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Final Report

USE OF SALINE WATER IN ENERGY DEVELOPMENT

by

C. Earl Israelsen, V. Dean Adams, J. Clair Batty,
Dennis B. George, Trevor C. Hughes, Alberta J.
Seierstad, H. C. Wang, and H. P. Kuo

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ABSTRACT

Maps were made of the Upper Colorado River Basin showing locations of coal deposits, oil and gas, oil shale, uranium, and tar sand, in relationship to cities and towns in the area. Superimposed on these are locations of wells showing four ranges of water quality; 1,000-3,000 mg/l, 3,000-10,000 mg/l, 10,000-35,000 mg/l, and over 35,000 mg/l. Information was assembled relative to future energy-related projects in the upper basin, and estimates were made of their anticipated water needs.

Using computer models, various options were tested for using saline water for coal-fired power plant cooling. Both cooling towers and brine evaporation ponds were included. Information is presented of several proven water treatment technologies, and comparisons are made of their cost effectiveness when placed in various combinations in the power plant makeup and blowdown water systems. A relative value scale was developed which compares graphically the relative values of waters of different salinities based on three different water treatment options and predetermined upper limits of cooling tower circulating salinities.

Coal from several different mines was slurried in waters of different salinities. Samples were analyzed in the laboratory to determine which constituents had been leached from or absorbed by the coal, and what possible deleterious effects this might have on the burning properties of the coal, or on the water for culinary use or irrigation.

ACKNOWLEDGMENTS

CONVERSION FACTORS

Acre - 43,560 square feet; 0.4046873 hectare
Acre foot - 0.123 hectare meter
Centimeter - 0.032808 foot; 0.39370 inch
Cubic centimeter - 0.061023 cubic inch; 0.99997 milliliter
Cubic foot - 7.481 gallons; 0.02831701 cubic meter; 28.316 liters
Cubic inch - 16.387162 cubic centimeters
Cubic meter - 35.314445 cubic feet; 264.173 gallons
Foot - 0.3048006 meter
Gallon - 0.13368 cubic foot; 231.00 cubic inches; 0.0037854 cubic
    meter; 3.7853 liters
Gram - 0.00220462 pound; 0.0352740 ounce
Gram per square millimeter - 1.42 pounds per square inch
Hectare - 2.471044 acres; 1.0764×10^5 square feet
Hectare meter - 8.1 acre feet
Inch - 2.540005 centimeters
Kilogram - 2.2046223 pounds
Kilometer - 0.62137 mile
Kilogram per cubic meter - 0.062428 pound per cubic foot
Liter - 0.26417762 gallon; 0.035316 cubic foot; 1.056710 quarts
Meter - 1.093611 yards; 3.280833 feet; 39.3700 inches
Micron - 0.000039 inch; 0.001 millimeter
Mile - 1.60935 kilometers
Ounce - 28.349527 grams
Pound - 0.453592 kilogram; 453.5924 grams
Pound per cubic foot - 16.018365 kilograms per cubic meter
Pound per square inch - 0.703067 gram per millimeter
Quart - 0.946333 liter
Square centimeter - 0.15500 square inch
Square foot - 0.09290341 square meter
Square inch - 645.16258 square millimeters
Square meter - 10.76387 square feet
Square yard - 0.83613 square meter
Ton - 907.185 kilograms (tonnage = weight in tons)
Yard - 0.91440183 meter

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Background

As energy costs continue to rise throughout the world, the United States looks more and more to the development of domestic fossil fuel reserves, many of which are located in the semiarid regions of the intermountain west. Unfortunately, the development of these resources requires large amounts of water, and the water supplies in these areas are for the most part already appropriated for culinary, irrigation, and cooling water uses, with the largest share going to agriculture. Water that has not yet been appropriated is largely underground, and much of it is very saline or briny, as measured on the salinity scale shown in Table 1.*

These highly saline waters have been generally considered a liability rather than a resource. The greatest interest in the low quality water in the area, was as a possible contributor to the salinity of the Colorado River. Most well drilling has been for gas or oil, and so in many instances, data on the water encountered during drilling were not gathered. Even when water was sought, if it were saline, the well was often capped and the driller moved to a new location.

Now the demand for water is shifting from agricultural to energy uses. This western region has an abundance of energy reserves, all of which require water for their development. As competition for water increases, prices paid for it will rise to the point that farmers can no longer afford to use it for farming. For example the Intermountain Power Project (IPP), planned for construction in Lynndyl, Utah, paid in excess of $1700 per acre foot for water purchased from agriculture. This is a big incentive for farmers in the area to abandon farming and sell all their water to energy developers. Existing developed supplies of fresh and slightly saline water are not sufficient for agriculture and energy development, too.

One approach would be to supply some users with more saline water than has been used heretofore. As mapped by Feth et al.

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*Throughout this report, all calculations are made with the assumption that parts per million (ppm) and milligrams per liter (mg/1) are equal, and they are used interchangeably.

Table 1. Water salinity scale (U.S. Geological Survey).

Class	Dissolved Solids (milligrams per liter)
Fresh	0 – 1,000
Slightly saline	1,000 – 3,000
Moderately saline	3,000 – 10,000
Very saline	10,000 – 35,000
Briny	over 35,000

(1965) in Figure 1, much of the energy-rich western United States is underlain by saline water at relatively shallow depths. If at least some of the energy development needs could be met with this low quality water that is not now being used for anything else, it would free large amounts of fresh water for agricultural, municipal, and other uses. The purpose of the present study is to investigate the availability of such water in the area and some of the possible uses that could be made of it in energy development.

Study Area

Much thought and consideration were expended in selecting the Upper Colorado River Basin as a study area. First of all, many completed studies provide background data and information. The area has potential for many different kinds of energy development schemes, processes, and opportunities. Energy resource deposits in the basin include coal, oil, oil shale, tar sands, uranium, and natural gas, all of which are currently in various stages of development. Fresh water is in short supply, and saline water is available.

Coal gasification plants proposed for the basin, if constructed, would require upwards of 100,000 ac-ft of water per year. Coal-fired power generating facilities projected for the area would use more than 500,000 ac-ft of water per year. In addition there are plans to construct coal-slurry pipelines, process oil shale, and increase mining of ores, and production of coal, uranium, and other energy related products, all of which will require water. Unless additional water sources can be found, most of the existing supplies in the basin may be utilized for developing energy, and agriculture will suffer. Before this is allowed, careful consideration should be

Figure 1. Depth to saline water (more than 1000 mg/1 dissolved solids) below land surface (adapted from Feth et al. 1965).

given to the use of saline water for energy development.

Figure 2 is a map of the study area showing the location of underground water of different qualities. The current study provides additional refinement to the information presented here, particularly in areas that are near significant energy resource deposits.

Scope and Objectives of the Study

The research was divided into three major categories, and personnel were assigned to pursue them simultaneously. One involved the collection and evaluation of physical data on water supplies, energy resources, and projections for future water use. A second involved the development of a computer model for investigating alternatives for cooling a coal-fired power plant with brackish or saline water. The third research group studied the interacting effects of coal and saline water slurried together in a pipeline, and the use implications of these effects. Each of these three research areas will be elaborated in the presentation that follows.

Figure 2.   Locations of underground water of different qualities
(Hagen et al. 1971, p. 84).

RESEARCH ACCOMPLISHMENTS

Data Collection and Evaluation

Introduction

The Upper Colorado River Basin is very sparsely populated, and much of it is virtually wasteland. Rainfall is generally light, and irrigated agriculture is limited. Hydrologic data are lacking, particularly as they pertain to underground water. For many years drilling has been done for oil and gas, and much of the available geologic and hydrologic data have been gleaned from these efforts. More recently the nation's increasing interest in energy has resulted in numerous studies being made of energy resource reserves and water supplies to develop them. These have increased significantly the amount of information available, particularly in specific areas. For example, the environmental impact statement prepared for the Intermountain Power Project (IPP) (1976) site near Cainesville, Utah, contains a wealth of information on underground and surface water supplies, and other natural resources of the area. If comparable data were available for the rest of the basin (which are not), planning to meet the water needs for development of the energy reserves would be greatly enhanced.

Numerous agencies, industries, and individuals have contributed to the information presented herein. New data are becoming available continuously, and projections change in accordance with them. Information presented in this report and conclusions drawn from it were as good as could be done at the time. However, plans and procedures for the basin should be updated regularly as more details are obtained.

Energy Reserves

Oil and gas production has been going on in the basin for many years. Hundreds of wells have been drilled and many of them are still producing. Figure 3 shows locations and relative sizes of known deposits of these important commodities. Figure 4 shows the locations of coal in the basin, and emphasizes the fact that most of the reserves are not accessible at present coal prices, because of being either too deep or in beds that are too thin. A small percentage of coal in the basin is strip-mined, and the remainder is mined underground.

In addition to coal, oil, and gas deposits, the basin contains considerable uranium. There are also large deposits of oil shale and tar sands of economic signifi-

cance (Figure 5). A map of the basin was constructed showing locations and sizes of these known reserves of energy resources, and their proximities to underground water supplies. To present more detail, the map was divided into six segments, shown in Figures 6 through 11. More information concerning water quality and quantity is presented in the following sections.

Water Supply

Surface water

Most of the surface water in the basin is of fairly good quality and has already been appropriated for municipal, industrial, and agricultural uses. When new industries enter, the needed water is generally purchased from agriculture and converted to a different use. Some shallow aquifers also contain good water, but all of these supplies together cannot meet the anticipated needs of the basin. There are also limited surface supplies of low quality water.

Irrigation return flow. One important source of brackish water is irrigation return flows. In many of the smaller tributaries of the Green and Colorado Rivers, almost all flow is diverted for irrigation use near the upper ends of valleys during most of the year. The flows in the lower reaches are therefore principally irrigation return flows as both point (ends of canals) and nonpoint sources drain into the river. Such flows usually have high TDS (total dissolved solids) due mainly to salt concentration and salt pickup during subsurface percolation through shale type formations. A typical example is the San Rafael River Basin (which is in close proximity to major coal deposits). The upper reaches of the tributaries to this river at the irrigation points of diversion have excellent water quality with TDS levels of 150 to 300 mg/l. However, reaches of these tributaries below the irrigated areas are of a much lesser quality as summarized in Table 2.

The annual flow of the Colorado River at Lees Ferry averages about 9,619,000 ac-ft at 647 mg/l TDS. The San Rafael River annual flow averages 66,000 ac-ft at 2,261 mg/l TDS. The San Rafael obviously adds to the salinity problem in the Lower Colorado (an 11 mg/l increase) and any consumptive use of this brackish water by fossil fuel developments (without return flow of salt) would have a beneficial impact upon the river as well as providing water for energy production.

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Figure 3.   Oil and gas fields in the Upper Colorado River Basin (Colorado River Regional Assessment Study, Utah Water Research Laboratory, Utah State University, 1975).

Figure 4.   Coal deposits in the Upper Colorado River Basin (Colorado River Regional Assessment Study, Utah Water Research Laboratory, Utah State University, 1975).

Figure 5. Oil shale and tar sands deposits in the Upper Colorado River Basin (Colorado River Regional Assessment Study, Utah Water Research Laboratory, Utah State University, 1975).

Table 2. Flow and quality within the San Rafael River Basin below irrigated areas.

Stream	Minimum Flows (cfs)	Approximate TDS Range (mg/1)
Ferron Creek	4 – 8	2,000 – 4,000
Cottonwood Creek	4 – 9	1,000 – 4,000
Huntington Creek	6 – 20	2,000 – 7,000
Upper San Rafael	6 – 100	2,000 – 4,000
Lower San Rafael	11 – 100	2,000 – 6,000

Saline springs. Other possible sources of high TDS water for energy development are mineral springs and uncapped artesian flows from oil exploration test wells. One constraint on this concept is the very high salinity levels of many such flows. For example, a natural salt dome in the Paradox Valley, Colorado, creates drainage at 260,000 mg/1 TDS. Obviously use of such water would entail major difficulties.

However, flows such as the 11,000 to 14,000 TDS from Crystal Geyser, an abandoned oil test hole in Utah, are more usable. The

flow averages 93 gpm and therefore is too small for a major supply, but keeping even this much salt out of the Green River would have significant benefit. The geyser is located near Green River, Utah, very close to planned coal and possibly nuclear powered generating plants.

One of the largest single point sources of salt on the Upper Colorado is a group of springs near Dotsero, Colorado--which average 14,200 mg/l for a flow of 16 cfs.

Groundwater

Quality. Groundwater data for the basin are very limited except in localized areas. Even though there have been hundreds of wells drilled in the basin over the years, most of these were drilled for oil or gas, and information pertaining to the presence of water or its quality were generally not recorded. The U.S. Geological Survey has examined many hundreds of oil and gas well logs within the basin, and extracted whatever water data they could identify, and all of these were made available to the current study (Appendix A). In addition, data and information from other available sources were obtained.

The total amount of high TDS (low quality) groundwater existing in the study area is extremely large (many millions of ac-ft); however, economic and environmental factors may limit their use. For example, much of the brackish water is overlain with fresh water. Wells to develop brackish water can be perforated in only the brackish water depths, but long term pumping of some such wells may leak fresh water into the brackish portion of the aquifer. This will decrease the availability of fresh water for other purposes and thereby obviate the extra costs associated with developing the brackish water.

Because of the large size of the Upper Colorado River Basin and the time and financial constraints of this study, only water quality situations in the vicinity of economically significant coal deposits have been mapped (Figures 6 through 11).

At least two serious deficiencies exist in the data shown: 1) Very little information is available concerning the depths from which the samples came. Some of the wells are 10,000 feet deep, and the water quality shown may be of water near the surface, very deep, or a composite of the entire geologic profile. 2) With few exceptions, no information is available concerning quantities of existing groundwater or the amount of the total that can be recovered. Some estimates have been made by people familiar with aquifer conditions in the area, but the cost of pumping tests to obtain more data is greatly beyond the scope of the present study.

Quantity. Even without making a detailed inventory, it is evident that the amount of brackish and saline water in the basin is very large. As a general rule salinity of groundwater increases with depth as is indicated by actual measurements, shown in the three-dimensional map in Figure 12. Work done by Feth et al. (1965) (Figure 1) indicates that about two-thirds of the study area is underlain by water containing in excess of 1,000 mg/l TDS at less than 500 foot depths. Figure 2 shows that according to best estimates, this saline water is not overlain by fresh water in about one-third of the Upper Colorado River Basin.

One possible approach to estimating quantities of brackish water is the analysis of electrical resistivity logs from oil and gas test holes. For example, such well logs were used in Louisiana to map the depths to various groundwater salinity thresholds (Turcan and Winslow 1970). The concept used was to estimate a representative formation resistivity factor R_f and then calculate water resistivity Rw (from which TDS can be estimated) as the ratio of the well log resistivity to the formation resistivity factor ($Rw = R_o/R_f$). In Louisiana results were reasonably accurate within the lower salinity ranges (10,000 mg/l and below). However, considerable effort was required in that it was necessary to screen 200,000 well logs to select a sample of 1,000 representative logs; then to analyze that sample by quantifying the following variables: depth, log resistivity, changes in geologic formation with depth, temperature (for correcting resistivity/TDS factors), porosity, and permeability of each formation.

This level of effort was not undertaken for the Upper Colorado River Basin for this study for the following reasons:

1. Analysis of resistivity logs requires a specialist with an understanding of both the geologic formations and the anomalies which occur in resistivity levels as the geology and water occurrence and quality change with depth. The use of such specialists for the extended period required to analyze many hundreds of well logs was not possible within the budget limitations of this study.

2. If the water TDS levels had been successfully mapped, it would then be necessary to associate each quality reading with estimated formation porosity in order to estimate the volume of water in each quality range in each aquifer. One would then proceed with estimated permeability in order to estimate the rates of flow possible from wells in areas and at depths of interest. The permeability of the Colorado Plateau sandstone varies over several orders of magnitude making estimates questionable unless actual permeability field tests have been made (see item 3). For example, the Navajo sandstone specific yield (which is

Figure 6. Water quality sampling sites near energy
           deposits (Part I).

Figure 7. Water quality sampling sites near energy
           deposits (Part II).

WATER QUALITY (mg/l)
⊙ 1,000-3,000
∗ 3,000-10,000
△ 10,000-35,000
H >35,000

▨ COAL
▨ OIL & GAS
▨ OIL SHALE
▨ URANIUM
◎ CITY OR TOWN

GRAND MESA
COAL FIELD

CRESTED BUTTE
COAL FIELD

39°

NUCLA-NATURITA
COAL FIELD

INDEX MAP

WYO.

UT.   COLO.

ARIZ.   N MEX.

38°

CORTEZ

DURANGO
COAL FIELD

SAN JUAN COAL REGION

DURANGO

37°

109°   108°   107°

BARKER
CREEK

AZTEC

HOGBACK   FARMINGTON

NAVAJO

TODDLENA   NEWCOMB   BISTI

CHACO CANYON

STANDING ROCK

STAR LAKE

CROWN POINT

INDEX MAP

37°

36°

WYO.

UT.   COLO.

ARIZ.   N MEX

35°

▨ COAL
▨ OIL & GAS
▨ OIL SHALE
▨ URANIUM
◎ CITY OR TOWN

WATER QUALITY (mg/l)
⊙ 1,000-3,000
∗ 3,000-10,000
△ 10,000-35,000
H >35,000

109°   108°   107°

10

Figure 8.   Water quality sampling sites near energy
deposits (Part III).

Figure 9.   Water quality sampling sites near energy
deposits (Part IV).

Figure 10. Water quality sampling sites near energy deposits (Part V).

Figure 11. Water quality sampling sites near energy deposits (Part VI).

11

+

+ 40°

+

110° 30'

110° 00'

FEET

UINTA
BASIN

< 2,000

10,000

8,000

2,000-35,000

UTAH CO.

UTAH CO. DUCHESNE CO.

DUCHESNE CO.

6,000

CARBON CO.

CARBON CO.

> 35,000

4,000

APPROXIMATE DISSOLVED
SOLIDS CONCENTRATION
IN GROUND WATER IN mg/l

2,000

SANPETE CO.

CARBON CO.
EMERY CO.

PRICE

0

BOUNDARY OF STUDY
AREA, BROKEN ALONG MAJOR
DRAINAGE DIVIDE.

VERTICAL
SCALE

39°30'
+

WELL

BOTTOM OF WELL

UINTA CO.

CARBON CO.
EMERY CO.

UINTA
GRAND CO.

COUNTY LINE

GRAND CO.

UTAH
COLORADO

WASATCH PLATEAU

12

BOOK CLIFFS

UINTA CO.
GRAND CO.

39°00'
+

SANPETE
SEVIER CO.

EMERY CO.

SAN
RAFAEL
SWELL

UTAH
COLORADO

111°30' SEVIER CO.
+   EMERY CO.

111°00'
+

110°30'
+

110°00'
EMERY CO.   GRAND CO.

109°30'
+

GRAND CO.

WAYNE CO.

WAYNE CO.   SAN JUAN CO.

SAN JUAN CO.

Figure 12. Three dimensional map section of area near Price, Utah, showing general increase in groundwater salinity
with depth (U.S.G.S. Open File Report 79-988 Hydrologic Recon. of the Wasatch Plateau-Book Cliffs Coal
Fields Area, Utah, by K. M. Waddel et al. 1979).

much more stable than horizontal permeability) averages about 5 percent while that of the Ferron sandstone is about 0.4 percent.

3. Most of the resistivity logs in the study region which include drill stem tests and would therefore yield good permeability information, have already been analyzed in groundwater studies by the U.S. Geological Survey. The reports themselves were available and used.

The calculated amount of water that would drain freely from the upper 100 feet of sandstone in one-half of the 108,000 square mile Upper Colorado River Basin area (assuming a specific yield of 8 percent) is 277 million ac-ft. Of course, not all of these aquifers would produce wells with sufficient yield to make groundwater production economically feasible. But on the other hand, much of the saline water is in alluvial deposits in valleys which would yield considerably more than the sandstone aquifers indicated above.

Individuals who have studied parts of the Colorado River Basin area are confident that great quantities of underground water are there, probably well in excess of 200 million ac-ft, and they also believe that much of this can probably be recovered. This estimate corresponds roughly with the above calculation.

Water Requirements for Energy Development

Water is used in many aspects of energy development including mining, reclamation of mined land, onsite processing, transportation, power plant cooling, refining, and conversion of the mined fuels to other forms of energy. Projections of water requirements for the basin vary greatly with time, and with the individual making the projection, but the general concensus is that more will be required than is presently available. This means that not only will present uses have to change but additional sources will need to be developed.

Figure 13, made in 1978, depicts ongoing and projected energy related projects in the Upper Colorado River Basin. Numbers of projected facilities, identified on this map, are itemized by type in Table 3. An estimate of the amount of water required to operate these projects can be made by utilizing data from Tables 4 and 5a in conjunction with those from Table 3. Table 5b indicates the expected percent increase in market price of various energy products if saline water were used requiring treatment costing $500/ac-ft more than high quality waters. One might infer that it is economically realistic to utilize saline waters in energy development even if relatively high treatment costs are involved. The present study is interested primarily in water for coal-fired power plant cooling, and water as a transport medium for slurrying coal in

Table 3. Number of future energy-related projects, by type of facility. (From Figure 13.)

Type of Facility	Number
Strip Coal Mines	31
Underground Coal Mines	51
Coal-fired Electric Generating Plants	9
Coal Conversion Plants	3
Oil Shale Projects	10
Uranium Mines	30
Uranium Mills and Enrichments	5
Oil Refineries	5
Natural Gas Projects	3
Tar Sands Projects	2
Coal Slurry Pipelines	2
Petroleum and Natural Gas Pipelines	2
Total Facilities	153

Table 4. Btu yield of various energy sources (Water and Energy 1974).

Sources	Units	Btu Yield
Bituminous Coal	1 ton	$15 - 26 \times 10^6$
Oil	1 barrel	5.8×10^6
Electrical Output	1 kwhr	3412
Natural Gas	1 ft^3	1032
Synthetic Gas	1 ft^3	900

pipelines. Calculations indicate that water for the coal-fired electric generating plants, which will total about 12,500 MWe output capacity, will be roughly 167,000 ac-ft per year. Water required for coal slurry pipelines is about equal in weight to the tonnage of coal to be shipped. Only two of these lines are shown on the map, but more will be needed to move coal within the basin as well as to transport it to locations on the outside.

If low quality water can be utilized successfully for these two purposes, nearly equivalent amounts of good water will be made available for other uses. The following sections of the report discuss these possibilities.

Conclusions

1. Surface water supplies in the Upper Colorado River Basin are apparently sufficient to continue to provide for a moderate amount of energy development with only a minimal adverse effect on irrigated agriculture.

2. As world energy costs continue to rise, the rate of development of energy resources (coal, oil, natural gas, oil shale, tar sand, and uranium) in the Upper Colorado River Basin will increase, and additional sources of water will be required.

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3. Groundwater data for the basin are limited, but an approximate inventory makes it clear that the amounts of currently unused brackish and saline groundwater in the basin are large relative to the anticipated quantities of water that will be required for anticipated energy development in the basin.

4. Any brackish or saline water that can be used for energy development purposes will have the effect in the system of a new source of supply, and will free water of a better quality for other uses.

5. An immediate source of low quality water in the basin is saline springs and irrigation return flows. Use of this water for energy development would improve the overall quality of the Colorado River.

Recommendations

1. Conduct detailed inventories of the depth, quantity, and quality of brackish and saline groundwater in areas where significant demand for these waters for energy development seem likely. This will necessitate drilling wells and conducting pumping tests.

2. Conduct more detailed inventories to determine the quantity, quality, availability, and location of brackish and saline surface water that may be available for energy development purposes, such as saline springs and irrigation return flow.

Figure 13. Future energy-related projects in the Upper Colorado River Basin (Rich 1978).

Table 5a. Amount of water required for energy development (gal/10^6 Btu).

Energy Development	References: Process	(1) Min.	(1) Max.	(2) Min.	(2) Max.	(3) Aver.	(4) Aver.	Other Aver.	Total Aver.
Coal Mining						2	0.8		1.4
Coal Slurry						23	9		16.
Coal Gasification	Synthane	14.5	25						
	Hygas	16	22						
	Lurgi	15.5	25						
	Water-cooling			72	158				
	Part. Air-cooling			37	79			(5)	
	Average	15.3	24	55	118	35	83	29.4	50.7
Coal Liquefaction	Synthoil	13.5	19.5	31	200	46	72		62.5
Clean Coal	SRC	7.5	12.5						10.
Oil Production							2.2		2.2
Gas Production							1.2		1.2
Oil Refining				6.7	6.7		5.5		6.1
Oil Shale	Paraho D.	19	19						
	Paraho ID.	31	31						
	Tosco II	31	31					(5)	
	Average	27	27	19	29	25	20	80	35.2
Tar Sands	Arizona							(6)	
	Fuel Co.							3.6	
	Fairbirm							3.4	
	Average						2.4	3.5	3.0
Uranium				14	14				14.
Power Plant	Geothermal			527	527				527.
Power Plant	Fossil-fuel			146	146	154			
	Nuclear			234	234	324			
	Average			190	190	239	118		182.3

Note: (1) Probstein and Bold 1978. (2) David and Wood 1974. (3) Water and energy ..., 1974. (4) Mace 1976.
(5) Beychok 1975. (6) In the matter ..., 1974.

Table 5b. Estimated percent increase in the market price of the energy product for various types of energy development if treatment costs of saline water were $500/ac-ft more than treatment costs for high quality water used in conventional systems.

Type of Development	Rate of Water Use (Based on Table 5a)	Assumed Market Value	Percent Increase in Market Price of Product
Coal Mining	85 x 10^{-6} ac-ft/ton of coal	$25/ton	0.17%
Coal Slurry	982 x 10^{-6} ac-ft/ton of coal	$25/ton	1.9 %
Coal Gasification	140 x 10^{-6} ac-ft/1000 SFC	$ 3/1000 SFC	2.3 %
Coal Liquefaction	1100 x 10^{-6} ac-ft/bbl	$30/bbl	1.8 %
Oil Shale	625 x 10^{-6} ac-ft/bbl	$30/bbl	1.0 %
Tar Sands	53 x 10^{-6} ac-ft/bbl	$30/bbl	0.09%
Fossil Fuel Power Plant	1.6 x 10^{-6} ac-ft/kW·h	$0.03/kW·h	2.6 %

Feasibility of Using Saline Water for Power Plant Cooling

Introduction

A large coal-fired electric generating plant is truly a staggeringly complex multi-billion dollar technological marvel requiring a vast aggregate of technical expertise to put it together and make it run. In spite of the practical complexities the basic principles of converting coal into kilowatts are quite simple. Depicted in Figure 14 is a schematic of the essential elements of a plant based on the Rankine power cycle. The working fluid circulates at high pressure through the boiler where energy is added as high temperature heat. Leaving the boiler as a super-heated vapor at high pressure, the fluid expands across the turbine which drives the generator to emerge as a very low pressure vapor. This low pressure vapor is then condensed again to a liquid to be pumped back up to a high pressure thus completing the cycle. It is in the condenser that immense quantities of heat must be rejected from the power cycle working fluid to a cooling fluid, usually water. In turn the heat is then rejected to the atmosphere.

Cooling towers are often employed to enhance the transfer of heat to the atmosphere and permit recycling of the cooling water. Indicated in Figure 15 are typical flow rates in the conventional cooling water loop of a power plant producing 1,000 MWe. The makeup water must be provided from an external source. The blowdown water contains all of the minerals entering with the makeup water except for small quantities of salt escaping with cooling tower drift. Under the total containment philosophy the blowdown water, in which are concentrated the incoming minerals, is not allowed to return to any waterway and must be disposed of in an environmentally acceptable manner. It follows that high quality water with low concentrations of minerals and ions is preferable to brackish or saline waters for power plant cooling on many accounts. However, under circumstances where fresh water supplies are limited and the possibility of using brackish or saline water exists, the feasibility of doing so should be closely examined. Power plants recently built along the East Coast such as Chalk Point (Washington, D.C.), Turkey Point (Florida), and Forked River (New Jersey) use brackish water or seawater directly, ranging from 7,800 mg/l TDS to 45,000 mg/l TDS before blowdown, and difficulties they may have encountered should be studied. Planners contemplating power plant cooling with saline water are faced with a variety of questions such as:

1. What technologies are available for treating saline water?

2. What are the relative costs of implementing various water treatment tech-nologies? In other words, what are the relative values of water of various salinity concentrations used for power plant cooling?

3. Under the total containment phi-losophy, what are the disposal implications of using saline waters for cooling? Is evaporation of brine waters the best option? How do evaporative brine ponds perform as a function of salinity, humidity, solar insola-tion, and air temperature?

4. Is mineral recovery from cooling systems using saline makeup water a viable notion?

5. Could reduced fresh water supplies be effectively supplemented by lower quality waters in conventional systems under drought conditions?

6. What are the relative merits of spray ponds or cooling ponds as opposed to cooling towers where only lower quality makeup water is available?

7. Does dry cooling become preferable to wet cooling at certain salinity concentra-tion levels of makeup water and if so, what are those threshold levels?

The answers to these questions depend in part on the particular ions and minerals making up the salinity. Since this study could not look at all possible combinations, the wide variety of water chemistries which might be encountered in the geographical study area was represented by obtaining analyses of typical waters from the region. The particular analyses used are shown in Table 6. The broad implications of using these kinds of waters in conventional power plant cooling are examined. The study has not considered the option of using saline groundwaters in a once-through cooling mode because of the immense quantities of water that would require.

Figure 14. Rankine cycle power plant.

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Figure 15. Typical water flow rates in the conventional cooling water loop of a 1000 MWe power plant.

The notion of cooling with low quality water seems to be gaining momentum with an impressive rate of technological advancement. The study has certainly not considered every possible strategy for using saline water in power plant cooling, but attempts have been made to evaluate some of the more promising options.

The modeling associated with this study assumed a hypothetical 1,000 MWe power plant operating at 40 percent thermal efficiency. This is roughly equivalent to a 1,000 MWe plant operating at 35 percent thermal efficiency and 80 percent load factor.

Table 6. Concentration of constituents in cooling tower makeup waters.

Constituent	Sample 1 TDS = 1000 to 3000 mg/l	Sample 2 TDS = 3000 to 10,000 mg/l	Sample 3 TDS = > 10,000 mg/l
Al	0.25	0.72	1.14
B	0.1	0.5	0.7
Ca	156.	343.	312.
CO_3	117.	361.	550.
Cl	592.	138.	4880.
F	0.17	0.68	0.46
Fe	<0.02	<0.02	<0.02
Mg	48.	267.	109.
Mn	<0.01	0.25	0.50
NO_3-N	<0.04	0.50	1.02
$O-PO_4$	0.71	0.72	0.98
K	4.	20.	102.
SiO_2	11.	22.	35.
Na	458.	620.	4300.
SO_4	700.	2740.	2770.
TDS	2220.	4640.	13180.
pH	7.6	8.3	7.8

The Cooling Tower-Condenser Loop

Wet cooling towers reject the energy acquired in the condenser to the atmosphere by evaporating part of the cooling water, thus enabling the remaining cooling water to be cycled back through the system supplemented by makeup water (Figure 16.) In the conventional wet tower, the warmed cooling water leaving the condenser is introduced at the top of the tower through distributing nozzles and falls through a series of trays, plates or baffles, which expose large wetted surface areas to the air moving through the tower, thus enhancing evaporation.

The relatively small amount of entrained water lost as fine liquid droplets in the upwelling air stream is referred to as drift loss. For mechanical draft towers, drift losses of 0.1 percent to 0.3 percent of the circulating water flow rate are considered typical.

The nonvolatile minerals and ions present in the makeup water become increasingly concentrated in the recirculating cooling water as evaporation proceeds. The total dissolved solids (TDS) level, as well as the level of suspended solids thus builds up. Keeping these concentration levels below the maximum limits that can be tolerated by physical hardware necessitates the removal of some of the circulating water from the system. This discharged water is referred to as blowdown.

In order to examine the impact on these flow rates of using waters of various salinity levels for cooling tower makeup, the following procedures were developed.

An energy balance across the cooling tower is written,

$$\dot{Q} = \dot{M}_1 h_{f1} - \dot{M}_2 h_{f2} \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

Figure 16. Basic elements of the cooling tower.

where

$\dot{Q}$ = rate of heat rejection from the 1,000 MWe power plant, operating at 40 percent thermal efficiency. This is

$$\dot{Q} = 1000 \text{ MWe} \left(\frac{1-0.40}{0.40}\right) = 1500 \text{ MWe} = 5.12 \times 10^9 \text{ Btu/hr.} \qquad \ldots \ldots \ldots \quad (2)$$

$\dot{M}_1$ = mass flow rate of water entering the tower.

$\dot{M}_2$ = mass flow rate of water leaving the tower.

h_{f1} = specific enthalpy of circulating water entering the tower.

h_{f2} = specific enthalpy of circulating water leaving the tower.

Temperatures of water entering and leaving the cooling tower are assumed to be T_1 = 110°F (43.3°C) and T_2 = 80°F (26.7°C).

The evaporation flow rate was estimated from the literature (Caplan 1975; Kunz et al. 1977) as 1 percent of the circulating water flow rate for each ten degree reduction in temperature (°F), giving:

$$\dot{M}_{evap} = 0.01 \dot{M}_1 (T_1 - T_2)/10 = 0.001 \dot{M}_1 (T_1 - T_2) \qquad \ldots \ldots \quad (3)$$

Drift loss is taken as 0.1 percent of circulation (Caplan 1975)

$$\dot{M}_{drift} = 0.001 \dot{M}_1 \qquad \ldots \ldots \quad (4)$$

A mass balance for the water may thus be written as,

$$\boxed{\text{Makeup}} = \boxed{\begin{array}{c}\text{Drift}\\\text{Loss}\end{array}} + \boxed{\begin{array}{c}\text{Evaporation}\\\text{Loss}\end{array}} + \boxed{\text{Blowdown}}$$

$$\dot{M}_{mu} = \dot{M}_{drift} + \dot{M}_{evap} + \dot{M}_{bd} \qquad \ldots \ldots \ldots \quad (5)$$

A mass balance for the salt is similarly expressed as

$$\boxed{\begin{array}{c}\text{Makeup}\\\text{Salt}\end{array}} = \boxed{\begin{array}{c}\text{Drift}\\\text{Salt}\end{array}} + \boxed{\begin{array}{c}\text{Blowdown}\\\text{Salt}\end{array}}$$

$$\dot{M}_{mu}C_{mu} = \dot{M}_{drift}C_{cir} + \dot{M}_{bd}C_{bd} \qquad \ldots \ldots \quad (6)$$

where

C_{mu} = salt concentration of makeup water.

C_{cir} = salt concentration of circulating water.

C_{bd} = salt concentration of blowdown water.

Also, another mass balance for the water through the cooling tower is written as

$$\boxed{\begin{array}{c}\text{Water}\\\text{Leaving}\\\text{the}\\\text{Tower}\end{array}} = \boxed{\begin{array}{c}\text{Water}\\\text{Entering}\\\text{the}\\\text{Tower}\end{array}} - \boxed{\begin{array}{c}\text{Drift}\\\text{Loss}\end{array}} - \boxed{\begin{array}{c}\text{Evaporation}\\\text{Loss}\end{array}}$$

$$\dot{M}_2 = \dot{M}_1 - \dot{M}_{drift} - \dot{M}_{evap} \qquad \ldots \ldots \quad (7)$$

The above equations and assumptions provide sufficient information to calculate makeup and blowdown water requirements as a function of their salt concentrations for the cooling option (called option 1 and depicted in Figure 35) in which no water treatment other than biocide is specified. Results are shown in Table 7.

As may be expected the required quantities of makeup and blowdown waters increase significantly as the salinity of the makeup water increases. For example, with the maximum allowable TDS of the circulating water set at 8,000 mg/1, increasing the TDS of the makeup water from 1,000 mg/1 to 2,000 mg/1 increases the makeup water by 17 percent and the blowdown water to be disposed of by 174 percent. An increase in the TDS of the makeup water from 6,000 mg/1 to 7,000 mg/1 increases the makeup water requirement by 100 percent and the blowdown by 135 percent. The results plotted in Figures 17 and 18 emphasize the nonlinearity of the impact of makeup water salinity on the annual volumes of makeup water which must be obtained, and blowdown water which must be discharged. The maximum allowable salinity of the circulating water also has an important impact and is largely determined by the design and selection of material in the cooling loop system.

The Brine Evaporation Pond

Even though possibilities exist to concentrate the brine before it leaves the plant and to utilize the briny blowdown waters for such purposes as ash quenching and stack gas scrubbing, very substantial quantities of blowdown waters must be disposed of, and the amount increases with the salinity of the makeup water as shown in Figure 18. One option for blowdown disposal is the evaporation pond, wherein sunshine evaporates the water leaving the minerals behind in a hopefully impervious basin. This section of the study predicts the required evaporation pond area as a function of the salinity of

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Table 7. Makeup and blowdown water requirements for 1000 MWe power plant under Option 1.

Circulating Salinity (mg/l) → 1000 ac-ft/yr Makeup Salinity (mg/l) ↓	8,000 Blow-down	8,000 Make-up	9,000 Blow-down	9,000 Make-up	10,000 Blow-down	10,000 Make-up	11,000 Blow-down	11,000 Make-up	12,000 Blow-down	12,000 Make-up	15,000 Blow-down	15,000 Make-up	18,000 Blow-down	18,000 Make-up	21,000 Blow-down	21,000 Make-up	24,000 Blow-down	24,000 Make-up	27,000 Blow-down	27,000 Make-up
1,000	1.73	18.06	1.45	17.78	1.23	17.56	1.05	17.38	0.91	17.24	0.60	16.92	0.40	16.72	0.26	16.57	0.16	16.46	0.08	16.37
1,500	3.12	19.45	2.63	18.96	2.26	18.59	1.97	18.29	1.73	18.06	1.23	17.55	0.91	17.22	0.69	17.00	0.53	16.82	0.40	16.69
2,000	4.74	21.07	3.99	20.32	3.42	19.75	2.98	19.31	2.63	18.96	1.90	18.22	1.45	17.76	1.14	17.44	0.91	17.21	0.74	17.03
2,500	6.66	22.99	5.55	21.88	4.74	21.07	4.12	20.45	3.63	19.96	2.63	18.95	2.02	18.33	1.61	17.91	1.31	17.61	1.08	17.37
3,000	8.96	25.29	7.37	23.70	6.25	22.57	5.40	21.73	4.74	21.07	3.42	19.74	2.63	18.95	2.10	18.41	1.73	18.03	1.45	17.73
3,500	11.76	28.09	9.53	25.86	7.98	24.31	6.85	23.17	5.98	22.37	4.28	10.60	3.28	19.60	2.63	18.94	2.17	18.47	1.82	18.11
4,000	15.28	31.61	12.12	28.44	10.01	26.34	8.50	24.83	7.37	23.70	5.22	21.54	3.98	20.30	3.19	19.49	2.63	18.93	2.22	18.51
4,500	19.79	36.12	15.28	31.60	12.40	28.73	10.41	26.74	8.95	25.28	6.24	22.56	4.74	21.05	3.78	20.09	3.11	19.41	2.63	18.92
5,000	25.81	42.14	19.23	35.56	15.27	31.60	12.64	28.97	10.76	27.08	7.37	23.69	5.55	21.86	4.41	20.71	3.63	19.92	3.06	19.35
5,500	34.24	50.57	24.31	40.63	18.79	35.11	15.27	31.60	12.84	29.17	8.62	24.94	6.42	22.74	5.07	21.08	4.16	20.46	3.51	19.80
6,000	46.88	63.21	31.08	47.41	23.18	39.50	18.43	34.76	15.27	31.60	10.00	26.32	7.37	23.68	5.79	22.09	4.73	21.03	3.98	20.27
6,500	67.95	84.28	40.56	56.89	28.82	45.15	22.30	38.62	18.14	34.47	11.55	27.87	8.40	24.71	6.55	22.86	5.33	21.63	4.47	20.76
7,000	110.10	126.43	54.78	71.11	36.34	52.67	27.12	43.45	21.59	37.92	13.29	29.61	9.52	25.84	7.36	23.67	5.97	22.27	4.99	21.28
7,500	236.52	252.85	78.49	94.81	46.88	63.21	33.33	49.66	25.80	42.13	15.27	31.59	10.75	27.07	8.24	24.55	6.64	22.94	5.54	21.83
8,000	–	–	125.89	142.22	62.68	79.01	41.61	57.93	31.07	47.40	17.52	33.84	12.10	28.42	9.19	25.49	7.36	23.66	6.11	22.40
8,500	–	–	268.11	284.44	89.01	105.34	53.19	69.52	37.84	54.17	20.13	36.45	13.60	29.91	10.21	26.51	8.12	24.42	6.72	23.01
9,000	–	–	–	–	141.69	158.01	70.57	86.90	46.87	63.20	23.16	39.49	15.26	31.58	11.31	27.62	8.94	25.24	7.36	23.65
9,500	–	–	–	–	299.70	316.03	99.54	115.87	59.51	75.83	26.75	43.08	17.12	33.43	12.51	28.82	9.81	26.11	8.03	24.32
10,000	–	–	–	–	–	–	157.48	173.80	78.47	94.79	31.06	47.38	19.21	35.52	13.82	30.13	10.74	27.04	8.75	25.04

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the makeup water to the power plant under a variety of assumptions.

The required pond area is basically a function of the solar insolation, air temperature, humidity, wind shear, precipitation, quantity, temperature, and concentration of the blowdown waters to be disposed of. In turn, the quantity, temperature, and concentration of blowdown waters for a 1,000 MWe power plant depend upon the quality and quantity of the makeup water and the type of water treatment utilized. The computer model developed for the process is presented here in brief summary.

Energy Balance for the Brine Evaporation Pond

An energy balance is written as

Rate of Change of Energy Stored in the Pond	=	Rate at which Pond Receives Energy via Solar Insolation and Blowdown Water	−	Rate at which Pond Loses Energy via Convection, Evaporation, Radiation

or

$$d(\rho CDAT)/dt = \dot{Q}_{solar} + \dot{Q}_{blowdown} - (\dot{Q}_{conv} + \dot{Q}_{evap} + \dot{Q}_{rad})$$

where
. . . . (8)

ρ = brine density taken as 80.04 lb/ft^3 (1282.1 kg/m^3)

C = specific heat of brine taken as 0.77 Btu/lb·°F (3.22 kJ/kg·°K)

D = average pond depth

A = pond area

T = pond temperature

t = time

The temperature and water-salt composition of the shallow evaporation pond are assumed to be uniform throughout. This assumption is consistent with Pancharatnam's (1972) observation that where the wind speed is 5 mph (4 ft above brine surface), a pond is generally well mixed.

Figure 17. The impact of makeup salinity increases on the annual volume of makeup water necessary for cooling a 1000 MWe power plant under option 1 conditions.

Figure 18. The impact of makeup salinity increases on the annual volume of blowdown water necessary for cooling a 1000 MWe power plant under option 1 conditions.

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The energy balance neglects heat exchange with the soil beneath the pond. This is in accordance with the suggestion (Pancharatnam 1972) that where pond depth exceeds 2 feet, ground conduction is negligible. Also neglected is the energy contribution due to precipitation. (See Figure 19.)

$\dot{Q}_{solar}$ is the rate at which solar energy enters the pond. In this evaporation pond model, solar insolation is divided into hourly values based on weather station observations. The energy absorptivity of the surface depends on the angle of solar incidence which varies over time in a carefully modeled pattern. The rate at which blowdown water brings energy into the pond is modeled as

$$\dot{Q}_{blowdown} = \dot{M}_{bd} C_{bd} (T_{bd} - T) \quad . \quad . \quad (9)$$

where

$\dot{M}_{bd}$ = mass flow rate of blowdown

C_{bd} = specific heat of blowdown taken as 0.77 Btu/lb·°F (3.22 kJ/kg·°K)

T_{bd} = temperature of blowdown treated as a constant at 80 °F (26.7°C)

T = temperature of the evaporation pond

The three energy loss equations are as follows

$$\dot{Q}_{conv} = hA (T - T_{air}) \quad . \quad . \quad . \quad (10)$$

where

h is the convective heat transfer coefficient taken as a linearized function of wind velocity, V (mph).

$$h = 1 + 0.3V \; (Btu/hr - ft^2 - {}^\circ F)$$

$$(Pancharatnam \; 1972) \; . \quad . \quad . \quad . \quad (11)$$

(V assumed to be 10 mph in this study)

T_{air} is the air temperature. A typical 24 hour profile was assumed, based on weather station observations of average maximum daily temperature for a given month as indicated in Figure 20 and calculated from

$$T_{air} = (0.9 + 0.1 \sin (I\pi/12) \; T_{max}. \quad . \quad (12)$$

where I is the hour of the day beginning with noon equals zero. I is actually varied from 2 to 25 to avoid computational difficulties with the computer.

$$\dot{Q} \; evap = \dot{M} \; evap \; h_{fg} \quad . \quad . \quad . \quad (13)$$

where

$$\dot{M}_{evap} = K \; (P_b - P_v) \; A$$

and K = mass transport coefficient taken as

$$K = (1.9 + 0.476V) \times 10^{-3}, \; with \; V = 10 \; mph$$

$$(Pancharatnam \; 1972) \; . \quad . \quad . \quad . \quad (14)$$

giving K = 6.66 x 10-3 lb/hr·ft^2·mmHg

P_b = vapor pressure of the brine, calculated as a function of pond temperature T and brine concentration. Values for the saturation pressure, P_g, of pure H_2O are based on data from steam tables fitted to a fifth power polynomial as follows:

$$P_g = 0.0158T^5 - 4.08T^4 + 4.29T^3 - 8.08T^2 + 0.028T$$

$$- 0.0072 \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

P_b = $\phi_b P_g$, where $\phi_b \simeq 0.75$ when measured over saturated brine for the temperature range of 10°C to 40°C (Betz Laboratories 1962).

P_v is the partial pressure of H_2O vapor in the air above the pond $P_v = \phi_a P_g$, where ϕ_a is the relative humidity of the atmosphere based on weather station observations.

$$\dot{Q}_{rad} = 0.97 \; \sigma \; (T^4 - \beta T_{air}^4) . \quad . \quad . \quad (16)$$

$\dot{Q}_{rad}$ is the net rate at which the pond reradiates energy back to the surroundings. According to Raphael (1962)

Figure 19. Cross-section of brine evaporation pond showing energy flows.

where σ is the Stefan-Boltzman constant, 0.1714×10^{-8} Btu/hr-ft^2 R^4, β is a function of cloud cover and vapor pressure, assumed to be 0.85 in this study.

Mass Balance for Water in Brine Evaporation Pond

Referring again to Figure 19, a mass balance for the water may be written as

$$d(\rho DA)/dt = \dot{M}_{bd} + \dot{M}_{precip} - \dot{M}_{evap} \qquad (17)$$

where

ρ = mass density of water, taken as 63 lbs/ft^3

$\dot{M}_{bd}$ = mass flow rate of blowdown water

$\dot{M}_{precip}$ = rate at which precipitation enters pond. Those values are based on weather station observations and entered as average monthly values.

$\dot{M}_{evap}$ = rate of evaporation discussed earlier

Computational procedure

The solution of the transient non-equilibrium problem represented by the above equations requires specification of the initial conditions. If the area of the pond were specified and the temperature and depth of the brine in the evaporation pond were known at some point in time, a numerical solution giving temperature T and depth D as a function of time would be straightforward. In this case we do not have the initial conditions and the area of the evaporation pond is critical to the energy balance because the blowdown input is not expressible on a per unit area basis unless A is known. These difficulties are circumvented by the following procedures:

1. Assume a value for pond area A, based on a reasonable estimate of the annual evaporation rate and the annual precipitation for the location and the known amount of blowdown waters to be disposed of annually.

$$A_{est} = \frac{\text{Annual Volume of Blowdown}}{\begin{array}{c}\text{Annual}\\ \text{Evaporation} \ - \ \begin{array}{c}\text{Annual}\\ \text{Precipitation}\end{array}\\ \text{Depth}\end{array}} \cdot \cdot \quad (18)$$

2. Assume a value for pond temperature T and depth D at a given point in time. (1 hour before sunrise on January 1.)

Figure 20.   Typical 24 hour profile of air temperature.

3. Assume that the depth, D, may be treated as constant for any given 24 hour period.

4. Assume that the temperature of the pond at the end of the first 24 hour period is only negligibly different from the temperature at the beginning of that period.

5. Using the energy and mass balance equations and the assumed values for T, D, and A calculate the hourly value of T for the first 24 hour period. Iterate with T until (T at 0 hour) - (T at 24 hour) < ΔT, where ΔT is an arbitrarily small difference.

6. Using the value of T established in the iteration procedure as the pond temperature at time zero, numerically solve for T as a function of time throughout the year. The pond depth is adjusted at the end of each 24 hour period.

7. Calculate a new pond area as:

$$A = \frac{\sum\limits_{year} \dot{M}_{blowdown} \, \Delta t}{\sum\limits_{year} \left(\dfrac{\dot{M}_{evap}}{A} - \dfrac{\dot{M}_{precip}}{A} \right) \Delta t} \qquad (19)$$

8. Repeat above calculation using the calculated area in place of the estimated area.

9. Continue until the area calculated on the Ith iteration differs from the area calculated on the (I + 1)th iteration by a negligible quantity.

The pond should be designed to handle the blowdown water in years of maximum precipitation and/or minimum evaporation. The term "critical year" refers to that year (1941) identified over the 74 year period from 1901 to 1975, where net evaporation was lowest. The term "average years" represents average conditions over that same period.

Table 8 gives the weather data on which the calculations are based.

Predicted evaporation pond temperature patterns are shown in Figures 21-25 for both average and critical years. The difference between minimum and maximum temperatures on any given day is about 6°F. There were no measured pond temperature data with which to compare these results, but there is some concern about the rather low temperatures predicted by the model in the winter months. One factor, not included in the model, but which could cause higher temperatures is the tendency for precipitation to float on top of the heavier brines creating an insulating layer which would allow higher temperature in the brine. This model assumed a well mixed pond by wind and did not take stratification into account.

Figures 26 and 27 give the predicted total month by month evaporation rate for average and critical years. Integrated over the full year these rates are equivalent to 3.95 ft in an average year and 3.6 ft in the critical year. Subtracting the precipitation inputs from Table 8 give net values of 3.32 ft and 2.07 ft respectively. This may be compared with an average annual net evaporation of 3.2 ft for fresh water reservoirs in the same area predicted from a widely accepted model based on evaporation pan measurements (Hughes et al. 1974). Recognizing that the evaporation would be stimulated by the introduction of warm blowdown waters but retarded by the presence of salt we conclude that the evaporation model used here should have reasonable credibility.

Figures 28 and 29 show the predicted month by month brine depth for average years and the critical year. The values, in feet, are shown in Tables 9 and 10.

Cost estimates for evaporation pond

Brine evaporation pond costs are highly site specific depending on such factors as price of the land, type of soil, and liner requirements. For this cost estimate we assumed:

a) the pond to be constructed on perfectly flat land surrounded by an embankment on all four sides,

b) material for the embankment to be entirely excavated from the bottom of the pond,

c) allowance to be made for mineral deposition on bottom for 40 years and still allow depth of brine to be 3 feet,

d) unit costs to be

soil excavation and placement.....$4/yd^3
land..............$0.02/ft^2 ($870/acre)
liner.........................$0.20/ft^2
piping......................$0.052/ft^2.

The cost per unit area of evaporation ponds is somewhat size dependent but generally falls in the range of $35,000-$40,000/acre. By way of comparison, an independent estimate for clay lined evaporation ponds in the study area is $30,000/acre (Kunberger et al. 1979). The annual cost of the evaporation

Table 8. Weather data used in predicting evaporation pond performance.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Solar Radiation Average Years Langley/day	244	319	437	539	620	698	668	586	513	383	324	219
Solar Radiation 1941 (Langley/day)	210	198	360	460	516	608	602	438	402	292	215	186
Air Temperature Average Years (F)	23.9	28.9	36.5	44.6	53.3	61.4	67.8	66.0	58.2	47.9	35.0	26.8
Air Temperature 1941 (F)	25.	31.	36.6	40.2	54.4	57.8	65.8	64.8	54.	44.5	36.6	27.5
Precipitation Average Years (in/month)	0.48	0.52	0.44	0.39	0.58	0.53	0.85	1.19	0.91	0.80	0.35	0.51
Precipitation 1941 (in/month)	0.92	0.70	0.92	2.10	1.78	1.40	0.49	2.63	1.44	3.58	1.50	0.88

Note: Data from Emery, Utah, weather station. "Average Years" represent average conditions over the 74 year period from 1901 to 1975, where 1941 is the critical year during the same period.

1 Langley = 3.687 Btu/ft^2.

BRINE TEMP (°F)

50
49
48
47
46
45
44
43
42
41
40

t_1 t_2 t_3 HOUR OF THE DAY t_{24} t_{25}

($t_1 = t_{25}$ = The hour just before sunrise.)

Figure 21. The predicted evaporation pond temperature pattern for a typical day in April of the average year.

BRINE TEMP. (°F)

70

60

50

40

30

20

(7) JUL.
(8) AUG.
(6) JUN.
(9) SEP.
(5) MAY
(4) APR.
(10) OCT.
(3) MAR.
(11) NOV.
(2) FEB.
(12) DEC.
(1) JAN.

t_1 t_2 t_3 t_4 t_{24} t_{25}

HOUR OF THE DAY

($t_1 = t_{25}$ = The hour just before sunrise.)

Figure 22. The predicted evaporation pond temperature pattern for a typical day in each month of the average year.

24

Figure 23. The predicted average daily temperature in brine evaporation pond for each month of an average year.

HOUR OF THE DAY

$(t_1 = t_{25} = $ The hour just before sunrise.$)$

Figure 24. The predicted evaporation pond temperature pattern for a typical day in each month of the critical year (1941).

25

Table 9. Predicted month by month brine depth in evaporation pond for an average year.

Month	Brine Depth (ft)	Month	Brine Depth (ft)
Jan.	3.201	Jul.	2.874
Feb.	3.365	Aug.	2.717
Mar.	3.449	Sep.	2.647
Apr.	3.438	Oct.	2.704
May	3.340	Nov.	2.822
Jun.	3.119	Dec.	3.018

Table 10. Predicted month by month brine depth in evaporation pond for critical year.

Month	Brine Depth (ft)	Month	Brine Depth (ft)
Jan.	3.121	Jul.	2.709
Feb.	3.204	Aug.	2.643
Mar.	3.232	Sep.	2.583
Apr.	3.305	Oct.	2.807
May	3.225	Nov.	2.922
Jun.	3.042	Dec.	3.037

pond is calculated assuming 10 percent interest amortized over 40 years.

$$\text{Annual Cost} = \frac{i \text{ (Capital Cost)}}{1 - (1+i)^{-n}} \quad . \quad . \quad (20)$$

where

$$i = 0.10$$
$$n = 40$$

The cost per ac-ft of brine disposed of via the evaporation pond is thus calculated as:

$$\frac{\text{Cost}}{\text{ac-ft of Brine}} = \frac{\text{Annual Pond Cost}}{\text{ac-ft of Blowdown/yr}} \quad . \quad . \quad (21)$$

A Few Proven Water Treatment Technologies

The use of saline water for power plant cooling would necessitate increased treatment costs or increased capital investment in facilities or both. A question addressed in this section is: Are proven technologies available for treating saline waters and what associated costs might be expected? This is not intended to be a comprehensive review of all possible or even all existing water treatment technologies, but rather is simply an attempt to identify some workable processes enabling the use of saline water and to determine if costs of doing so are reasonable.

Figure 25. The predicted average daily temperature in the brine evaporation pond for the critical year (1941).

Figure 26. The predicted total month by month evaporation rate for an average year.

Figure 27. The predicted total month by month evaporation rate for the critical year (1941).

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Figure 28. The predicted month by month brine depth for an average year.

Figure 29. The predicted month by month brine depth for the critical year (1941).

It is recognized that certain devices such as colloidal suspension equipment to prevent scale formation (Colloid-A-Tron 1977) show promise and possibly may be used extensively to supplement or complement standard treatment practices. Ion exchange techniques and electrodialysis while surely being technically possible are not discussed here. Consideration will be given in subsequent sections to a rationale for combining cycles to desalinate water as well as to produce power. Consideration is given also to the advisability of using wet-dry cooling systems rather than highly saline water.

A separate section is devoted to a discussion of a promising new cooling technology referred to as the Binary Cooling Tower (BCT) process.

The cold process softener

The term cold process softener refers to a series of operations intended to reduce the TDS of the feed water. The word "cold" implies a working temperature less than 110°F. The principal treatment is the addition of lime (CaO) to facilitate the precipitation of Mg^{++} and Ca^{++} according to the following reactions:

$$Ca(HCO_3)_2 + Ca(OH)_2 \rightleftharpoons 2\ CaCO_3 \downarrow + 2\ H_2O \quad . \quad . \quad (22)$$

$$Mg(HCO_3)_2 + 2\ Ca(OH)_2 \rightleftharpoons Mg(OH)_2 \downarrow + 2\ CaCO_3 \downarrow + 2\ H_2O$$
$$. \quad . \quad . \quad . \quad . \quad (23)$$

In addition silica coprecipitates with $Mg(OH)_2$ at the rate of about 1 gm SiO_2 per 7 gm Mg^{++} (Gold et al. 1976). The lime treatment is followed by sand filter and/or clarifier to remove the suspended solids. The following assumptions were included in modeling the cold process softener:

(1) when $Ca_{feed} < 35\ mg/l$; $Ca_{product} = Ca_{feed}$ (24)

when $Ca_{feed} \geq 35\ mg/l$; $Ca_{product} = \frac{35}{150}\ Ca_{feed}$ (25)

(2) when $Mg_{feed} < 60\ mg/l$; $Mg_{product} = Mg_{feed}$ (26)

when $Mg_{feed} \geq 60\ mg/l$; $Mg_{product} = \frac{60}{100}\ Mg_{feed}$ (27)

(3) when $SiO_{2feed} < 19\ mg/l$; $SiO_{2product} = SiO_{2feed}$ (28)

when $SiO_{2feed} \geq 19\ mg/l$; $SiO_{2product} = \frac{7}{20}\ SiO_{2feed}$
$. \quad . \quad . \quad . \quad (29)$

All other chemical constituents were assumed to be unaffected by the cold process softener. The following relationships were utilized in the computer model of cold process treatment:

If the concentration of Ca^{++} in the feed water ≥ 35 mg/l, the amount of lime required to precipitate the Ca^{++} is

$$(Lime)_{Ca} = (Ca^{++}) \times (74/162) \times (150-35)/150 \quad (30)$$

If the concentration of Mg^{++} in the feed water ≥ 60 mg/l, the amount of lime required to precipitate the Mg^{++} is

$$(Lime)_{Mg} = (Mg^{++}) \times (148/146.3) \times (100-60)/100 \quad (31)$$

so that the total lime required in mg/l of feed water is

$$(Lime)_{total} = 0.35\ (Ca^{++})_{feed} + 0.405\ (Mg^{++})_{feed}$$
$$(32)$$

Knowing the feedwater flow rates and its chemical analysis, the rate of lime addition can be estimated.

The reject water flow rate is assumed to be 2 percent of the feed water flow rate. In calculating the costs of the cold process softener, the following assumptions were made:

Capital Cost = $0.341/GPD of capacity

A 10 percent investment credit on those components having an expected life greater than 7 years was assumed.

The annual cost was calculated as

$$\frac{i(Capital\ Cost)(0.9)}{1 - (1+i)^{-n}} \quad . \quad . \quad . \quad (33)$$

where

i = interest (assumed to be 10 percent)
n = 15 years

The cost of lime is taken as $0.089/lb.

Reverse osmosis

Great strides have been made over the past two decades in bringing reverse osmosis (R.O.) treatment of water from the realm of scientific speculation to a strong, growing, economically competitive industry. The development and state-of-the-art of R.O. is widely described in the literature (for example Curran et al. 1976) and will not be discussed in detail here. The basic notion of R.O. treatment is depicted in Figure 30. The saline feed water is introduced at relatively high pressure (150 to 400 psi) to one side of a selectively permeable membrane that permits the passage of water but restricts the passage of the ions and minerals in solution. The membrane must be mechanically supported and three basic configurations have evolved. They are:

1) The tubular design in which the membranes are wound around either the interior or exterior surfaces of a perforated or porous tube.

2) The spiral wound design in which large flat membranes are separated by a water conducting mesh, and the entire sandwich is rolled up with appropriate connections for feed, product, and reject fluids.

3) The hollow fine fiber design wherein the membrane is cast in such a fashion as to

Figure 30. The basic notion of R.O. treatment.

produce immense numbers of very fine fibers. The small diameter of these fibers permits large pressure differences to be maintained by the membrane material thus eliminating the necessity of a supportive back up material.

Commercial R.O. plants currently utilize either the spiral wound design or the hollow fine fiber type due primarily to greater surface area of membrane per unit volume of the R.O. module. In this study DuPont hollow fine fiber type systems are assumed. Typically 50 percent to 80 percent of the feed water passes through the membrane wall carrying roughly 2 percent to 15 percent of the ions and minerals present in the feed water. Figure 31 shows the typical quantities and qualities of water flows associated with R.O. treatment of feed water containing 15,000 mg/l.

The concentration of brines on the high pressure side of the membranes (and hence the TDS of the reject brines) is limited in order to reduce membrane fouling by over concentrating. The manufacturers recommendations for limiting concentration are:

a) Solubility product constant for $CaSO_4$ in the brine side should be less than 1×10^{-3}, that is,

$$[Ca^{++} mol/liter]_{feed} \times [SO_4^{--} mol/liter]_{feed} \leq 1 \times 10^{-3}$$

b) The concentration of SiO_2 should be less than 150 mg/l. For these reasons, R.O. is always presumed to be preceded by a cold process treatment which reduces these troublesome constituents.

Table 11 shows the percent of the particular ion or mineral present in the feedwater which is presumed to pass through the membrane with the product water.

The following terms are defined in connection with Figure 31.

CF = concentration factor

$$= \frac{TDS \ of \ Brine \ Rejected}{TDS \ of \ Feed \ Water} \qquad \cdot \ \cdot \ \cdot \ (34)$$

RF = recovery factor

$$= \frac{Flow \ Rate \ of \ Product \ Water}{Flow \ Rate \ of \ Feed \ Water} \qquad \cdot \ \cdot \ \cdot \ (35)$$

The concentration factor and the recovery factor are related as

$$RF = 1 - \frac{1}{CF} \qquad \cdot \ \cdot \ \cdot \ (36)$$

Figure 31. Typical performance characteristics of R.O. side stream circulating water treatment system for a plant utilizing 15,000 mg/l circulating water.

Table 11. R.O. membrane performance presumed in this study (Water & Power Technologies, Inc., Salt Lake City, Utah).

Constituent	% Passed by Membrane	% Rejected by Membrane
Ca^{++}	4	96
Mg^{++}	4	96
Na^+	10	90
K^+	10	90
PO_4^{---}	2	98
SO_4^{--}	4	96
Cl^-	10	90
NO_3^-	15	85
SiO_2	15	85

The following step by step procedure was utilized in modeling R.O. system performance.

Step 1. Knowing the concentrations of Ca^{++}, SO_4^{--}, and SiO_2 in the makeup water, the assumed cycles of concentration of the circulating water, and the effectiveness of the preliminary cold process softener, calculate the concentrations of Ca^{++}, SO_4^{--}, and SiO_2 in the R.O. feed water.

Step 2. Calculate the maximum allowable concentration factor for the R.O. system from

$$CF \left[Ca^{++} \text{ mol/liter} \right]_{feed} \times CF \left[SO_4^{--} \text{ mol/liter} \right]_{feed}$$

$$= 1 \times 10^{-3} \qquad \qquad \text{. . . . . . (37)}$$

$$CF \left[SiO_2 \text{ mg/liter} \right]_{feed} = 150 \quad \text{. . . . . (38)}$$

Step 3. Using the smaller of the values of CF calculated in Step 2, calculate the recovery factor as

$$RF = 1 - \frac{1}{CF} \qquad \text{. . . . (39)}$$

Step 4. Calculate the salinity of the product water in terms of

$$TDS_{product} = \sum_i \left[conc_i \right] \left[\text{fraction transmitted}_i \right] \quad (40)$$

where i represents each chemical constitutent and the fractions transmitted are listed in Table 11.

Step 5. Calculate the salinity of the reject water in terms of the recovery factor and the feed water flow rate from

$$\dot{M}_{reject} = \dot{M}_{feed} \times (1 - RF) \quad \text{. . . . . . (41)}$$

$$\dot{M}_{project} = \dot{M}_{feed} \times RF \quad \text{. . . . . (42)}$$

$$\dot{M}_{feed} TDS_{feed} = \dot{M}_{product} TDS_{product} + \dot{M}_{reject} TDS_{reject}$$
$$\text{. . . . . . (43)}$$

Costs for the R.O. system are estimated in terms of capacity as

Capital costs....$0.90/GPD of feed water
Operating costs..........$0.70/1000 gal.
Interest is assumed to be 10 percent.
System amortized over 15 years.
Membrane replacement costs are calculated as part of the operating costs.
A 10 percent investment credit is assumed on the capital investment in those components having expected life greater than 7 years.

The manufacturer suggests the pH of water exposed to the membrane be maintained at pH less than 7 which necessitates the addition of acid. The quantities of acid required were estimated from an approximate relationship provided by Water and Power Technologies Inc. of Salt Lake City, Utah, and depicted in Figure 32. The cost of H_2SO_4 was taken as $0.056/lb.

Figure 32. The quantity of H_2SO_4 required for pH control in a reverse osmosis system. (Courtesy Water and Power Technologies, Inc., Salt Lake City, Utah.)

The brine concentrator

Brine concentrators, designed and constructed by the Resources Conservation Co. (RCC) of Seattle, Washington, are currently installed in at least three major power plants in the Colorado River Basin:

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San Juan Generating Station - operated by the Public Service Company of New Mexico.

Navajo Generating Station - operated by the Salt River Project.

Huntington Generating Station - operated by the Utah Power & Light Co.

The principle of operation of the vapor compression units is depicted in Figure 33 and described as follows. The brine to be concentrated enters a feed tank for pH control and is then pumped through a heat exchanger using the sensible heat of the hot product condensate as an energy source. The warm feed water then passes through a deaerator and into the falling film evaporator. The vapor passes from the evaporator through a compressor to have its pressure increased about 2 psi above the evaporator pressure. This increased pressure results in a corresponding saturation temperature increase enabling condensation on the shell side of the evaporator and returning the latent heat to the evaporation process. The only external energy required is the electrical energy to drive the compressor which amounts to about 90 kW·h per 1000 gallons of feed water. The product condensate typically has less than 10 mg/l TDS with 90 to 98 percent recovery of water.

For purpose of this analysis the following assumptions were made:

1. The recovery is 93%

$$\dot{M}_{product} = 0.93 \ \dot{M}_{feed} \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \ (44)$$

$$\dot{M}_{reject} = 0.07 \ \dot{M}_{feed} \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \ (45)$$

2. Product salinity is 10 mg/l

$$\dot{M}_{reject} \ TDS_{reject} = \dot{M}_{feed} \ TDS_{feed} - \dot{M}_{product} \ (10 mg/l)$$

$$\quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \ (46)$$

or

$$TDS_{reject} = \frac{TDS_{feed} - 0.93(10)}{0.07} \quad \cdot \quad \cdot \ (47)$$

The above assumptions permit the calculation of water and mineral flow rates in terms of the feed water properties and flow rates.

Brine concentrator costs were based on data provided by RCC (Anderson 1976).

Capital costs are given as a function of capacity of feed water as shown in Figure 34. For purpose of computer modeling the curve was fitted by a polynomial as:

$$Capital \ cost \ (10^6 \ \$/yr) = 2.91 \ \dot{M}^3_{feed}$$

$$- 7.19 \ \dot{M}^2_{feed} + 10.9 \ \dot{M}_{feed} + 0.38 \quad \cdot \quad \cdot \quad \cdot \ (48)$$

Operating costs are calculated assuming 90 kW·h/1000 gal. of feed water treated and that power at the plant has a value of $0.01/kW·h.

Acid treatment for pH control was estimated at $0.10/1000 gal. of feed water.

Capital costs were amortized at 10 percent interest over 15 years.

A 10 percent investment credit was assumed.

Figure 33. Brine concentration simplified system schematic. (Courtesy Resources Conservation Co., Seattle, Washington.)

Figure 34. Capital cost of brine concentrator. (Based on data provided by Resources Conservation Co., Seattle, Washington.)

Some Water Treatment Options

The incremental cost of utilizing saline groundwater for power plant cooling depends on the particular treatment or combination of treatments utilized. There is undoubtedly some combination of R.O. chemical treatment, brine concentration, or blowdown evaporation that is economically optimal, but optimization techniques were not used to determine that particular configuration. Rather three treatment options were considered and attempts were made to estimate incremental costs of using saline water of various concentrations.

Option 1. No treatment--disposal in evaporation ponds

The approach taken in the first option (Figure 35) is to introduce the makeup water directly into the circulating loop with no treatment other than biocide applied. Biocide is assumed to be added into the tower condenser loop at a cost of $0.875/1000 gal. of blowdown water. The makeup water is cycled in the cooling tower condenser loop to an arbitrary concentration, and the blowdown water disposed of via the brine evaporation ponds. It may be observed from Tables 7 and 12 that as the salinity of the makeup water approaches the concentration of the circulating water, a once-through cooling configuration is approached and makeup water and evaporation pond requirements become unrealistic. These segments of the tables make the point that the salinity of the makeup water must be substantially less than the maximum allowable concentration in the circulating loop. This point is further emphasized by Table 13 which shows the evaporation pond costs estimated as previously described.

Figure 35. Simplified system schematic of option 1 in which no treatment other than biocide is applied.

Option 2. Softening of makeup water plus side stream treatment

Under this option (Figure 36) the makeup water is passed through a cold process softener to reduce the Mg^{++}, Ca^{++}, and SiO_2. As the salinity builds up in the circulating loop to a specified TDS, a side stream treatment may become necessary to control scaling. Adequate side stream treatment is provided to insure the sum of the concentrations of Mg^{++} + Ca^{++} + SiO_2 does not exceed 400 mg/l. It is assumed that system components will be designed to resist the corrosion which otherwise would be a problem at high TDS values of the circulating water.

By utilizing conservation of mass equations for the water and each of the chemical constituents in the makeup water, it

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Table 12. Brine evaporation pond area required for a 1000 MWe power plant under water treatment option 1.

Pond Area (acres) / Makeup Salinity (mg/l) \ Circulating Salinity (mg/l)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year	Normal Year	Critical Year
1,000	510	910	430	760	360	650	310	560	270	480	180	320	120	210	78	140	47	84	24	43
1,500	920	1600	780	1400	670	1200	580	1000	510	910	360	650	270	480	200	360	160	280	120	210
2,000	1400	2500	1200	2100	1000	1800	880	1600	780	1400	560	1000	430	760	340	600	270	480	220	390
2,500	2000	3500	1600	2900	1400	2500	1200	2200	1100	1900	780	1400	600	1100	480	850	390	690	320	570
3,000	2700	4700	2200	3900	1800	3300	1600	2800	1400	2500	1000	1800	780	1400	620	1100	510	910	430	760
3,500	3500	6200	2800	5000	2400	4200	2000	3600	1800	3200	1300	2300	970	1700	780	1400	640	1100	540	960
4,000	4500	8100	3600	6400	3000	5300	2500	4500	2200	3900	1500	2700	1200	2100	940	1700	780	1400	660	1200
4,500	5900	10000	4500	8100	3700	6500	3100	5500	2700	4700	1800	3300	1400	2500	1100	2000	920	1600	780	1400
5,000	7600	14000	5700	10000	4500	8100	3700	6700	3200	5700	2200	3900	1600	2900	1300	2300	1100	1900	910	1600
5,500	10000	18000	7200	13000	5600	9900	4500	8100	3800	6800	2600	4500	1900	3400	1500	2700	1200	2200	1000	1800
6,000	14000	25000	9200	16000	6900	12000	5500	9700	4500	8100	3000	5300	2200	3900	1700	3000	1400	2500	1200	2100
6,500	20000	36000	12000	21000	8500	15000	6600	12000	5400	9600	3400	6100	2500	4400	1900	3500	1600	2800	1300	2400
7,000	33000	58000	16000	29000	11000	19000	8000	14000	6400	11000	3900	7000	2800	5000	2200	3900	1800	3100	1500	2600
7,500	70000	120000	23000	41000	14000	25000	9900	18000	7600	14000	4500	8000	3200	5700	2400	4300	2000	3500	1600	2900
8,000	–	–	37000	66000	19000	33000	12000	22000	9200	16000	5200	9200	3600	6400	2700	4800	2200	3900	1800	3200
8,500	–	–	79000	140000	26000	47000	16000	28000	11000	20000	6000	11000	4000	7200	3000	5400	2400	4300	2000	3500
9,000	–	–	–	–	42000	75000	21000	37000	14000	25000	6900	12000	4500	8000	3300	6000	2600	4700	2200	3900
9,500	–	–	–	–	89000	160000	29000	52000	18000	31000	7900	14000	5100	9000	3700	6600	2900	5200	2400	4200
10,000	–	–	–	–	–	–	47000	83000	23000	41000	9200	16000	5700	10000	4100	7300	3200	5700	2600	4600

Table 13. Water treatment and disposal costs estimated for a 1000 MWe power plant under option 1.

Circulating Salinity (mg/l) $\rightarrow$ 10^6 \$/yr Makeup Salinity (mg/l)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.
1,000	2.5	3.9	2.1	3.3	1.7	2.8	1.5	2.4	1.3	2.1	0.87	1.4	0.58	0.93	0.38	0.61	0.23	0.37	0.12	0.19
1,500	4.4	7.1	3.7	6.0	3.2	5.1	2.8	4.5	2.5	3.9	1.8	2.8	1.3	2.1	0.99	1.6	0.76	1.2	0.58	0.93
2,000	6.7	11	5.6	9.1	4.9	7.8	4.2	6.7	3.7	6.0	2.7	4.4	2.1	3.3	1.6	2.6	1.3	2.1	1.1	1.7
2,500	9.4	15	7.9	13	6.7	11	5.8	9.4	5.1	8.3	3.8	6.1	2.9	4.7	2.3	3.7	1.9	3.0	1.6	2.5
3,000	13	20	10	17	8.8	14	7.6	12	6.7	11	4.9	7.9	3.8	6.1	3.0	4.9	2.5	4.0	2.1	3.3
3,500	17	27	13	22	11	18	9.7	16	8.5	14	6.2	9.9	4.7	7.6	3.8	6.1	3.1	5.0	2.6	4.2
4,000	22	35	17	28	14	23	12	19	10	17	7.5	12	5.8	9.2	4.6	7.3	3.8	6.1	3.2	5.1
4,500	28	45	22	35	18	28	15	24	13	20	9.0	14	6.8	11	5.5	8.7	4.5	7.2	3.8	6.1
5,000	37	59	27	44	22	35	18	29	15	24	11	17	8.0	13	6.4	10	5.2	8.4	4.4	7.0
5,500	49	78	34	55	27	43	22	35	18	29	12	20	9.3	15	7.3	12	6.0	9.6	5.1	8.1
6,000	66	110	44	71	33	53	26	42	22	35	14	23	11	17	8.4	13	6.8	11	5.7	9.2
6,500	96	150	57	92	41	66	32	51	26	41	17	27	12	19	9.5	15	7.7	12	6.5	10
7,000	160	250	78	120	51	83	38	62	31	49	19	31	14	22	11	17	8.6	14	7.2	12
7,500	340	540	110	180	66	110	47	76	37	59	22	35	16	25	12	19	9.6	15	8.0	13
8,000	–	–	180	290	89	140	59	95	44	71	25	40	17	28	13	21	11	17	8.8	14
8,500	–	–	380	610	130	200	75	120	54	86	29	46	20	31	15	24	12	19	9.7	15
9,000	–	–	–	–	200	320	100	160	66	110	33	53	22	35	16	26	13	21	11	17
9,500	–	–	–	–	420	680	140	230	84	140	39	62	25	39	18	29	14	23	12	19
10,000	–	–	–	–	–	–	220	360	110	180	45	72	28	44	20	32	16	25	13	20

Figure 36. Simplified schematic of water treat-
ment option 2 in which Mg, Ca, and
SiO_2 are controlled within speci-
fied limits.

Figure 37. Schematic of option 3 in which
makeup water is softened and blow-
down concentration is provided.

is possible to calculate the required side
stream flow and the blowdown and reject flow
rates. The results are tabulated in Tables
14-16.

Option 3. Makeup water softening with
treatment and concentration of blowdown

As schematically depicted in Figure 37,
this option provides for softening of the
makeup water coupled with blowdown concentra-
tion using reverse osmosis and brine concen-
trator. The advantage of such a tandem
approach is that the concentration of the
R.O. reject may be kept relatively low
enabling that system to operate efficiently
while simultaneously reducing the amount of
water to be evaporated by the brine concen-
trator. This approach reduces the required
evaporation pond area for ultimate disposal.
A similar option would be to also run the
reject waters from the makeup softener
through the brine concentrator, which feature
would reduce the required evaporation pond
area even more dramatically. Also the high
quality water emerging from the brine concen-
trator might be better utilized as boiler
feed water rather than injected back into the
cooling loop as shown.

The results of calculations based on
option 3 are summarized in Tables 17-19.

Discussion of Treatment Options

Option 1, in which no treatment other
than biocide is provided for, is not a
practical alternative in part because of the
scaling problems that would be encountered
and the large evaporation ponds required for
ultimate disposal. It is included to em-
phasize the difference between treatment and
disposal costs associated with the potential
use of saline waters.

Both the capital and operating costs of
the tower-condenser loop tend to increase as
the maximum allowable TDS of the circulating
water increases, but these costs are not
reflected in the models. These models thus
simply indicate how treatment and disposal
costs might be expected to increase as the
salinity of the makeup water increases.

Disposal costs are greatly reduced as
the circulating salinity limit is allowed to
increase as indicated by Figures 38, 39, and
40. Figures 41 through 43 show that costs
can be expected to increase quite dramatical-
ly as the salinity of the makeup water
increases, particularly when the operating
policy is to maintain lower TDS levels in the
circulating loop.

Table 14. Makeup and blowdown water requirements for a 1000 MWe power plant under option 2.

Circulating Salinity (mg/l) → / Makeup Salinity (mg/l) ↓ (1000 ac-ft/yr)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up
1,000	1.72	18.05	1.48	17.81	1.30	17.63	1.15	17.48	1.03	17.36	0.77	17.09	0.60	16.91	0.48	16.79	0.39	16.69	–	–
1,500	2.81	19.14	2.42	18.75	2.12	18.45	1.88	18.21	1.69	18.02	1.27	17.60	1.01	17.33	0.82	17.14	0.69	16.99	0.58	16.88
2,000	4.04	20.37	3.46	19.79	3.02	19.35	2.67	19.00	2.40	18.72	1.81	18.13	1.44	17.76	1.18	17.50	1.00	17.30	0.85	17.15
2,500	5.46	21.79	4.64	20.97	4.03	20.36	3.55	19.88	3.17	19.50	2.39	18.71	1.90	18.22	1.57	17.88	1.32	17.63	1.14	17.43
3,000	7.07	23.40	5.96	22.29	5.14	21.47	4.51	20.84	4.01	20.34	3.00	19.32	2.38	18.70	1.96	18.27	1.66	17.96	1.43	17.73
3,500	8.69	25.02	7.24	23.57	6.20	22.53	5.42	21.74	4.80	21.13	3.57	19.89	2.82	19.14	2.32	18.63	1.96	18.26	1.69	17.99
4,000	10.82	27.15	8.90	25.23	7.55	23.88	6.55	22.88	5.78	22.11	4.25	20.57	3.34	19.66	2.74	19.06	2.32	18.62	2.00	18.29
4,500	13.35	29.68	10.82	27.15	9.08	25.41	7.81	24.14	6.85	23.18	4.99	21.31	3.90	20.22	3.19	19.50	2.69	18.99	2.31	18.61
5,000	16.41	32.74	13.05	29.38	10.82	27.15	9.23	25.56	8.04	24.37	5.78	22.10	4.49	20.81	3.66	19.97	3.07	19.38	2.64	18.94
5,500	20.17	36.50	15.68	32.01	12.81	29.14	10.81	27.14	9.35	25.68	6.63	22.95	5.11	21.43	4.15	20.46	3.48	19.78	2.99	19.28
6,000	24.91	41.24	18.82	35.15	15.11	31.44	12.61	28.94	10.81	27.14	7.55	23.87	5.78	22.09	4.66	20.97	3.90	20.20	3.34	19.63
6,500	31.06	47.39	22.66	38.99	17.82	34.15	14.67	30.99	12.45	28.78	8.55	24.87	6.48	22.80	5.20	21.51	4.33	20.64	3.71	20.00
7,000	39.36	55.69	27.43	43.76	21.03	37.36	17.03	33.36	14.30	30.63	9.63	25.95	7.23	23.55	5.77	22.08	4.79	21.10	4.09	20.38
7,500	51.19	67.52	33.53	49.86	24.90	41.23	19.79	36.12	16.41	32.73	10.81	27.13	8.03	24.35	6.37	22.09	5.27	21.57	4.48	20.78
8,000	69.41	85.74	41.61	57.94	29.68	46.01	23.05	39.37	18.82	35.15	12.11	28.43	8.89	25.21	7.01	23.32	5.77	22.07	4.89	21.19
8,500	101.08	117.41	52.82	69.15	35.71	52.04	26.94	43.27	21.62	37.95	13.53	29.86	9.82	26.13	7.68	23.99	6.29	22.60	5.32	21.62
9,000	129.92	146.25	69.41	85.74	43.55	59.88	31.70	48.03	24.90	41.23	15.11	31.43	10.81	27.13	8.39	24.70	6.84	23.15	5.77	22.06
9,500	131.97	148.30	96.45	112.78	54.18	70.51	37.63	53.96	28.81	45.13	16.86	33.18	11.88	28.20	9.15	25.46	7.42	23.73	6.23	22.53
10,000	–	–	148.42	164.75	69.40	85.73	45.24	61.57	33.53	49.85	18.82	35.14	13.04	29.35	9.95	26.26	8.03	24.33	6.72	23.01

Table 15. Brine evaporation pond area required for a 1000 MWe power plant under option 2.

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Circulating Salinity (mg/l) → / Makeup Salinity (mg/l) ↓ Pond Area (acres)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.
1,000	510	900	440	780	390	680	340	600	310	540	230	400	180	310	140	250	120	200	--	--
1,500	830	1500	720	1300	630	1100	560	990	500	890	380	670	300	530	240	430	200	360	170	310
2,000	1200	2100	1000	1800	900	1600	790	1400	710	1300	540	950	430	760	350	620	300	520	250	450
2,500	1600	2900	1400	2400	1200	2100	1100	1900	940	1700	710	1300	560	1000	460	820	390	700	340	600
3,000	2100	3700	1800	3100	1500	2700	1300	2400	1200	2100	890	1600	710	1300	580	1000	490	870	420	750
3,500	2600	4600	2100	3800	1800	3300	1600	2800	1400	2500	1100	1900	840	1500	690	1200	580	1000	500	890
4,000	3200	5700	2600	4700	2200	4000	1900	3400	1700	3000	1300	2200	990	1800	810	1400	690	1200	590	1000
4,500	4000	7000	3200	5700	2700	4800	2300	4100	2000	3600	1500	2600	1200	2100	950	1700	800	1400	690	1200
5,000	4900	8600	3900	6900	3200	5700	2700	4900	2400	4200	1700	3000	1300	2400	1100	1900	910	1600	780	1400
5,500	6000	11000	4700	8200	3800	6700	3200	5700	2800	4900	2000	3500	1500	2700	1200	2200	1000	1800	890	1600
6,000	7400	13000	5600	9900	4500	7900	3700	6600	3200	5700	2200	4000	1700	3000	1400	2500	1200	2000	990	1800
6,500	9200	16000	6700	12000	5300	9400	4400	7700	3700	6500	2500	4500	1900	3400	1500	2700	1300	2300	1100	1900
7,000	12000	21000	8100	14000	6200	11000	5100	9000	4200	7500	2900	5100	2100	3800	1700	3000	1400	2500	1200	2100
7,500	15000	27000	10000	18000	7400	13000	5900	10000	4900	8600	3200	5700	2400	4200	1900	3400	1600	2800	1300	2400
8,000	21000	36000	12000	22000	8800	16000	6800	12000	5600	9900	3600	6400	2600	4700	2100	3700	1700	3000	1500	2600
8,500	30000	53000	16000	28000	11000	19000	8000	14000	6400	11000	4000	7100	2900	5200	2300	4000	1900	3300	1600	2800
9,000	39000	68000	21000	36000	13000	23000	9400	17000	7400	13000	4500	7900	3200	5700	2500	4400	2000	3600	1700	3000
9,500	39000	69000	29000	51000	16000	28000	11000	20000	8500	15000	5000	8900	3500	6200	2700	4800	2200	3900	1800	3300
10,000	--	--	44000	78000	21000	36000	13000	24000	9900	18000	5600	9900	3900	6900	3000	5200	2400	4200	2000	3500

Table 16. Annual cost of treatment and evaporation pond for a 1000 MWe power plant under option 2.

Circulating Salinity (mg/1) → 10^6 \$/yr ↓ Makeup Salinity (mg/1)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.
1,000	3.2	4.7	2.8	4.1	2.6	3.7	2.4	3.3	2.2	3.1	1.8	2.5	1.6	2.1	1.4	1.8	1.3	1.6	–	–
1,500	4.8	7.3	4.3	6.3	3.8	5.7	3.5	5.1	3.2	4.6	2.6	3.7	2.2	3.1	2.0	2.7	1.8	2.3	1.6	2.1
2,000	6.7	10	5.8	8.8	5.2	7.8	4.7	7.0	4.3	6.3	3.5	5.0	2.9	4.2	2.5	3.6	2.3	3.1	2.1	2.8
2,500	8.8	14	7.6	12	6.7	10	6.0	9.1	5.5	8.2	4.4	6.4	3.7	5.3	3.2	4.5	2.8	3.9	2.5	3.5
3,000	11	17	9.8	15	8.6	13	7.6	12	6.9	10	5.5	8.1	4.5	6.6	3.9	5.6	3.5	4.9	3.1	4.4
3,500	14	22	12	18	11	16	9.4	14	8.4	13	6.7	9.9	5.5	8.0	4.8	6.8	4.2	5.9	3.8	5.3
4,000	18	27	15	22	13	19	11	17	10	15	7.8	11	6.5	9.3	5.5	7.9	4.9	6.9	4.4	6.1
4,500	22	33	18	27	15	23	13	20	12	18	9.1	13	7.4	11·	6.3	9.1	5.6	7.9	5.0	7.0
5,000	26	40	21	32	18	27	16	23	14	21	10.3	15	8.4	12	7.2	10	6.3	8.9	5.6	7.9
5,500	32	50	25	39	21	32	18	27	16	24	12	18	9.5	14	8.0	12	7.0	10	6.2	8.8
6,000	40	61	30	47	25	38	21	32	18	28	13	20	11	16	9	13	7.8	11	6.9	9.8
6,500	49	76	37	56	29	44	24	37	21	32	15	22	12	17	10.0	14	8.6	12	7.6	11
7,000	62	96	44	68	34	52	28	43	24	36	17	25	13	19	11	16	9.4	14	8.3	12
7,500	81	120	54	82	40	62	33	50	27	41	19	28	15	22	12	17	10	15	9	13
8,000	110	170	67	100	48	74	38	58	31	47	21	32	16	24	13	19	11	16	10.0	14
8,500	160	250	84	130	58	88	44	67	36	54	24	35	18	26	14	21	12	18	11	15
9,000	210	320	110	170	70	110	52	79	41	63	26	39	19	29	16	23	13	19	11	16
9,500	220	340	150	240	87	130	61	94	48	72	29	44	21	31	17	25	14	21	12	18
10,000	–	–	240	360	110	170	74	110	55	84	32	49	23	34	18	27	15	22	13	19

Table 17. Makeup and blowdown water requirements for a 1000 MWe power plant under option 3.

Circulating Salinity (mg/l) → Makeup Salinity (mg/l) ↓ (1000 ac-ft/yr)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up	Blow-down	Make-up
1,000	0.371	16.70	0.366	16.70	0.362	16.69	0.358	16.69	0.356	16.68	0.349	16.67	0.343	16.66	0.339	16.65	0.335	16.64	–	–
1,500	0.397	16.73	0.390	16.72	0.384	16.71	0.379	16.71	0.375	16.70	0.366	16.69	0.359	16.68	0.353	16.67	0.349	16.65	0.345	16.64
2,000	0.423	16.75	0.414	16.74	0.407	16.74	0.401	16.73	0.395	16.72	0.383	16.71	0.374	16.69	0.368	16.68	0.362	16.67	0.357	16.65
2,500	0.450	16.78	0.439	16.77	0.429	16.76	0.422	16.75	0.415	16.74	0.401	16.72	0.390	16.71	0.382	16.69	0.376	16.68	0.370	16.67
3,000	0.476	16.81	0.463	16.79	0.452	16.78	0.443	16.77	0.436	16.76	0.418	16.74	0.406	16.72	0.397	16.71	0.389	16.69	0.383	16.68
3,500	0.495	16.83	0.480	16.81	0.468	16.80	0.458	16.79	0.450	16.78	0.431	16.75	0.418	16.74	0.408	16.72	0.400	16.70	0.393	16.69
4,000	0.521	16.85	0.504	16.83	0.490	16.82	0.479	16.81	0.470	16.80	0.448	16.77	0.433	16.75	0.422	16.73	0.413	16.72	0.405	16.70
4,500	0.547	16.88	0.528	16.86	0.512	16.84	0.500	16.83	0.489	16.82	0.465	16.79	0.448	16.77	0.436	16.75	0.426	16.73	0.418	16.71
5,000	0.573	16.90	0.551	16.88	0.534	16.86	0.520	16.85	0.509	16.84	0.482	16.81	0.464	16.78	0.450	16.76	0.439	16.74	0.430	16.73
5,500	0.599	16.93	0.575	16.91	0.557	16.89	0.541	16.87	0.528	16.86	0.499	16.82	0.479	16.80	0.464	16.78	0.452	16.76	0.443	16.74
6,000	0.625	16.96	0.599	16.93	0.579	16.91	0.562	16.89	0.548	16.88	0.516	16.84	0.495	16.81	0.478	16.79	0.466	16.77	0.455	16.75
6,500	0.651	16.98	0.623	16.95	0.601	16.93	0.583	16.91	0.568	16.90	0.534	16.86	0.510	16.83	0.493	16.80	0.479	16.78	0.468	16.76
7,000	0.677	17.01	0.647	16.98	0.623	16.95	0.604	16.93	0.587	16.92	0.551	16.87	0.526	16.84	0.507	16.82	0.492	16.80	0.480	16.78
7,500	0.703	17.03	0.671	17.00	0.646	16.98	0.625	16.95	0.607	16.93	0.568	16.89	0.541	16.86	0.521	16.83	0.506	16.81	0.493	16.79
8,000	0.730	17.06	0.696	17.03	0.668	17.00	0.646	16.97	0.627	16.95	0.585	16.91	0.557	16.87	0.535	16.85	0.519	16.82	0.506	16.80
8,500	0.756	17.09	0.720	17.05	0.691	17.02	0.667	17.00	0.647	16.97	0.603	16.93	0.572	16.89	0.550	16.86	0.532	16.84	0.518	16.81
9,000	0.783	17.11	0.744	17.07	0.713	17.04	0.688	17.02	0.667	16.99	0.620	16.94	0.588	16.91	0.564	16.88	0.546	16.85	0.531	16.83
9,500	0.809	17.14	0.769	17.10	0.736	17.07	0.709	17.04	0.687	17.01	0.637	16.96	0.603	16.92	0.579	16.89	0.559	16.86	0.544	16.84
10,000	–	–	0.793	17.12	0.759	17.09	0.730	17.06	0.707	17.03	0.655	16.98	0.619	16.94	0.593	16.90	0.573	16.88	0.556	16.85

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Table 18. Brine evaporation pond area required for a 1000 MWe power plant under option 3.

Circulating Salinity (mg/l)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
Pond Area (acres) / Makeup Salinity (mg/l)	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.
1,000	110	190	110	190	110	190	110	190	110	190	100	180	100	180	100	180	99	180	–	–
1,500	120	210	120	210	110	200	110	200	110	200	110	190	110	190	100	190	100	180	100	180
2,000	130	220	120	220	120	210	120	210	120	210	110	200	110	200	110	190	110	190	110	190
2,500	130	240	130	230	130	230	130	220	120	220	120	210	120	210	110	200	110	200	110	190
3,000	140	250	140	240	130	240	130	230	130	230	120	220	120	210	120	210	120	200	110	200
3,500	150	260	140	250	140	250	140	240	130	240	130	230	120	220	120	210	120	210	120	210
4,000	150	270	150	260	150	260	140	250	140	250	130	240	130	230	130	220	120	220	120	210
4,500	160	290	160	280	150	270	150	260	150	260	140	240	130	240	130	230	130	220	120	220
5,000	170	300	160	290	160	280	150	270	150	270	140	250	140	240	130	240	130	230	130	230
5,500	180	310	170	300	170	290	160	280	160	280	150	260	140	250	140	240	130	240	130	230
6,000	190	330	180	320	170	300	170	300	160	290	150	270	150	260	140	250	140	240	140	240
6,500	190	340	180	330	180	320	170	310	170	300	160	280	150	270	150	260	140	250	140	250
7,000	200	360	190	340	190	330	180	320	170	310	160	290	160	280	150	270	150	260	140	250
7,500	210	370	200	350	190	340	190	330	180	320	170	300	160	280	150	270	150	270	150	260
8,000	220	380	210	370	200	350	190	340	190	330	170	310	170	290	160	280	150	270	150	270
8,500	220	400	210	380	200	360	200	350	190	340	180	320	170	300	160	290	160	280	150	270
9,000	230	410	220	390	210	380	200	360	200	350	180	330	170	310	170	300	160	290	160	280
9,500	240	430	230	400	220	390	210	370	200	360	190	340	180	320	170	300	170	290	160	290
10,000	–	–	240	420	230	400	220	380	210	370	190	340	180	330	180	310	170	300	170	290

Table 19.   Annual cost of the treatment and evaporation pond for a 1000 MWe power plant under option 3.

Circulating Salinity (mg/1) 10^6 \$/yr / Makeup Salinity (mg/1)	8,000		9,000		10,000		11,000		12,000		15,000		18,000		21,000		24,000		27,000	
	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.
1,000	1.8	2.1	1.7	2.0	1.6	1.9	1.5	1.8	1.4	1.7	1.3	1.6	1.1	1.4	0.96	1.3	0.83	1.1	–	–
1,500	2.5	2.9	2.4	2.7	2.2	2.6	2.1	2.5	2.0	2.4	1.8	2.1	1.6	2.0	1.5	1.8	1.4	1.7	1.2	1.5
2,000	3.2	3.6	3.0	3.4	2.9	3.2	2.7	3.1	2.6	3.0	2.3	2.7	2.1	2.5	2.0	2.3	1.8	2.2	1.7	2.0
2,500	4.0	4.4	3.7	4.1	3.5	3.9	3.3	3.7	3.2	3.5	2.9	3.2	2.6	3.0	2.4	2.8	2.3	2.6	2.2	2.5
3,000	4.8	5.2	4.5	4.9	4.3	4.7	4.1	4.5	3.9	4.3	3.5	3.9	3.2	3.5	2.9	3.3	2.7	3.1	2.6	2.9
3,500	5.7	6.1	5.3	5.8	5.1	5.5	4.9	5.3	4.7	5.1	4.3	4.6	3.9	4.3	3.7	4.0	3.5	3.8	3.3	3.6
4,000	6.4	6.9	6.1	6.5	5.8	6.2	5.5	5.9	5.3	5.7	4.9	5.2	4.5	4.9	4.2	4.6	4.0	4.4	3.8	4.2
4,500	7.1	7.6	6.7	7.2	6.4	6.9	6.2	6.6	5.9	6.3	5.4	5.8	5.0	5.4	4.8	5.1	4.5	4.9	4.3	4.7
5,000	8.0	8.5	7.5	8.0	7.2	7.6	6.9	7.3	6.6	7.0	6.0	6.4	5.6	6.0	5.2	5.6	5.0	5.4	4.8	5.2
5,500	8.8	9.3	8.3	8.8	7.9	8.4	7.6	8.1	7.3	7.8	6.7	7.1	6.2	6.6	5.8	6.2	5.5	5.9	5.2	5.6
6,000	9.6	10	9.1	9.6	8.6	9.1	8.3	8.8	8.0	8.4	7.3	7.7	6.8	7.2	6.4	6.8	6.1	6.5	5.8	6.2
6,500	10	11	9.8	10	9.3	9.8	8.9	9.4	8.6	9.1	7.9	8.3	7.3	7.8	6.9	7.4	6.6	7.0	6.4	6.8
7,000	11	12	11	11	10	10	9.5	10	9.2	9.7	8.4	8.9	7.9	8.3	7.5	7.9	7.1	7.5	6.8	7.3
7,500	12	13	11	12	11	11	10	11	9.9	10	9.1	9.6	8.4	8.9	7.9	8.4	7.6	8.0	7.3	7.7
8,000	13	13	12	13	12	12	11	12	11	11	9.7	10	9.1	9.6	8.6	9.0	8.2	8.6	7.8	8.3
8,500	14	14	13	13	12	13	12	12	11	12	10	11	9.6	10	9.1	9.6	8.7	9.2	8.4	8.8
9,000	14	15	14	14	13	13	12	13	12	12	11	11	10	11	9.7	10	9.3	9.7	8.9	9.4
9,500	15	16	14	15	14	14	13	14	13	13	11	12	11	11	10	11	9.7	10	9.4	9.9
10,000	–	–	15	16	14	15	14	14	13	14	12	13	11	12	11	11	10	11	9.8	10

MAKEUP SALINITY = 1000 mg/l

MAKEUP SALINITY = 5000 mg/l

10^6 $/yr

CIRCULATING WATER SALINITY (X 10^3 mg/l)

OPTION 2

OPTION 3

OPTION 1

OPTION 1

OPTION 2

OPTION 3

2
3
1

10^6 $/yr

CIRCULATING WATER SALINITY (X 10^3 mg/l)

Figure 38. Water treatment and disposal costs as a function of the allowable TDS of circulating loop water assuming the salinity of the makeup water is 1000 mg/l.

Figure 39. Water treatment and disposal costs as a function of the allowable TDS of circulating loop water assuming the salinity of the makeup water is 5,000 mg/l.

Figure 40. Water treatment and disposal costs as a function of the allowable TDS of circulating loop water assuming the salinity of the makeup water is 10,000 mg/l.

Figure 41. Water treatment and disposal costs as a function of makeup water salinity assuming the TDS limit of the circulating water is 10,000 mg/l.

CIRCULATING SALINITY LIMIT = 15,000 mg/l

OPTION I

OPTION 2

OPTION 3

10^6 \$/yr

100

50

0

MAKEUP WATER SALINITY (X 10^3 mg/l)

1 2 3 4 5 6 7 8 9 10

Figure 42.   Water treatment and disposal costs as a function of makeup water salinity assuming the TDS limit of the circulating water is 15,000 mg/l.

CIRCULATING SALINITY LIMIT = 24,000 mg/l

OPTION I

OPTION 2

OPTION 3

10^6 \$/yr

20

15

10

5

0

2
1
3

MAKEUP WATER SALINITY (X 10^3 mg/l)

1 2 3 4 5 6 7 8 9 10

Figure 43.   Water treatment and disposal costs as a function of makeup water salinity assuming the TDS limit of the circulating water is 24,000 mg/l.

A Relative Value Scale for Saline Water

With the information provided in the previous section it is possible to present the concept of a relative value scale for waters of various salinities. The rationale for the development of this scale is as follows: Suppose lower quality water (for example TDS = 5,000 mg/l) is available and can be delivered to the plant at a cost of $100/ac-ft, and better quality water (for example TDS = 1,000 mg/l) is available but the cost delivered to the plant is $500/ac-ft. While the lower quality water costs less per unit volume, a greater volume will be required and treatment and disposal costs are greater. All other factors being equal, which water is economically preferable for cooling purposes?

To establish a relative value scale for makeup waters of various salinities, the following is written:

$$MU_i \times VALUE_i + COST_i = MU_5 \times VALUE_5 + COST_5 \quad (49)$$

where

MU_i = quantity (ac-ft) of makeup water of salinity i required under the given treatment option

$VALUE_i$ = value of the makeup of salinity i expressed in $/ac-ft

$COST_i$ = water treatment and disposal costs when water of salinity i is used as makeup water

MU_5 = quantity (ac-ft) of 5,000 mg/l makeup water

$VALUE_5$ = price of 5,000 mg/l makeup water delivered to the plant

$COST_5$ = water treatment and disposal costs when 5,000 mg/l water is used as makeup water

The value of makeup water of salinity i is thus calculated as

$$VALUE_i = \frac{(MU_5 \times VALUE_5 + COST_5 - COST_i)}{MU_i} \quad . \quad . \quad (50)$$

If the system operates under option 2, utilizing 15,000 mg/l circulating water, from Table 16 the treatment cost of 5,000 mg/l water is $10.3 x 10^6 while the treatment cost of 1,000 mg/l water is $1.8 x 10^6 under normal year conditions. From Table 14, 22,100 ac-ft per year of the 5,000 mg/l water would be required while 17,090 ac-ft of the 1,000 mg/l water would do the job. Assuming the price of 5,000 mg/l makeup water is $100/ac-ft, the total cost of utilizing 5,000 mg/l water is

$$22,100 \text{ ac-ft} \times \$100/\text{ac-ft} + \$10.3 \times 10^6$$

The total cost of utilizing 1,000 mg/l water is

$$17,090 \text{ ac-ft} \times (\text{value of } 1,000 \text{ mg/l} \\ \text{water/ac-ft}) + \$1.8 \times 10^6$$

Equating these two values gives

$$\text{Value of } 1,000 \text{ mg/l water} = \frac{(2.21 + 10.3 - 1.8) \times 10^6}{17,090}$$

$$= \$627/\text{ac-ft} \quad (51)$$

If the cost of 5,000 mg/l water delivered to the plant were $100/ac-ft one would be advised by these calculations to utilize 1,000 mg/l water if it could be delivered to the plant for less than $627 per ac-ft. A relative value scale computed in this manner is useful in assessing the demand for water as it relates to salinity. Shown in Tables 20 through 22 are relative values of water of various salinities calculated according to this procedure. Figures 44 through 46 show the same information in graphical form. The negative values simply indicate that if 5,000 mg/l water is available for $100/ac-ft the value of water of some higher salinity for purposes of power plant cooling would be negative.

Table 20. Water value by quality given 5000 mg/l water is available for $100 per ac-ft (circulating salinity = 10,000 mg/l).

Makeup Water Salinity (mg/l)	Option		
	1	2	3
1,000	1336.0	1027.5	436.5
1,500	1181.3	916.8	400.1
2,000	1025.9	801.8	357.6
2,500	876.2	688.4	321.4
3,000	724.6	564.3	273.3
3,500	582.5	431.2	225.4
4,000	423.7	323.1	183.5
4,500	249.3	224.9	147.6
5,000	100.0	100.0	100.0
5,500	-52.4	-9.8	58.4
6,000	-198.4	-136.3	16.9
6,500	-350.8	-242.6	-24.5
7,000	-490.5	-355.6	-65.7
7,500	-646.1	-467.7	-124.5
8,000	-807.9	-593.0	-183.2
8,500	-995.1	-716.5	-183.0
9,000	-1106.4	-823.1	-241.4
9,500	-1249.3	-940.1	-299.6

Table 21. Water value by quality given 5000 mg/l water is available for $100 per ac-ft (circulating salinity = 15,000 mg/l).

Make-Up Water Salinity (mg/l)	Option		
	1	2	3
1,000	738.3	609.1	382.8
1,500	659.3	546.0	352.4
2,000	585.3	480.4	322.0
2,500	504.7	417.4	285.9
3,000	428.9	347.3	249.8
3,500	348.1	277.0	201.9
4,000	272.5	214.4	165.8
4,500	193.6	145.9	135.9
5,000	100.0	100.0	100.0
5,500	54.9	9.2	58.3
6,000	−23.9	−33.1	22.6
6,500	−130.2	−112.2	−13.0
7,000	−190.1	−184.6	−42.6
7,500	−273.2	−250.3	−84.0
8,000	−343.6	−309.2	−119.4
8,500	−428.8	−394.8	−137.0
9,000	−497.1	−438.8	−195.9
9,500	−594.9	−506.0	−195.7
10,000	−667.4	−563.2	−254.4

Table 22. Water value by quality given 5000 mg/l water is available for $100 per ac-ft (circulating salinity = 24,000 mg/l).

Make-Up Water Salinity (mg/l)	Option		
	1	2	3
1,000	423.0	415.7	351.2
1,500	382.2	378.9	316.8
2,000	342.4	343.2	292.4
2,500	300.6	308.5	262.2
3,000	260.3	263.8	238.1
3,500	221.6	221.1	190.1
4,000	179.2	179.3	159.9
4,500	138.7	138.9	129.9
5,000	100.0	100.0	100.0
5,500	58.3	62.6	70.0
6,000	18.7	21.7	34.2
6,500	−23.4	−17.5	4.4
7,000	−63.2	−55.1	−25.4
7,500	−104.9	−81.7	−55.1
8,000	−160.8	−125.1	−90.7
8,500	−196.8	−166.5	−120.3
9,000	−230.0	−205.7	−155.8
9,500	−260.6	−242.8	−179.5
10,000	−325.6	−277.9	−197.0

Wet-Dry Cooling

It is, of course, possible to eliminate much of the evaporative water consumption in electrical power generating plants through dry cooling or a combination of wet-dry cooling. Dry cooling has not been widely embraced by the electric utilities primarily because of cost. The cost of conserving water in this fashion may be determined by comparing the costs of such systems with conventional wet systems.

In this section the question is addressed: How do the costs of utilizing lower quality waters of various levels of salinity compare with the costs of dry or wet-dry cooling? Based on the data indicated in Table 23, and assuming a 1,000 MWe power plant operating at 80 percent load factor, the values in Table 24 may be developed. Additional information on the trade offs is shown in Figures 47 through 49.

Table 23. Relative costs for various systems in the Upper Colorado Basin. (From Hu et al. (1978) and Gold et al. (1979).)

Type of Cooling System	Cost (Mills/kwhr)	Water Consumed (gal/kwhr)
(a) Mechanical Wet	1.11	0.707
(b) 40% Wet-Dry	2.21	0.085[a]
(c) 10% Wet-Dry	2.86	0.007[a]
(d) Mechanical Dry	4.07	0.0

[a]Estimated from best available data.

Table 24. Comparison of various types of cooling systems. (Based on data in Table 23.)

Cooling System	Water Used ac-ft/yr	Compared to System (a)		Compared to System (b)		Compared to System (c)	
		Water Saved ac-ft/yr	Cost of Water Saved $/ac-ft	Water Saved ac-ft/yr	Cost of Water Saved $/ac-ft	Water Saved ac-ft/yr	Cost of Water Saved $/ac-ft
(a) mech. wet	21500	0	−	−	−	−	−
(b) 40% wet-dry	2585	18915	$407	−	−	−	−
(c) 10% wet-dry	213	21287	$576	2372	$1920	−	−
(d) mech. dry	0	21500	$965	2585	$5042	213	$39810

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Figure 44. Relative value of makeup waters assuming 5000 mg/l water is available at $100 per ac-ft and circulating water salinity limit is 10,000 mg/l.

Figure 45. Relative value of makeup water assuming 5000 mg/l water is available at $100 per ac-ft and circulating water salinity limit is 15,000 mg/l.

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Figure 46.   Relative value of makeup water assuming 5000
mg/l water is available at $100 per ac-ft
and circulating water salinity limit is
24,000 mg/l.

Figure 47.   Comparison of the costs of utilizing partial
dry cooling with all wet cooling using saline
makeup water for option 1 treatment and dis-
posal.

Figure 48.   Comparison of the costs of utilizing partial dry cooling with all wet cooling using saline makeup water for option 2 treatment and disposal.

Figure 49.   Comparison of the costs of utilizing partial dry cooling with all wet cooling using saline makeup water for option 3 treatment and disposal.

The Binary Cooling Tower

An innovative approach to using low quality water in power plant cooling has been developed by Tower Systems, Inc., of Tacoma, Washington. Their Binary Cooling Tower (BCT) process utilizes a heat exchange system designed such that air and low quality water can be circulated through the evaporative secondary loop as shown in the schematic of Figure 50.

Very high salinities can be tolerated in the secondary loop by use of corrosion resistant materials together with feed and side stream softening to prevent scaling. Heat exchanger detail is shown in Figure 51. The heat exchanger panels are composed of plastic framing materials, water manifolds, and Mylar sheets. Effective heat transfer rates are achieved through the Mylar sheets in spite of their relatively low thermal conductivity due to the thinness of the

Figure 50. BCT system flow diagram. (Courtesy Tower Systems Inc., Tacoma, Washington.)

Figure 51. BCT heat exchanger detail. (Courtesy Tower Systems Inc.)

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sheeting and the falling film configuration of the primary cooling water on one side and the high salinity evaporating loop water on the other.

The BCT system was successfully tested over an 11 week period (March-June 1979) at the Nevada Power Company's Sunrise Station at Las Vegas. The results of that test (Slate et al. 1979) are impressive. The system operated satisfactorily with secondary evaporation loop TDS levels of 80,000 to 130,000 mg/l. Another important feature of the BCT system is drift suppression. Test results indicate that splashing and thus drift losses are almost totally eliminated by the falling film configuration. This could be crucial wherever an attempt is made to utilize high salinity water for purposes of power plant cooling.

With circulation loop salinities of 24,000 mg/l in a conventional cooling tower without drift suppression, approximately 17,000 tons of salt per year would escape into the atmosphere and be deposited on the surrounding countryside. The area subjected to this drift salt depends on prevailing winds and the problem is intensified as the circulating loop salinities increase. At levels of 120,000 mg/l the rate of salt drift in a conventional tower would approach 83,000 tons per year.

A comparison was made between the estimated costs of utilizing the BCT integrated system depicted in Figure 50 and conventional systems with treatment option 3 utilizing reverse osmosis and brine concentrators, based on the BCT model shown in Figure 52.

The integrated BCT-cooling tower system is modeled as a conventional cooling tower system except that the makeup water is cycled up to 120,000 mg/l and the drift losses are reduced to 0.0001 times the drift of conventional towers. The Mg^{++}, Ca^{++}, and SiO_2 levels are controlled by cold process softening as in option 2. The annualized cost of the BCT system above the conventional system is estimated on the basis of information provided by Tower Systems, Inc., for a 350 MWe plant and multiplied by a factor of $(1000/350)^{0.65}$ to scale up to a 1,000 MWe plant.

The results are in Table 25. It may be observed that treatment and disposal costs are estimated as being less for option 3 (R.O. plus brine concentration) provided the quality of the makeup water is sufficiently high. At makeup water salinities of ~ 2300 mg/l and above the BCT becomes considerably less expensive. Figure 53 shows this graphically.

Figure 54 indicates the relative value of makeup water of various salinities compared with 5,000 mg/l water arbitrarily

valued at $100/ac-ft. If the BCT system is utilized, high salinity waters become much more valuable. Thus the BCT approach very probably offers an important technology for effectively utilizing rather highly saline water for power plant cooling.

Figure 52.   BCT unit operated with treatment option 3.

Figure 53.   Cost comparison of the BCT system with conventional towers using reverse osmosis and brine concentration as a function of makeup water salinity.

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Table 25. Computer generated comparison between integrated BCT system with TDS of circulating water at 120,000 mg/l and option 3 with TDS of circulating water at 24,000 mg/l for 1,000 MWe plant.

Makeup Salinity (mg/l)	Blowdown Water (ac-ft/yr)		Makeup Water (ac-ft/yr)		Brine Evaporation Pond (acre)		Treatment & Disposal Cost (10^6 $/yr)	
	BCT With Softening	Option 3 RO plus Brine Conc.	BCT With Softening	Option 3 RO plus Brine Conc.	BCT With Softening	Option 3 RO plus Brine Conc.	BCT With Softening	Option 3 RO plus Brine Conc.
1,000	351	335	12,870	16,640	104	99	1.8	0.8
1,500	392	349	12,900	16,650	112	100	1.9	1.4
2,000	432	362	12,960	16,670	128	110	2.0	1.8
2,500	480	376	13,000	16,680	144	110	2.1	2.3
3,000	528	389	13,048	16,690	152	120	2.3	2.7
3,500	568	400	13,088	16,700	168	120	2.6	3.5
4,000	608	413	13,136	16,720	184	120	2.8	4.0
4,500	656	426	13,176	16,730	192	130	2.9	4.5
5,000	704	439	13,224	16,740	208	130	3.1	5.0
5,500	752	452	13,272	16,760	224	130	3.2	5.5
6,000	792	466	13,320	16,770	240	140	3.4	6.1
6,500	840	479	13,368	16,780	248	140	3.5	6.6
7,000	880	492	13,408	16,800	264	150	3.7	7.1
7,500	936	506	13,456	16,810	280	150	3.9	7.6
8,000	984	519	13,504	16,820	296	150	4.0	8.2
8,500	1,032	532	13,560	16,840	304	160	4.2	8.7
9,000	1,080	546	13,608	16,850	320	160	4.4	9.3
9,500	1,136	559	13,656	16,860	336	170	4.5	9.7
10,000	1,184	573	13,704	16,880	352	170	4.7	10.0

Reservoir Cooling

Under certain conditions the evaporative reservoir (Figure 55) offers an alternative to the evaporative cooling tower.

Reservoir analysis

The reservoir system offers several advantages, not the least of which is that it eliminates the need for the costly mechanical systems of the cooling tower which are subject to corrosion and fouling. Presented in that which follows are some factors which should be considered if the makeup water to the evaporative reservoir is saline groundwater.

Cooling pond performance can be analyzed in a manner similar to that described

Figure 54. Relative value of makeup water of various salinities compared with 5000 mg/l water arbitrarily valued at $100/ac-ft.

for predicting the performance of brine evaporation ponds, but there are important differences. Instead of only blowdown water entering the pond one has both the makeup water and the condensor effluent. The energy balance may be written as

$$\frac{d}{dt} (\rho \, CDAT) = \dot{Q}_{solar} + \dot{Q}_o + \dot{Q}_{mu} - \dot{Q}_{conv} - \dot{Q}_{evap} \quad (52)$$
$$- \dot{Q}_{rad}$$

where

$\dot{Q}_o$ = rate of energy rejected from the power plant. For a 1,000 MWe plant operating at 40 percent efficiency, $\dot{Q}_o$ = 1,500 MWe = 5.12 x 10^9 Btu/hr

$\dot{Q}_{mu}$ = rate of energy entering the reservoir from makeup water, $\dot{Q}_{mu} = M_{mu} \, Cp_{mu} (T_{mu} - T)$

$\dot{M}_{mu}$ = mass flow rate of the makeup water

Cp_{mu} = specific heat of the makeup water

T_{mu} = temperature of the makeup water

T = temperature of the reservoir

The other terms are defined as for Equation 8 in the analysis of the brine evaporation pond.

Figure 55. Schematic showing basic parameters involved in modeling the cooling reservoir.

For purposes of this analysis, it is assumed that the depth of the cooling reservoir remains constant over the time period under consideration, or

$$\frac{d}{dt}\left[(1-Conc)\,\rho\,DA\right] = (1-Conc_{mu})\,\dot{M}_{mu} + \dot{M}_{precip} - \dot{M}_{evap} = 0$$
$$\cdots \cdots (53)$$

where

$\dot{M}_{precip}$ is based on weather station data

$\dot{M}_{evap}$ is calculated as indicated in the brine evaporation pond analysis

Conc = concentration of cooling reservoir salinity

$Conc_{mu}$ = concentration of makeup water salinity

There is no outflow from the reservoir under total containment philosophy.

The numerical procedure for solving the above equations is as follows:

1) Make a reasonable estimate of the rate of makeup required as

$$\sum_{year} (\dot{M}_{mu})_{estimate}\,(1-Conc_{mu})\Delta t = \frac{\sum_{year}\dot{Q}_o\,\Delta T}{h_{fg}} \quad (54)$$

2) Make a reasonable estimate of pond area as

$$A = \frac{\sum_{year}(\dot{M}_{mu})_{estimate}\,\Delta t}{(Annual\ evap.\ -\ Annual\ precip.)_{estimate}}$$
$$\cdots \cdots (55)$$

where the annual depths of evaporation and precipitation are estimated.

3) Assign a minimum depth D to be maintained in the pond. (In this analysis, that depth is taken as 10 ft.)

4) Assume the temperature of the makeup water is constant. (For this study, $T_{mu} = 60°F$.)

5) Use the estimated values of $\dot{M}_{mu}$, D, and A with the iterational procedure outlined in steps 4 and 5 described on page 22 in calculating the initial brine evaporation temperature at time t = 0.

6) Calculate the value of $\dot{M}_{mu}$ required on that first day to maintain constant depth D.

7) Repeat steps 5 and 6 until values of $\dot{M}_{mu}$ agree on two successive iterations.

8) Using T at t = 0 and $\dot{M}_{mu}$ on the first day calculate T and $\dot{M}_{mu}$ for entire year.

9) Calculate cooling reservoir area A as

$$A = \frac{\sum\limits_{year} \dot{M}_{mu} (1-Conc_{mu}) \Delta t}{\sum\limits_{year} \left(\frac{\dot{M}_{evap}}{A} - \frac{\dot{M}_{precip}}{A} \right) \Delta t} \qquad . \quad . \quad . \quad (56)$$

10) Repeat steps 5 to 9 until the areas calculated on two successive iterations agree.

The required cooling pond area for a 1000 MWe power plant as calculated by this numerical procedure and for average solar insolation and average air temperature data for central Utah is 811 acres or 3.28×10^6 m^2. The total volume of makeup water required is 8,631 ac-ft/year or 1.06×10^7 m^3/year. Figures 56 and 57 depict annual variations in average daily reservoir temperature for an average year and the critical year. Figures 58 and 59 show the month by month average daily reservoir temperature for an average year and the critical year.

The effects of depth, wind velocity, and air temperature on cooling pond temperature

A cooling pond is considered to be shallow if its depth is on the order of 8 to 20 ft. Cooling ponds whose depths exceed 20 ft are characterized as deep ponds (Senges 1979). In this study, only shallow ponds are considered. These shallow ponds are assumed to be well mixed and have a uniform temperature throughout. This assumption may not be entirely justifiable.

According to the computer model used here, variations in hourly pond temperatures over a 24 hour period tend to decrease with increasing pond depth. The deeper the pond, the longer are the response times to weather or changes in the loading characteristics from plant effluents.

A cooling pond should be designed so that the prevailing wind during the summer is directed from the condenser intake to the condenser discharge, thus reducing short circuiting during the pond's most critical season. Wind-generated waves cause vertical mixing and wind-induced currents force warm waters into outlying regions. A third effect is the piling up of warm waters on the down-wind shore. In this study, the second and the third effects are neglected; however, the model does replicate the fact that the wind increases convective heat transfer

and evaporation rates and thus reduces pond temperatures. Assuming a wind velocity of 10 mph, the natural evaporation rate (without power plant loading) per year is calculated to be 5.4 ft. When the wind velocity is reduced to 5 mph, the calculated natural evaporation rate drops to 4.0 ft per year. Power plant loading raises the peak pond temperature from 80°F to 90°F (with roughly the same pond area).

Figure 60 shows the computed hourly pond temperature and air temperature for a typical day in June. Nighttime air temperatures are approximately 20°F lower than the pond water temperatures. Figures 57 and 58 show the variation in hourly temperatures for each month of the average and critical years. The average daily temperatures for each month of the average and critical years are shown in Figures 59 and 60 respectively.

Rate of salinity buildup in cooling reservoir

Because the evaporating water leaves its salt content behind, there is inevitably a buildup of salinity in a cooling pond with no outlet. The more saline the makeup water added to maintain the cooling pond water level, the faster is the rate of salinity buildup. At first glance, it might seem that the salinity buildup problem alone would preclude use of saline groundwater for makeup. It is instructive, however, to examine the problem in greater detail before passing judgment.

Option 1. Condenser-reservoir loop--no treatment

For a constant volume cooling reservoir (Figure 61), the rate of salt accumulation may be determined from

$$\frac{d}{dt} (\rho \, Vol \, Conc) = \dot{M}_{mu} \, Conc_{mu} \qquad . \quad . \quad (57)$$

where

ρ = density of brines and is a function of the concentration,

$$= \frac{M_{H_2O} + M_{salt}}{Vol} = \frac{M_{H_2O}}{Vol} + \frac{M_{salt}}{Vol} \; (lb/ft^3) \quad (58)$$

$$\frac{M_{salt}}{Vol} \; (lb/ft^3) = Conc \; (mg/l) \times 28.317 \; (lb/ft^3)$$

$$\times \; 0.221 \times 10^{-6} (lb/mg) \cdot \quad . \quad (59)$$

$$\rho_{H_2O} = \frac{M_{H_2O}}{Vol} \qquad . \quad . \quad . \quad . \quad (60)$$

$$\rho = \rho_{H_2O} + 6.258 \times 10^{-6} \; Conc \qquad . \quad . \quad (61)$$

Figure 56. Computed cooling pond temperature with the associated air temperature during a typical day in June.

Figure 57. The predicted cooling pond temperature pattern for a typical day in each month of an average year.

Figure 58.   The predicted cooling pond temperature pattern for a typical day in each month of the critical year.

Figure 59.   Predicted average daily cooling pond temperature for each month of an average year.

57

90

80

70

TEMPERATURE (°F)

60

50

40

POND TEMP.

AIR TEMP.

t1 t2 t3

t23 t24

HOURS OF A DAY IN JULY (t1 IS THE HOUR JUST BEFORE SUNRISE)

Figure 60. Predicted average daily cooling pond temperature for each month of the critical year.

OPTION 1. NO TREATMENT

Q OUT = 1500 MW

POWER PLANT
CONDENSER

COOLING RESERVOIR

MAKEUP

Figure 61. The cooling reservoir-condenser loop, option 1.

58

Vol = volume of the cooling reservoir, found previously and treated as a constant

Conc = salinity concentration of reservoir

$Conc_{mu}$ = salinity concentration of makeup water

or

$$\frac{d}{dt} (\rho_{H_2O} + 6.258 \times 10^{-6} \; Conc) \times Conc = \frac{\dot{M}_{mu} \; Conc_{mu}}{Vol}$$

$$. \quad . \quad . \quad . \quad . \quad . \quad (62)$$

where it is assumed that at $t = 0$, $Conc = Conc_{mu}$. The computed salinity levels for time horizons from 1 to 40 years are shown in Table 26.

Option 2. Direct cold process softening of makeup water

In this option, as depicted in Figure 62, makeup water salinity is reduced by a cold process softener. The calculated salinity levels, assuming a 30-percent salinity reduction by the softener, are also shown in Table 26.

Option 3. Sidestream water treatment

The schematic for this option is given in Figure 63. It is assumed that sidestream water treatment can remove 30 percent of the salt from the feed water without significantly affecting the mass flow rate of the circulating water, thus controlling the salinity of the reservoir. In this study the controlled salinity level is assumed as 25,000 mg/l. The procedure to calculate the mass flow rate of sidestream is

$$Salt_{in} = Salt_{out} \quad . \quad . \quad . \quad . \quad (63)$$

or

$$\dot{M}_{mu} \times Conc_{mu} = \dot{M}_{side} \times 25000 \times 0.30$$

$$. \quad . \quad . \quad . \quad (64)$$

then

$$\dot{M}_{side} = \frac{\dot{M}_{mu} \times Conc_{mu}}{7500} \quad . \quad . \quad . \quad (65)$$

where

$\dot{M}_{side}$ = mass flow rate of sidestream

Because the makeup water flow rate is taken as a constant, 8,631 ac-ft per year or 1.122×10^7 lb/hr, the mass flow rate required of the sidestream is, therefore, a linear function of the makeup water salinity. For example, when the salinity of the makeup water is 1,000 mg/l the sidestream flow rate is calculated as 1.50×10^6 lb/hr; when the salinity of the makeup water increases to

10,000 mg/l the sidestream flow rate increases to 1.50×10^7 lb/hr.

It is concluded from Table 26 that if the makeup water salinity exceeded 500 mg/l in option 1, after 40 years the concentration of salinity in the reservoir will be higher than that of sea water. With option 2, the salinity of the makeup water should not exceed 1,000 mg/l in order not to have the salinity of the reservoir exceed 35,000 mg/l after 40 years.

Mineral Recovery

Extracting minerals from saline groundwater or power plant brine disposal ponds is technically feasible, but the low market value for the major mineral products (salt, magnesia, and potash) and small amounts of the more valuable salts generally found in the brines tend to make mineral recovery from power plant brine disposal ponds uneconomical at present. Certain minerals find use as fertilizers, but there are problems even here. For example, sylvite (KCl) is suspected of staining the tobacco plant leaf and reducing the quality and quantity of tree and plant growth. Thus fertilizers made with KCl are rejected by citrus and tobacco growers in favor of those made with K_2SO_4 (Blake 1974). Especially when considering mineral recovery from limited amounts of brine, the brine evaporation pond and the cooling reservoir discussed previously, the market potential becomes even less economical.

Phase rule processes

Several processes are available to recover valuable minerals from the concentrated brine. Phase rule processes are attractive since no raw materials are needed except the brine itself. The flow diagram procedure is depicted in Figure 64, and the principal processes are:

1. Solar evaporation of concentrated brine to 1.27 specific gravity to remove sodium chloride (NaCl).

2. Dilution with 15 percent (volume) fresh water.

3. Cooling to -15°C to recover pure mirabilite crystals ($Na_2SO_4 \cdot 10H_2O$).

4. A second evaporation to 1.29 specific gravity to remove additional sodium chloride.

5. Dilution with 5 percent (volume) fresh water.

6. A second cooling to recover pure sylvite (KCl).

OPTION 2   PRETREAT MAKEUP WATER USING COLD PROCESS SOFTENER

Figure 62.   The cooling reservoir-condenser loop, option 2.

Figure 63.   The cooling reservoir-condenser loop, option 3.

Table 26. Salinity buildup in a cooling reservoir at various time horizons.

End of Year	1 Year		5 Year		10 Year		20 Year		40 Year	
Pond (mg/1) / Make Up (mg/1)	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2	Option 1	Option 2
500	1031	721	3152	2207	5803	4062	11099	7772	21676	15183
1,000	2061	1443	6302	4412	11598	8122	22174	15532	43259	30321
1,500	3091	2164	9450	6617	17387	12178	33225	23280	64750	45413
2,000	4121	2885	12596	8821	23170	16230	44251	31017	86150	60459
2,500	5151	3606	15740	11023	28946	20280	55253	38741	107460	75461
3,000	6181	4327	18883	13225	34715	24326	66231	46453	128681	90419
3,500	7210	5048	22023	15426	40478	28369	77186	54154	149814	105333
4,000	8239	5769	25162	17626	46234	32408	88117	61843	170861	120203
4,500	9269	6489	28298	19825	51984	36445	99024	69520	191823	135030
5,000	10298	7210	31433	22023	57728	40478	109908	77186	212700	149814
5,500	11327	7931	34565	24220	63464	44508	120769	84840	233493	164556
6,000	12355	8651	37696	26416	69194	48535	131607	92482	254204	179256
6,500	13384	9372	40825	28612	74918	52558	142422	100114	274834	193914
7,000	14412	10092	43952	30806	80635	56579	153215	107733	295383	208531
7,500	15441	10812	47077	32999	86346	60596	163985	115342	315852	223107
8,000	16469	11532	50201	35192	92050	64610	174732	122939	336243	237642
8,500	17497	12252	53322	37383	97749	68621	185457	130524	356556	252137
9,000	18524	12972	56441	39574	103441	72629	196160	138099	376792	266592
9,500	19552	13692	59559	41763	109126	76633	206841	145662	396952	281007
10,000	20579	14412	62675	43952	114805	80635	217500	153215	417037	295383

7. A third evaporation to recover carnallite ($MgCl_2 \cdot KCl \cdot 6H_2O$) and a strong $MgCl_2$ brine.

The yield of sylvite (KCl) is low but an alternative process is available. When sea water brine is evaporated to a magnesium concentration of 4 percent by weight, pure epsomite ($MgSO_4 \cdot 7H_2O$) is obtained during the first cooling step instead of mirabilite ($Na_2SO_4 \cdot 10H_2O$).

Electrodeposition of minerals
in sea water (Hilbertz 1979)

By establishing a direct electrical current between electrodes in an electrolyte like sea water, calcium carbonates ($CaCO_3$), magnesium hydroxide ($Mg(OH)_2$) are precipitated and hydrogen (H_2) is released at the cathode, while the anode produces oxygen (O_2) and chlorine (Cl_2). The fuel value of the hydrogen thus collected is widely recognized and recent experiments have demonstrated the feasibility of using the electrodeposited minerals for a wide variety of purposes, including the construction of artificial reefs as ocean sites for Ocean Thermal Energy Conversion (OTEC) plants. The experiments show the compressive strength of electrodeposited minerals (average = 4267.5 psi) is greater than that of concrete which is typically used for stairs and steps, sidewalks, driveways, and basement wall

Figure 64.   Phase rule processes flow diagram (from Glassett 1970).

constructions (3500 psi). Another advantage of using electrodeposited minerals as sites for OTEC plants is that slowly or suddenly occurring damage to the wall sections can be repaired by placing an anode in the vicinity of the damaged portion, thus facilitating, for instance, cementation of cracks and replacement of lost materials. A concrete or steel element in sea water, once broken or decayed, is useless because it cannot economically be repaired.

Other Uses of Saline Water

Dual-purpose power
and water plants

In a dual-purpose power and water plant, the steam is expanded in the power-generating turbine to 121°C (250°F) and sent to the brine heater of the distillation plant producing fresh water. Because this water temperature is sufficient for distillation even though energy at these temperatures has little economic value for other purposes, combination of power and water production facilities in one plant may be more economical than a plant for water only or power only.

There is more interest in the use of nuclear reactors than of coal fired electric plants for combined power and water supplies. This is explained by the difference in the cost breakdown between conventional boilers and nuclear reactors. Most conventional boilers have low capital cost and high operating cost. Nuclear reactors on the other hand have high capital cost and low operating cost. Thus nuclear reactors are normally used to generate baseload electricity and conventional boilers are used more for peaking power. Also, nuclear power plants have lower thermal efficiencies and thus more heat has to be rejected in the condenser resulting in a lower product ratio. The lower thermal efficiency of nuclear power only plants makes more heat available for water production as depicted in Figure 65.

Three cycles are possible as alternative designs for a dual-purpose plant (Porteous 1975):

1. Back-Pressure Cycle. Depicted in Figure 66 is a basic dual-purpose plant employing a nuclear reactor with a fossil-fueled boiler as its heat source, a conventional steam turbine and generator for power production, and an MSF (multi-stage flash) plant for water production. The main advantage of this back-pressure cycle is that it has a low product ratio, i.e., produces the least amount of electricity for a given amount of water and is, therefore, a candidate for adoption in regions where quantities of water are required but not power. The chief disadvantage is a loss in operational flexibility in that the desalting plant cannot be shut down and power only produced unless arrangements are made to condense the exhaust steam.

2. Extraction Cycle. Figure 67 shows an extraction cycle where steam for brine heating is extracted at a suitable point on the turbine, the remainder being completely expanded in the turbine and exhausted to a standard condenser. This cycle normally has a high product ratio and is usually specified where water requirements are small. By varying the extraction rate, larger amounts of water can be provided when needed. This cycle is capable of flexible operation over a wide range as it is even possible for the distillation plant to be shut down and power only produced.

3. Multi-Shaft Cycle. Figure 68 depicts a multi-shaft cycle which is similar to Figure 66 except that the back-pressure cycle is operated in parallel with a standard condensing turbine. The water production is governed by the back-pressure cycle, but power output can be very high. This cycle also is capable of shut down of the distillation plant to produce only power.

Inland sea food industry

Use of cooling reservoirs in conjunction with coal-fired power plants will produce warm brines which may be used to advantage. For a pond depth of 10 feet, the calculated water temperature would vary between 45° and 80°F, which is an appropriate range for possibly raising oyster, shrimp, eel, yellowtail, sea bream, and whitefish (Parkhurst and McLain 1978). Such a seafood source could be particularly attractive in inland areas.

Salt gradient solar ponds

Saline water could well play an important role in the collection of solar energy via the salt gradient solar pond. Figure 69 shows the basic features of the solar pond configuration. At the bottom of the pond is a convecting layer of dense salt brine called the storage zone. Next comes an insulating layer which is nonconvecting because of a salinity gradient. The salinity gradient insures that the lower levels always have greater density than the upper levels even if lower level temperatures are greater. On top of the pond floats a relatively thin layer of less saline waters exposed to the atmosphere. Temperatures in excess of 100°C have been observed in properly designed salt gradient solar ponds which will trap in the storage zone 20-25 percent of the solar energy incident on the pond surface. Major advantages of the solar pond over other kinds of solar collectors include:

a) Large areas may be covered at relatively low cost. Estimates are in the $2-4 per ft^2 range compared with $20-$40 per ft^2 for conventional collectors.

b) Collector and storage medium are combined. By increasing the depth of the pond storage layer, energy collected in summer may be stored until winter.

Figure 65.   Power plant thermal efficiencies compared with dual purpose plant.

Figure 66.   Back-pressure cycle--entire turbine exhaust used in brine water.

Figure 67. Extraction cycle--brine heater steam is extracted at some point in the expansion.

Figure 68. Multi-shaft cycle--use parallel condensing and non-condensing turbines.

65

Figure 69. Configuration of the salt gradient solar pond. Solar energy is trapped by the dense brines which remain on the bottom even though bottom temperatures became high.

It does not seem improbable that power plant evaporation ponds or cooling ponds might one day be converted to salt gradient solar ponds.

Conclusions

This evaluation of the suitability of highly saline waters for meeting some of the energy development needs is based on a literature search plus extensive computer modeling. The results may be summarized as follows:

1. Cooling systems using saline makeup water are technologically feasible. Power plants along the East Coast such as Chalk Point (Washington, D.C.), Turkey Point (Florida), and Forked River (New Jersey) use brackish water or seawater directly, ranging from 7,800 mg/l TDS to 45,000 mg/l TDS before blowdown.

2. Several technologies for treating saline water are available. In this study the cold process softener, reverse osmosis, and brine concentrator were applied to three different cooling tower water treatment options.

3. It is possible to eliminate much of the evaporative water consumption in power plant cooling systems through dry cooling or a combination of wet-dry cooling, but neither of them has been widely embraced by the electric utilities primarily because of cost. Comparison between wet-dry cooling and wet cooling with saline water treatment shows that as water acquisition and treatment costs exceed $\sim$ \$500/ac-ft the wet-dry approach seems advisable.

4. The Binary Cooling Tower (BCT), an innovative approach to using low quality water in power plant cooling, has been developed by Tower Systems, Inc., of Tacoma, Washington. The cost comparison between BCT and the R.O.-Brine Concentrator approach (option 3) indicates that as salinity of makeup water exceeds $\sim$ 2000 mg/l the BCT system is economically superior. Above about 5000 mg/l makeup water, the BCT system has a very decided advantage and seems economically superior to conventional wet-dry systems.

5. Under certain conditions, the evaporative cooling reservoir offers an alternative to the evaporative cooling tower. According to the model used in this study, the cooling reservoir requires approximately half the makeup water required by the cooling tower. Other possible advantages of the cooling reservoir approach include the creation of a warm inland sea with apparently ideal conditions for producing seafood.

6. Spray canals or reservoirs require much less water surface area and volume than do normal cooling reservoirs and this would seriously increase the rate of salinity buildup in a terminal system. Accordingly such an approach is not recommended for systems using saline makeup waters.

7. Extracting minerals from saline water is technically feasible but the problems of low or no market value for major mineral products and insufficient amounts of more valuable minor products suggest that mineral recovery is uneconomical at present.

8. The dual-purpose power and water plant offers a method of producing large quantities of fresh water from saline water in conjunction with power generation. An in depth economic analysis was not conducted, but a need for substantial quantities of fresh water for municipal purposes in a community overlying a large saline aquifer may make a dual-purpose plant both politically attractive and cost effective.

9. The large quantities of salt accumulated as a result of using saline groundwater for power plant cooling could possibly find use in salt gradient solar ponds.

Recommendations

1. Since the use of saline waters in cooling towers and ponds appears feasible and promises to reduce the demand of energy development for fresh water in the water-short Upper Colorado River Basin, more attention should be given to perfecting the technical performance and design optimization of these systems. More detailed modeling of the salt, water, and energy budgets is needed for developing minimum cost designs.

2. The use of multipurpose cooling reservoirs using saline makeup water needs more investigation. Some potentially profitable spin-off development may be possible, particularly concerning food production.

3. Since economic incentives to power companies are generally to use fresh water in preference to saline water, whereas the general public interest would sometimes favor development of otherwise unused saline waters, the rules governing water transfer from agriculture to energy industries need to be carefully reviewed and modified as appropriate to provide incentives more in the public interest.

Use of Saline Water as a Transport Medium for Coal Slurries in Pipelines

Introduction

Coal slurry pipelines have a large fixed cost but offer a distinct economic advantage for transporting large volumes of coal, particularly over long distances. A study by the Office of Technology Assessment specifically outlines its advantages (Chem. and Eng. News 1979). Eight pipelines are now in existence or being constructed in the United States. Arizona's Black Mesa pipeline alone transports 5 million tons of coal per year (Wasp et al. 1973).

In arid climates, water availability is another important consideration in choosing between coal slurry and rail transport. In fact, one advantage of transporting coal from the mine site to another location for conversion to electrical energy is to make water more readily available at the generating site. This advantage still exists even though the transportation is by coal slurry pipeline because on site power generation requires seven or eight times as much water as do coal slurry pipelines (Chem. and Eng. News 1979).

The purpose of this project was to examine the technical feasibility of using saline water as the transport medium in coal slurry pipelines. In order to minimize competition for fresh water, it would be advantageous to use low quality (i.e., saline) groundwater for shipment out of arid or semiarid regions. Of course, it would also be advantageous to be able to use the water at the terminus of the pipeline for beneficial purposes. Possible uses would include irrigation, livestock watering, and in the cooling towers of power plants. For irri-

gation and sometimes stock watering, preliminary treatment would be necessary to at least reduce salinity. The technical feasibility issue was examined by looking at the interactions between waters of varying salinities and the coal matrix, and at how these interactions affect the suitability of the water for subsequent use for other purposes at the end of the pipeline.

Materials and Methods

Sampling

Location of coal mines. Four subsurface mines in central and southeastern Utah were chosen for sampling sites. Mines selected were some of those showing an interest in the construction of coal slurry pipelines at some future date. The mines are located in the coal fields of the Wasatch Plateau and the Book Cliffs area.

General slurrying procedure. The slurrying procedure at the mines involves first crushing the coal and then grinding it to a fine powder (20 percent passing a 325 mesh sieve). In some cases, the coal is mixed with the transport medium after grinding. In other instances, the transport medium is added while the coal is being ground to specification. The slurry is then pumped into temporary storage vats or directly into the pipelines for transport.

If the coal is allowed to stand in contact with an oxidizing atmosphere for an extended period of time, the exposed surfaces oxidize to some degree and the nature of subsequent interactions with a liquid phase could be altered. The mining companies do not anticipate allowing the coal to stand in contact with the atmosphere for any length of time before slurrying. So, in order to simulate actual conditions, it became necessary to store the samples of coal in an inert atmosphere. Nitrogen was chosen as an inert storage medium for the coal until the time of grinding and slurrying.

Figure 70 illustrates the 55 gallon barrels used for storing and transporting coal samples. Each barrel was lined with teflon to provide an unreactive surface. Each barrel lid was equipped with a rubber gasket and a clamp to facilitate a tight seal. A brass off-on needle valve was welded into the lid of each barrel and on the side close to the bottom. The bottom valve was then fitted to a cross-shaped structure of one-half inch copper tubing inside the barrel also shown in Figure 70. Holes were drilled in the tubing to allow a more ef-

ficient aspiration of nitrogen gas through the coal after samples were taken.

Before being used, each barrel was washed thoroughly with a bicarbonate solution, rinsed with tap water, followed by an acid (0.1 N-HCl) wash and six rinsings with high quality deionized water.

In all cases, the coal samples were freshly crushed, unoiled, and less than one hour old. Approximately 150 pounds of crushed coal were placed in each barrel and the lids were sealed. All four mines were sampled on the same day, but the samples were not placed in a nitrogen atmosphere until they arrived at the laboratory. In no case was any sample exposed to an air atmosphere for a period longer than 24 hours.

Each coal-filled barrel was sealed and purged with nitrogen from a compressed gas cylinder for at least 2 hours. The barrels were purged from the bottom to the top, and the needle valves placed in the closed position after the purging process was completed. During the next few months, whenever a sample of coal was removed for grinding, the remaining sample was repurged with nitrogen.

Three saline transport media were evaluated. These media were not directly taken from saline sources in Utah, but were synthetics whose makeup was determined by averaging USGS groundwater quality data from saline water sources in the vicinity of the mines from which coal samples were taken. These data originated with the U.S. Geological Survey and from previous water quality work done by the Utah Water Research Laboratory (Israelsen and Haws 1978). The data were grouped into three salinity levels, 1,000-3,000, 3,000-10,000 and > 10,000 mg/l. The data and averaging are shown in Tables 27, 28, and 29.

Sample preparation. Each coal sample was very finely ground in a McCool pulverizer so that at least 20 percent (Table 30) passed through a 325 mesh sieve. After each sample was ground, the inside of the grinder was wiped clean with a cloth. An initial small portion of the next sample was discarded to reduce possible cross-contamination.

The finely ground coal was then stored in 4-liter aspirator jars (Figure 71) that were previously acid washed and rinsed as described above. These storage containers lent themselves well to purging with nitrogen gas. Each jar was equipped with a glass port near the bottom and a one-hole rubber stopper with a piece of glass tubing at the top. The rubber stopper was fitted tightly and secured with copper wire around the neck

Figure 70. Fifty-five gallon drum used to store crushed coal in an inert (nitrogen) atmosphere.

Figure 71. Aspirator jar used to store finely ground coal in an inert (nitrogen) atmosphere.

of the aspirator jar. Short pieces of latex tubing and screw compressor clamps were added to each port to aid in sealing after purging. Nitrogen flow was not monitored during the purging process, but flow from the compressed gas cylinder was adjusted until gas could be felt emerging from the top port. The aspirator jars were surrounded by safety shields during the purging process to prevent injury in case of breakage or explosion. After purging for 30 minutes with nitrogen gas, the pieces of latex tubing were folded over and clamped. The finely ground coal was stored in this manner until the time of slurrying.

Sample processing

Synthetic saline transport media. Three synthetic saline transport media were prepared and slurried with the finely ground coal. In each case, the salinity was characterized by total dissolved solids in milligrams per liter (TDS in mg/l). The TDS values of the three media were 2,220, 4,640 and 13,180 mg/l, respectively (Table C-36, Appendix C), approximately matching the average values on Tables 27, 28, and 29.

Laboratory and analytical grade reagents were chosen to make up these media. All chemicals were weighed accurately and dissolved in known amounts of mili-Q reagent grade water. Carbon dioxide gas bubbling through the saline transport media overnight proved to be the best way to dissolve the constituents, even though dissolution was never complete. At all salinity levels, the dissolution of iron (as ferric chloride) posed a problem; dissolution could not be forced to any detectable quantity. Also, certain constituents (Mn, NO_3-N, Si-SiO_2) were present in increasing concentrations as salinity was increased. Values for these parameters were not always available from USGS or other sources. Preliminary data indicated possible significant trends for these parameters, so increasing quantities with salinity were added to monitor these possible trends. Overall, the three synthetic

Table 27. Data from saline groundwaters for preparation of Synthetic Saline Transport Medium Slurry One. TDS 1000-3000 mg/l (Israelsen and Haws 1978).

Parameter (mg/l)	Saline Groundwaters				
	USU/IPP	OW/Stanolind	TW-1	OW-ICPA	$\bar{x}$
Al	0.40	$-^a$	–	–	0.40
B	0.63	–	0.37	0.30	0.43
Ca	105.	136.	84.	259.	146.
Cl	623.	454.	847.	623.	637.
CO_3	113.	149.	142.	118.	130.
F	0.3	–	0.9	0.5	0.6
Fe	<0.08	–	0.54	0.8	0.67
K	3.	4.2	4.0	4.8	4.0
Mg	58.	46.	30.	105.	60.
Na	360.	475.	823.	495.	538.
P	0.04	0.03	–	0.20	0.09
SiO_2	3.6	8.5	9.6	12.0	8.4
SO_4	560.	652.	600.	1022.	709.
TDS	2130.	2010.	2660.	2820.	2405.

[a] Data for this parameter not available.

Note for Tables 27, 28, 29: The last column headed "$\bar{x}$" represents the average of the parameters for the saline waters. The synthetic saline transport medium for each slurry was prepared using these values.

Table 28. Data from saline groundwaters for preparation of synthetic saline transport medium. Slurry 2. TDS 3000-10,000 mg/l.

Parameter (mg/l)	Saline Groundwaters (USGS)								
	385159111 1545-01	38515111 1545-02	385224111 1426-02	385225111 1300-01	385249111 1309-01	385303111 1313-01	385506111 0952-01	383317110 5705-01	$\bar{x}$
Ca	160.	100.	140.	380.	510.	470.	420.	500.	335.
Cl	170.	540.	20.	100.	45.	96.	46.	85.	138.
CO_3	469.	520.	330.	490.	6.	510.	600.	219.	393.
F	1.0	–	–	–	–	–	–	0.4	0.7
Fe	10.							0.02	5.0
K	10.	9.9	48.	9.3	8.3	16.	5.8	94.	25.
Mg	200.	160.	220.	260.	370.	400.	310.	330.	281.
N	0.46	–	–	–	–	–	–	–	0.46
Na	1200.	1300.	760.	480.	240.	320.	140.	220.	583.
SiO_2	12.	12.	21.	11.	18.	13.	25.	10.	15.
SO_4	3100.	2400.	2500.	2400.	3000.	2900.	2000.	2900.	2650.
TDS	5100.	4780.	3870.	3880.	4200.	4470.	3240.	4250.	4220.

Note: For Tables 28 and 29. The above USGS data for each site are labeled with latitude and longitude coordinates in degrees (Appendix A).

Table 29.   Data from saline groundwaters for preparation of synthetic saline transport medium. Slurry 3.   TDS > 10,000 mg/l.

Parameter (mg/l)	Saline Groundwater (USGS)									
	390625111 0138-01	395707111 1227-01	401131110 4201-02	401159110 4815-01	401225110 3716-01	401225110 3716-01	402444110 0102-01	402444110 0102-01	382450110 2651-01	$\bar{x}$
Ca	270.	90.	78.	193.	655.	270.	11.	14.	1200.	309.
Cl	1400.	4100.	5850.	3450.	6800.	4550.	3700.	3700.	7100.	4520.
CO_3	660.	750.	708.	1050.	293.	622.	2501.	2210.	664.	1051.
K	26.	29.	68.	45.	140.	56.	--	52.	130.	68.
Mg	310.	190.	19.	28.	35.	17.	5.	3.	512.	124.
Na	2700.	7600.	4090.	4000.	4650.	4040.	4000.	3940.	4000.	4340.
SiO_2	10.	12.	--	--	--	--	--	--	--	11.
SO_4	5100.	7000.	331.	3490.	2020.	2580.	1300.	1600.	3100.	2950.
TDS	10100.	19400.	10800.	11700.	14500.	11820.	10400.	10400.	16400.	12800.

Table 30.   Sieve analyses.

Sample Coal From Mine	% Passing 325 Mesh Sieve		
	Slurry 1	Slurry 2	Slurry 3
1	26.1	26.1	26.7
2	23.0	23.0	22.3
3	22.0	22.0	29.5
4	22.2	22.2	25.2

Table 31.   Concentration of constituents in synthetic saline transport media.

Parameter (mg/l)	Slurry 1 (TDS 1000-3000 mg/l)	Slurry 2 (TDS 3000-10,000 mg/l)	Slurry 3 (TDS >10,000 mg/l)
Al	0.25	0.72	1.14
B	0.1	0.5	0.7
Ca	156.	343.	312.
CO_3	117.	361.	550.
Cl	592.	138.	4880.
F	0.17	0.68	0.46
Fe	<0.02	<0.02	<0.02
Mg	48.	267.	109.
Mn	<0.01	0.25	0.50
NO_3-N	<0.04	0.50	1.02
pH[a]	7.6	8.3	7.8
o-PO_4	0.71	0.72	0.98
K	4.	20.	102.
SiO_2	11.	22.	35.
Na	458.	620.	4300.
SO_4	700.	2740.	2770.
TDS	2220.	4640.	13180.

[a] In pH units.

media simulated the area's known groundwater supplies quite closely.

Each saline transport medium was stirred to remove excess carbon dioxide and filtered to remove residues of constituents which did not dissolve. Tables C-1 - C-37 in Appendix C show the concentrations of all constituents based on subsequent analysis of each filtered synthetic saline transport medium. Table 31 lists the levels of the major parameters for all three media.

Lab-scale slurries. On each of three separate dates, a mini slurry was set up with finely ground coal and saline transport medium mixed on an equal weight-to-weight basis. For example, in a 500 ml erlenmeyer flask, 150 ml of saline transport medium was slurried with 150 g of coal. The above procedure was followed for slurries one and two. Ten or eleven replicates were set up for each sample. (These replicates were later composited to provide an adequate volume of filtered transport medium to perform all analyses.) In slurry three, 4-liter erlenmeyer flasks were substituted as the slurrying vessels. Each flask held 1.5 kg of coal and 1.5 kg of saline transport medium.

Since coal slurry pipelines are pumped full of the slurry mixture, there should be very little opportunity for air oxidation or air contact during the time the slurry remains in the pipeline. In order to mimic pipeline conditions and provide an inert atmosphere, the air space above the slurry in each slurrying vessel was purged with nitrogen gas and sealed.

Slurry vessels were fastened securely to orbital shaker tables for 6 days at approximately 200 rpm to simulate slurrying. All samples were checked carefully during the first few days to make certain the coal and saline media were mixing properly and not partitioning into separate phases.

Portions of the media were also poured into slurrying vessels and were not mixed with coal. These samples were carried through the shaking process involved in slurrying and exposed to an inert nitrogen atmosphere. All analyses were completed on the above samples, along with the saline transport media that had not been slurried.

Filtration and analysis of coal extracts. After 6 days of slurrying, the samples were filtered through Whatman No. 1 filter paper in a ceramic buchner funnel. The extract was then passed through a Millipore apparatus (0.45 micron). This filtration procedure is a suitable means to handle a lab-scale slurry. A similar procedure might prove beneficial to coal mine operations, which generally use a centrifuge method.

Table 32 lists the analyses run on the filtered transport media for slurries 1, 2, and 3. Immediately after filtering, each sample was partitioned and treated using standard sample preservation techniques (APHA 1975; U.S. EPA 1974). All sample bottles were washed in a bicarbonate solution, rinsed with tap water, acid-rinsed (with the acid appropriate to the test), rinsed five or six times with mili-Q reagent grade water and, finally, three times with the sample itself. Metal samples were preserved with HNO_3 to pH < 2 and stored in stoppered glass containers. Samples for boron, silica, sulfate, and fluoride determinations were stored in plastic bottles. They required no preservation as they were analyzed within 7 days. Samples for total organic carbon were preserved with conc. H_3PO_4 to pH < 2 and stored in glass. Nitrate-nitrogen, nitrite-nitrogen, orthophosphate, total phosphate, alkalinity, and pH were determined on each sample immediately. The remainder of each sample was stored in a glass container at 4°C for the determination of the other parameters.

Table 32. Analyses performed on the filtered transport media after slurrying (APHA 1975; USEPA 1974).

Alkalinity (Carbonate)	Mercury
Aluminum	Molybdenum
Arsenic	Nickel
Barium	Nitrate
Beryllium	Nitrite
Boron	Organic Carbon
Cadmium	pH
Calcium	Phosphate, Ortho-
Chloride	Phosphorus, Total
Chromium	Potassium
Cobalt	Selenium
Conductivity	Silica
Copper	Silver
Fluoride	Sodium
Iron	Strontium
Lead	Sulfate
Lithium	Total Dissolved Solids
Magnesium	Zinc
Manganese	

Although there were some constraints caused by the volume of sample, analyses were completed in duplicate or triplicate whenever possible.

Coal analysis. A previous study suggested a number of complex interactions between the coal matrix and saline water transport media (Israelsen and Haws 1978). In order to determine and evaluate the possible effects on the elemental constituency of the coal itself, samples of each coal, one in a slurried and the second in an unslurried state, were analyzed and compared.

After slurring was completed, the coal from each mine was allowed to air-dry overnight. Portions of this slurried coal along with corresponding samples of unslurried coal were sent to the Commercial Testing and Engineering Co. in Denver, Colorado, for proximate and ultimate analysis. These methods are referenced in the Annual Book of ASTM Standards, Part 26, 1979.

Results and Discussion

Introduction

Ramakka (1979) quotes from a Department of the Interior Environmental Impact Statement regarding the opening of new mines in Utah:

Due to the low sulfur content of coal in the area and the alkaline nature of the water it would come in contact with, predictions were made that the chemical quality of the water would not likely be affected by coal mining. However, concentrations of trace elements in waters close to existing mines were at least occasionally in excess of recommended limits.

This EIS did not concern itself with the type of contact which would occur between fine coal particles and a saline water transport medium in a slurry pipeline.

The experimental results reflected complex interactions between the saline transport media and the large surface area of the coal matrix. In certain instances, constituents were leached from the coal and released into the transport media. These were detected by constituent concentrations that were significantly higher than those in the saline transport media initially. In some cases, this phenomenon occurred consistently with all four coal samples and with all three salinity levels. Other times the phenomenon was unique to the coal from one mine only, and may or may not vary with salinity.

Other constituents present in the saline transport media were absorbed by the coal matrix. Significantly reduced quantities of these constituents were detected in the saline transport media after the slurrying

process. Again, these effects were not necessarily common to the coal from all four mines, nor the media of all three salinities.

Still other parameters showed no significant alteration upon slurrying. Appendix C, Tables C-1 - C-37, lists the concentration of each parameter initially present in the three transport media. Each table also indicates the variation in that parameter after being in contact with each of the four coal samples for 6 days. Appendix D details the statistical analyses performed to determine the significance of any absorption or leaching.

Absorption by the coal matrix

Certain constituents in the transport media were consistently and significantly absorbed by the coal matrix. Orthophosphate and nitrate-nitrogen were most conspicuous in their affinity for the coal matrix structure.

Since the coal was slurried on an equal weight-to-weight basis with the transport medium, the milligrams of constituent absorbed per kilogram of coal could be calculated by subtracting the concentration of the constituent in the medium after slurrying from that before slurrying.

Phosphorus. The coal samples from all mines showed a marked ability to absorb orthophosphate from the transport media at all salinities (Table 33). In all cases, the final phosphorus concentrations in the saline media were close to the limits of detection.

The total phosphorus data in Table 34 also illustrate the ability of the coal matrix to absorb phosphorus. The data do not indicate a significant tendency for conversion to another form of soluble phosphorus, such as certain organophosphates which would not be accounted for in the orthophosphate test. The coal's ability to remove this nutrient could enhance the value of the effluent at the end of the pipeline by reducing problems with algal blooms and aquatic plant growth.

If the groundwater used as a slurrying medium contained large quantities of phosphorus, the phosphorus content of the coal itself could be increased significantly. Possible problems with air pollution upon subsequent burning of the coal must be considered. However, phosphorus in the air is usually present in a particulate form arising from sources such as phosphate-based fertilizers, and emissions from vehicles and

Table 33. Coal absorption of orthophosphate.

Sample	Slurry 1 (2,220 mg/l TDS)		Slurry 2 (4,640 mg/l TDS)		Slurry 3 (13,200 mg/l TDS)	
	P (mg/l)	mg P Absorbed per kg Coal	P (mg/l)	mg P Absorbed per kg Coal	P (mg/l)	mg P Absorbed per kg Coal
Saline Transport Media	0.71	–	0.72	–	0.98	–
Coal from Mines:						
1	0.01	0.70	<0.01	~0.72	<0.01	~0.98
2	0.01	0.70	0.04	0.68	0.01	0.97
3	0.01	0.70	0.05	0.67	<0.01	~0.98
4	0.02	0.69	0.01	0.71	<0.01	~0.98

Table 34. Coal absorption of total phosphorus.

Sample	Slurry 1[a] (2,220 mg/l TDS)		Slurry 2 (4,640 mg/l TDS)		Slurry 3 (13,200 mg/l TDS)	
	P (mg/l)	mg P Absorbed per kg Coal	P (mg/l)	mg P Absorbed per kg Coal	P (mg/l)	mg P Absorbed per kg Coal
Saline Transport Media	–	–	0.72	–	0.98	–
Coal from Mines:						
1	–	–	0.12	0.60	0.09	0.89
2	–	–	0.04	0.68	0.04	0.94
3	–	–	0.05	0.67	0.06	0.92
4	–	–	0.05	0.67	0.03	0.95

[a]Total phosphorus was not run on Slurry 1.

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aircraft using phosphorus as corrosion inhibitors in their fuel (Painter 1974). Gaseous forms of phosphorus pollution are apparently only present under high temperature situations. Increased levels of phosphorus in coal could pose problems in catalytic incinerators during the burning process.

Attempts were made to increase the phosphate concentration in the synthetic media of each succeeding slurry to test the absorption capacity of the coals. The chemical nature of each transport medium apparently did not allow dissolution in quantities greater than 1 mg/l. However, these levels of phosphorus are characteristic of many groundwater supplies.

Nitrogen. The synthetic transport medium for slurry one contained no detectable quantity of nitrogen in the form of nitrogen, thus the coal samples displayed no matrix absorption of nitrate. Large quantities of nitrate were absorbed by the coal transported with slurries two and three. Table 35 shows that significant amounts of nitrate-nitrogen are removed.

The potential of increasing air pollution levels during the burning of slurried coal must be evaluated. Nitrate in groundwater may reach levels as high as 10 or 20 mg/l in some areas. Depending upon the amount of nitrogen absorbed by the coal matrix, the levels of nitrogen oxides produced by burning coals transported in slurries of high nitrogen content could be appreciable.

The coal's ability to remove nitrate could increase the value of the transport medium for use as irrigation water at the pipeline terminus. Since, like phosphorus, nitrate is also a nutrient for algae and submergent plants, reductions in its concentration would be advantageous.

High levels of nitrate can be hazardous to homoiothermic animals when conditions are favorable for reduction to nitrite. Under specific circumstances this chemical reduction can occur in the gastrointestinal tract, producing methemoglobin and impairing oxygen transport (McKee and Wolf 1963; U.S. EPA 1974). Thus the pipeline medium with lowered levels of nitrate would be more suitable for livestock watering.

Silica. Silica originally present in the transport media increased in concentration from slurry one to slurry three (Table 36). When silica is present at the lowest level, the saline transport medium leached a large quantity of silica from the coal from mine no. 1 under the conditions of the first slurry. Silica was present in higher quantities in the transport media of slurry two and three. Under these conditions, appreciable quantities of silica were removed by the coal from the aqueous phase.

It does not appear that the presence or absence of silica is particularly important in irrigation water or stock watering supplies, but in certain industrial uses, its absence is favorable. Silica is undesirable in the feedwaters of boilers because it forms hard deposits in heaters and on steam turbine blades.

Other absorbed substances. Other absorbed substances did not follow consistent trends in salinity or origin of the coal sample. For instance, the coal from mine no. 4 in slurry three absorbed a large quantity of magnesium. Magnesium absorption was not significant at other salinities (Appendix C, Table C-18). In some cases, fluoride was absorbed by the coal; and in other cases, fluoride levels increased in the transport medium after slurrying. All fluoride analyses were completed with a fluoride selective ion electrode. There is evidence that these electrodes do not function properly and

Table 35. Coal absorption of nitrate-nitrogen.

Sample	Slurry 1 (2,220 mg/l TDS)		Slurry 2 (4,640 mg/l TDS)		Slurry 3 (13,200 mg/l TDS)	
	N (mg/l)	mg N Absorbed per kg Coal	N (mg/l)	mg N Absorbed per kg Coal	N (mg/l)	mg N Absorbed per kg Coal
Saline Transport Media	<0.04	–	0.50	–	1.02	–
Coal from Mines:						
1	0.09	*	0.12	0.38	<0.04	∿1.02
2	0.07	*	0.16	0.34	0.33	0.69
3	0.10	*	0.29	0.21	<0.04	∿1.02
4	0.08	*	0.10	0.40	0.04	0.98

*No significant absorption occurred.

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Table 36. Coal absorption of silica.

Sample	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)		Slurry 3 (13,200 mg/1 TDS)	
	SiO_2 (mg/1)	mg SiO_2 Absorbed per kg Coal	SiO_2 (mg/1)	mg SiO_2 Absorbed per kg Coal	SiO_2 (mg/1)	mg SiO_2 Absorbed per kg Coal
Saline Transport Media	11.	–	22.	–	35.	–
Coal from Mines:						
1	53.	*	8.	14.	5.	30.
2	11.	*	12.	10.	10.	25.
3	13.	*	16.	6.	7.	18.
4	14.	*	17.	5.	12.	23.

*
No significant absorption occurred.

repeatably under the salinity conditions imposed by this project (U.S. EPA 1979). So, it is unclear whether these fluoride measurements are accurate and indicative of any trends. At the onset of this research, fluoride was purported to leach readily from coal samples at toxic levels.

Carbonates were absorbed by the coal under slurry three conditions (Appendix C, Table C-1). However, slurry three was made up mainly of sodium, chloride, sulfate, and potassium. When compared to slurry two, it contained similar or smaller quantities of calcium and magnesium.

Under certain conditions, aluminum, potassium, and sodium were absorbed in significant but small quantities by the coal matrix (Appendix C, Tables C-2, C-29 and C-33). However, at other times these consitutents were leached from the coal structure and appeared at higher levels in the transport media.
For the coal from mines 1, 2, and 3, calcium was consistently absorbed at all salinity levels (Appendix C, Table C-8). Calcium was leached from the coal from mine 4 in slurry one and three to a small but significant extent.

Leaching from the coal matrix

Some constituents were detected in greater concentrations in the filtered transport media after slurrying. Significant increases appear in boron, organic carbon, and strontium. Appendix D presents statistical data indicating the increases significant at the 99 percent confidence level. Tables in the following sections illustrate the quantities of various parameters leached on a milligram per kilogram of coal basis.

Boron. Boron was consistently leached from the coal matrix (Table 37). In the first two slurries, each coal released remarkably consistent quantites of boron on a

per kilogram basis. It would seem that each coal leached boron in quantities characteristic of the coal itself. This principle, however, was not confirmed by the third slurry. The explanation is probably related to the fact that slurry three varied in composition from the other media in that a larger part of the "salinity" was due to sodium, potassium, chloride, and sulfate, rather than calcium, magnesium, and other constituents.

Romney (1977) documented the presence of boron in vegetation related to a coal burning power plant. Plants grown in water from an ash settling pond, those grown in a greenhouse in soil to which coal ash had been added, and native plants growing around the ash ponds at the site all had elevated boron concentrations in their tissue.

If the water at the terminus of the pipeline is to be used for irrigation without pretreatment for boron, the elevated boron concentrations from all four mines will cause toxicity problems for a number of crops. Boron is essential in small quantities for plant nutrition but toxicity is evident at higher concentrations. Table 38 suggests that all sensitive, many semitolerant, and even some tolerant crops would show signs of boron injury if the water shown in Table 37 were used for irrigation over a prolonged period. Roots absorb boron from the soil and the water held there. The boron is transported to the leaves where water is lost by the process of transpiration. When toxic levels of boron accumulate in the leaf tips and margins, yellowing and burning result. Leaves may drop prematurely and productivity can be severely reduced. Stone fruit trees are particularly susceptible to boron (Table 38), but the symptoms are different. Little discoloration and burning occurs since boron does not accumulate in the leaf. However, twigs die back, larger branches accumulate gummy substances, and growth and yield are reduced (Wilcox 1960).

The Environmental Protection Agency (1976) recommends a boron concentration not to exceed 750 µg/l for long term irrigation. However, if the soil has a high absorption capacity (neutral or alkaline), then there is some evidence that water containing up to 2 mg/l boron can be used for some time without injury to sensitive plants (Biggar 1960).

Previous work by Israelsen and Haws (1978) indicates that boron leaching is also a problem when higher quality water (TDS < 1,000 mg/l) is used as a slurrying medium. It appears that mining and irrigation companies would do well to consider pretreatment of coal slurry effluents for removal of boron.

Boron is not a hazard to animals. McKee and Wolf (1963) recommend an acceptable limit of 20 mg/l in drinking water. Water used for livestock and wildlife can contain up to 2,500 mg/l before inhibition of growth takes place. The lethal dose varies from 1.2 to 3.45 g/kg body weight.

Treatments for removing boron include ion exchange and reverse osmosis. These methods are typically expensive and sophisticated. Laboratory studies are needed to test the economic feasibility of various treatment methods which can be successfully applied to coal slurry effluents.

Table 37. Boron leached from coal.

Sample	Slurry 1 (2,220 mg/l TDS)		Slurry 2 (4,640 mg/l TDS)		Slurry 3 (13,200 mg/l TDS)	
	B (mg/l)	mg B Leached per kg Coal	B (mg/l)	mg B Leached per kg Coal	B (mg/l)	mg B Leached per kg Coal
Saline Transport Media	0.1	–	0.5	–	0.7	–
Coal from Mines:						
1	1.4	1.3	1.7	1.2	1.1	0.4
2	2.8	2.7	3.2	2.7	2.0	1.3
3	1.3	1.2	1.9	1.4	2.1	1.4
4	2.4	2.3	2.7	2.2	1.9	1.2

Table 38. Limits of boron in irrigation water for crops (from Wilcox 1960).

Tolerant	Semitolerant	Sensitive
4.0 ppm of Boron	2.0 ppm of Boron	1.0 ppm of Boron
Athel (Tamarix aphylla)	Sunflower (Native)	Pecan
Asparagus	Potato	Walnut (Blace and Persian, or English)
Palm (Phoenix canariensis)	Cotton (Acala and Pima)	Jerusalem Artichoke
Date Palm (P. dactylifera)	Tomato	Navy Bean
Sugar Beet	Sweet Pea	American Elm
Mangel	Radish	Plum
Garden Beet	Field Pea	Pear
Alfalfa	Ragged-robin Rose	Apple
Gladiolus	Olive	Grape (Sultanina and Malaga)
Broadbean	Barley	Kadora Fig
Onion	Wheat	Persimmon
Turnip	Corn	Cherry
Cabbage	Milo	Peach
Lettuce	Oat	Apricot
Carrot	Zinnia	Thornless Blackberry
	Pumpkin	Orange
	Bell Pepper	Avocado
	Sweet Potato	Grapefruit
	Lima Bean	Lemon
2.0 ppm of Boron	1.0 ppm of Boron	0.3 ppm of Boron

Strontium. Although the coal from mine no. 1 did not exhibit a definite trend, significant quantities of strontium were leached from the other coal samples at all salinities (Table 39). The magnitude of strontium leached seems to be generally characteristic of the coal itself. Strontium in nature generally occurs as celestite ($SrSO_4$) or strontianite ($SrCO_3$). It is not readily absorbed by soils and would probably not cause hazardous effects in irrigation water at these levels (McKee and Wolf 1963). Romney's (1977) studies on the effects of boron on vegetation also made mention of strontium. Elevated strontium levels are characteristic of coal ash leachate. However, these levels did not deter growth of the plant species he studied.

Literature on the effects of nonradioactive Sr is scant. An annotated bibliography prepared by Wasserman (1961) states that Sr and calcium are taken up by the body simultaneously and fixed in calcified tissues such as bone, dentine, and enamel. Excretory mechanisms rid the body of Sr in soft tissue faster than Sr accumulates in bone. X-ray diffraction studies show that Sr actually becomes part of the internal structure of the inorganic crystalline structures of bone. Normal concentrations of Sr in bone reach 120-134 mg/kg body weight. Sr acts in conjunction with the calcification mechanism and can actually stimulate bone growth and

osteid formation in the early stages of healing following fractures.

McKee and Wolf (1963) state that the literature shows no evidence of toxic effects of Sr to man and other homoiothermic animals. However, Wasserman (1961) reports the occurrence of strontium rickets in rats and mice when they are fed extremely large quantities of strontium (at much higher levels than those occurring in coal leachates). Strontium at these extreme levels actively inhibits the calcification mechanism causing brittle bones.

Organic carbon. All synthetic saline transport media leached fairly consistent quantities of organic carbon. These show indications of being peculiar to the coal itself (Table 40). Further work is necessary to characterize the organics present in these leachates. Certain of these compounds may be toxic to humans or plant tissues with prolonged exposure. Also, the possibility of mutagenicity must be considered.

Treatment to remove organic carbon is usually accomplished with columns of activated carbon. Unless the organics present are large and complex, such as certain polycyclic aromatics, treatment would pose no special problems except those of cost constraints.

Table 39. Coal absorption of strontium.

Sample	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)		Slurry 3 (13,200 mg/1 TDS)	
	Sr (mg/1)	mg Sr Leached per kg Coal	Sr (mg/1)	mg Sr Leached per kg Coal	Sr (mg/1)	mg Sr Leached per kg Coal
Saline Transport Media	0.07	—	0.78	—	0.30	—
Coal from Mines:						
1	0.43	0.36	0.85	0.07	0.62	0.32
2	8.28	8.21	10.10	9.32	9.00	8.70
3	1.71	1.64	2.41	1.63	2.36	2.06
4	1.84	1.77	3.05	2.27	2.91	2.61

Table 40. Organic carbon leached from coal.

Sample	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)		Slurry 3 (13,200 mg/1 TDS)	
	C (mg/1)	mg C Leached per kg Coal	C (mg/1)	mg C Leached per kg Coal	C (mg/1)	mg C Leached per kg Coal
Saline Transport Media	<1.	—	2.	—	1.	—
Coal from Mines:						
1	30.	∿30.	29.	27.	24.	23.
2	8.	∿8.	7.	5.	12.	11.
3	4.	∿4.	3.	1.	5.	4.
4	8.	∿8.	7.	5.	7.	6.

Other leached substances.   Leaching of manganese showed no trend over all coal samples at all salinities.   Data from slurry one seemed to indicate some tendency for the transport media to leach manganese from the coal structure.   Slurries two and three did not produce data to support this trend (Appendix C, Table C-19).   Manganese is not considered to be of toxicological significance in drinking water, but acceptable limits have been set largely due to the unpleasant taste resulting when concentrations exceed 0.5 mg/l (McKee and Wolf 1963).

Aluminum, calcium, potassium, and sodium can exhibit either leaching or absorption phenomena.   Barium also was leached to some degree under slurry one conditions (Appendix C, Table C-4).   As salinity increased, leaching was significant only for the coal from mine no. 4 during slurry three.

With the exception of the third salinity level, chloride leaching was evident and quite consistent (Appendix C, Table C-9). However, alarmingly high levels of chloride were not observed.

The leaching of iron occurs sporadically and can result in fairly high concentrations in the transport media.   This phenomenon should cause no adverse effects.

Slurries two and three exhibited significant, but not alarming leaching of sulfate (Appendix C, Table C-35).   It is interesting to note that the sulfate levels in the transport media for slurries two and three were the same initially.   But, the conditions of slurry two did not allow statistically significant leaching, whereas leaching in slurry three was significant.

With the exception of the coal from mine no. 1 in slurry three, small quantities of lithium consistently appeared in the saline transport medium (Appendix C, Table C-17). The leaching of molybdenum was also quite consistent (Appendix C, Table C-21), but it does not appear that either of these metals was leached to a point to cause concern.

Proximate and ultimate analyses

Table 41 lists the results of the proximate and ultimate analyses (ASTM Standard 1979) and compares the parameters on the slurried and unslurried coals.   The coal from all mines showed an increase in moisture as a result of the slurrying.   This resulted in approximately a 1,000 Btu per pound loss in energy output.   When these slurried coals were dried, the Btu output was not significantly different from the Btu output of the unslurried coals.   The levels of other parameters, such as carbon, sulfur, and nitrogen, did not appear to change significantly as a consequence of the slurrying process.

Salinity effects on analytical methods

Table 42 is concerned with a series of standard additions of boron (spikes) made to the samples from slurry three.   Another synthetic saline water was prepared which is referred to as matrix water.   It contained all of the major constituents of the saline transport media at essentially the same concentrations (calcium, magnesium, sodium, potassium, carbonate, sulfate, and chloride). This matrix water was designed to mimic all parameters of the synthetic transport media, excluding minor ones.   It was intended to use in place of deionized water in the makeup of standards when detecting the presence of minor constituents.

Data from Table 42 indicate that when matrix water is used to produce a standard curve, the spikes come closer to the theoretical values.   However, the deviations from theoretical experience when deionized water is used are by no means drastic.   Salinity appears to have a minimal effect on the determination of boron by the Carmine method.

The strontium samples from slurry three were also spiked and the results are listed in Table 43.   Again, the deviations from the expected theoretical concentrations did not appear to be cause for concern.

Fluoride samples were also spiked in a similar manner.   However, here the deviations from theoretical were large and not systematic.   These results are not presented in tabular form.

Conclusions

1.   In general, coal slurrying with saline water can be viewed as a feasible alternative to using good quality water as a transport medium.   It also appears that, with pretreatment, the effluent at the pipeline terminus can be used for purposes such as stock watering and irrigation.

2.   The coals tested showed an ability to almost completely remove any orthophosphorus and nitrate-nitrogen existing in the transport media.   Subsequent burning of this coal could increase the levels of nitrogen oxide emissions into the atmosphere. The increased phosphorus levels could poison catalytic incinerators upon burning.

3.   In some instances silica was absorbed from the water by the coal matrix. Although this would have no detrimental affect on the effluent's applicability for irrigation and stock watering, it would decrease the amount of scale that could form in boilers if the water were used for cooling purposes.

4.   Boron was consistently leached from all coal samples by water of each salinity

Table 41. Proximate and ultimate coal analyses.

	Coal From Mine 1				Coal From Mine 2			
	Unslurried		Slurried		Unslurried		Slurried	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Proximate Analysis								
% Moisture	2.09	---	11.28	---	3.31	---	6.01	---
% Ash	12.66	12.93	10.97	12.36	8.96	9.27	8.89	9.46
% Volatile	41.89	42.78	38.02	42.85	39.28	40.62	37.89	40.31
% Fixed Carbon	43.36	44.29	39.73	44.79	48.45	50.11	47.21	50.23
Btu/pound	12340.	12603.	11452.	12908.	12579.	13010.	12309.	13096.
% Sulfur	0.59	0.60	0.49	0.55	1.07	1.11	1.05	1.12
Ultimate Analysis								
% Moisture	2.09	---	11.28	---	3.31	---	6.01	---
% Carbon	68.68	70.15	63.31	71.36	70.69	73.11	68.67	73.06
% Hydrogen	5.11	5.22	4.69	5.29	4.96	5.13	4.88	5.19
% Nitrogen	1.43	1.46	1.34	1.51	1.13	1.17	1.04	1.11
% Chlorine	0.05	0.05	0.02	0.02	0.05	0.05	0.07	0.07
% Sulfur	0.59	0.60	0.49	0.55	1.07	1.11	1.05	1.12
% Ash	12.66	12.93	10.97	12.36	8.96	9.27	8.89	9.46
% Oxygen (diff)	9.39	9.59	7.90	8.91	9.83	10.16	9.39	9.99

	Coal From Mine 3				Coal From Mine 4			
	Unslurried		Slurried		Unslurried		Slurried	
	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis	As Received	Dry Basis
Proximate Analysis								
% Moisture	5.19	---	10.21	---	7.24	---	11.11	---
% Ash	7.12	7.51	8.15	9.08	9.75	10.51	9.34	10.51
% Volatile	43.79	46.19	41.93	46.70	39.52	42.60	37.67	42.38
% Fixed Carbon	43.90	46.30	39.71	44.22	43.49	46.89	41.88	47.11
Btu/pound	12309.	12983.	11958.	13318.	11554.	12456.	11052.	12433.
% Sulfur	0.57	0.60	0.51	0.57	0.48	0.52	0.46	0.52
Ultimate Analysis								
% Moisture	5.19	---	10.21	---	7.24	---	11.11	---
% Carbon	69.09	72.87	65.78	73.26	65.26	70.35	63.44	71.37
% Hydrogen	5.21	5.49	4.97	5.53	4.60	4.96	4.33	4.87
% Nitrogen	1.27	1.34	1.17	1.30	1.13	1.22	1.14	1.28
% Chlorine	0.08	0.08	0.05	0.06	0.05	0.05	0.04	0.05
% Sulfur	0.57	0.60	0.51	0.57	0.48	0.52	0.46	0.52
% Ash	7.12	7.51	8.15	9.08	9.75	10.51	9.34	10.51
% Oxygen (diff)	11.47	12.11	9.16	10.20	11.49	12.39	10.14	11.40

level tested, making the water unsuitable for long-term irrigation of certain crops without its being pretreated. Previous work has shown that slurrying with higher quality water would not eliminate the need to pretreat for boron when the effluent is applied to crops. Boron concentrations in the effluents studied would not preclude their use for watering livestock.

5. Nonradioactive strontium was leached in significant quantities from three of the four coals tested, by each of the saline transport media. There is no evidence that these levels of strontium would be detri-

mental to the growth of plants, or toxic when ingested by homoiothermic animals.

6. Organics are leached from particular coal samples during the slurrying process. Investigation of possible detrimental effects (i.e., carcinogenicity, mutagenicity) of these organics was beyond the scope of this project.

Recommendations

1. Characterize and further study the organics leached from the coal matrix. These compounds, depending on their nature, could

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Table 42. Salinity effects on the determination of boron by the Carmine method.

Sample	Theor. Conc. of Spike (μg B/ℓ)	Exp. Conc. of Spike (μg B/ℓ) Using Standards in		% Deviation from Theor. Using Standards in	
		Deionized Water	Matrix Water	Deionized Water	Matrix Water
Saline Transport Media (Slurry 3)	510.	370.	440.	-27.	-14.
		450.	500.	-12.	-2.0
	1000.	980.	1000.	-2.0	0.0
		1000.	1100.	0.0	+10.
Coal from Mines:					
1	780.	740.	780.	-5.1	0.0
		740.	780.	-5.1	0.0
	1300.	1200.	1300.	-7.7	0.0
		1100.	1100.	-15.	-15.
2	1600.	1400.	1400.	-12.	-12.
		1600.	1600.	0.0	0.0
	2100.	2100.	2100.	0.0	0.0
		2100.	2100.	0.0	0.0
3	1300.	1300.	1400.	0.0	+7.7
		1300.	1300.	0.0	0.0
	1800.	1800.	1800.	0.0	0.0
		1800.	1800.	0.0	0.0
4	--a	--	--		
		--	--		
	--a	--	--		
		--	--	$\bar{x} = -5.4\%$	$\bar{x} = -1.6\%$

[a]Insufficient sample to complete analysis.

Table 43. Salinity effects on the determination of strontium by flame atomic absorption.

Sample	Theor. Concen. of Spike (mg Sr/l)	Exp. Concen. of Spike (mg Sr/l)	% Deviation from Theor.
Saline Transport Media (Slurry 3)	0.50	0.50	0.0
	0.62	0.61	-1.6
Coal from Mines			
1	1.20	1.17	-2.5
	1.42	1.38	-2.8
2	21.6	22.1	+2.3
	24.6	25.0	+1.6
3	6.71	6.18	-7.9
	7.91	6.96	-12.0
4	7.48	6.51	-13.0
	8.68	7.81	-10.0

pose toxicity or treatment problems. Ames tests should also be conducted to determine if isolated compounds are mutagenic and/or carcinogenic.

2. Construct a recirculating coal slurry pipeline to further delineate the interactions between the finely divided coal matrix and the saline transport media. Sampling should continue over varying periods of time to determine changes (if any) in leaching and absorption trends.

3. Using bench scale treatment processes, determine the most cost effective system to remove contaminants from the water discharged at the terminus of the pipeline. Treatment processes such as reverse osmosis electrodialysis, ion exchange, carbon adsorption and coagulation should be evaluated.

4. Using soil lysimeters, apply the untreated discharge water to various salt-tolerant root and forage crops under controlled conditions. Statistical comparison of the results with those from controls irrigated with unslurried water will determine differences in crop production as influenced by the chemical characteristics of the soil water matrix.

5. Evaluate alternative processes for dewatering coal. Research needs to be conducted on the treatment of coal with hydrophobic compounds to reduce bound water and, therefore, increase its dewaterability after slurrying. Processes such as these may also decrease the quantities of constituents leached from the coal matrix that cause treatment problems at the end of the pipeline.

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Included in this section are all of the conclusions and recommendations that were developed elsewhere in the report. Justification appears in the research section of the report for each conclusion drawn. Recommendations identify apparently needed research that is beyond the scope of the present study.

Conclusions

1. Surface water supplies in the Upper Colorado River Basin are apparently sufficient to continue to provide for a moderate amount of energy development with only a minimal adverse effect on irrigated agriculture.

2. As world energy costs continue to rise, the rate of development of energy resources (coal, oil, natural gas, oil shale, tar sands, and uranium) in the Upper Colorado River Basin will increase, and additional sources of water will be required.

3. Groundwater data for the area are limited, but an approximate inventory makes it clear that the amounts of currently unused brackish and saline groundwater in the basin are large relative to the quantities of water that will be required for anticipated energy development in the basin.

4. Any brackish or saline water that can be used for energy development purposes will have the effect on the system of a new source of supply, and will free water of a better quality for other uses.

5. An immediate, inexpensive source of low quality water in the basin is saline springs and irrigation return flows. Use of this water for energy development would improve the overall quality of the Colorado River.

6. Cooling systems using saline makeup water are technologically feasible. Power plants along the East Coast such as Chalk Point (Washington, D.C.), Turkey Point (Florida), and Forked River (New Jersey) use brackish water or seawater directly, ranging from 7,800 mg/l to 45,000 mg/l before blowdown.

7. Several technologies for treating saline water are available. In this study the cold process softener, reverse osmosis, and brine concentrator were applied to three different cooling tower water treatment options.

8. It is possible to eliminate much of the evaporative water consumption in power plant cooling systems through dry cooling or a combination of wet-dry cooling, but neither of these has been widely embraced by the electric utilities, primarily because of cost. Comparison between wet-dry cooling and wet cooling with saline water treatment shows that as water acquisition and treatment costs exceed about $500/ac-ft, the wet-dry approach seems advisable.

9. The Binary Cooling Tower (BCT), an innovative approach to using low quality water in power plant cooling, has been developed by Tower Systems, Inc. of Tacoma, Washington. The cost comparison between BCT and the R.O.-brine concentrator approach (option 3) indicates that as salinity of makeup water exceeds about 2,000 mg/l the BCT system is economically superior. Above about 5,000 mg/l makeup water, the BCT system has a very decided advantage and seems economically superior to conventional wet-dry systems.

10. Under certain conditions, the evaporative cooling reservoir offers an alternative to the evaporative cooling tower. According to the model used in this study, the cooling reservoir requires approximately half the makeup water required by the cooling tower. Other possible advantages of the cooling reservoir approach include the creation of a warm inland sea with apparently ideal conditions for producing seafood.

11. Spray canals or reservoirs require much less water surface area and volume than do normal cooling reservoirs, and this would seriously increase the rate of salinity buildup in a terminal system. Accordingly such an approach is not recommended for systems using saline makeup waters.

12. Extracting minerals from saline waters is technically feasible, but the problems of low or no market value for major mineral products and insufficient amounts of more valuable minor products suggest that mineral recovery is not economical at present.

13. The dual-purpose power and water plant offers a method of producing large quantities of fresh water from saline water in conjunction with power generation. An indepth economic analysis was not conducted, but a need for substantial quantities of fresh water for municipal purposes in a community overlying a large saline aquifer may make a dual-purpose plant both politically attractive and cost effective.

14. The large quantities of salt accumulated as a result of using saline ground-

water for power plant cooling could possibly find use in salt gradient solar ponds.

15. In general, coal slurrying with saline water can be viewed as a feasible alternative to using good quality water as a transport medium. It also appears that, with pretreatment, the effluent at the pipeline terminus can be used for purposes such as stock watering and irrigation.

16. The coals tested showed an ability to almost completely remove any orthophosphorus and nitrate-nitrogen existing in the transport media. Subsequent burning of this coal could increase the levels of nitrogen oxide emissions into the atmosphere. The increased phosphorus levels could poison catalytic incinerators upon burning.

17. In some instances silica was absorbed from the water by the coal matrix. Although this would have no detrimental effect on the effluent's applicability for irrigation and stock watering, it would decrease the amount of scale that could form in boilers if the water were used for cooling purposes.

18. Boron was consistently leached from all coal samples by water of each salinity level tested, making the water unsuitable for long-term irrigation of certain crops without its being pretreated. Previous work has shown that slurrying with higher quality water would not eliminate the need to pretreat for boron when the effluent is applied to crops. Boron concentration in the effluents studied would not preclude their use for watering livestock.

19. Nonradioactive strontium was leached in significant quantities from three of the four coals tested, by each of the saline transport media. There is no evidence that these levels of strontium would be detrimental to the growth of plants, or toxic when ingested by homoiothermic animals.

20. Organics are leached from particular coal samples during the slurrying process. Investigation of possible detrimental effects (i.e., carcinogenicity or mutagenicity) of these organics was beyond the scope of the project.

Recommendations

1. Conduct detailed inventories of the depth, quantity, and quality of brackish and saline groundwater in areas where significant demand for these waters for energy development seem likely. Particularly lacking are quantity and depth information. This will necessitate the drilling of wells and conductance of pumping tests.

2. Conduct detailed inventories to determine the quantity, quality, availability, and location of brackish and saline surface water that may be available for energy development purposes, such as saline springs and irrigation return flow.

3. Since the use of saline waters in cooling towers and ponds appears feasible and promises to reduce the demand of energy development for fresh water in the water-short Upper Colorado River Basin, more attention should be given to perfecting the technical performance and design optimization of these systems. More detailed modeling of the salt, water, and energy budgets is needed for developing minimum cost designs.

4. The use of multipurpose cooling reservoirs using saline makeup water needs more investigation. Some potentially profitable spin-off developments may be possible, particularly concerning food production.

5. Since economic incentives to power companies are generally to use fresh water in preference to saline water, whereas the general public interest would sometimes favor development of otherwise unused saline waters, the rules governing water transfer from agriculture to energy industries need to be carefully reviewed and modified as appropriate to provide incentives more in the public interest.

6. Characterize and further study the organics leached from the coal matrix. These compounds, depending on their nature, could pose toxicity or treatment problems. Ames tests should also be conducted to determine if isolated compounds are mutagenic and/or carcinogenic.

7. Construct a recirculating coal slurry pipeline to further delineate the interactions between the finely divided coal matrix and the saline transport media. Sampling should continue over extended periods of time to determine changes (if any) in leaching and absorption trends.

8. Using bench scale treatment processes, determine the most cost effective system to remove contaminants from the water at the terminus of the pipeline. Treatment processes such as reverse osmosis, electrodialysis, ion exchange, carbon adsorption, and coagulation should be evaluated.

9. Using soil lysimeters, apply the untreated discharge water to various salt-tolerant root and forage crops under controlled conditions. Statistical comparison of the results with those from controls irrigated with unslurried water will determine differences in crop production as influenced by the chemical characteristics of the soil-water matrix.

10. Evaluate alternative processes for dewatering coal. Research should be conducted on the treatment of coal with hydrophobic compounds to reduce bound water, and thus increase its dewaterability after slurrying. Processes such as these may also vary the quantities of constituents leached from the coal matrix that cause treatment problems at the end of the pipeline.

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APPENDIX A

WELLS IN THE UPPER COLORADO RIVER BASIN (U.S. GEOLOGICAL SURVEY)

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)
355014108262501	1650	1
355037109480601	2165	240
355046107184401	7550	1
355051107183201	2740	1
355125407201701	2510	1
355213107245801	1320	1
355302107130501	8240	1
355328107220801	1880	1
355328107221001	1900	1
355353109390801	1510	92
355356107273501	2000	1
355415107252801	2770	790
355425107314401	1700	1
355426108250501	1730	1
355443107220001	1610	1
355435107411101	2060	1
355450110144701	1190	473
355507107374601	1940	1
355521107293401	2740	1
355534107275701	1750	1
355543110121801	1530	1017
355558107293301	2340	1
355558107293401	2630	550
355563110064901	1190	471
355703107361201	4890	1
355708107361401	1300	1
355713110070201	1830	490
355716110101501	1120	570
355723107312201	3430	1
355752108084601	1770	1
355822107244601	2460	1
355833107255901	1930	1
355915109444701	3190	173
355918110001301	4410	600
355920107411001	1420	1
355933109494101	2450	213
355955109031901	1160	489
360017107223901	2290	2450
360141109381501	3330	117
360147110045201	1430	700
360200107540001	13500	1
360200107550001	2160	1
360200107560003	2010	1
360303110021001	1430	695
360313107473401	3485	5076
360336107501801	2350	1
360344107515601	8320	1
360351110074101	1530	688
360430109530901	1420	125
360521108161301	1600	1
360601107565101	1470	15
360618110134301	1188	1500
360623110120201	1100	235
360645108065501	1130	1
360706110124801	1357	443
360731107494701	4680	436
360734107523101	1605	185
360822107561601	1940	285
360823107544001	2053	190
360826109584001	1640	385
360849107561801	2470	205
360857107531001	3550	59
360913109353901	13900	216
360916107543901	7355	474
360927110035801	1600	650
360941107561601	6350	58
361002106162601	1060	1
361003107543901	8105	290
361057108022301	1670	1
361109109460901	4270	471
361130108203001	1630	1
361135108180501	1010	1
361142108220401	1017	8
361207108192701	1800	1
361208110064401	1825	763
361235107374001	1430	1
361240108514701	5030	1
361256110140901	2080	690
361305108182001	1280	1
361318108151401	1263	8
361318108494101	1430	1
361341108092201	1860	369
361343109533101	2380	902
361407108031901	3530	274
361435108093001	4157	350
361445108140601	5050	9803
361446108083701	11850	67
361446108090801	5445	150
361457108031901	4240	394
361503108243301	9763	8
361508108333901	1390	1
361537109460201	1850	899
361542108252801	1320	1
361545108075101	6987	4896
361636108471901	1620	1
361659108500101	2070	1
361803109215601	1510	950
362034109566001	2180	205
362037110033901	1820	191
362058107092101	4890	1
362116109370301	1035	290
362145108331901	1310	8
362149109463301	3760	360
362150109591801	2840	1172
362222108285501	2110	1

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)
362411108352701	3120	1
362428109521901	1020	1515
362430109522701	2520	230
362458108173901	1400	1
362500109370701	1470	160
362617108283301	2370	1
362637108181201	2340	1
362732108434001	2030	1
362742110132301	4050	417
362756109522201	3160	750
362806107125901	1220	1
363112109541201	1120	1160
363113108333001	2310	1
363113108333501	1930	11
363122110042701	1197	1640
363134110050201	1270	770
363159108440401	1530	1
363330109131701	1236	806
363431108334501	2800	1
363503108342101	1168	8
363504107150001	1080	1
363537109572201	1150	212
363550109033501	1220	551
363615108382601	3850	1
363753107521701	3910	1
363835108314101	2510	5
363844107394001	1120	1
363858108430301	1220	1
364105107252801	1150	1
364227107292601	3350	1
364311109374701	1770	210
364325108353001	2788	10
364445108312701	2910	1
364453108312801	2710	1
364459108312701	2140	1
364500108312901	1860	1
364505107345601	2560	1
364510107360301	2290	1
364523108312701	2360	1
364534108244801	6600	250
364555108082501	1550	1
364613108221801	3830	500
364705108234301	11400	450
364744108225001	9475	730
364750108214701	6165	582
364755108255101	27900	26
364826108234301	7450	60
364835108254601	20400	30
364845108214204	4930	715
364916108234301	4200	600
365035108265601	12200	1
365059108275901	1870	1
365418109063001	1073	950
365427109061801	1073	1168
365536107523601	6750	750
365554108120501	1220	1
365808109034801	7250	5689
365921108111201	1340	1
370118107522700	1480	1
370122107522700	3490	138
370256108053700	3800	1
370310107335000	2110	115
370325108050500	2710	1
370346108044800	4450	1
370429107362000	1230	1
370436107013900	2910	1
370449108041900	3140	1
370506107360000	1310	1
370506107360300	1310	61
370508107311000	1190	850
370519107361700	1720	1
370556107343500	1240	1
370610111402501	1060	1
370611108040400	1120	1
370620107442700	1630	1
370628107343500	1010	1
370657107435700	1630	1
370703111290201	1750	1
370707107462700	1360	1
370735111290501	4710	1
370839107415900	2210	958
371052108083200	3500	1
371105111220001	3520	1
371142107032600	1240	1
371215111364501	1140	1
371327107105400	1250	1
371342108130800	3350	1
371401107550600	1140	1
371447107574000	1040	1
371507107571600	1090	1
371520111343501	2160	1
371532111372501	1500	1
371550107003100	3310	1
371551107003500	3320	1
371552107003700	3183	1
371555107003700	3300	1
371555111352300	1230	1
371600107010000	3010	1
371601107004200	3320	1
371605111344001	1240	1
371630111341001	1060	1
371630111351501	1530	1
371655111345001	1100	1
371743107570200	1570	1
371847107482800	4820	1
371906108035200	4110	1
372326107505200	3340	1
372330107505200	3240	1
372453111391801	1650	1

STATION NUMBER	TLD (FEET)	TOTAL DEPTH (FT)
372650107481700	3880	1
372653107482300	3670	1
372707107482000	3887	1
372827111472801	1780	1
373235108440400	1410	1
373609108515200	1860	1
373811110425801	3380	1
374021110504401	3960	8362
374115108014400	2745	1
374117108014400	2790	1
374119108014400	2745	1
374120108014500	2250	1
374135110542800	2390	1
374238110442400	2790	1
374414111591001	9140	7510
374448108070200	1630	1
374859110433100	1780	1
375342110581800	8830	1
375449110561001	1410	1
375504108353201	4830	115
375525108365801	5290	350
375629108372001	5290	325
375733108370501	9810	901
375739110000300	1080	1
375802108362601	3760	1
380041111015600	2320	1
380121110512000	6780	1
380220111015001	1060	1
380250110040001	1406	1
380358108315100	5380	57
380406110272401	2140	5175
380431110404001	10400	6683
380450111003101	1990	1
380516110150501	14100	5534
380543110584101	1170	1
380938110243301	1460	650
381334110295801	48760	6128
381411111039401	7420	4000
381427108304201	1200	1
381431111039201	2140	500
381441110362801	8835	6584
381441110362802	4600	2245
381448108323801	1560	335
381528110104201	1720	2750
381636110173401	85500	6886
381749110512901	4487	8174
381749111313901	1200	500
381816111310601	3840	1
381916110403801	6105	2847
381932108542801	1800	205
381934111032302	1171	1350
382019111070801	1390	800
382020111034601	2547	1250
382024111043001	1920	764
382025108530401	1560	1
382027111041601	3328	761
382029111090201	1311	2353
382058108475000	2570	1
382136110222001	2390	1
382224110433501	1254	407
382227108481101	1830	1
382233110432201	1053	392
382238110440201	1700	503
382304111075901	2250	1
382355110443201	7540	7301
382424108562801	4040	1
382447110414601	2930	750
382450110265101	16400	6820
382517110100501	28700	6867
382518110173201	30000	8096
382622110320601	11000	7664
382649111142601	1132	1
382707110002301	2410	1
382708111371201	1200	285
382717111365601	1220	285
382717111370101	1165	1
382727110245701	5380	6523
382822111001501	4660	1
382823111001501	5500	1
382824111004401	4310	1
382839111123401	9390	440
382839111123402	70300	950
382852110361301	9030	6430
382943110245401	4980	5940
383055110255201	6990	6007
383145110322501	2150	400
383153110531202	1160	1
383211110560601	1810	1
383223111123201	5955	6704
383317110570501	4250	1
383406110260101	12800	5750
383424110050901	18050	6498
383508111050501	2540	767
383514101345101	3500	290
383606110102201	40600	6701
383652110034001	31780	7225
383724110143001	26167	6396
383829110143001	210000	6470
383921110080901	94700	7393
385000107314801	3100	1
385032107380601	2100	1
385022107383200	2010	1
385026110531901	1214	690
385031111008550 1	174000	9450
385037109440101	6530	535
385045111171801	1290	720
385047107332301	8220	66
385049111153101	2410	1
385100108031100	2770	1
385102108031500	2780	1
385122107290301	7500	53
385123110020101	203900	10293
385127111170201	1230	406
385138111151801	3454	1
335159111154501	5100	1
385159111154502	4780	1
385217110055201	22200	1
385224111142602	3370	150
385225111130001	3880	1
385225111152601	1350	1
385230110064401	103300	9508
385233111130301	1530	1
385235110502101	1673	1200
385238111130201	1140	1
385249111130901	4200	1
385300111153701	1420	1
385303111131301	4470	1
385335110585401	7450	1
385360111122901	2440	1
385506111095201	3240	1
385554110074701	394000	5896
385619110080601	13500	2627
385714112264701	1940	1
385715112271201	1255	787
385732110002201	165900	11895
385801110132901	290900	10600
385819110265701	3080	1
385920108264001	1570	1
385939112272303	1080	1
390021110092301	3290	16
390044106532600	1910	1
390045112281201	1520	1
390131111080501	6450	1
390327111030401	5340	1
390334108351801	1630	1
390354111003401	46800	1
390404111080101	50566	7299
390406111014201	6870	1
390454110083201	1310	30
390535112370001	2070	1
390540112370001	1990	1
390625111013801	10100	1
390628112201401	1300	1
390637108400601	2000	1
390653111005401	8120	1
390708110410801	2250	1
390710109370301	6810	4760
390822110525101	3280	1
390933108405701	5050	1
391027110472101	3550	476
391049110240901	39995	8431
391049110240902	41200	3800
391119108405301	4340	1
391315110570301	5080	1
391317110234701	42697	7083
391333107132800	2804	1
391334107133000	2780	1
391350107133600	2960	1
391404111402601	1130	1
391410111393001	1180	1
391419111391900	3120	1
391556110204901	4170	3180
391559110204901	4734	30
391629108540101	3670	1
392002108244401	1780	1
392110108260601	1780	1
392128108145701	3780	1
392209108155600	3760	1
392210108300300	1490	1
392213108314801	1180	1
392228108343701	1030	1
392236110262301	2438	1
392242108213701	2180	1
392247108214500	2290	1
392314108063600	1110	1
392328108223301	1440	1
392348111053701	1300	1
392350107111400	1460	1
392352108051400	9320	1
392428107064500	1840	1
392439110331801	29683	7132
392447107091000	2350	1
392449107091800	1130	1
392617108023900	1050	1
392630108031300	1660	1
392710109272001	104400	8116
392712110515301	73650	11675
392727107142300	2630	1
392732108040000	1390	1
392745107142400	2320	1
392815109243001	88050	10348
392826107160800	1160	1
392828107161301	1010	1
392920108001400	2460	1
392935109330101	15735	5700
392948110453801	23570	10854
393000108225001	1340	1
393102112194501	1430	406
393102112194510	1330	1
393107110285901	84600	9153
393113110302001	1080	1
393147110372801	35780	8509
393148110361601	67770	9174
393149110381301	3607	3114
393154112192901	1983	203
393221112221801	1034	303
393234110240601	1330	1
393244110251401	1790	66
393258107191000	17600	1

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)
39 3259 10719 1700	18000	1
39 3259 10719 1800	20400	1
39 3259 10719 1900	19950	1
39 3300 10719 2700	18900	1
39 3301 10719 1500	19900	1
39 3302 10719 0400	18050	1
39 3305 10719 0000	18000	1
39 3314 10720 0800	21500	1
39 3314 11222 3301	2580	1
39 3316 10718 5100	18300	1
39 3316 10720 0800	21300	392
39 3412 10943 0601	24547	6792
39 3527 11154 1701	1770	120
39 3527 11154 1601	1655	1
39 3700 10942 5001	4711	7300
39 3730 10718 0000	18400	1
39 3737 10706 0000	9040	1
39 3739 10706 2200	10280	1
39 3745 10706 0000	10500	392
39 3924 10919 5401	4190	1
39 3929 10918 5001	2913	1295
39 3930 10919 3001	2720	1
39 3955 10908 3701	1480	1
39 4006 11051 2101	4040	210
39 4039 11215 5301	1240	150
39 4100 11150 4501	1477	90
39 4109 10932 5501	1086	81
39 4109 10932 5502	1978	20
39 4113 10903 2701	4740	1
39 4126 10852 5601	2785	1
39 4126 10943 4901	1460	129
39 4135 10916 4901	4248	82
39 4135 10916 4902	3294	42
39 4136 11151 2001	1030	1
39 4422 10920 2701	6030	119
39 4221 10920 2702	27800	40
39 4252 10920 1501	5965	1
39 4445 10812 2700	1005	1
39 4450 10810 0500	1010	1
39 4458 10639 3201	2370	1
39 4503 10921 1201	7904	82
39 4503 10921 1202	17520	19
39 4505 10921 1201	7730	1
39 4505 10921 1202	16700	1
39 4527 10916 2001	1649	1402
39 4530 10827 1200	1100	1
39 4540 10819 1201	1680	655
39 4540 10819 1202	2170	1040
39 4454 10851 4001	3720	1
39 4545 10819 0300	1085	1
39 4550 10813 5500	1125	1
39 4557 10822 5300	4090	1
39 4617 10851 4701	3725	1
39 4627 10822 4300	1015	1
39 4632 10917 4201	19575	5515
39 4719 10817 2600	1180	1
39 4719 10817 3200	1120	1
39 4719 10817 5601	1110	1
39 4722 10817 5700	1170	1
39 4736 10813 4300	10267	1
39 4747 10821 4901	1390	1
39 4749 10812 0700	29800	1
39 4800 10805 1100	1530	1
39 4800 10914 0001	2080	1
39 4811 10904 3601	3316	38
39 4815 10817 3200	1215	1
39 4822 10945 2301	5030	1
39 4824 10813 3500	1284	1
39 4830 11015 2201	1100	1
39 4835 10808 4900	1620	1
39 4835 10924 3901	3750	1497
39 4851 10811 2800	1727	1
39 4852 10813 5800	1276	1
39 4853 10314 3600	1500	1
39 4857 10812 2100	1413	1
39 4859 10813 5100	1313	1
39 4929 10924 5401	14400	97
39 5000 10914 1501	3150	1
39 5020 10814 3500	1001	1
39 5021 10904 4501	2016	798
39 5028 10819 2700	1190	1
39 5030 10955 4001	3480	1
39 5031 10816 2000	1130	1
39 5034 10934 2501	1060	3560
39 5035 10906 2201	5800	6300
39 5035 10907 4001	3660	77
39 5040 10907 5201	3416	44
39 5040 10907 5202	3304	18
39 5050 10944 1801	5418	90
39 5059 10618 5601	1210	1
39 5100 10818 5200	1130	1
39 5102 10815 5000	1205	1
39 5105 10818 5400	1275	1
39 5112 10827 3400	1043	1
39 5112 10827 3701	1050	1
39 5115 10917 1801	1140	1
39 5118 11013 0501	2440	1
39 5131 10818 3800	1054	1
39 5136 10818 3000	1060	1
39 5139 10826 0401	1120	1
39 5141 10825 5800	1160	1
39 5155 10812 3100	1210	495
39 5215 10817 1800	1302	1
39 5215 10817 2300	1342	1
39 5218 10817 2800	1428	1
39 5226 10909 1201	4203	29
39 5226 10909 1202	4077	21
39 5228 10916 3401	1130	5840
39 5229 10909 1201	4230	70
39 5233 10915 1601	1127	6569
39 5237 10828 4600	1040	1
39 5237 10936 2601	18685	8500
39 5238 10828 4400	1130	1
39 5238 10916 0801	1965	1950
39 5239 10813 3900	6400	1
39 5251 11012 3001	35560	4860
39 5303 10830 0300	1800	1
39 5318 10916 2101	1030	5950
39 5325 10827 1501	1000	1
39 5326 10837 4001	1850	1
39 5327 10817 3500	1830	1
39 5327 10823 2000	1530	1
39 5327 11007 0101	4719	5296
39 5328 10830 4300	2840	1
39 5328 10830 4301	1350	1
39 5331 10827 1500	1088	1
39 5336 10829 1500	1292	1
39 5338 10831 1900	2854	1
39 5345 10925 3001	23400	5445
39 5347 10827 0000	2480	1
39 5348 10826 5800	4250	1
39 5359 10909 3201	3560	50
39 5410 11159 0801	1040	1
39 5412 10914 2201	20265	6947
39 5424 10817 4200	5415	1
39 5425 10830 0001	1310	1
39 5428 10925 4001	2970	1
39 5430 11156 2501	1780	1
39 5430 11157 3201	2388	1
39 5433 10938 1701	2110	5672
39 5439 10822 3302	1157	1715
39 5443 10646 3400	3150	1
39 5445 10817 3900	11500	1
39 5445 10817 4300	4345	1
39 5447 10819 2100	3580	1
39 5449 10912 5201	19540	7050
39 5453 10911 1001	1856	540
39 5455 11155 1501	1889	1
39 5500 10912 4401	1746	627
39 5503 10645 1700	2320	1
39 5507 11031 4401	9674	5500
39 5508 10817 5700	1845	1
39 5510 10909 4901	2544	90
39 5512 11003 1901	34390	5250
39 5515 10909 4901	2260	60
39 5515 10909 4902	2810	31
39 5524 10829 0300	19263	1
39 5524 10829 0301	6185	1
39 5524 10829 0302	2640	1
39 5529 10817 3300	2610	1
39 5530 10831 2700	1137	1
39 5535 10913 4901	1418	612
39 5548 10904 5001	23900	1
39 5548 10903 0701	1022	1176
39 5554 10917 2701	3340	38
39 5554 10917 2702	1852	17
39 5554 10917 2703	3160	20
39 5559 10826 0500	1212	1
39 5600 10813 4600	2058	1
39 5601 10818 4000	1026	1
39 5603 10912 0801	2590	620
39 5606 10930 5501	3460	1
39 5614 10911 1401	4807	650
39 5617 10913 4401	2879	317
39 5617 10913 4402	1406	504
39 5620 10950 4001	67750	5710
39 5625 11007 0701	8070	9265
39 5626 10916 5401	1941	6486
39 5628 10916 2901	1268	41
39 5629 10916 3901	1152	44
39 5630 10817 0600	6720	42
39 5633 10938 4601	8353	76
39 5633 10938 4602	10820	42
39 5635 10910 1501	4231	400
39 5651 10914 0201	5821	27
39 5651 10914 0202	2940	24
39 5657 10932 5401	2197	5606
39 5658 10952 0001	55065	7160
39 5707 10909 3101	3270	127
39 5707 10909 3102	3778	100
39 5707 10909 3401	4010	15
39 5707 11001 1001	2327	6262
39 5707 11112 2701	19400	1
39 5710 10909 3201	3750	14
39 5710 11155 3501	5151	1
39 5710 11157 1801	1652	1
39 5710 12034 0000	6610	1
39 5715 10927 2001	6843	6454
39 5722 10934 3901	1350	1
39 5722 10934 4901	1334	21
39 5722 10934 4902	1646	38
39 5728 10942 5701	49933	5730
39 5729 11151 1500	1320	1
39 5733 10909 5401	4231	486
39 5734 11151 3001	1630	1
39 5737 10941 2901	15355	6308
39 5737 11005 0101	16985	6303
39 5751 10909 4501	1402	220
39 5752 10957 2001	3190	1
39 5755 10821 1401	3746	1755
39 5801 10924 5801	18320	36
39 5804 10907 1701	1626	34
39 5804 10907 1702	1718	22
39 5814 11155 2501	1503	495

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)
395817109403701	4832	6233
395823109440801	9080	6679
395840108222500	1490	1
395841108151000	2180	1
395850109305201	8380	2540
395852109172801	29940	1
395904108164600	3425	1
395906109362801	55300	3234
395935108211600	1540	1
400001108210100	1470	1
400015108145200	1685	1
400020109205101	64300	1
400023111543401	1229	1
400028110261101	1210	161
400030108145000	1520	1
400045108131401	1220	2400
400045110002601	1600	22
400054108204200	1475	1
400057111503001	2650	100
400103108203000	1670	1
400113108274700	1500	1
400119108153901	7770	1
400136112020501	6540	1
400146109064601	13300	1100
400150111525501	1179	1
400158108333501	1450	1
400202107512200	17400	1
400206107502200	21800	1
400207107502700	7625	1
400210107502100	17500	1
400210108153000	32050	1
400210108153001	16250	1
400210109195501	65100	1
400211109123901	2200	1
400214111314201	6360	1
400216108154000	6120	1
400218108170600	1260	1060
400223108245400	1346	1122
400223108245401	2214	1510
400224107505900	17700	1
400226108152700	26050	1
400226108152800	20150	1
400231106064200	1180	1
400245108462600	2050	665
400301108165000	29370	1
400302108145000	5571	·1
400318107511800	12200	1
400320109242201	1868	22
400320109242202	1128	20
400325108152700	6160	1
400330108462001	1480	908
400334108150200	3350	1
400338110372801	2710	1
400349108181500	12778	1
400353108152000	2145	1
400400108193600	29350	1
400400108201200	24300	3140
400400108201201	24300	3140
400417111543500	1093	1
400417111543501	1090	1
400430110303001	1840	1
400430110303101	1860	1
400431106064400	1200	1
400432106064500	1190	1
400433106064300	1198	1
400433106064400	1200	1
400433106064500	1203	1
400433106430000	1197	1
400439108141000	3200	1
400500109402501	9060	55
400508108202000	2020	1
400518109403601	2340	125
400518110293001	1100	1
400519109403801	2400	80
400544109350401	33000	5539
400601106155000	1560	1
400601108212500	1935	1
400601108212501	1760	1
400607108212901	1820	1
400614108522701	31200	7500
400653110401001	1700	1
400655108212900	1960	1
400700110401501	1770	1
400719109220201	26225	1
400725108250400	14387	1
400736110352601	2820	1
400748110163801	6743	7600
400755110391701	8330	1
400759109561001	52415	5400
400800110383701	7320	1
400800110385501	7700	1
400802110383001	4270	1
400808110202001	178200	3595
400808110212501	38800	3582
400808110220301	109400	3048
400819109151301	4105	4880
400834109124101	2390	1
400835109135001	43740	1
400845109262601	6585	5811
400845111482500	6140	1
400856110261501	7520	7465
400857109254101	32233	1
400857110130201	2360	56
400913110140001	1170	70
400918109263701	51700	6008
400932109265201	37900	1
400945110135801	1910	250
400955112260001	2180	1
400957110131001	2090	1
401003109104401	1636	1
401004110223401	1740	225
401005109151401	7530	1
401012110292101	1230	200
401015110161201	2110	36
401017109091701	3633	1
401017110081702	4480	40
401024109254001	29350	5876
401027110161901	3010	1
401030109124101	72015	1
401039110174401	3890	58
401044109200101	17470	1
401045110235701	13470	4800
401049109232401	18500	6200
401056109125801	148000	1
401059112010701	2020	200
401100110291001	1500	1
401104111364201	1092	1
401111110234101	1940	300
401114107493601	1090	1
401116110442401	2890	100
401119110264401	11800	1
401126109124001	118000	18607
401130109233901	2360	1
401131110065101	1110	32
401131110420102	108000	11670
401135109131501	1170	5261
401135110240101	4070	5257
401136109124101	4397	5373
401155109252401	15000	6081
401159110481501	11700	12500
401214109180201	4940	1
401215109111501	2980	1
401215109122401	6944	1
401215109223401	4690	6359
401216110424902	1550	90
401223110392801	6264	10840
401225110371601	13160	10360
401226110350301	7510	8211
401227109174501	5830	5835
401229109185401	6030	1
401234109341801	46010	7070
401235110451801	3690	340
401240110502101	1282	110
401244110502602	4430	548
401256110112001	8413	75
401300111523001	6240	1
401305108012901	1480	1
401308109111701	3950	1
401308109194501	6714	1
401317110362701	10637	5507
401330110364301	24730	6000
401334109140601	6180	5640
401343111515501	1430	1
401358109481101	1440	40
401402111515201	1570	1
401410110124601	1260	52
401415107522801	1930	1
401424110353501	23200	6379
401437107522500	1350	1
401446107515801	1310	1
401447110375501	15604	9251
401450109272301	14065	1
401502109274701	30200	6705
401511111592101	1230	223
401520110130801	1571	1
401524109031201	1900	1420
401539107472601	1020	1
401539108424601	2500	3365
401551109323701	20227	7650
401619107502901	1250	1
401626110083501	1590	200
401656109480601	26120	11950
401714110292401	6190	10120
401729106575701	2920	1
401801107470301	1250	1
401806109505901	1320	20
401811109581701	6720	560
401811110313501	1410	43
401825108061201	1740	1
401854107474901	1220	1
401903110385601	1540	80
401906107472901	1790	1
401907109390401	15900	8041
401917109225801	1060	40
401955109141401	1420	1
401955109523401	1010	375
402000109164101	1830	2650
402002109340501	10650	7884
402005107200101	1060	1
402043109205901	2320	28
402045110014401	1820	1
402046109564901	1680	260
402050111540501	1390	1
402056111541901	1450	1
402100111541701	1420	1
402115111540501	1420	1
402118109495001	1030	442
402120109225001	4230	1
402125111550501	1230	1
402135111541501	1440	1
402136111534502	1320	1
402139109241901	1700	4243
402139109240301	1690	4166
402139109243901	1360	4251

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)
402139109245501	1330	4287
402144109240601	1585	4230
402152109242001	1400	4203
402153109243501	1960	4130
402153109250301	1130	4278
402159109242101	1500	4235
402203108034301	1840	1
402209109250701	1090	4152
402211109251301	2020	4293
402212108234301	1370	1
402213109213601	3170	1
402222111545301	1380	1
402236107025301	1780	200
402249109530601	11450	9393
402249109533901	11350	9391
402303111553001	1590	1
402305110221501	1510	1
402306109223801	2600	60
402327108590001	6560	1
402327109570401	8495	12740
402333106503600	1070	1
402344107195001	1450	1
402346106590000	1660	1
402346106590001	1690	1
402347107351900	1020	1
402356107171701	1110	1
402420111535701	1140	1
402422109182901	1300	733
402424110092401	29864	11860
402437109420601	2035	6915
402444110010201	10400	10950
402457110045901	13310	11130
402457110045902	29550	10510
402459107154901	1050	1
402514109275701	10000	56
402515111544301	3110	1
402519109200501	3490	57
402524110053401	15336	10600
402525109314001	2420	35
402526107231601	1460	1
402536110082301	8420	12520
402545107073901	2260	1
402605109182401	3962	29
402623109192001	2620	1
402630109472301	1400	200
402632110053901	18000	11230
402633107080101	1050	1
402638109150801	1058	33
402643107153301	1360	1
402652109353701	1950	60
402752109342501	1292	7960
402801107571000	1155	1
402802107571101	1180	1
402805111555001	1085	157
402814107490001	1190	425
402822107564200	1170	1
402855107101701	1120	1
402857107104101	1490	1
402857107385101	4230	1
402858107104001	1510	1
402902106502300	4530	1
402902107101801	1860	1
402903107105101	2030	1
402903107105301	2110	1
402905107110701	1020	1
402909111551901	1210	1
402911111561901	1300	50
402915111544001	1525	1
402918106502700	6170	1
402921107103801	1380	1
402931107311401	2750	1
402932107171801	1140	1
403027109121201	2730	1
403035107304401	2970	1
403056109551701	1300	7250
403312110012901	3560	6674
403543109334601	1910	1
403602109263601	2790	1
403725109240402	1840	1
405753110183101	7290	15630
405840108222500	1380	1
410025109224501	2400	1
410027109100401	1210	1
410043109475701	4100	1
410207108162901	2160	1
410245108462201	1240	1
410258107252001	2300	1
410323107530401	1520	1
410352107304101	1090	1
410352107304701	1050	1
410504107570001	1320	1
410511109114001	2380	1
410546108035901	1520	1
410610108113201	1105	710
410732107554301	3110	1
411016108490001	2400	145
411133108014801	2750	1
411149107534401	7210	1
411201107413801	3590	110
411311111021401	2460	15
411313108392401	2590	1
411349108401001	1270	0
411444109482201	1030	1
411445109353001	1690	2218
411506109355001	1690	2218
411608107373701	1830	1
411749109405901	6590	2405
411827110374201	9710	0
411831110153101	4290	65
411927107371701	1640	71
412006110401601	1110	0
412052109264901	1070	990
412053107380401	1190	2933
412058107374401	1190	1
412058110002901	1770	10
412105109270501	1070	990
412228110155801	1590	1865
412234107470301	2490	400
412333107285801	1540	1
412416109254101	1860	0
412547108030801	2590	0
412625110234001	1480	62
412815110362501	1070	0
412815110362502	3440	0
412820110010001	3210	15
412827108550201	1290	1
412932108062401	3270	0
413025109495501	25800	1799
413118108171701	1570	0
413140107230101	1480	1
413140109410001	1050	30
413142109280201	1210	764
413149107313501	1650	0
413205107265001	1670	1
413211109513401	3775	2149
413245108430001	1280	4930
413246108425900	1135	1
413300108063001	3450	0
413320110234701	1390	0
413330109320001	2480	15
413339109181401	1160	150
413355107304901	57700	1
413402110332001	1467	1005
413410109191001	1510	0
413415109475501	45200	1621
413431107171301	1100	1
413434108412601	1010	1
413450108163001	1340	190
413450109163001	1340	190
413455109153001	1740	20
413507109132501	9430	1
413556108400401	3360	1
413658110421701	1090	0
413709109043501	7220	1
413720108160001	1050	1060
413725108170001	1580	500
413741107513801	2430	0
413758110342000	3340	100
413839109171101	1180	59
413850108582501	2970	161
413910108170001	1630	300
413910108180001	2370	300
413915108582501	7860	30
413958107310001	1040	1
414054108472001	1090	0
414100107323301	10300	22
414310109450501	53700	1645
414335107431501	4100	1
414505108083001	1520	93
414506109200001	1420	0
414514109182300	1370	0
414514109542401	1160	973
414545108115001	1120	6161
414625110192000	1560	180
414625110192001	1560	28
414646107125001	6660	1
414658107254801	2635	340
414716107135101	1650	1
415110107554001	1780	105
415210110082201	1220	616
415307108454301	1170	0
415528109353701	6964	998
415553109232400	1320	1
415606103441700	1240	1500
415638108125801	1050	2250
415641109363601	6670	1
415645108131501	1090	2250
415716109360501	6120	1
415814109290601	1080	1029
415814109340101	4680	228
415851109363201	3820	1
415933109481501	99400	1
415942109125301	1010	1
415945108154501	1080	1
420055110024301	1290	1
420210108300001	1070	52
420235109482001	26525	430
420235109482002	1053	3203
420327107101501	1080	115
420401109301501	1645	1
420513109504701	5030	72
420515109295501	2180	1
420532109232001	1050	131
420605109223401	2550	265
420646109264902	2350	500
420655109205701	1180	75
420700109271001	1030	265
420713108514201	1810	1
421120109255601	2510	75
421134109090401	1190	1000
421258110100401	1560	300
421346110152201	2610	200
421501110115001	1660	265

STATION NUMBER	TDS (PPM)	TOTAL DEPTH (FT)			
			422505109451001	6510	290
			422515109551001	1650	300
			422615109395001	1880	1
421621109321801	1220	0	423045109334001	1780	200
421755109552001	7020	493	424632110020001	1030	1
421835107272801	4920	120	430116109325001	2390	1
421847109512101	1040	205	431636110005701	1140	1
421905109512001	1030	349	431702110010001	1000	0
422034109580301	1520	725	431745109555501	1010	0
422125109500501	2440	268	421515109501801	3130	349
422133110085201	1020	600	421540110114101	1430	92
422135109472501	4070	1	421545109495501	3630	205
422150109554001	1730	420	421551110120701	1510	55
422335109463501	3160	218			

SOLAR RADIATION ON A BRINE EVAPORATION POND

Part A. Calculate the Hourly Direct and Indirect Solar Radiation

The position of the sun relative to the pond surface can be described in terms of several angles (Duffie 1974).

ϕ = latitude (north, positive).
δ = declination (north, positive).
ω = hour angle (solar noon, ω = 0; A.M., positive).
θ = the angle of incidence of beam radiation.

With these angles we can calculate the Zenith angle, θ_z, which is the angle between the sun and the vertical,

$$\theta_z = \cos^{-1} (\sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega)$$

and sun rise hour angle, ω_s; hours of sunshine per day, t_s:

$$\omega_s = - \cos^{-1} (\tan \phi \tan \delta)$$

$$t_s = 24 \omega_s / \pi \quad \text{(hours)}$$

The total daily solar radiation (direct and indirect) on a horizontal surface, q_h, is available from weather stations at different locations.

$$q_h = \int_0^{t_s} a \sin \omega t \, dt = 2 a t_s / \pi$$
$$\text{(Btu/ft}^2\text{-day)}$$

where $a = q_h \pi / (2 t_s)$

Then we separate total daily solar radiation into hourly basis in order to calculate the brine temperature on hourly basis (see Figure B-1, the shaded area is the total hourly solar radiation on a horizontal surface, q_{hh})

$$q_{hh} = \int_{t_j}^{t_{j+1}} a \sin \omega t \, dt$$

$$= \frac{q_h}{2} \left[\cos \left(\frac{\pi t_{j+1}}{t_s} \right) - \cos \left(\frac{\pi t_j}{t_s} \right) \right]$$

$$\text{(Btu/ft}^2\text{-hr)}$$

Then we divide the total hourly solar radiation into direct solar radiation, q_{hd}, and indirect solar radiation, q_{hi}, on a horizontal surface.

Figure B-1. Total daily and hourly solar radiation.

$$q_{hh} = q_{hd} + q_{hi}$$

$$q_{hi} = \{0.46 \tan h [3.2(0.5 - C)]$$
$$+ 0.48\} q_{hh}$$

where

C = sky factor (smaller when cloudy)

$$= \frac{q_h}{I_{se} \cos \theta_z}$$

I_{se} = solar intensity outside of atmosphere

$$= 428.881 \{1 + 2 \{0.01673 \sin$$
$$[2\pi (\text{day} + 81)/365]\}\} \quad \text{(Btu/ft}^2)$$

Part B. Calculate Absorptance of the Brine

Part of the solar radiation transmits through the brine surface (see Figure B-2, $\theta_1 = \theta_z$).

$$\theta_2 = \sin^{-1} \left(\frac{n_1}{n_2} \right) \sin \theta_1$$

Reflectance, Ref, is defined as

$$\text{Ref} = \frac{1}{2} \left[\frac{\sin^2 (\theta_2 - \theta_1)}{\sin^2 (\theta_2 + \theta_1)} + \frac{\tan^2 (\theta_2 - \theta_1)}{\tan^2 (\theta_2 + \theta_1)} \right];$$

$$\text{when} \quad \theta_1 \neq 0$$

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Figure B-2.   Transmission of solar radiation.

$$\text{Ref} = \left[\frac{\frac{n_1}{n_2} - 1}{\frac{n_1}{n_2} + 1}\right]^2 = \left[\frac{n_1 - n_2}{n_1 + n_2}\right]^2 ; \text{ when } \theta_1 \approx 0$$

   Assumed the solar radiation transmitted through the brine surface is totally absorbed by the brine (see Figure B-3), i.e. absorptance of the brine is equal to (1 - Ref). Then the reflected solar energy, I_2, and the absorbed solar energy, I_1, can simply be described as

$$I_2 = I_0 \text{ Ref}$$
$$I_1 = I_0 (1\text{-Ref})$$

where I_0 is the solar incidence.

Figure B-3.   Transmission and absorption of solar radiation.

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APPENDIX C

SUMMARY OF ANALYSES COMPLETED ON SLURRIED AND

UNSLURRIED FILTERED TRANSPORT MEDIA

Each saline transport medium was filtered and run as a control before and after slurrying. All analyses on the coal extracts were performed on the same filtered transport media after slurrying.

Slurry 1 represents the lowest salinity level (TDS 2,220 mg/l), slurry 2 is intermediate (TDS 4,640 mg/l), and slurry 3 is the highest (TDS 13,200 mg/l).

In cases where triplicate analyses were performed, the Duncan's multiple range test was applied to the data (99 percent confidence limits). Appendix D summarizes these results in detail. For the sake of clarity, the final results of the statistical analyses appear here also. A "Y" indicates that the quantity of that particular constituent detected in the slurried and filtered transport medium is significantly different from the levels initially present for that salinity level. An "N" indicates that no significant statistical difference was found at the 99 percent confidence level. The phenomena of absorption and leaching are explained in the text.

Table C-1. Alkalinity (carbonate); mg CO₃/liter.

Table C-1. Alkalinity (carbonate); mg CO_3/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	117.	361.	550.
Coal from Mines:			
1	100.	Y 352.	Y 332.
2	118.	Y 400.	Y 364.
3	108.	Y 413.	Y 326.
4	110.	Y 412.	Y 308.

Table C-2. Aluminum; mg Al/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	0.28	0.74	1.11
Coal from Mines:			
1	Y 0.74	Y 0.56	Y 0.80
2	N 0.31	Y 0.65	N 1.10
3	N 0.30	N 0.71	Y 0.98
4	Y 0.35	Y 0.97	Y 1.25

Table C-3. Arsenic; μg As/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<0.5	<0.6	<2.
Coal from Mines:			
1	<0.5	<0.6	<2.
2	a	<0.6	<2.
3	<0.5	<0.6	12.
4	<0.5	<0.6	<2.

[a] Insufficient sample to complete analysis.

Table C-4. Barium; μg Ba/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<60.	95.	57.
Coal from Mines:			
1	Y 80.	N 127.	N 85.
2	Y 73.	N 124.	N 71.
3	Y 93.	N 113.	N 33.
4	Y 95	N 102	Y 201.

Table C-5. Beryllium; μg Be/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<5.	<5.	8.
Coal from Mines:			
1	<5.	<5.	<3.
2	<5.	<5.	<3.
3	<5.	<5.	<3.
4	<5.	<5.	8.

Table C-6. Boron; mg B/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	0.1	0.5	0.7
Coal from Mines:			
1	Y 1.4	Y 1.7	Y 1.1
2	Y 2.8	Y 3.2	Y 2.0
3	Y 1.3	Y 1.9	Y 2.1
4	Y 2.4	Y 2.7	Y 1.9

Table C-7. Cadmium; μg Cd/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<3.	<3.	<9.
Coal from Mines:			
1	<3.	<3.	<9.
2	<3.	<3.	<9.
3	<3.	<3.	<9.
4	<3.	<3.	<9.

Table C-8. Calcium; mg Ca/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	156.	343.	309.
Coal from Mines:			
1	Y 151.	Y 234.	Y 194.
2	Y 115.	Y 252.	Y 281.
3	Y 136.	Y 289.	Y 266.
4	Y 161.	N 315.	Y 398.

Table C-9. Chloride; mg Cl/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	592.	138.	4960.
Coal from Mines:			
1	Y 667.	Y 189.	N 4830.
2	Y 750.	Y 270.	N 4990.
3	Y 614.	Y 179.	N 4740.
4	N 600.	Y 151.	N 5120.

Table C-10. Chromium; µg Cr/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<17.	<18.	<55.
Coal from Mines:			
1	<17.	<18.	<55.
2	<17.	<18.	<55.
3	<17.	<18.	<55.
4	<17.	<18.	<55.

Table C-11. Cobalt; µg Co/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	a	<2.	<2.
Coal from Mines:			
1	a	N 3.	N <2.
2	a	N 5.	N <2.
3	a	N <2.	N <2.
4	a	N <2.	N <2.

^{a}Insufficient sample to complete analysis.

Table C-12. Conductivity; µmhos/cm.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	a	3580.	16000.
Coal from Mines:			
1	8240.	4690.	15900.
2	8780.	5780.	17100.
3	10700.	4960.	14200.
4	14200.	4660.	15700.

^{a}Insufficient sample to complete analysis.

Table C-13. Copper; µg Cu/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	12.	14.	45.
Coal from Mines:			
1	N 13.	N 16.	Y 38.
2	N 15.	N 17.	Y 38.
3	N 15.	N 12.	Y 35.
4	Y 17.	N 12.	Y 40.

Table C-14. Fluoride; mg F/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	0.17	0.68	0.47
Coal from Mines:			
1	0.35	0.88	N 0.47
2	0.30	0.81	Y 0.39
3	0.18	0.58	Y 0.29
4	0.12	0.46	Y 0.13

Table C-15. Iron; µg Fe/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<23.	<16.	<15.
Coal from Mines:			
1	Y 508.	Y 46.	Y 273.
2	N <23.	N <16.	Y 47.
3	N <23.	N 17.	Y 585.
4	N 31.	N <16.	Y 16.

Table C-16. Lead; µg Pb/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<1.	3.	9.
Coal from Mines:			
1	<1.	N 5.	N <1.
2	<1.	N 8.	N 17.
3	<1.	N <1.	N <1.
4	<1.	N <1.	Y 27.

Table C-17.   Lithium; µg Li/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	2.	3.	5.
Coal from Mines:			
1	Y 15.	Y 40.	N 5.
2	Y 19.	Y 48.	Y 12.
3	Y 16.	Y 36.	Y 14.
4	Y 19.	Y 41.	Y 12.

Table C-18.   Magnesium; mg Mg/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	48.	267.	109.
Coal from Mines:			
1	59.	249.	121.
2	60.	241.	129.
3	70.	243.	123.
4	86.	253.	19.

Table C-19.   Manganese; mg Mn/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<0.01	0.25	0.50
Coal from Mines:			
1	Y 0.69	Y 0.72	Y 0.54
2	Y 0.09	Y 0.19	Y 0.29
3	Y 0.26	Y 0.23	Y 0.48
4	Y 0.26	Y 0.21	Y 0.48

Table C-20.   Mercury; µg Hg/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	6.	7.	5.
Coal from Mines:			
1	3.	7.	5.
2	2.	6.	4.
3	3.	7.	5.
4	1.	6.	6.

Table C-21.   Molybdenum; µg Mo/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	13.	14.	56.
Coal from Mines:			
1	Y 37.	Y 31.	N 52.
2	Y 34.	Y 53.	Y 86.
3	Y 29.	Y 36.	N 65.
4	Y 51.	Y 27.	N 49.

Table C-22.   Nickel; µg Ni/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<14.	a	a
Coal from Mines:			
1	<14.	a	a
2	<14.	a	a
3	<14.	a	a
4	<14.	a	a

[a]The nickel hollow cathode lamp failed and was backordered. Analyses could not be completed.

Table C-23.   Nitrate; mg N/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<0.04	0.50	1.03
Coal from Mines:			
1	0.09	0.12	Y <0.04
2	0.07	0.16	Y 0.33
3	0.10	0.29	Y <0.04
4	0.08	0.10	Y 0.04

Table C-24.   Nitrite; µg N/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	3.	5.	6.
Coal from Mines:			
1	3.	2.	Y 3.
2	2.	6.	Y 78.
3	2.	10.	Y 2.
4	<2.	3.	Y 3.

Table C-25. Organic carbon; mg C/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<1.	2.	1.
Coal from Mines:			
1	Y 30.	Y 29.	Y 24.
2	Y 7.	Y 7.	Y 12.
3	Y 4.	N 3.	Y 5.
4	Y 8.	Y 7.	Y 7.

Table C-29. Potassium; mg K/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	4.	19.	102.
Coal from Mines:			
1	Y 16.	Y 33.	Y 116.
2	Y 7.	Y 15.	Y 68.
3	Y 9.	Y 17.	Y 82.
4	Y 9.	Y 15.	Y 75.

Table C-26. pH; pH units.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	7.6	8.3	7.8
Coal from Mines:			
1	7.7	8.1	8.2
2	8.0	8.2	8.2
3	7.9	8.3	8.1
4	8.0	8.3	8.0

Table C-30 Selenium; µg Se/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	<1.	<1.	<2.
Coal from Mines:			
1	<1.	<1.	<2.
2	<1.	3.	5.
3	<1.	1.	<2.
4	<1.	<1.	<2.

Table C-27. Phosphate, ortho-; mg P/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	0.71	0.72	0.98
Coal from Mines:			
1	0.01	<0.01	Y <0.01
2	0.01	0.04	Y 0.01
3	0.01	0.05	Y <0.01
4	0.02	0.01	Y <0.01

Table C-31. Silica; mg SiO_2/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	11.	22.	35.
Coal from Mines:			
1	Y 53.	8.	Y 5.
2	N 11.	12.	Y 10.
3	Y 13.	16.	Y 7.
4	Y 14.	17.	Y 12.

Table C-28. Phosphorus, total; mg P/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	a	0.72	0.98
Coal from Mines:			
1	a	0.12	Y 0.09
2	a	0.04	Y 0.04
3	a	0.05	Y 0.06
4	a	0.05	Y 0.03

Table C-32. Silver; µg Ag/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	7.	20.	61.
Coal from Mines:			
1	N 8.	N 17.	N 54.
2	Y 10.	Y 33.	N 72.
3	N 6.	N 17.	N 54.
4	N 9.	Y 28.	Y 47.

[a] Total phosphorus was not run on the samples from slurry 1.

Table C-33. Sodium; mg Na/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	461.	613.	3400.
Coal from Mines:			
1	Y 512.	Y 676.	N 3320.
2	Y 707.	Y 873.	N 3680.
3	N 483.	Y 697.	N 3400.
4	Y 406.	N 606.	Y 3100.

Table C-36. Total dissolved solids.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	2220.	4640.	13,200
Coal from Mines:			
1	2430.	4380.	Y 12,900
2	2920.	5100.	Y 14,100
3	2430.	4500.	Y 13,000
4	2360.	4380.	Y 12,800

Table C-34. Strontium; mg Sr/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	0.07	0.78	0.30
Coal from Mines:			
1	Y 0.43	N 0.85	Y 0.62
2	Y 8.28	Y 10.10	Y 9.00
3	Y 1.71	Y 2.41	Y 2.36
4	Y 1.84	Y 3.05	Y 2.91

Table C-37. Zinc; μg Zn/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	16.	17.	38.
Coal from Mines:			
1	Y 7.	Y <4.	Y <4.
2	Y 9.	N 13.	Y 5.
3	N 15.	N 14.	Y 6.
4	Y 23.	Y 10.	Y 15.

Table C-35. Sulfate; mg SO_4/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport Media	700.	2740.	2740.
Coal from Mines:			
1	Y 780.	N 3040.	Y 3070.
2	Y 1030.	N 3320.	Y 3570.
3	Y 790.	N 2380.	Y 3080.
4	Y 820.	N 2950.	Y 3040.

APPENDIX D

RESULTS OF DUNCAN'S MULTIPLE RANGE STATISTICAL ANALYSES

In the following tables, the Duncan's multiple range analyses of the slurried and unslurried filtered transport media for each salinity level rank the samples from the lowest concentration at the top to the highest concentration at the bottom. The slurry number (1, 2 or 3) is listed in the middle column. Samples in any group which are not significantly different from each other are connected by a vertical line of asterisks to the right of the ranking list and slurry number. For each slurry and each parameter, the initial value of the saline transport medium is compared to the final value after being in contact with coal from each of four mines. If a significant absorption trend is observed in all four coal samples (i.e. orthophosphate), the saline transport medium will appear at the bottom of the listing with an asterisk not paired with any others. When all four coal samples exhibit a significant leaching trend (i.e. strontium, boron) the saline transport medium will be placed at the top of the listing. In some instances, the sample appearing at the top of the listing is not accompanied by an asterisk. This simply indicates that this sample is largely and significantly different from all other samples evaluated on that run of the Duncan's multiple range test.

Table D-1. Alkalinity, CO_3.

Sample   Slurry No.

Sample	Slurry No.		
COAL MINE ONE	2		
SALINE TRANS MEDIA	2	*	
COAL MINE TWO	2		*
COAL MINE FOUR	2	*	
COAL MINE THREE	2	*	

Table D-2. Alkalinity, CO_3.

Sample   Slurry No.

Sample	Slurry No.		
COAL MINE FOUR	3		*
COAL MINE THREE	3	*	*
COAL MINE ONE	3	*	
COAL MINE TWO	3	*	
SALINE TRANS MEDIA	3	*	

Table D-3. Aluminum, Al.

Sample   Slurry No.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		*
COAL MINE THREE	1	*	*
COAL MINE TWO	1	*	*
COAL MINE FOUR	1	*	
COAL MINE ONE	1	*	

Table D-4. Aluminum, Al.

Sample   Slurry No.

Sample	Slurry No.		
COAL MINE ONE	2		
COAL MINE TWO	2		*
COAL MINE THREE	2	*	
SALINE TRANS MEDIA	2	*	
COAL MINE FOUR	2	*	

Table D-5. Aluminum, Al.

Sample   Slurry No.

Sample	Slurry No.		
COAL MINE ONE	3		
COAL MINE THREE	3	*	
COAL MINE TWO	3	*	
SALINE TRANS MEDIA	3	*	
COAL MINE FOUR	3	*	

Table D-6. Barium, Ba.

Sample   Slurry No.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE TWO	1	*	
COAL MINE ONE	1	*	
COAL MINE THREE	1	*	
COAL MINE FOUR	1	*	

Table D-7. Barium, Ba.

Sample   Slurry No.

Sample	Slurry No.		
SALINE TRANS MEDIA	2	*	
COAL MINE FOUR	2	*	
COAL MINE THREE	2	*	
COAL MINE TWO	2	*	
COAL MINE ONE	2	*	

Table D-8. Barium, Ba.

Sample   Slurry No.

Sample	Slurry No.		
COAL MINE THREE	3	*	
SALINE TRANS MEDIA	3	*	
COAL MINE TWO	3	*	
COAL MINE ONE	3	*	
COAL MINE FOUR	3	*	

Table D-9. Boron, B.

Sample   Slurry No.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE THREE	1		*
COAL MINE ONE	1		*
COAL MINE FOUR	1	*	
COAL MINE TWO	1	*	

Table D-10. Boron, B.

Sample   Slurry No.

Sample	Slurry No.		
SALINE TRANS MEDIA	2		
COAL MINE ONE	2		*
COAL MINE THREE	2		*
COAL MINE FOUR	2	*	
COAL MINE TWO	2	*	

Table D-11.   Boron, B.

Sample	Slurry No.	
SALINE TRANS MEDIA	3	
COAL MINE ONE	3	*
COAL MINE FOUR	3	*
COAL MINE TWO	3	*
COAL MINE THREE	3	*

Table D-12.   Calcium, Ca.

Sample	Slurry No.	
COAL MINE TWO	1	
COAL MINE THREE	1	*
COAL MINE ONE	1	*
SALINE TRANS MEDIA	1	*
COAL MINE FOUR	1	*

Table D-13.   Calcium, Ca.

Sample	Slurry No.	
COAL MINE ONE	2	*
COAL MINE TWO	2	*
COAL MINE THREE	2	*
COAL MINE FOUR	2	* *
SALINE TRANS MEDIA	2	*

Table D-14.   Calcium, Ca.

Sample	Slurry No.	
COAL MINE ONE	3	
COAL MINE THREE	3	*
COAL MINE TWO	3	*
SALINE TRANS MEDIA	3	*
COAL MINE FOUR	3	*

Table D-15.   Chloride, Cl.

Sample	Slurry No.	
SALINE TRANS MEDIA	1	*
COAL MINE FOUR	1	*
COAL MINE THREE	1	*
COAL MINE ONE	1	*
COAL MINE TWO	1	*

Table D-16.   Chloride, Cl.

Sample	Slurry No.	
SALINE TRANS MEDIA	2	
COAL MINE FOUR	2	*
COAL MINE THREE	2	*
COAL MINE ONE	2	*
COAL MINE TWO	2	*

Table D-17.   Chloride, Cl.

Sample	Slurry No.	
COAL MINE THREE	3	*
COAL MINE ONE	3	*
SALINE TRANS MEDIA	3	*
COAL MINE TWO	3	*
COAL MINE FOUR	3	*

Table D-18.   Cobalt, Co.

Sample	Slurry No.	
COAL MINE THREE	2	*
COAL MINE FOUR	2	*
SALINE TRANS MEDIA	2	*
COAL MINE ONE	2	*
COAL MINE TWO	2	*

Table D-19.   Cobalt, Co.

Sample	Slurry No.	
COAL MINE ONE	3	*
COAL MINE TWO	3	*
SALINE TRANS MEDIA	3	*
COAL MINE FOUR	3	*
COAL MINE THREE	3	*

Table D-20.   Copper, Cu.

Sample	Slurry No.	
SALINE TRANS MEDIA	1	*
COAL MINE ONE	1	* *
COAL MINE THREE	1	* *
COAL MINE TWO	1	* *
COAL MINE FOUR	1	*

Table D-21. Copper, Cu.

Sample	Slurry No.		
COAL MINE THREE	2	*	
COAL MINE FOUR	2	*	
SALINE TRANS MEDIA	2	*	*
COAL MINE ONE	2	*	*
COAL MINE TWO	2	*	

Table D-22. Copper, Cu.

Sample	Slurry No.		
COAL MINE THREE	3	*	
COAL MINE TWO	3	*	*
COAL MINE ONE	3	*	*
COAL MINE FOUR	3	*	
SALINE TRANS MEDIA	3		

Table D-23. Fluoride, F.

Sample	Slurry No.		
COAL MINE FOUR	3		
COAL MINE THREE	3	*	
COAL MINE TWO	3	*	
COAL MINE ONE	3	*	
SALINE TRANS MEDIA	3	*	

Table D-24. Iron, Fe.

Sample	Slurry No.		
COAL MINE THREE	1	*	
COAL MINE TWO	1	*	
SALINE TRANS MEDIA	1	*	
COAL MINE FOUR	1	*	
COAL MINE ONE	1	*	

Table D-25. Iron, Fe.

Sample	Slurry No.		
SALINE TRANS MEDIA	2	*	
COAL MINE TWO	2	*	*
COAL MINE FOUR	2	*	*
COAL MINE THREE	2	*	
COAL MINE ONE	2	*	

Table D-26. Iron, Fe.

Sample	Slurry No.		
SALINE TRANS MEDIA	3		
COAL MINE FOUR	3		*
COAL MINE TWO	3	*	
COAL MINE ONE	3	*	
COAL MINE THREE	3	*	

Table D-27. Lead, Pb.

Sample	Slurry No.		
COAL MINE THREE	2	*	
COAL MINE FOUR	2	*	
SALINE TRANS MEDIA	2	*	*
COAL MINE ONE	2	*	*
COAL MINE TWO	2	*	

Table D-28. Lead, Pb.

Sample	Slurry No.		
COAL MINE THREE	3	*	
COAL MINE ONE	3	*	
SALINE TRANS MEDIA	3	*	*
COAL MINE TWO	3	*	*
COAL MINE FOUR	3	*	

Table D-29. Lithium, Li.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE ONE	1	*	
COAL MINE THREE	1	*	
COAL MINE TWO	1	*	
COAL MINE FOUR	1	*	

Table D-30. Lithium, Li.

Sample	Slurry No.		
SALINE TRANS MEDIA	2		
COAL MINE THREE	2	*	
COAL MINE ONE	2	*	
COAL MINE FOUR	2	*	
COAL MINE TWO	2	*	

Table D-31.   Lithium, Li.

Sample	Slurry No.	
COAL MINE ONE	3	*
SALINE TRANS MEDIA	3	*
COAL MINE TWO	3	*
COAL MINE FOUR	3	*
COAL MINE THREE	3	*

Table D-32.   Manganese, Mn.

Sample	Slurry No.	
SALINE TRANS MEDIA	1	
COAL MINE TWO	1	*
COAL MINE FOUR	1	*
COAL MINE THREE	1	*
COAL MINE ONE	1	*

Table D-33.   Manganese, Mn.

Sample	Slurry No.	
COAL MINE TWO	2	
COAL MINE FOUR	2	*
COAL MINE THREE	2	*
SALINE TRANS MEDIA	2	*
COAL MINE ONE	2	*

Table D-34.   Manganese, Mn.

Sample	Slurry No.	
COAL MINE TWO	3	
COAL MINE FOUR	3	*
COAL MINE THREE	3	*
SALINE TRANS MEDIA	3	*
COAL MINE ONE	3	*

Table D-35.   Molybdenum, Mo.

Sample	Slurry No.	
SALINE TRANS MEDIA	1	
COAL MINE THREE	1	*
COAL MINE TWO	1	*
COAL MINE ONE	1	*
COAL MINE FOUR	1	*

Table D-36.   Molybdenum, Mo.

Sample	Slurry No.		
SALINE TRANS MEDIA	2		
COAL MINE FOUR	2	*	
COAL MINE ONE	2	*	*
COAL MINE THREE	2	*	
COAL MINE TWO	2	*	

Table D-37.   Molybdenum, Mo.

Sample	Slurry No.		
COAL MINE FOUR	3	*	
COAL MINE ONE	3	*	*
SALINE TRANS MEDIA	3	*	*
COAL MINE THREE	3	*	
COAL MINE TWO	3	*	

Table D-38.   Nitrate, N.

Sample	Slurry No.	
COAL MINE THREE	3	*
COAL MINE ONE	3	*
COAL MINE FOUR	3	*
COAL MINE TWO	3	*
SALINE TRANS MEDIA	3	*

Table D-39.   Nitrite, N.

Sample	Slurry No.	
COAL MINE THREE	3	
COAL MINE FOUR	3	*
COAL MINE ONE	3	*
SALINE TRANS MEDIA	3	*
COAL MINE TWO	3	*

Table D-40.   Organic carbon, C.

Sample	Slurry No.	
SALINE TRANS MEDIA	1	
COAL MINE THREE	1	*
COAL MINE TWO	1	*
COAL MINE FOUR	1	*
COAL MINE ONE	1	*

Table D-41. Organic carbon, C.

Sample	Slurry No.				
SALINE TRANS MEDIA	2			*	
COAL MINE THREE	2			*	
COAL MINE TWO	2		*		
COAL MINE FOUR	2		*		
COAL MINE ONE	2	*			

Table D-42. Organic carbon, C

Sample	Slurry No.				
SALINE TRANS MEDIA	3				
COAL MINE THREE	3			*	
COAL MINE FOUR	3			*	
COAL MINE TWO	3		*		
COAL MINE ONE	3	*			

Table D-43. Phosphate, ortho-, P.

Sample	Slurry No.		
COAL MINE ONE	3	*	
COAL MINE THREE	3	*	
COAL MINE FOUR	3	*	
COAL MINE TWO	3	*	
SALINE TRANS MEDIA	3	*	

Table D-44. Phosphorus, total, P.

Sample	Slurry No.			
COAL MINE FOUR	3			*
COAL MINE TWO	3		*	*
COAL MINE THREE	3		*	
COAL MINE ONE	3	*		
SALINE TRANS MEDIA	3	*		

Table D-45. Potassium, K.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE TWO	1		*
COAL MINE THREE	1	*	
COAL MINE FOUR	1	*	
COAL MINE ONE	1	*	

Table D-46. Potassium, K.

Sample	Slurry No.				
COAL MINE TWO	2			*	
COAL MINE FOUR	2			*	
COAL MINE THREE	2		*		
SALINE TRANS MEDIA	2		*		
COAL MINE ONE	2	*			

Table D-47. Potassium, K.

Sample	Slurry No.			
COAL MINE TWO	3			
COAL MINE FOUR	3			*
COAL MINE THREE	3		*	
SALINE TRANS MEDIA	3		*	
COAL MINE ONE	3	*		

Table D-48. Silica, SiO_2.

Sample	Slurry No.			
COAL MINE TWO	1			*
SALINE TRANS MEDIA	1			*
COAL MINE THREE	1		*	
COAL MINE FOUR	1	*		
COAL MINE ONE	1	*		

Table D-49. Silica, SiO_2.

Sample	Slurry No.			
COAL MINE ONE	3			
COAL MINE THREE	3			*
COAL MINE TWO	3		*	
COAL MINE FOUR	3	*		
SALINE TRANS MEDIA	3	*		

Table D-50. Silver, Ag.

Sample	Slurry No.			
COAL MINE THREE	1		*	
SALINE TRANS MEDIA	1		*	*
COAL MINE ONE	1	*	*	*
COAL MINE FOUR	1	*	*	
COAL MINE TWO	1	*		

Table D-51. Silver, Ag.

Sample	Slurry No.		
COAL MINE THREE	2		*
COAL MINE ONE	2		*
SALINE TRANS MEDIA	2		*
COAL MINE FOUR	2	*	
COAL MINE TWO	2	*	

Table D-52. Silver, Ag.

Sample	Slurry No.		
COAL MINE FOUR	3		*
COAL MINE THREE	3	*	*
COAL MINE ONE	3	*	*
SALINE TRANS MEDIA	3	*	*
COAL MINE TWO	3	*	

Table D-53. Sodium, Na.

Sample	Slurry No.		
COAL MINE FOUR	1		
SALINE TRANS MEDIA	1		*
COAL MINE THREE	1	*	*
COAL MINE ONE	1		*
COAL MINE TWO	1	*	

Table D-54. Sodium, Na.

Sample	Slurry No.		
COAL MINE FOUR	2		*
SALINE TRANS MEDIA	2		*
COAL MINE ONE	2	*	
COAL MINE THREE	2	*	
COAL MINE TWO	2	*	

Table D-55. Sodium, Na.

Sample	Slurry No.		
COAL MINE FOUR	3		*
COAL MINE ONE	3	*	*
SALINE TRANS MEDIA	3	*	*
COAL MINE THREE	3	*	*
COAL MINE TWO	3	*	

Table D-56. Strontium, Sr.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE ONE	1		*
COAL MINE THREE	1		*
COAL MINE FOUR	1	*	
COAL MINE TWO	1	*	

Table D-57. Strontium, Sr.

Sample	Slurry No.		
SALINE TRANS MEDIA	2		*
COAL MINE ONE	2		*
COAL MINE THREE	2		*
COAL MINE FOUR	2	*	
COAL MINE TWO	2	*	

Table D-58. Strontium, Sr.

Sample	Slurry No.		
SALINE TRANS MEDIA	3		
COAL MINE ONE	3		*
COAL MINE THREE	3		*
COAL MINE FOUR	3	*	
COAL MINE TWO	3	*	

Table D-59. Sulfate, SO_4.

Sample	Slurry No.		
SALINE TRANS MEDIA	1		
COAL MINE ONE	1		*
COAL MINE THREE	1		*
COAL MINE FOUR	1	*	
COAL MINE TWO	1	*	

Table D-60. Sulfate, SO_4.

Sample	Slurry No.		
COAL MINE THREE	2		*
SALINE TRANS MEDIA	2	*	*
COAL MINE FOUR	2	*	*
COAL MINE ONE	2	*	
COAL MINE TWO	2	*	

Table D-61. Sulfate, SO_4.

Sample   Slurry No.

```
SALINE TRANS MEDIA 3
COAL MINE FOUR     3      *
COAL MINE ONE      3      *
COAL MINE THREE    3      *
COAL MINE TWO      3    *
```

Table D-62. Total dissolved solids, TDS.

Sample   Slurry No.

```
COAL MINE FOUR     3            *
COAL MINE ONE      3        *  *
COAL MINE THREE    3          *
SALINE TRANS MEDIA 3      *
COAL MINE TWO      3    *
```

Table D-63. Zinc, Zn.

Sample   Slurry No.

```
COAL MINE ONE        1          *
COAL MINE TWO        1            *
COAL MINE THREE      1        *
SALINE TRANS MEDIA 1         *
COAL MINE FOUR       1      *
```

Table D-64. Zinc, Zn.

Sample   Slurry No.

```
COAL MINE ONE        2
COAL MINE FOUR       2            *
COAL MINE TWO        2        *  *
COAL MINE THREE      2        *  *
SALINE TRANS MEDIA 2        *
```

Table D-65. Zinc, Zn.

Sample   Slurry No.

```
COAL MINE ONE        3            *
COAL MINE TWO        3        *  *
COAL MINE THREE      3          *
COAL MINE FOUR       3      *
SALINE TRANS MEDIA 3    *
```