS Concentration of Treated Water is 866 mg/l
TDS Concentration of Brine is 27,900 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 0.93

Table E-100. Simulation 3-2 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	585.	213433.
Avg. Net Evaporation Rate	140.	51178.
Avg. Net Evap. Rt. when temp>32F	164.	
Avg. Brine Production Rate	275.	100389.

Table E-101. Simulation 3-2 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	179.	218.
Surface Dimension	ft	271.	234.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	66876.	47677.
	acres	1.54	1.09
Max. liq. volume	cuft	948886.	47677.
	bbl	169015.	8492.
Max. Ice Volume	cuft		1497827.
Max. Ice Melt Volume	bbl		213433.
Max. Height of Ice	ft		40.
Liner required	sqft	86112.	65357.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	82156.	49017.
Total Cost for Ponds and Pads			$ 131174.

Table E-102. Simulation 3-2 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	289.gpm 18.HP	3028.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	3." dia.	1984.
Piping for Ponds	ft	615.	5." dia.	10791.
3-way Automatic Valves	ea	3.	5." dia.	10701.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 41689.

Total Installed Capital Cost = $ 172862.

Table E-103. Simulation 3-2 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-104. Simulation 3-2 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	6297.
Sample Analyses	1500.
Maintenance	6914.
Depreciation	8643.
Property Tax and Insurance	7779.
Total Annual Expenses	34953.

Table E-105. Simulation 3-2 Economic Results.

Parameter		Value
Loan	$	86431.
Equity	$	86431.
Loan Life		20. yr
Loan Payment	$	10152. yr
Total Annual Expenses	$	45105./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13808./yr
Required Annual Net Profit	$	5165./yr
Required Annual Gross Revenues	$	53052./yr

Water Treatment/Disposal Cost = $ .25 per bbl

Table E-106. Simulation 3-3 Input Variables.

Northwestern New Mexico Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 2,600 mg/l
TDS Concentration of Treated Water is 240 mg/l
TDS Concentration of Brine is 12,500 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.01

Table E-107. Simulation 3-3 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	653.	238269.
Avg. Net Evaporation Rate	152.	55387.
Avg. Net Evap. Rt. when temp>32F	177.	
Avg. Brine Production Rate	195.	71344.

Table E-108. Simulation 3-3 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	177.	231.
Surface Dimension	ft	268.	247.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	65740.	53225.
	acres	1.51	1.22
Max. liq. volume	cuft	944414.	53225.
	bbl	168218.	9480.
Max. Ice Volume	cuft		1672119.
Max. Ice Melt Volume	bbl		238269.
Max. Height of Ice	ft		40.
Liner required	sqft	84806.	71826.
Inst. Liner Cost	$/sqft	.96	.75
Total Installed Cost	$	81093.	53870.
Total Cost for Ponds and Pads			$ 134963.

Table E-109. Simulation 3-3 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	285.gpm 17.HP	3003.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	3." dia.	1977.
Piping for Ponds	ft	638.	5." dia.	11153.
3-way Automatic Valves	ea	3.	5." dia.	10664.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 41983.

Total Installed Capital Cost = $ 176945.

Table E-110. Simulation 3-3 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-111. Simulation 3-3 Annual Operating Expenses.

Expense	$/yr
Salaries	2320.
Operator Vehicle/Fuel	1500.
Electricity	6212.
Sample Analyses	1500.
Maintenance	7078.
Depreciation	8847.
Property Tax and Insurance	7963.
Total Annual Expenses	35420.

Table E-112. Simulation 3-3 Economic Results.

Parameter		Value
Loan	$	88473.
Equity	$	88473.
Loan Life		20. yr
Loan Payment	$	10392. yr
Total Annual Expenses	$	45812./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14135./yr
Required Annual Net Profit	$	5287./yr
Required Annual Gross Revenues	$	53946./yr

Water Treatment/Disposal Cost = $ .23 per bbl

Table E-113. Simulation 4-1 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 10,700 mg/l
TDS Concentration of Treated Water is 430 mg/l
TDS Concentration of Brine is 69,500 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.44

Table E-114. Simulation 4-1 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	725.	264444.
Avg. Net Evaporation Rate	126.	46084.
Avg. Net Evap. Rt. when temp>32F	174.	
Avg. Brine Production Rate	149.	54472.

Table E-115. Simulation 4-1 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	168.	243.
Surface Dimension	ft	259.	259.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	60996.	59072.
	acres	1.40	1.36
Max. liq. volume	cuft	860430.	59072.
	bbl	153259.	10522.
Max. Ice Volume	cuft		1855807.
Max. Ice Melt Volume	bbl		264444.
Max. Height of Ice	ft		40.
Liner required	sqft	79363.	78594.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	75456.	58945.
Total Cost for Ponds and Pads			$ 134401.

Table E-116. Simulation 4-1 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	152.gpm 9.HP	2046.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1690.
Piping for Ponds	ft	654.	4." dia.	9768.
3-way Automatic Valves	ea	3.	4." dia.	9113.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37802.

Total Installed Capital Cost = $ 172203.

Table E-117. Simulation 4-1 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-118. Simulation 4-1 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3313.
Sample Analyses	1500.
Maintenance	6888.
Depreciation	8610.
Property Tax and Insurance	7749.
Total Annual Expenses	32644.

Table E-119. Simulation 4-1 Economic Results.

Parameter		Value
Loan	$	86102.
Equity	$	86102.
Loan Life		20. yr
Loan Payment	$	10113. yr
Total Annual Expenses	$	42758./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13756./yr
Required Annual Net Profit	$	5146./yr
Required Annual Gross Revenues	$	50674./yr

Water Treatment/Disposal Cost = $ .19 per bbl

Table E-120. Simulation 4-2 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 8,690 mg/l
TDS Concentration of Treated Water is 410 mg/l
TDS Concentration of Brine is 47,900 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.48

Table E-121. Simulation 4-2 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	696.	253952.
Avg. Net Evaporation Rate	129.	47104.
Avg. Net Evap. Rt. when temp>32F	178.	
Avg. Brine Production Rate	175.	63944.

Table E-122. Simulation 4-2 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	166.	238.
Surface Dimension	ft	258.	254.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	60443.	56728.
	acres	1.39	1.30
Max. liq. volume	cuft	857035.	56728.
	bbl	152654.	10104.
Max. Ice Volume	cuft		1782181.
Max. Ice Melt Volume	bbl		253952.
Max. Height of Ice	ft		40.
Liner required	sqft	78788.	75887.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	74962.	56915.
Total Cost for Ponds and Pads			$ 131877.

Table E-123. Simulation 4-2 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	152.gpm 9.HP	2042.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1688.
Piping for Ponds	ft	642.	4." dia.	9585.
3-way Automatic Valves	ea	3.	4." dia.	9106.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37607.

Total Installed Capital Cost = $ 169484.

Table E-124. Simulation 4-2 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-125. Simulation 4-2 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3302.
Sample Analyses	1500.
Maintenance	6779.
Depreciation	8474.
Property Tax and Insurance	7627.
Total Annual Expenses	32267.

Table E-126. Simulation 4-2 Economic Results.

Parameter		Value
Loan	$	84742.
Equity	$	84742.
Loan Life		20. yr
Loan Payment	$	9954. yr
Total Annual Expenses	$	42220./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13539./yr
Required Annual Net Profit	$	5064./yr
Required Annual Gross Revenues	$	50012./yr

Water Treatment/Disposal Cost = $ .20 per bbl

Table E-127. Simulation 4-3 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 2,705 mg/l
TDS Concentration of Treated Water is 240 mg/l
TDS Concentration of Brine is 37,800 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.59

Table E-128. Simulation 4-3 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	794.	289875.
Avg. Net Evaporation Rate	139.	50886.
Avg. Net Evap. Rt. when temp>32F	193.	
Avg. Brine Production Rate	66.	24239.

Table E-129. Simulation 4-3 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	165.	254.
Surface Dimension	ft	256.	270.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	59772.	64753.
	acres	1.37	1.49
Max. liq. volume	cuft	843171.	64753.
	bbl	150185.	11534.
Max. Ice Volume	cuft		2034275.
Max. Ice Melt Volume	bbl		289875.
Max. Height of Ice	ft		40.
Liner required	sqft	77996.	85126.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	74111.	63845.
Total Cost for Ponds and Pads			$ 137956.

Table E-130. Simulation 4-3 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	150.gpm 9.HP.	2027.
Freezing Pad Sprinklers	ea	5.	-------	225.
Freezing Pad Piping	ft	200.	2." dia.	1990.
Piping for Ponds	ft	674.	4." dia.	10027.
3-way Automatic Valves	ea	3.	4." dia.	9079.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38353.

Total Installed Capital Cost = $ 176309.

Table E-131. Simulation 4-3 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-132. Simulation 4-3 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3263.
Sample Analyses	1500.
Maintenance	7052.
Depreciation	8815.
Property Tax and Insurance	7934.
Total Annual Expenses	33149.

Table E-133. Simulation 4-3 Economic Results.

Parameter		Value
Loan	$	88155.
Equity	$	88155.
Loan Life		20. yr
Loan Payment	$	10355. yr
Total Annual Expenses	$	43503./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	14084./yr
Required Annual Net Profit	$	5268./yr
Required Annual Gross Revenues	$	51608./yr

Water Treatment/Disposal Cost = $ .18 per bbl

Table E-134. Simulation 5-1 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 10,900 mg/l
TDS Concentration of Treated Water is 286 mg/l
TDS Concentration of Brine is 76,417 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.52

Table E-135. Simulation 5-1 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	727.	265446.
Avg. Net Evaporation Rate	133.	48562.
Avg. Net Evap. Rt. when temp>32F	184.	
Avg. Brine Production Rate	140.	50991.

Table E-136. Simulation 5-1 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	166.	244.
Surface Dimension	ft	257.	260.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	60266.	59296.
	acres	1.38	1.36
Max. liq. volume	cuft	851584.	59296.
	bbl	151683.	10562.
Max. Ice Volume	cuft		1862844.
Max. Ice Melt Volume	bbl		265446.
Max. Height of Ice	ft		40.
Liner required	sqft	78561.	78852.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	74691.	59139.
Total Cost for Ponds and Pads			$ 133830.

Table E-137. Simulation 5-1 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	151.gpm 9.HP	2036.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1686.
Piping for Ponds	ft	653.	4." dia.	9733.
3-way Automatic Valves	ea	3.	4." dia.	9095.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37737.

Total Installed Capital Cost = $ 171567.

Table E-138. Simulation 5-1 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-139. Simulation 5-1 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3287.
Sample Analyses	1500.
Maintenance	6863.
Depreciation	8578.
Property Tax and Insurance	7721.
Total Annual Expenses	32533.

Table E-140. Simulation 5-1 Economic Results.

Parameter		Value
Loan	$	85783.
Equity	$	85783.
Loan Life		20. yr
Loan Payment	$	10076. yr
Total Annual Expenses	$	42609./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13705./yr
Required Annual Net Profit	$	5127./yr
Required Annual Gross Revenues	$	50496./yr

Water Treatment/Disposal Cost = $ .19 per bbl

Table E-141. Simulation 5-2 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 8,360 mg/l
TDS Concentration of Treated Water is 206 mg/l
TDS Concentration of Brine is 49,500 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.58

Table E-142. Simulation 5-2 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	683.	249214.
Avg. Net Evaporation Rate	138.	50527.
Avg. Net Evap. Rt. when temp>32F	191.	
Avg. Brine Production Rate	179.	65259.

Table E-143. Simulation 5-2 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	165.	236.
Surface Dimension	ft	257.	252.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	59817.	55670.
	acres	1.37	1.28
Max. liq. volume	cuft	844527.	55670.
	bbl	150426.	9916.
Max. Ice Volume	cuft		1748930.
Max. Ice Melt Volume	bbl		249214.
Max. Height of Ice	ft		40.
Liner required	sqft	78053.	74662.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	74179.	55996.
Total Cost for Ponds and Pads			$ 130175.

Table E-144. Simulation 5-2 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	150.gpm 9.HP	2029.
Freezing Pad Sprinklers	ea	4.	-------	180.
Freezing Pad Piping	ft	160.	2." dia.	1684.
Piping for Ponds	ft	637.	4." dia.	9479.
3-way Automatic Valves	ea	3.	4." dia.	9081.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 37458.

Total Installed Capital Cost = $ 167633.

Table E-145. Simulation 5-2 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-146. Simulation 5-2 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3267.
Sample Analyses	1500.
Maintenance	6705.
Depreciation	8382.
Property Tax and Insurance	7543.
Total Annual Expenses	31981.

Table E-147. Simulation 5-2 Economic Results.

Parameter		Value
Loan	$	83817.
Equity	$	83817.
Loan Life		20. yr
Loan Payment	$	9845. yr
Total Annual Expenses	$	41826./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13391./yr
Required Annual Net Profit	$	5009./yr
Required Annual Gross Revenues	$	49532./yr

Water Treatment/Disposal Cost = $ .20 per bbl

Table E-148. Simulation 5-3 Input Variables.

Central Wyoming Plant Location
1000 bbl/day Produced Water Feed Rate
TDS Concentration of Produced Water is 2,640 mg/l
TDS Concentration of Treated Water is 200 mg/l
TDS Concentration of Brine is 46,620 mg/l
Conventional Evaporation Pond Design
Maximum Pond Depth is 20 ft
Slope of Pond Sidewall is 2 ft/ft
Pond Freeboard is 3 ft
Liner for Pond Berm and Anchor Trench is 6 ft
Pan Coefficient is 1.75

Table E-149. Simulation 5-3 Plant Performance (Annual Average).

	bbl/day	bbl/yr
Produced Water Rate	1000.	365000.
Avg. Treated Water Discharge Rate	794.	289794.
Avg. Net Evaporation Rate	153.	55811.
Avg. Net Evap. Rt. when temp>32F	211.	
Avg. Brine Production Rate	53.	19394.

Table E-150. Simulation 5-3 Design and Installed Cost Data for Ponds and Pads.

Item	units	Produced Water Pond/Still	Freezing Pad
Base Dimension	ft	162.	254.
Surface Dimension	ft	254.	270.
Max. fluid depth	ft	20.	4.
Evaporative area	sqft	58545.	64735.
	acres	1.34	1.49
Max. liq. volume	cuft	825464.	64735.
	bbl	147031.	11531.
Max. Ice Volume	cuft		2033713.
Max. Ice Melt Volume	bbl		289794.
Max. Height of Ice	ft		40.
Liner required	sqft	76620.	85106.
Inst. Liner Cost	$/sqft	.95	.75
Total Installed Cost	$	72751.	63829.
Total Cost for Ponds and Pads			$ 136581.

Table E-151. Simulation 5-3 Design and Installed Cost Data for Other Facility Requirements.

Item	Units	Units Required	Size	Installed Cost, $
Transfer/Circulation Pump	ea	1.	148.gpm 9.HP	2008.
Freezing Pad Sprinklers	ea	5.	-------	225.
Freezing Pad Piping	ft	200.	2." dia.	1982.
Piping for Ponds	ft	671.	4." dia.	9943.
3-way Automatic Valves	ea	3.	4." dia.	9043.
Temp/Pump Control Circuit	ea	1.	-------	945.
TDS/Valve Control Circuit	ea	1.	-------	1061.
Brine Storage Tanks	ea			5000.
Services				3000.
Buildings				5000.
Working Capital				0.
Total Cost for Other Facility Requirements				$ 38206.

Total Installed Capital Cost = $ 174787.

Table E-152. Simulation 5-3 Economic Parameters Used.

Parameter	Value
Load Factor	1.0
Plant Life	20. yr.
Equity	50. %
Bond Interest	10. %
Return on Equity	15. %
Tax Rate	35. %
Construction Period	negligible
Salvage Value	$ 0.
Working Capital	$ 0.

Table E-153. Simulation 5-3 Annual Operating Expenses.

Expense	$/yr
Salaries	2784.
Operator Vehicle/Fuel	1800.
Electricity	3212.
Sample Analyses	1500.
Maintenance	6991.
Depreciation	8739.
Property Tax and Insurance	7865.
Total Annual Expenses	32892.

Table E-154. Simulation 5-3 Economic Results.

Parameter		Value
Loan	$	87393.
Equity	$	87393.
Loan Life		20. yr
Loan Payment	$	10265. yr
Total Annual Expenses	$	43157./yr
Pres. Worth of Rec. Cap. and Sal	$	0.
Present Worth Factor		6.26
Required Annual Cash Flow	$	13962./yr
Required Annual Net Profit	$	5223./yr
Required Annual Gross Revenues	$	51192./yr

Water Treatment/Disposal Cost = $ .18 per bbl