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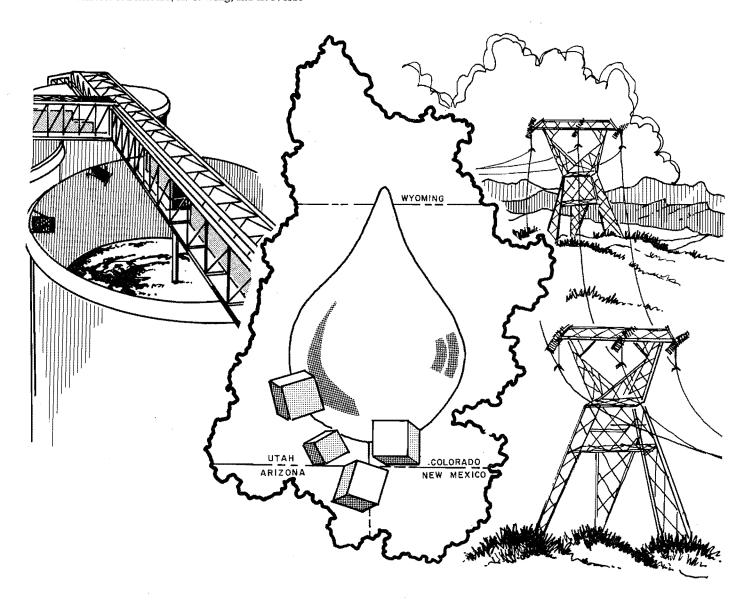
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USE OF SALINE WATER IN ENERGY DEVELOPMENT

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



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

The work on which this report is based was supported with funds provided by the State of Utah and by the U.S. Department of the Interior, Office of Water Research and Technology under P.L. 92-500, Project No. C80322S, Grant No. 14-34-0001-8553, Investigation Period September 1, 1978, to June 1, 1980.

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College of Engineering
Utah State University
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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

The work on which this report is based was supported with funds provided by the State of Utah and by the U.S. Department of the Interior, Office of Water Research and Technology under P.L. 92-500, Project C80322S, Grant No. 14-34-0001-8553, Investigation Period September 1, 1978, to June 1, 1980.

The principal investigators on this project were C. Earl Israelsen, Associate Professor of Civil and Environmental Engineering, Utah State University, and Hydrologist, Utah Water Research Laboratory; J. Clair Batty, Professor of Mechanical Engineering, Utah State University; V. Dean Adams, Research Associate Professor, Civil and Environmental Engineering, and the Utah Water Research Laboratory, Utah State University; Dennis B. George, Research Assistant Professor, Civil and Environmental Engineering, and the Utah Water Research Laboratory, Utah State University; Trevor C. Hughes, Associate Professor, Civil and Environmental Engineering and Utah Water Research Laboratory, Utah State University; and Alberta J. Seierstad, Research Scientist, Utah Water Research Laboratory. Other investigators were H. C. Wang and H. P. Kuo, graduate students who utilized data from this study for theses for partial fulfillment of requirements for MS degrees in Mechanical Engineering at Utah State University.

Special thanks are extended to the following: U.S. Geological Survey personnel in Salt Lake City, Utah; Cheyenne, Wyoming; and Denver, Colorado, for providing many of the water quality data used in the study; the Utah Geological and Mineral Survey, Salt Lake City, Utah, for energy resources maps and publications; Mr. Salvador Renteria of Water and Power Technologies, Inc., Salt Lake City, Utah, for his assistance in determining realistic costs of water treatment processes; Mr. Frank Davis, Utah Power and Light Company, Salt Lake City, Utah, for verbal and written help on matters pertaining to coal-fired power plant operation; Mr. Loren Kraigh, Tower Systems, Inc., Tacoma, Washington, for providing information relative to the Binary Cooling Tower (BCT) method of power plant cooling using saline water; and Resources Conservation Company, Seattle, Washington, for drawings and information pertaining to brine concentrators. Many others contributed also by making suggestions, reviewing manuscripts, and providing encouragement during the study. To all of these the writers are grateful, but the writers alone are responsible for the content of the report, the interpretation of the various contributions, and the conclusions drawn.

The writers are also indebted to UWRL editor, Donna Falkenborg; secretaries, Barbara South, Betty Hansen, and Annette Brunson; to senior graphics technician, Arthur L. Rivers; and draftspersons Joseph F. Gardner and Susan Marsh.

CONVERSION FACTORS

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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 x 105 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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GENERAL INTRODUCTION

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.

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

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

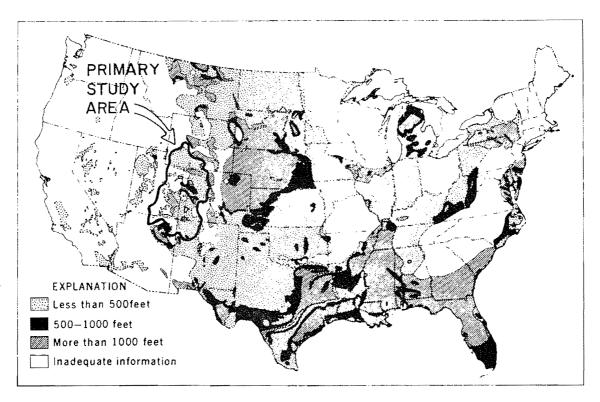


Figure 1. Depth to saline water (more than 1000~mg/1 dissolved solids) below land surface (adapted from Feth et al. 1965).

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.

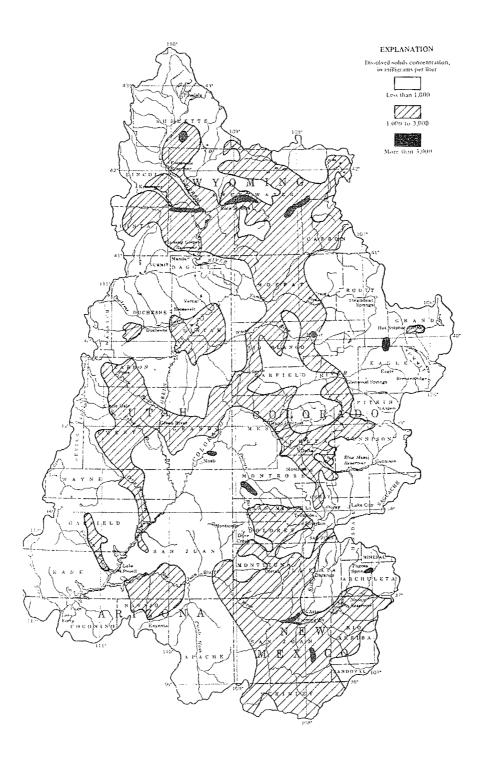


Figure 2. Locations of underground water of different qualities (Hagen et al. 1971, p. 84).

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 tually 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.

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).

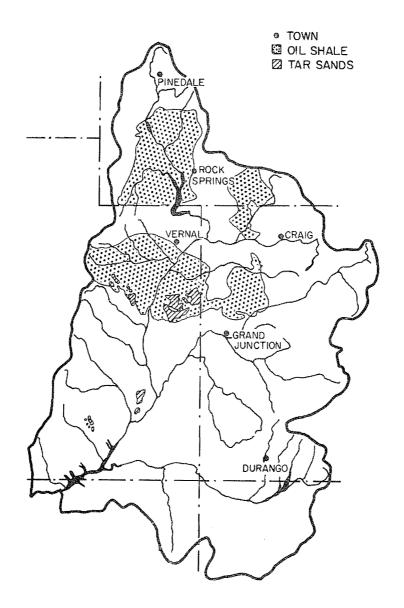


Figure 5. Oil shale and tar sands deposits in the Upper Colorado River Basin (Colorado River Regional Assessment Study, Utah Water Research Laboratory, Utah State University, 1975).

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/l 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).

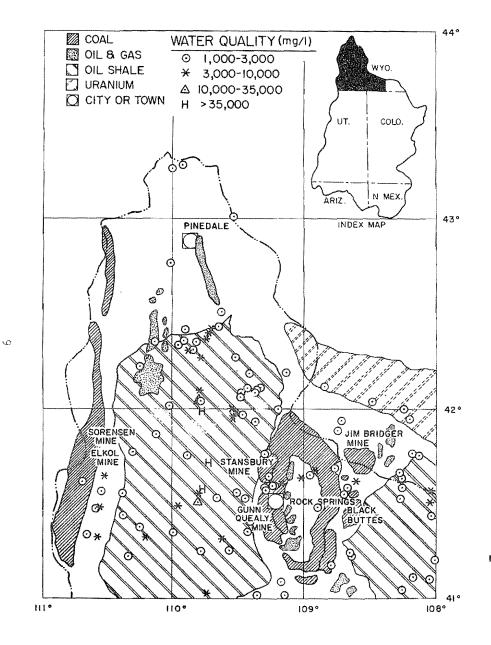
At least two serious deficiencies exist in the data shown: 1) Very little information is available concerning the depths from which the samples came. Some of the wells are 10,000 feet deep, and the water quality shown may be of water near the surface, very deep, or a composite of the entire geologic 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 $R_{\rm f}$ 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 $(Rw = R_{\rm o}/R_{\rm f})$. 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:

- l. 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



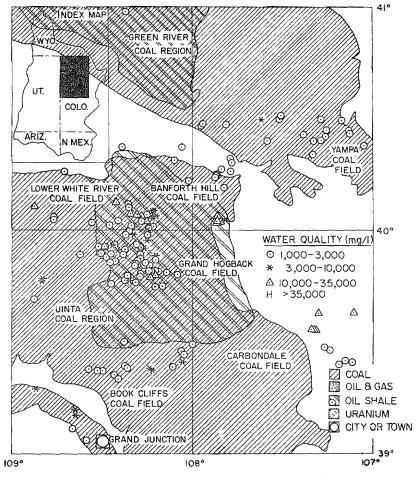


Figure 6. Water quality sampling sites near energy deposits (Part I).

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

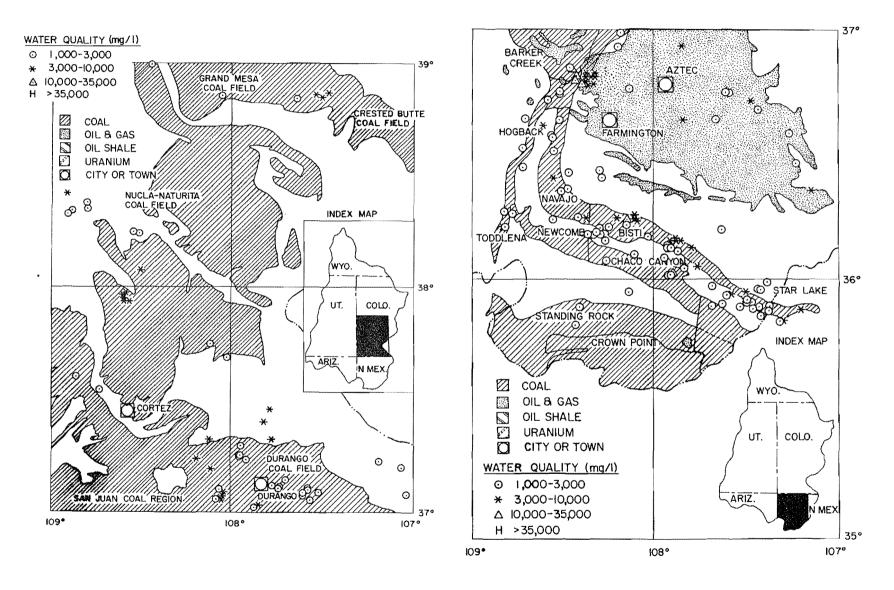


Figure 8. Water quality sampling sites near energy deposits (Part III).

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

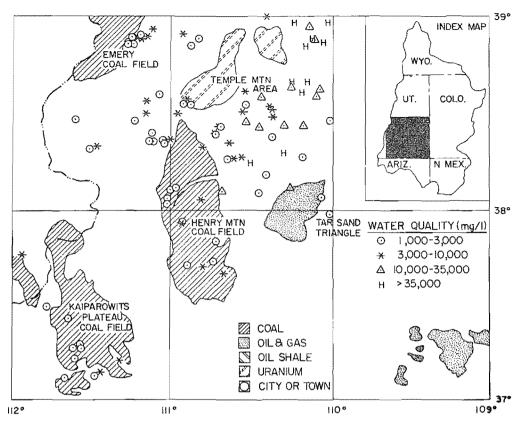


Figure 10. Water quality sampling sites near energy deposits (Part V).

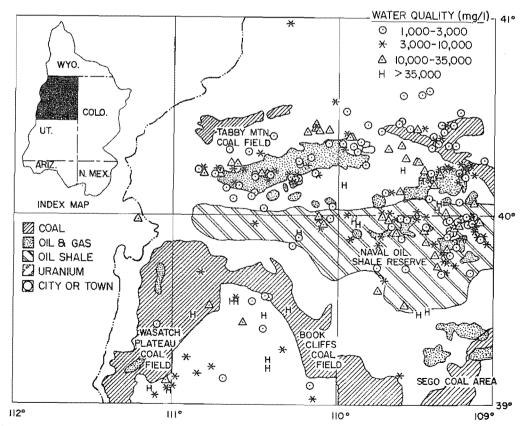


Figure 11. Water quality sampling sites near energy deposits (Part VI).

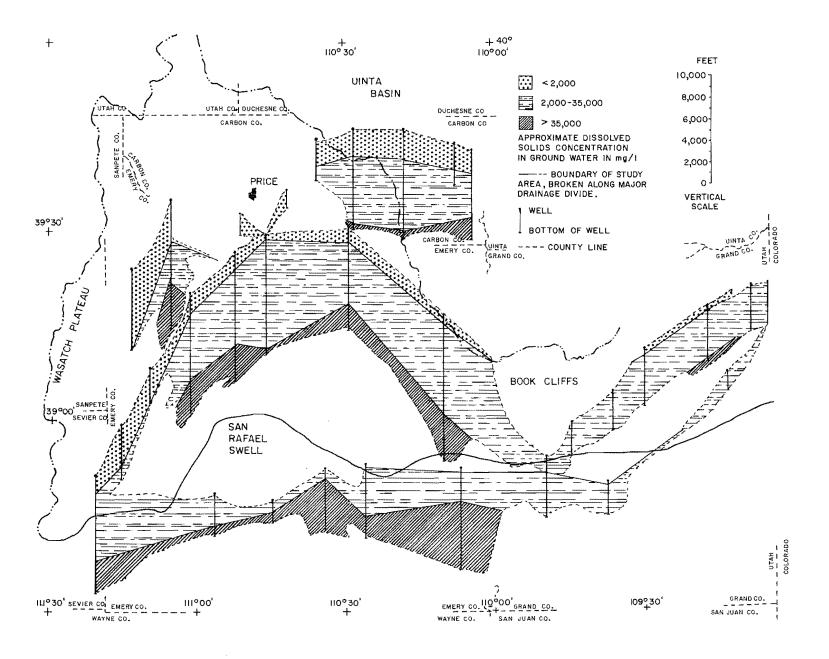


Figure 12. Three dimensional map section of area near Price, Utah, showing general increase in groundwater salinity with depth (U.S.G.S. Open File Report 79-988 Hydrologic Recon. of the Wasatch Plateau-Book Cliffs Coal Fields Area, Utah, by K. M. Waddel et al. 1979).

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
011 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	l ton	15 - 26 x 10 ⁶
Oil	l barrel	5.8 x 106
Electrical Output	1 kwhr	3412
Natural Gas	1 ft^3	1032
Synthetic Gas	l 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.

<u>Conclusions</u>

- 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.

- 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.

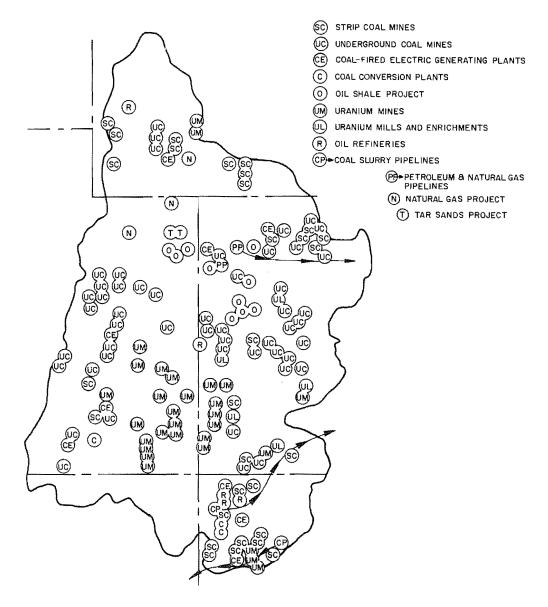


Figure 13. Future energy-related projects in the Upper Colorado River Basin (Rich 1978).

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

	References:		1)		2)	(3)	(4)	Other	Total
Energy Development	Process	Min.	Max.	Min.	Max.	Aver.	Aver.	Aver.	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.
Dil Production							2.2		2.2
Gas Production							1.2		1.2
Dil Refining				6.7	6.7		5.5		6.1
Dil Shale	Paraho D.	19	19						
	Paraho ID.	31	31						
	Tosco II	31	31					(5)	
	Average	27	27	19	29	25	20	80	35.2
far Sands	Arizona							(6)	
	Fuel Co.	15.5 25 72 158 37 79 15.3 24 55 118 35 83 13.5 19.5 31 200 46 72 7.5 12.5 6.7 6.7 6.7 5.5 19 19 31 31 31 31 27 27 19 29 25 20	3.6						
	Fairbirm							3.4	
	Average						2.4	3.5	3.0
Jranium				14	14				14.
Power Plant	Geothermal			527	527				527.
ower 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 Increas in Market Price of Product		
Coal Mining	85 x 10 ⁻⁶ ac-ft/to 982 x 10 ⁻⁶ ac-ft/to 140 x 10 ⁻⁶ ac-ft/10 1100 x 10 ⁻⁶ ac-ft/bb 625 x 10 ⁻⁶ ac-ft/bb 53 x 10 ⁻⁶ ac-ft/bb	n of coal	\$25/ton	0.17%		
Coal Slurry	982 x 10 ⁻⁶ ac-ft/to	n of coal	\$25/ton	1.9 %		
Coal Gasification	$140 \times 10^{-6} \text{ ac-ft/}10$	00 SFC	\$ 3/1000 SFC	2.3 %		
Coal Liquefaction	1100 x 10 ⁻⁶ ac-ft/bb	1	\$30/ьь1	1.8 %		
Oil Shale	625 x 10 ⁻⁶ ac-ft/bb	1	\$30/ЪЪ1	1.0 %		
Tar Sands	53 x 10 ⁻⁶ ac-ft/bb	1	\$30/ъъ1	0.09%		
Fossil Fuel Power						
Plant	$1.6 \times 10^{-6} \text{ ac-ft/kW}$	• 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 multibillion 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. 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:

- l. 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 philosophy, 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 insolation, 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 concentration 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.

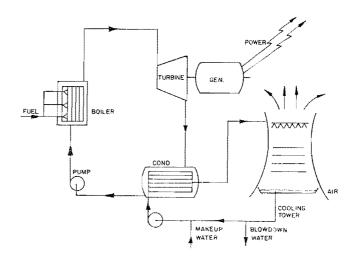


Figure 14. Rankine cycle power plant.

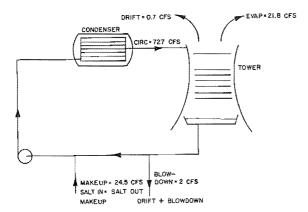


Figure 15. Typical water flow rates in the conventional cooling water loop of a 1000 MWe power plant.

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/1	Sample 2 TDS = 3000 to 10,000 mg/1	Sample 3 TDS = > 10,000 mg/1			
A1	0.25	0.72	1.14			
В	0.1	0.5	0.7			
Ca	156.	343.	312.			
CO3	117.	361.	550.			
C1	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			
NO3-N	<0.04	0.50	1.02			
O-PO4	0.71	0.72	0.98			
ĸ	4.	20.	102.			
SiO ₂	11.	22.	35.			
Na	458.	620.	4300.			
SO ₄	700.	2740.	2770.			
TDS	2220.	4640.	13180.			
pll	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,

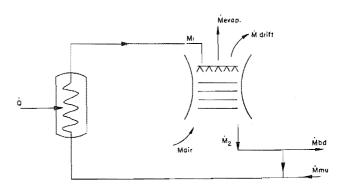


Figure 16. Basic elements of the cooling tower.

where

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

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

 M_1 = mass flow rate of water entering the tower.

M2 = mass flow rate of water leaving the tower.

hf1 = specific enthalpy of circulating
water entering the tower.

hf2 = 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:

$$\dot{M}_{\text{evap}} = 0.01 \,\dot{M}_1 \,(T_1 - T_2)/10 = 0.001 \,\dot{M}_1 (T_1 - T_2) \,... \,(3)$$

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

$$\dot{M}_{drift} = 0.001 \dot{M}_{1}$$
 (4)

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

C_{mu} = salt concentration of makeup

where

Ccir = salt concentration of circulating water.

 $C_{\mbox{bd}}$ = salt concentration of blowdown water.

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

Water Leaving the Tower =
$$\begin{bmatrix} Water \\ Entering \\ the \\ Tower \end{bmatrix}$$
 - $\begin{bmatrix} Drift \\ Loss \end{bmatrix}$ - $\begin{bmatrix} Evaporation \\ Loss \end{bmatrix}$

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/l, increasing the TDS of the makeup water from 1,000 mg/l to 2,000 mg/l 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/l to 7,000 mg/l 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

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

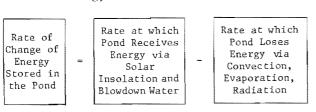
Circulating Salinity (mg/l)	8,00	00	9,0	000	10,0	000	11,0	00	12,0	000	15,0	000	18,0	000	21,0	000	24,0	000	27,0	000
1000 ac-ft yr Makeup Salinity (mg/1)	Blow- down	Make- up																		
1,000	1.73	18.06	1.45	17.78	1.23	17.56	1.05	17.38	0.91	17.24	0.60	16.92	0.40	16.72	0.26	16.57	0.16	16.46	0.08	16.37
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		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		126.43	54.78	71.11	36.34	52.67			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	_	-		284.44	89.01	105.34		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

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



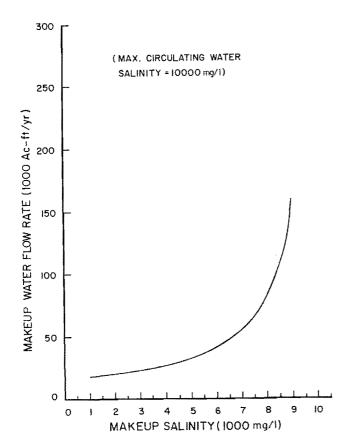


Figure 17. The impact of makeup salinity increases on the annual volume of makeup water necessary for cooling a 1000 MWe power plant under option 1 conditions.

OI

$$d(\rho CDAT)/dt = \dot{Q}_{solar} + \dot{Q}_{blowdown} - (\dot{Q}_{conv} + \dot{Q}_{evap} + \dot{Q}_{rad})$$
where . . . (8)

 ρ = brine density taken as 80.04 lb/ft³ (1282.1 kg/m³)

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.

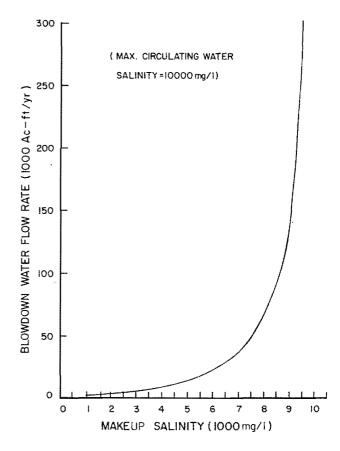


Figure 18. The impact of makeup salinity increases on the annual volume of blowdown water necessary for cooling a 1000 MWe power plant under option 1 conditions.

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

$$Q_{blowdown} = M_{bd}C_{bd} (T_{bd} - T) . . (9)$$
where

Mbd = 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

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

where

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

$$h = 1 + 0.3V (Btu/hr - ft^2 - {}^{0}F)$$
(Pancharatnam 1972) . . . (11)

(V assumed to be 10 mph in this study)

 $T_{\mbox{air}}$ 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

$$T_{air} = (0.9 + 0.1 \sin (I\pi/12) T_{max}$$
 (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} . . . (13)

where

$$M_{evap} = K (P_b - P_v) A$$

and K = mass transport coefficient taken as

$$K = (1.9 + 0.476V) \times 10^{-3}$$
, with $V = 10$ mph
(Pancharatnam 1972) . . . (14)

giving $K = 6.66 \times 10-3 \text{ lb/hr} \cdot \text{ft}^2 \cdot \text{mmHg}$

 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 H2O are based on data from steam tables fitted to a fifth power polynomial as follows:

$$P_{g} = 0.0158T^{5} - 4.08T^{4} + 4.29T^{3} - 8.08T^{2} + 0.028T$$
$$- 0.0072 \cdot \cdot \cdot \cdot \cdot \cdot \cdot (15)$$

 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 H2O 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.

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

Q_{rad} is the net rate at which the pond reradiates energy back to the surroundings. According to Raphael (1962)

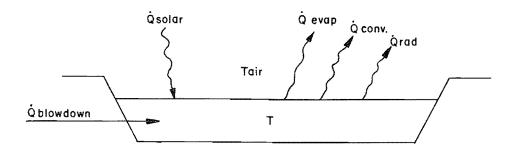


Figure 19. Cross-section of brine evaporation pond showing energy flows.

where σ is the Stefan-Boltzman constant, 0.1714 x 10-8 Btu/hr-ft² R⁴, 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 $% \left(1\right) =\left(1\right) +\left(1\right$

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

where

ρ = mass density of water, taken as 63 lbs/ft3

. Mbd = mass flow rate of blowdown water

Mprecip = rate at which precipitation enters pond. Those values are based on weather station observations and entered as average monthly values.

Mevap = 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:

l. 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.

$$A_{est} = \frac{Annual\ Volume\ of\ Blowdown}{Annual}$$

$$Evaporation\ - Annual$$

$$Depth Precipitation . . (18)$$

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

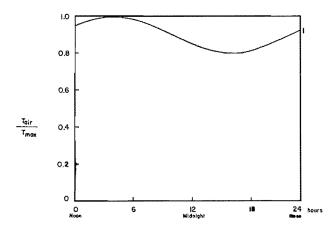


Figure 20. Typical 24 hour profile of air temperature.

- 3. Assume that the depth, D, may be treated as constant for any given $24\ \text{hour}$ 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:

$$A = \frac{\sum_{\text{year}} \dot{M}_{\text{blowdown}} \Delta t}{\sum_{\text{year}} \left(\frac{\dot{M}_{\text{evap}}}{A} - \frac{\dot{M}_{\text{precip}}}{A}\right) \Delta t}$$
(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. $\label{eq:table_problem}$

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:

- 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,
- 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/yd³

 land......\$0.02/ft² (\$870/acre)

 liner.......\$0.20/ft²

 piping......\$0.052/ft²

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.g	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/mon	th) 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 .

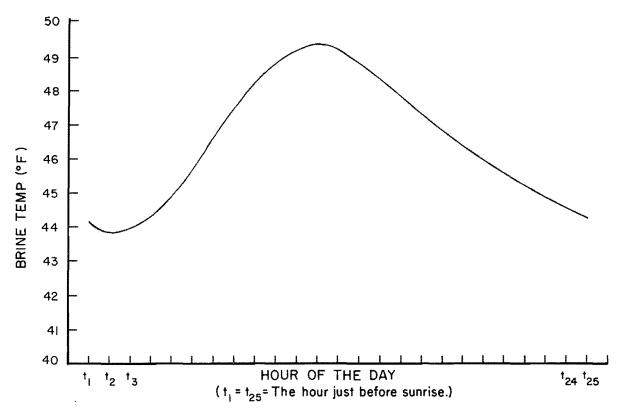


Figure 21. The predicted evaporation pond temperature pattern for a typical day in April of the average year.

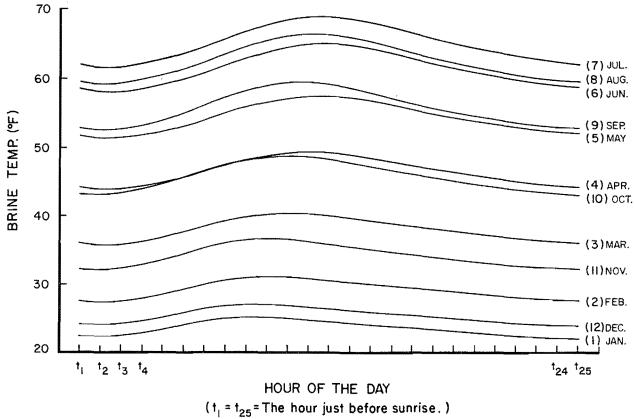


Figure 22. The predicted evaporation pond temperature pattern for a typical day in each month of the average year.

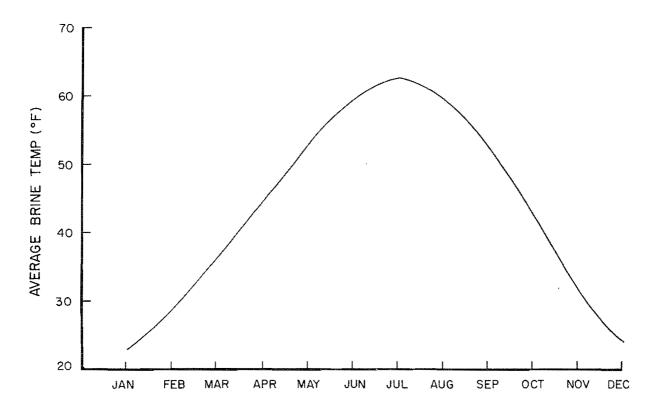


Figure 23. The predicted average daily temperature in brine evaporation pond for each month of an average year.

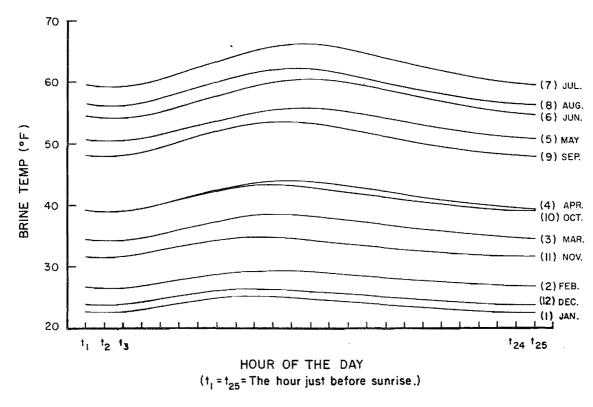


Figure 24. The predicted evaporation pond temperature pattern for a typical day in each month of the critical year (1941).

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

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

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

where

$$i = 0.10$$

 $n = 40$

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

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

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

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.

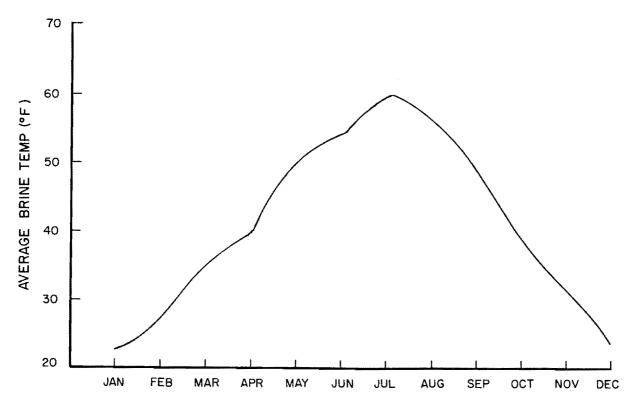


Figure 25. The predicted average daily temperature in the brine evaporation pond for the critical year (1941).

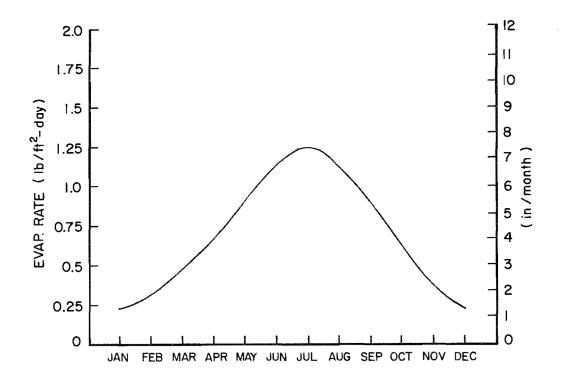


Figure 26. The predicted total month by month evaporation rate for an average year.

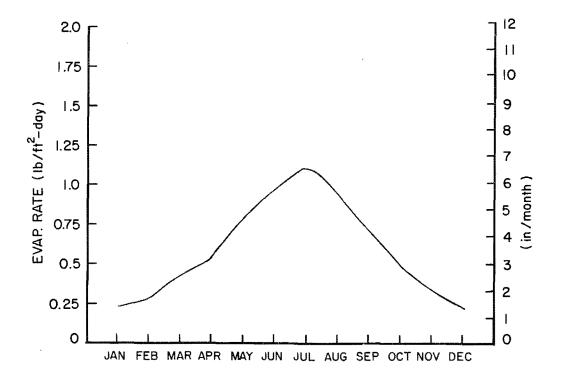


Figure 27. The predicted total month by month evaporation rate for the critical year (1941).

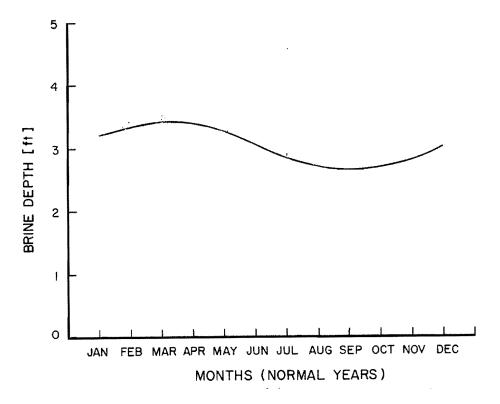


Figure 28. The predicted month by month brine depth for an average year.

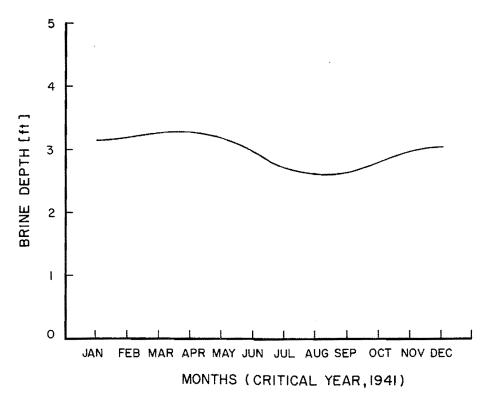


Figure 29. The predicted month by month brine depth for the critical year (1941).

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 $110^{\circ}F$. The principal treatment is the addition of lime (CaO) to facilitate the precipitation of Mg++ and Ca++ according to the following reactions:

$$Ca(HCO_3)_2 + Ca(OH)_2 \implies 2 CaCO_3 + + 2 H_2O$$
 . (22)

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

In addition silica coprecipitates with $Mg(OH)_2$ at the rate of about 1 gm SiO2 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
$$Ca_{feed} < 35 \text{ mg/1}$$
; $Ca_{product} = Ca_{feed}$ (24)

when
$$Ca_{feed} \ge 35 \,\text{mg/1}$$
; $Ca_{product} = \frac{35}{150} \,Ca_{feed}$ (25)

(2) when
$$Mg_{feed} < 60 \,mg/1$$
; $Mg_{product} = Mg_{feed}$ (26)

when
$$Mg_{feed} \ge 60 \text{ mg/1}$$
; $Mg_{product} = \frac{60}{100} Mg_{feed}$ (27)

(3) when
$$Sio_{2feed}^{2} < 19 \, mg/1$$
; $Sio_{2feed}^{2} = Sio_{2feed}^{2}$ (28)

when
$$SiO_{2feed} \ge 19 \text{ mg/1}$$
; $SiO_{2product} = \frac{7}{20} SiO_{2feed}$

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 \geq 35 mg/l, the amount of lime required to precipitate the Ca++ is

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

If the concentration of Mg++ in the feed water \geq 60 mg/l, the amount of lime required to precipitate the Mg++ is

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

so that the total lime required in $\ensuremath{\mathrm{mg}}/1$ of feed water is

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

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

where

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

The cost of lime is taken as \$0.089/1b.

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:

- 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

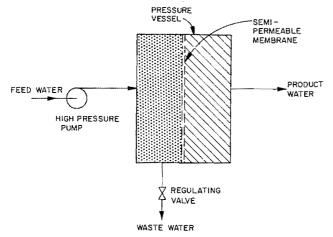


Figure 30. The basic notion of R.O. treatment.

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 x 10^{-3} , that is,

$$[Ca^{++}mol/liter]_{feed} \times [SO_4^{--}mol/liter]_{feed} \le lx10^{-3}$$

b) The concentration of ${\rm Si0_2}$ 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.

TDS of Feed Water

$$= \frac{\text{Flow Rate of Product Water}}{\text{Flow Rate of Feed Water}} . . . (35)$$

The concentration factor and the recovery factor are related as $% \left\{ 1,2,\ldots ,n\right\} =0$

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

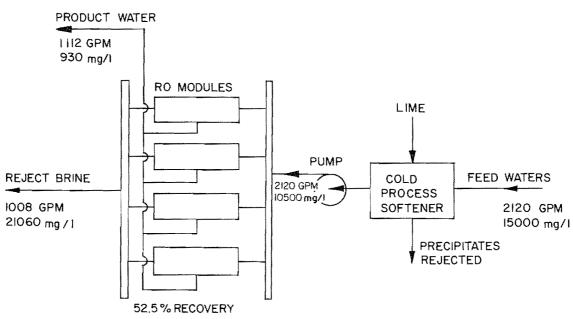


Figure 31. Typical performance characteristics of R.O. side stream circulating water treatment system for a plant utilizing 15,000 mg/l circulating water.

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++ Mg++ Na+ K+	4	96
Mg++	4	96
Na+	10	90
K +	10	90
P04	2	98
so ₄	4	96
C1	10	90
NO	15	85
SiÕ2	15	85

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

Step 1. Knowing the concentrations of Ca⁺⁺, S04⁻⁻, and Si02 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⁺⁺, S04⁻⁻, and Si02 in the R.O. feed water.

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

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

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

CF
$$\left[\text{Sio}_{2} \text{ mg/liter}\right]_{\text{feed}} = 150 \dots (38)$$

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

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

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

$$TDS_{product} = \sum_{i} [conc_{i}] [fraction transmitted_{i}]$$
 (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

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

$$M_{\text{project}} = M_{\text{feed}} \times RF$$
 (42)

Costs for the R.O. system are estimated in terms of capacity as $% \left\{ 1,2,\ldots ,2,\ldots \right\}$

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 H₂SO₄ was taken as \$0.056/1b.

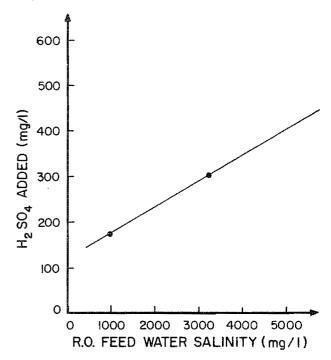


Figure 32. The quantity of H₂SO₄ required for pH control in a reverse osmosis system. (Courtesy Water and Power Technologies, Inc., Salt Lake City, Utah.)

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:

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:

2. Product salinity is 10 mg/1 $\dot{M}_{reject} = \dot{M}_{feed} = \dot{M}_{feed} = \dot{M}_{product} = \dot{M}_{product$

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
$$(10^6 \text{ $f/yr}) = 2.91 \text{ M}_{\text{feed}}^3$$

- $7.19 \text{ M}_{\text{feed}}^2 + 10.9 \text{ M}_{\text{feed}} + 0.38$. . . (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 $0.01/kW\cdot h$.

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.

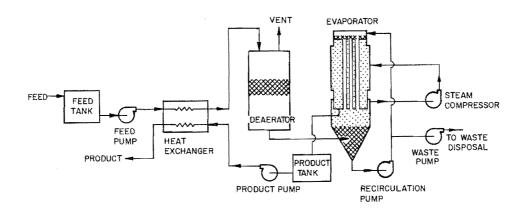


Figure 33. Brine concentration simplified system schematic. (Courtesy Resources Conservation Co., Seattle, Washington.)

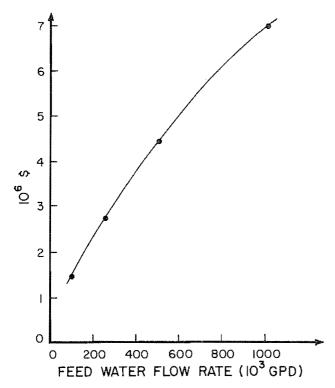


Figure 34. Capital cost of brine concentrator. (Based on data provided by Resources Conservation Co., Seattle, Washington.)

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.

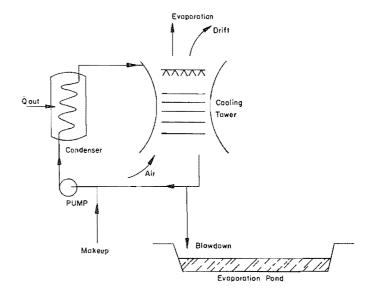


Figure 35. Simplified system schematic of option 1 in which no treatment other than biocide is applied.

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 SiO2. 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++ + SiO2 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.

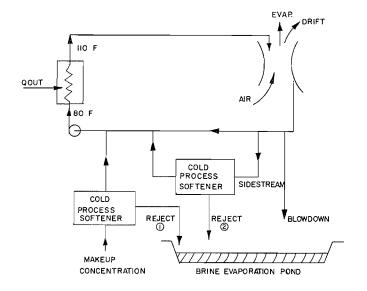
By utilizing conservation of mass equations for the water and each of the chemical constituents in the makeup water, it

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

Circulating Salinity (mg/1)	8,0	00	9,0	00	10,	000	11,0	000	12,0	000	15,0	000	18,0	900	21,0	000	24,0	900	27,0)00
Pond Area (acres) Makeup Salinity (mg/l)	Normal Year	Crití- cal Year	Normal Year	Criti- cal 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)	8,0	00	9,0	00	10,0	000	11,0	000	12,0	000	15,	000	18,6	000	21,0	000	24,0	00	27,0	00
10 ⁶ \$/yr Makeup Salinity (mg/1)	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal .	Max.	Normal	Max.	Normal	Мак.	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			12	20	9.3	15	7.3	12	6.0	9.6	5.1	
									18	29										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	7 5	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



OPTION 3 BIOCIDES EVAP. DRIFT άουτ ΔIR MCIRC PRODUCT PRODUCT② MSIDE COLD PROCESS BRINE CONCENTRATOR COLD PROCESS SOFTENER **M** REJECT **MREJECT** MREJECT **▼** BLOWDOWN MAKEUP BRINE EVAPORATION POND

Figure 36. Simplified schematic of water treatment option 2 in which Mg, Ca, and SiO₂ are controlled within specified limits.

Figure 37. Schematic of option 3 in which makeup water is softened and blowdown 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 concentration using reverse osmosis and brine concen-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 concentrator. 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 concentrator 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 emphasize 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 dramatically 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)	8,0	00	9,0	00	10,0	000	11,0	000	12,0	000	15,0	000	18,	000	21,0	00	24,0	00	27,	000
1000 ac-ft yr Makeup Salinity (mg/1)	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.

Circulating Salinity (mg/1)	8,0	000	9,0	00	10,0	000	11,0	000	12,0	000	15,	000	18,0	000	21,0	000	24,0	00	27,0	00
Pond Area (acres Makeup Salinity (mg/1)	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				5300			7700	3700	6500	2500	4500	1900	3400	1500	2700	1300	2300	1100	1900
7,000	12000	21000	8100	14000	6200	9400 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)	8,00	00	9,0	00	10,0	000	11,0	000	12,0	000	15,0	000	18,0	000	21,0	00	24,0	00	27,0	000
10 ⁶ \$/yr Makeup Salinity (mg/1)	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Norma1	Max.	Norma1	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.

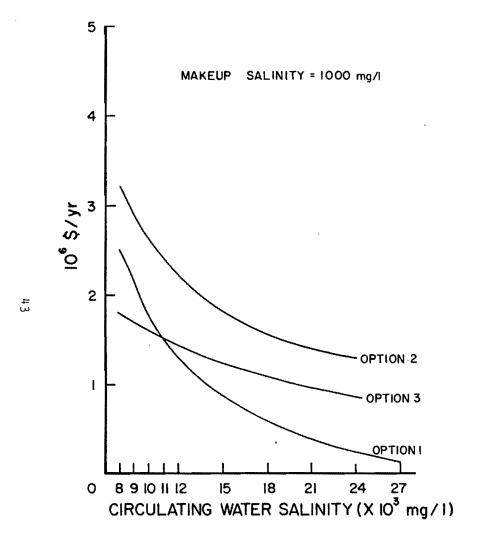
Circulating Salinity (mg/l)	8,0	00	9,00	00	10,0	000	11,0	00	12,0	00	15,	000	18,	000	21,0	000	24,0	00	27,0	100
1000 ac-ft yr Makeup Salinity (mg/l)	Blow- down	Make∽ up	Blow- down	Make- up																
1,000	0.371	16,70	0.366	16.70	0.362	16.69	0.358	16.69	0.356	16.68	0.349	16.67	0.343	16.66	0.339	16.65	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		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		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		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

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

Circulating Salinity (mg/1)	8,00	00	9,0	00	10,0	000	11,0	100	12,0	00	15,	000	18,0	000	21,0	000	24,0	100	27,0)00
Pond Area Yacres) Makeup Salinity (mg/1)	Normal	Max.	Normal	Мах.	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)	8,00	00	9,00	00	10,0	000	11,6	000	12,0	00	15,0	00	18,	000	21,0	000	24,0	000	27,0)00
10 ⁶ \$/yr Makeup Salinity (mg/1)	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Normal	Max.	Norma1	Max.	Normal	Max.	Normal	Max.
1,000	1.8	2.1	1.7	2.0	1.6	1.9	i.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
											6.0	6.4	5.6	6.0	5.2	5.6	5.0	5.4	4.8	5.2
5,000	8.0	8.5	7.5	8.0	7.2	7.6	. 6.9	7.3	6.6	7.0										
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	111	10	11	9.7	10	9.4	9.9
10,000	12		15	16	14	15	14	14	13	14	12		11	12	11		10			10



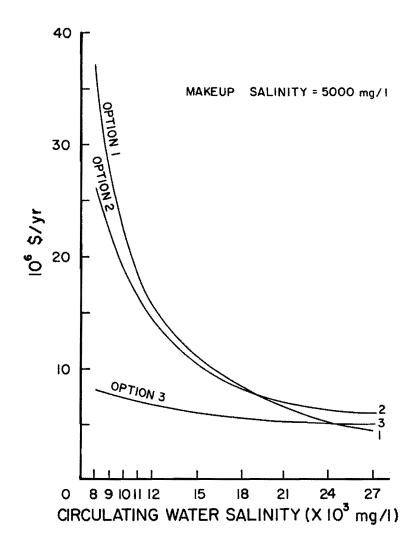
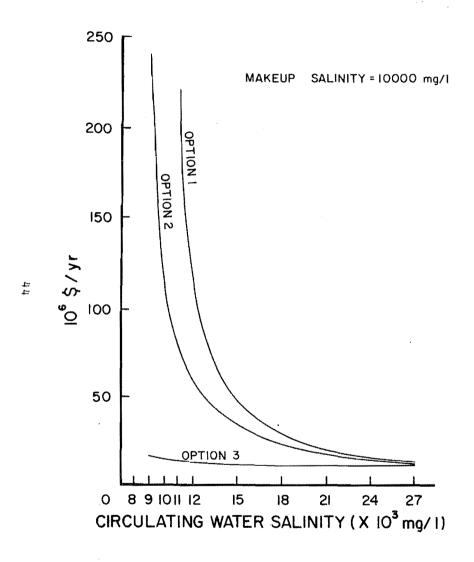


Figure 38. Water treatment and disposal costs as a function of the allowable TDS of circulating loop water assuming the salinity of the make-up water is 1000 mg/1.

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



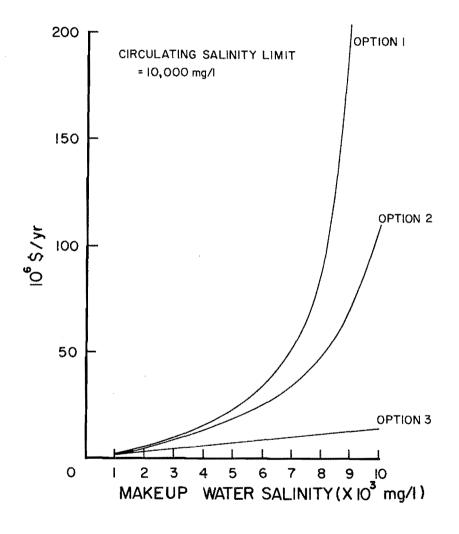


Figure 40. Water treatment and disposal costs as a function of the allowable TDS of circulating loop water assuming the salinity of the makeup water is 10,000 mg/l.

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.

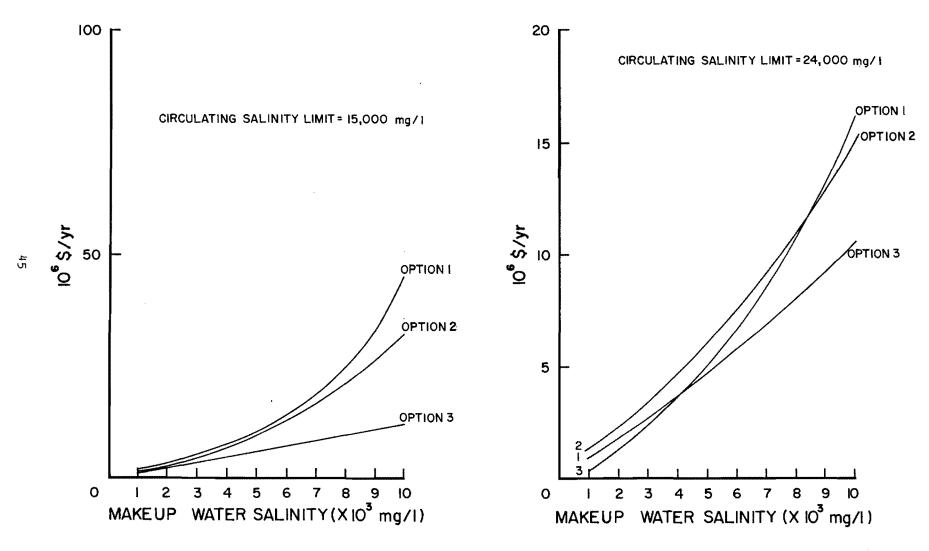


Figure 42. Water treatment and disposal costs as a function of makeup water salinity assuming the TDS limit of the circulating water is 15,000 mg/l.

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/1.

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:

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

where

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

VALUE; = value of the makeup of salinity i expressed in \$/ac-ft

 ${\rm COST_i}$ = 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

VALUE5 = price of 5,000 mg/l makeup water delivered to the plant

 ${
m COST}_5 = {
m water \ treatment \ and \ disposal \ costs \ when \ 5,000 \ mg/l \ water \ is used as makeup water }$

The value of makeup water of salinity ${\tt i}$ is thus calculated as

$$VALUE_{i} = \frac{(MU_{5} \times VALUE_{5} + COST_{5} - COST_{i})}{MU_{i}} . (50)$$

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 ac-ft x \$100/ac-ft + \$10.3 x 106

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

17,090 ac-ft x (value of 1,000 mg/1 water/ac-ft) + \$1.8 x 106

Equating these two values gives

Value of 1,000 mg/1 water =
$$\frac{(2.21 + 10.3 - 1.8) \times 10^6}{17,090}$$
$$= $627/ac-ft$$
(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	Option					
Salinity (mg/l)	1	2	3			
1,000	1336.0	1027.5	436.5			
1,500	1181.3	916.8	400.			
2,000	1025.9	801.8	357.6			
2,500	876.2	688.4	321.4			
3,000	724.6	564.3	273.			
3,500	582.5	431.2	225.4			
4,000	423.7	323.1	i83.5			
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).

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	Option			Make-Up Water	Option			
Salinity (mg/1)	1	2	3	Salinity (mg/1)	1	2	3	
1,000	738.3	609.1	382.8	1,000	423.0	415.7	351.2	
1,500	659.3	546.0	352.4	1,500	382.2	378.9	316.8	
2,000	585.3	480.4	322.0	2,000	342.4	343.2	292.4	
2,500	504.7	417.4	285.9	2,500	300.6	308.5	262.2	
3,000	428.9	347.3	249.8	3,000	260.3	263.8	238.1	
3,500	348.1	277.0	201.9	3,500	221.6	221.1	190.1	
4,000	272.5	214.4	165.8	4,000	179.2	179.3	159.9	
4,500	193.6	145.9	135.9	4,500	138.7	138.9	129.9	
5,000	100.0	100.0	100.0	5,000	100.0	100.0	100.0	
5,500	54.9	9.2	58.3	5,500	58.3	62.6	70.0	
6,000	-23.9	-33.1	22.6	6,000	18.7	21.7	34.2	
6,500	-130.2	-112.2	-13.0	6,500	-23.4	-17.5	4.4	
7,000	-190.1	-184.6	-42.6	7,000	-63.2	-55.1	-25.4	
7,500	-273.2	-250.3	-84.0	7,500	-104.9	-81.7	-55.1	
8,000	-343.6	-309.2	-119.4	8,000	-160.8	-125.1	-90.7	
8,500	-428.8	-394.8	-137.0	8,500	-196.8	-166.5	-120.3	
9,000	-497.1	-438.8	-195.9	9,000	-230.0	-205.7	-155.8	
9,500	-594.9	-506.0	-195.7	9,500	-260.6	-242.8	-179.5	
10,000	-667.4	-563.2	-254.4	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	0.085ª
(c)	10% Wet-Dry	2.86	0.007 ^a
(d)	Mechanical Dry	4.07	0.0

^aEstimated 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

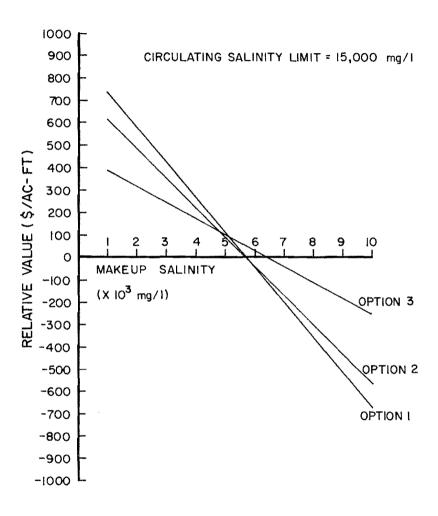
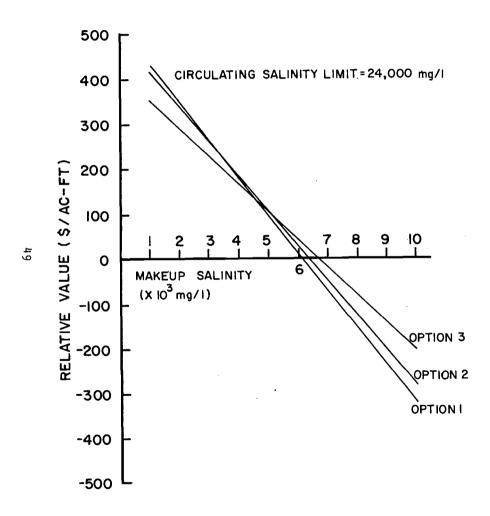


Figure 44. Relative value of makeup waters assuming 5000 mg/l water is available at \$100 per ac-ft and circulating water salinity limit is 10,000 mg/l.

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.



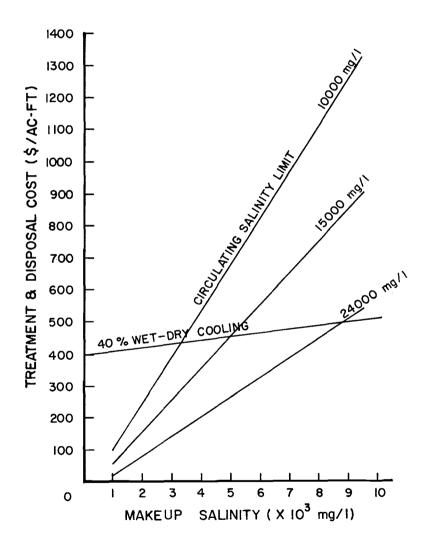


Figure 46. Relative value of makeup water assuming 5000 mg/l water is available at \$100 per ac-ft and circulating water salinity limit is 24,000 mg/l.

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

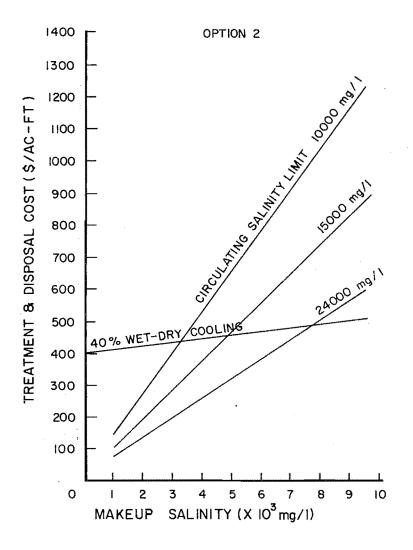


Figure 48. Comparison of the costs of utilizing partial dry cooling with all wet cooling using saline makeup water for option 2 treatment and disposal.

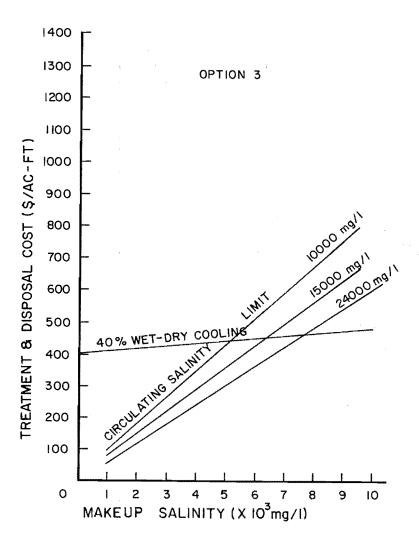


Figure 49. Comparison of the costs of utilizing partial dry cooling with all wet cooling using saline makeup water for option 3 treatment and disposal.

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

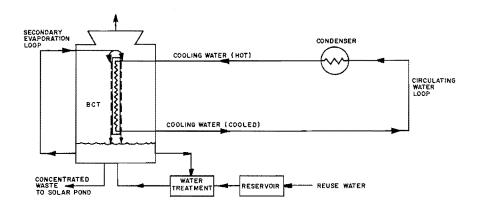


Figure 50. BCT system flow diagram. (Courtesy Tower Systems Inc., Tacoma, Washington.)

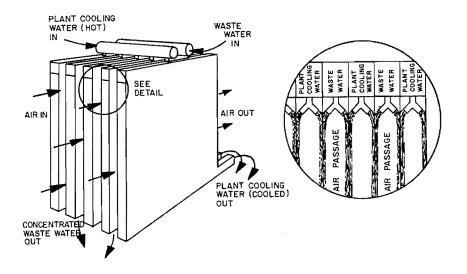


Figure 51. BCT heat exchanger detail. (Courtesy Tower Systems Inc.)

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 SiO2 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.

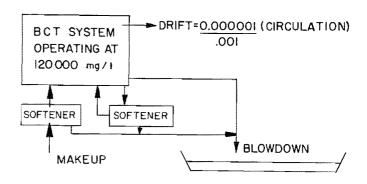


Figure 52. BCT unit operated with treatment option 3.

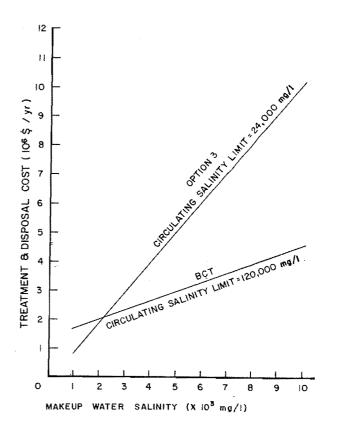


Figure 53. Cost comparison of the BCT system with conventional towers using reverse osmosis and brine concentration as a function of makeup water salinity.

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.

	Wa	down ter ft/yr)	Wa	keup ter ft/yr)	Po	ation	Dispos	ment & al Cost \$/yr)
Makeup Salinity (mg/l)	BCT With Soften- ing	Option 3 RO plus Brine Conc.	BCT With Soften- ing	Option 3 RO plus Brine Conc.	BCT	Option 3 RO plus Brine Conc.	BCT With Soften- ing	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	1,089	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

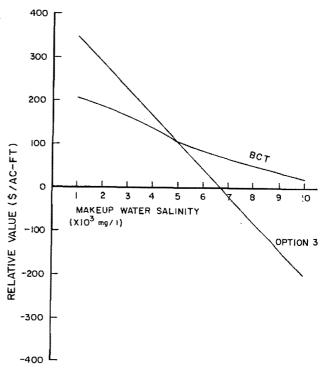


Figure 54. Relative value of makeup water of various salinities compared with 5000 mg/l water arbitrarily valued at \$100/ac-ft.

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

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

 Q_0 = rate of energy rejected from the power plant. For a 1,000 MWe plant operating at 40 percent efficiency, \dot{Q}_0 = 1,500 MWe = 5.12 x 10^9 Btu/hr

 $\begin{array}{lll} Q_{mu} & = & rate \ of \ energy \ entering \ the \\ & reservoir \ from \ makeup \ water, \\ & \dot{Q}_{mu} = \dot{M}_{mu} \ Cp_{mu} \ (T_{mu} - T) \end{array}$

 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.

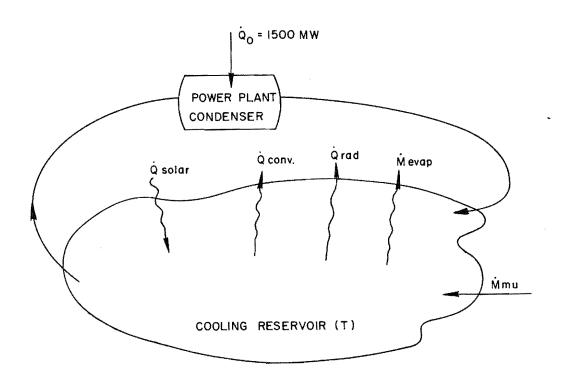


Figure 55. Schematic showing basic parameters involved in modeling the cooling reservoir.

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

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

$$. (53)$$

where

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

Conc = concentration of cooling reservoir salinity

 $\mathsf{Conc}_{mu} = \mathsf{concentration} \ \mathsf{of} \ \mathsf{makeup} \ \mathsf{water} \ \mathsf{salinity}$

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

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

 Make a reasonable estimate of the rate of makeup required as

$$\sum_{\text{year}} (M_{\text{mu}})_{\text{estimate}} (1-\text{Conc}_{\text{mu}}) \Delta t = \frac{\sum_{\text{o}} Q_{\text{o}} \Delta T}{h_{\text{fg}}}$$
 (54)

Make a reasonable estimate of pond area as

$$A = \frac{\sum_{y \in A} (M_{mu})^{estimate}}{(Annual evap. - Annual precip.)_{estimate}}$$

$$\cdot \cdot \cdot \cdot (55)$$

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, $T_{mu} = 60^{\circ}F$.)
- 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 ${\rm M}_{\rm mu}$ required on that first day to maintain constant depth D.
- . 7) Repeat steps 5 and 6 until values of $M_{\bar{m}u}$ 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

$$A = \frac{\sum_{\text{year}} \dot{M}_{\text{mu}} (1-\text{Conc}_{\text{mu}}) \Delta t}{\sum_{\text{year}} \left(\frac{\dot{M}_{\text{evap}}}{A} - \frac{\dot{M}_{\text{precip}}}{A} \right) \Delta t} . . . (56)$$

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 x 106 m². The total volume of makeup water required is 8,631 ac-ft/year or 1.06 x 107 m³/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 downwind 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

$$\frac{d}{dt} (\rho \text{ Vol Conc}) = M_{mu} \text{ Conc}_{mu} . . . (57)$$
where

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

$$= \frac{M_{H_20} + M_{salt}}{Vol} = \frac{M_{H_20}}{Vol} + \frac{M_{salt}}{Vol} (1b/ft^3)$$
 (58)

$$\frac{M_{salt}}{Vol}$$
 (lb/ft³) = Conc (mg/1) x 28.317 (lb/ft³)

$$\times 0.221 \times 10^{-6} (1b/mg)$$
 . (59)

$$\rho_{\text{H}_20} = \frac{{}^{\text{M}_{\text{H}_20}}}{\text{vol}} \qquad (60)$$

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

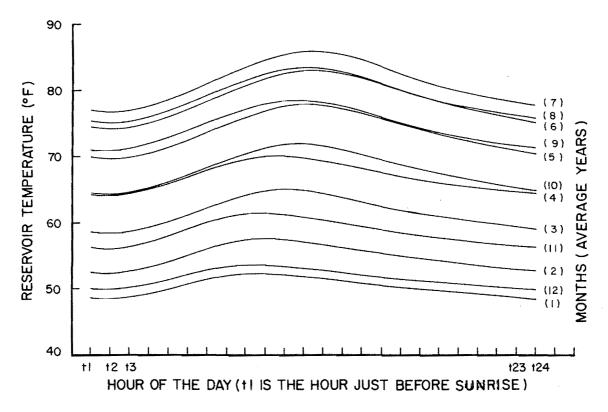


Figure 56. Computed cooling pond temperature with the associated air temperature during a typical day in June.

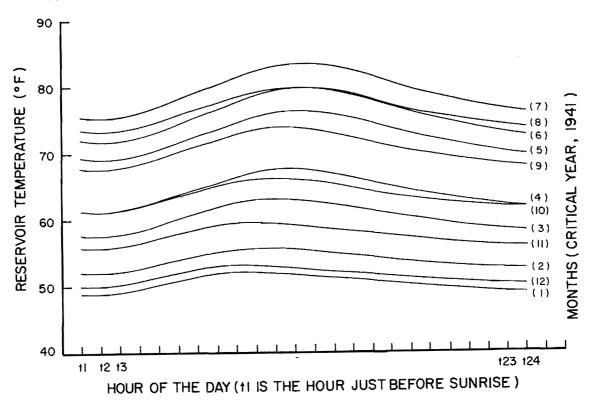


Figure 57. The predicted cooling pond temperature pattern for a typical day in each month of an average year.

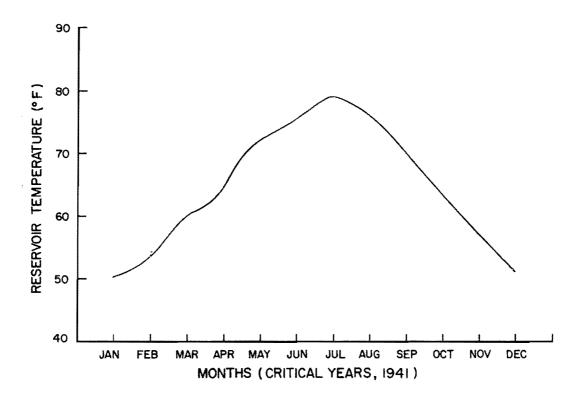


Figure 58. The predicted cooling pond temperature pattern for a typical day in each month of the critical year.

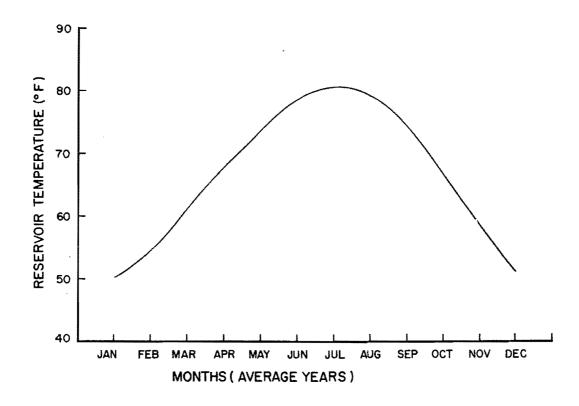


Figure 59. Predicted average daily cooling pond temperature for each month of an average year.

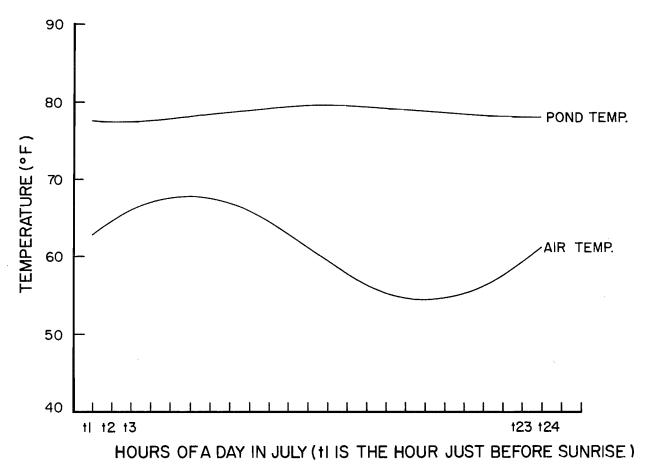


Figure 60. Predicted average daily cooling pond temperature for each month of the critical year.

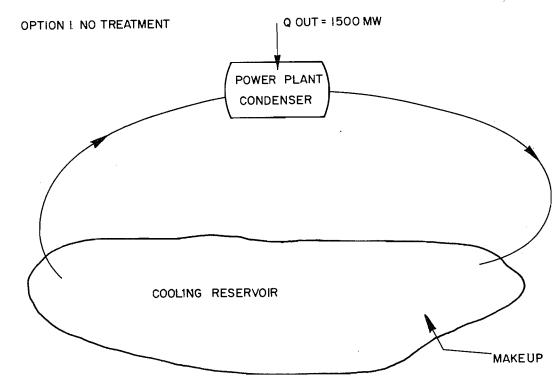


Figure 61. The cooling reservoir-condenser loop, option 1.

Conc = salinity concentration of reservoir

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

or

$$\frac{d}{dt} (\rho_{\text{H}_20} + 6.258 \times 10^{-6} \text{ Conc}) \times \text{Conc} = \frac{M_{\text{mu}} \text{ Conc}_{\text{mu}}}{\text{Vol}}$$

where it is assumed that at t = 0, Conc = ${\rm Conc_{mu}}$. 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

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

or

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

then

$$\dot{M}_{\text{side}} = \frac{\dot{M}_{\text{mu}} \times \text{Conc}_{\text{mu}}}{7500} \cdot \cdot \cdot (65)$$

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 x 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 x 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 x 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

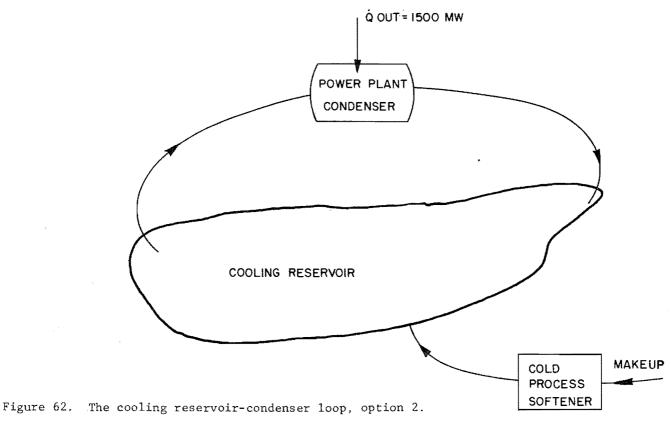
Extracting minerals from saline ground-water or power plant brine disposal ponds is technically feasible, but the low market value for the major mineral products (salt, magnesia, and potash) and small amounts of the more valuable salts generally found in the brines tend to make mineral recovery from power plant brine disposal ponds uneconomical at present. Certain minerals find use as fertilizers, but there are problems even here. For example, sylvite (KC1) is suspected of staining the tobacco plant leaf and reducing the quality and quantity of tree and plant growth. Thus fertilizers made with KC1 are rejected by citrus and tobacco growers in favor of those made with K2SO4 (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 (Na₂SO₄.10H₂O).
- 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 (KC1).

OPTION 2 PRETREAT MAKEUP WATER USING COLD PROCESS SOFTENER



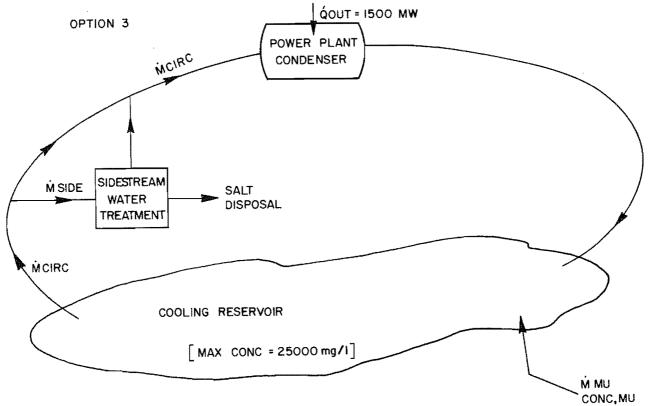


Figure 63. The cooling reservoir-condenser loop, option 3.

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

End of Year	1 1	lear (5 Y	ear	10 Y	ear	20 Y	ear	40	Year
Pond (mg/1) Make Up (mg/1)	Option 1	Option 2	Option	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 $_2$ 0) and a strong MgCl $_2$ brine.

The yield of sylvite (KC1) 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 (MgS0 $_4\cdot7$ H20) is obtained during the first cooling step instead of mirabilite (Na2S0 $_4\cdot1$ 0H2O).

Electrodeposition of minerals in sea water (Hilbertz 1979)

By establishing a direct electrical current between electrodes in an electrolyte

like sea water, calcium carbonates (CaCO3), magnesium hydroxide (Mg(OH)2) are precipitated and hydrogen (H2) is released at the cathode, while the anode produces oxygen (O2) and chlorine (Cl2). 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

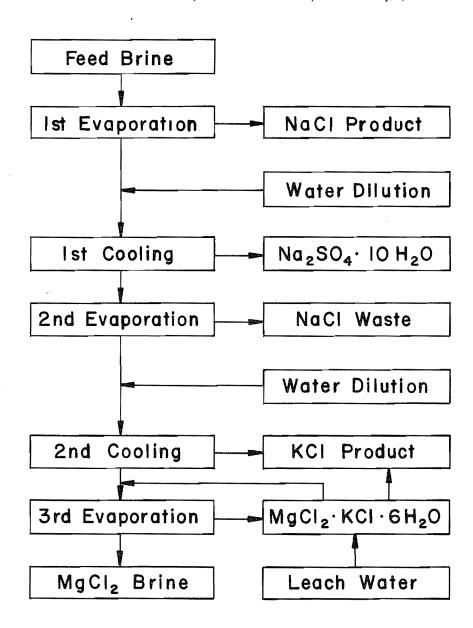


Figure 64. Phase rule processes flow diagram (from Glassett 1970).

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 Most conventional and nuclear reactors. boilers have low capital cost and high Nuclear reactors on the operating cost. other hand have high capital cost and low operating cost. Thus nuclear reactors are normally used to generate baseload elec-Thus nuclear reactors are tricity 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):

l. 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 ft² range compared with \$20-\$40 per ft² 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.

40%	ELECTRICITY	33%	ELECTRICITY	30%	ELECTRICITY
60%	REJECTED HEAT (WASTED)	67%	REJECTED HEAT (WASTE)	70%	PROCESS HEAT (WATER)
	E PURPOSE L FUEL)	SINGL (NUCL	E PURPOSE LEAR)	DUAL	PURPOSE

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

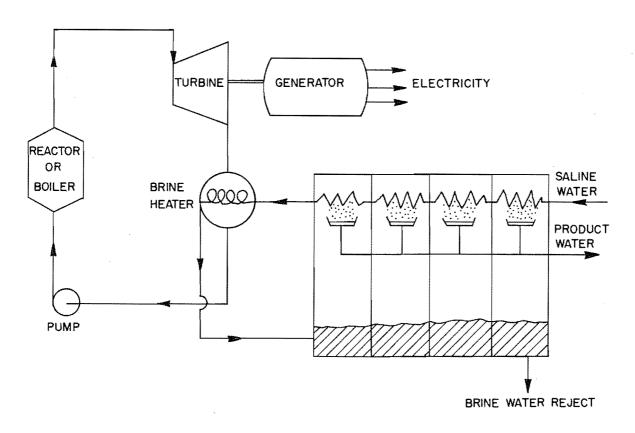


Figure 66. Back-pressure cycle--entire turbine exhaust used in brine water.

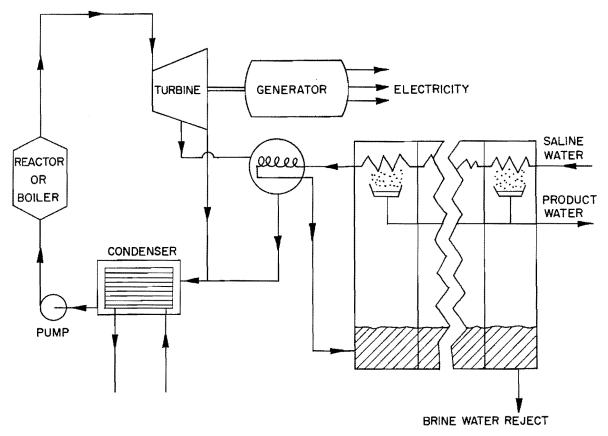


Figure 67. Extraction cycle--brine heater steam is extracted at some point in the expansion.

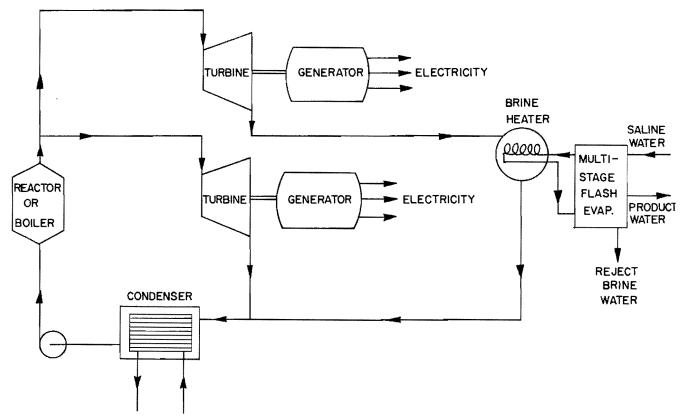


Figure 68. Multi-shaft cycle--use parallel condensing and non-condensing turbines.

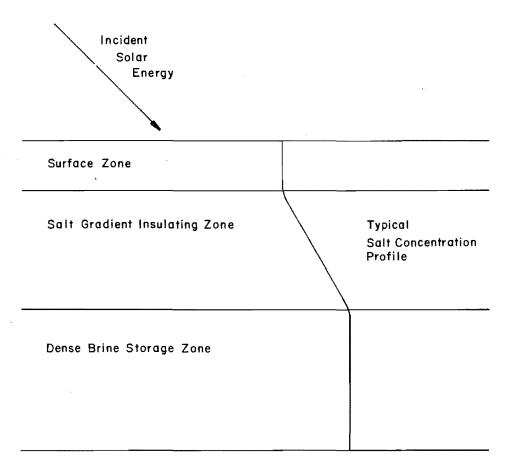


Figure 69. Configuration of the salt gradient solar pond. Solar energy is trapped by the dense brines which remain on the bottom even though bottom temperatures became high.

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 ~ \$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 ~ 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 watershort 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.

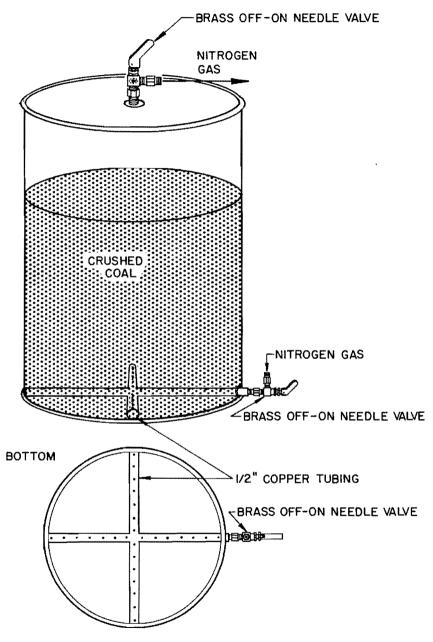
In all cases, the coal samples were freshly crushed, unoiled, and less than one hour old. Approximately 150 pounds of crushed coal were placed in each barrel and the lids were sealed. All four mines were sampled on the same day, but the samples were not placed in a nitrogen atmosphere until they arrived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

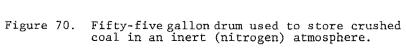
Each coal-filled barrel was sealed and purged with nitrogen from a compressed gas cylinder for at least 2 hours. The barrels were purged from the bottom to the top, and the needle valves placed in the closed position after the purging process was completed. During the next few months, whenever a sample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





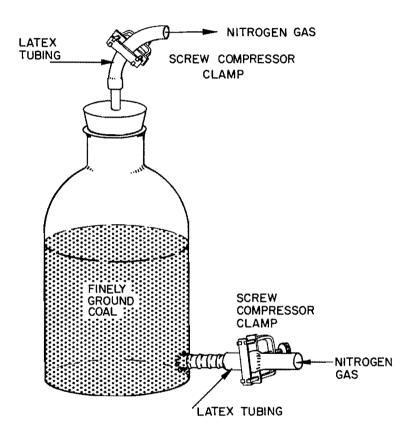


Figure 71. Aspirator jar used to store finely ground coal in an inert (nitrogen) atmosphere.

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

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	Saline Groundwaters							
(mg/1)	USU/IPP	OW/Stanolind	TW-1	OW-ICPA	x			
A1 B Ca C1 CO ₃	0.40 0.63 105. 623. 113.	_a - 136. 454. 149.	- 0.37 84. 847. 142.	0.30 259. 623. 118.	0.40 0.43 146. 637. 130.			
F Fe K	0.3 <0.08 3.	4.2	0.9 0.54 4.0	0.5 0.8 4.8	0.6 0.67 4.0			
Mg Na P SiO ₂ SO ₄ TDS	58. 360. 0.04 3.6 560. 2130.	46. 475. 0.03 8.5 652. 2010.	30. 823. 9.6 600. 2660.	105. 495. 0.20 12.0 1022. 2820.	60. 538. 0.09 8.4 709. 2405.			

^aData for this parameter not available.

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

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, NO3-N, Si-SiO2) 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 28. Data from saline groundwaters for preparation of synthetic saline transport medium. Slurry 2. TDS 3000-10,000 mg/1.

	Saline Groundwaters (USGS)									
Parameter (mg/l)	385159 <u>111</u> 1545-01	38515111 1545-02	385224 <u>111</u> 1426-02	385225 <u>111</u> 1300 - 01	385249 <u>111</u> 1309-01	385303 <u>111</u> 1313-01	385506 <u>111</u> 0952-01	383317 <u>110</u> 5705-01	x	
Ca	160.	100.	140.	380.	510.	470.	420.	500.	335.	
C1	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	inna	_	_	_	_	-	-	0.4	
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.

	Saline Groundwater (USGS)									
Parameter (mg/1)	390625 <u>111</u> 0138-01	395707 <u>111</u> 1227-01	401131 <u>110</u> 4201-02	401159 <u>110</u> 4815-01	401225 <u>110</u> 3716-01		402444110 0102-01	402444 <u>110</u> 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.
CO3	660.	750.	708.	1050.	293.	622.	2501.	2210.	664.	1051.
К	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, Ž	5100.	7000.	331.	3490.	2020.	2580.	1300.	1600.	3100.	2950
TDŠ	10100.	19400.	10800.	11700.	14500.	11820.	10400.	10400.	16400.	12800

Table 30. Sieve analyses.

Sample Coal From	5	% Passing 325 Mesh	Sieve
Mine	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/1)	Slurry 1 (TDS 1000- 3000 mg/1)	•	Slurry 3 (TDS >10,000 mg/1)
A1	0.25	0.72	1.14
В	0.1	0.5	0.7
Ca	156.	343.	312.
CO3	117.	361.	550.
C1 C	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
рНă	7.6	8.3	7.8
o-P04	0.71	0.72	0.98
K	4.	20.	102.
SiO ₂	11.	22.	35.
Na	458.	620.	4300.
50_{L}	700.	2740.	2770.
TDŠ	2220.	4640.	13180.

^aIn 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 HNO3 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. ${\rm H_{3}P04}$ to pH < 2 and stored in glass. Nitrate-nitrogen, nitritenitrogen, 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.

	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)	
Sample	P (mg/1)	mg P Absorbed per kg Coal	P (mg/1)	mg P Absorbed per kg Coal	P (mg/1)	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.

	Slurry 1 ^a (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)	
Sample	P (mg/1)	mg P Absorbed per kg Coal	P (mg/1)	mg P Absorbed per kg Coal	P (mg/1)	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

^aTotal phosphorus was not run on Slurry 1.

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. I 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/1 TDS)		Slurry 2 (4,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)	
	N (mg/1)	mg N Absorbed per kg Coal	N (mg/1)	mg N Absorbed per kg Coal	N (mg/1)	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.

Table 36. Coal absorption of silica.

C1-	Slurry 1 (2,220 mg/1 TDS)	Slurry 2 (4,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)		
Sample	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/l)	mg SiO ₂ Absorbed per kg Coal	
Saline Trans- port 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.	

 $^{^{\}star}$ 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.

 ${
m Boron.}$ 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 $\mu g/l$ 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.

	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4	,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)	
Sample	B (mg/1)	mg B Leached per kg Coal	B (mg/1)	mg B Leached per kg Coal	B (mg/1)	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		
Mange 1	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	0at	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. I 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 (SrSO4) or strontianite (SrCO3). 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.

	Slurry 1 (2,220 mg/1 TDS)	Slurry 2 (4,640 mg/1 TDS)	Slurry 3 (13,200 mg/1 TDS)		
Sample	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.

	Slurry 1 (2,220 mg/1 TDS)		Slurry 2 (4,640 mg/1 TDS)		Slurry 3 (13,200 mg/1 TDS)	
Sample	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	W** 600	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
Jltimate 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 Fr	om Mine 4		
	Unslurried		Slurried		Unslu	Unslurried		ried
	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

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

Sample	Theor.	Exp. Conc. of S Using Stan		% Deviation from Theor Using Standards in	
	Conc. of Spike (µg B/l)	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.
loal 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				
		man nan			
	a	construction			
				$\bar{x} = -5.4\%$	$\frac{-}{x} = -1.65$

^aInsufficient sample to complete analysis.

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

Sample	Theor. Concen. of Spike (mg Sr/1)	Exp. Concen. of Spike (mg Sr/1)	% 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.

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 watershort 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 salttolerant 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 (PFM)	TOTAL DEFTH	(FT)	362411103352701 362428109521901	3120 1020	1 1515
				362430109522701	2520	236
355014108262501	1650	1		362458 105 1739 01 3625 00 109 37 07 01	1400 1470	160
355037109480601 355046107184401	2165 7550	240 1		362617108283301	2370	1
355051107183201	2740	1		362637108181201 362732108434001	2340 2030	1
355125407201701 355213107245801	2510 1320	1		362742110132801	4050	417
355302107130501	8240	i		362756109522201	3160	750
355328107220801	1880	1		362806107125901 363112109541201	1220 1120	1160
355328 107221001 355353109390801	1900 1510	1 92		363113108333001	2310	1
355356107273501	2000	1		363113108333501	1980 1197	11 1640
355415107252801 355425107314401	2770 1700	79 0 I		363122110042701 363134110050201	1270	770
355426108250501	1730	i		363159108440401	1530	1
355435107220001	1610	I		363330109131701 363431108334501	1 2 3 6 28 0 0	806 1
355435107411101 355450110144701	119 O	1 473		363503108342101	1168	8
355507107374601	1940	1		363504107150001 363537109572201	1080 1150	1 212
355521107293401 355534107275701	2740 1750	1		363550109033501	1220	551
355548 10121801	1530	1017		363615108382601	3850	1
355558 10729 3301	2340	1		363753107521701 363835108314101	39 1 0 25 1 0	1 5
355558 10729 3401 3556331100649 01	2630 1190	550 471		363844107394001	1120	1
355703107361201	4890	1		363858108430301 364105107252801	1220 1150	1
355708107361401 355713110070201	1300 1830	490		364227107292601	3350	i
355716110101501	1120	570		364311109374701	1770	210 10
355723107312201 355752108084801	3430 1770	1		364325108353001 364445108312701	2788 2910	1
355822107244601	2460	i		364453108312801	2710	1
355833107255901	1930			364459108312701 364500108312901	2140 1860	1
3559 15 109 444701 3559 18 110001301	3190 4410	173 600		364505107345601	2560	i
355920107411001	1420	1		364510107360301	2290	i 1
3559 33109 49 4101 3559 55109 0319 01	2450 1160	213 489		364523108312701 364534108244801	2360 6600	250
360017107223901	2290	2450		364555108082501	1550	1
360141109381501	3330	117		364613108221801 364705108234301	3830 11400	500 450
360147110045201 360200107540001	1430 13500	700 1		364744108225001	9475	730
360200107550001	2160	j		364750108214701 364755108255101	6165 27900	58 2
360200107560003 360303110021001	2010 1430	1 69 5		3648 26108 234301	7450	26 60
360313107473401	3485	5076		3648 35103254601	20400	30
360336107501801	2350	3		364845108214204 364916108234301	49 3 0 4 2 0 0	715
360344107515601 360351110074101	8320 1530	1 688		365035108265601	12200	1
360430109530901	1420	125		365059108275901 3654181090630C1	1870 1073	1 950
360521108161301 360601107565101	1600 1470	1 15		365427109061801	1073	1168
360613110134301	1155	1500		3655361C7523601 365554108120501	6750	750
360623110120201	1100	235		3658 08 1 09 0 348 0 1	1226 7250	1 5689
360645108065501 360706110124801	1130	1 443		365921108111201	1340	i
360731107494701	4680	48 6		370118107522700 370122107522700	1 48 0 349 0	1 138
360734107523101 360822107561601	1605 1940	18 5 28 5		370236108053700	38 0 0	1
360323107544001	2053	190		370310107335000 370325108050500	2110 2710	115 1
360826109584001 360849107561801	1640 2470	38 5 205	•	370346108044800	4450	1
360857107531001	3550	59		370429107362000 370436107013900	1230 2910	1
360913109353901 360916107543901	13900 7355	216 474		370449108041900	3140	î
360927116035801	1600	650		370506107360000 370506107360300	1310 1310	1 61
360941107561601 361002108162601	6350 1060	58		370508107311000	1190	850
361003107543901	8105	29 0		370519107361700 370556107343500	1720 1240	1
361057103022301	1670	1		370610111402501	1060	1
361109109460901 361130108203001	4270 1630	471		370611108040400	1120	1
361135108180501	1010	ì		370620107442700 370628107343500	1620 1010	1
361142108220401 361207108192701	1017 1800	8		370657107435700	1630	i
361208110064401	1825	763		370703111290201 370707107462700	1750	1
361235107374001	1430	1		370735111290501	1360 4710	1
361240108514701 361256110140901	5080 2080	1 69 0		3708 39 1074159 00	2210	9 58
361305108182001	1 28 0	i		371052108083200 371105111220001	3500 3520	1
361318108151401 361318108494101	1263 1430	8		371142107032600	1240	i
361341108092201	1860	369		371215111364501 371327107105400	1140 1250	1
361343109533101	238 0° 3530	902 274		371342108130600	3350	1
361407103081901 361435108093001	4157	350		371401107550600 371447107574000	1140	1
361445108140601	5050	9803		371507107571600	1040 1090	1
361446108083701 361446108090801	11850 5445	67 150		371520111343501	2160	ı
361457103031901	4240	39 4		371532111372501 371550107003100	1500 3310	1
361503108243801 361508108333901	9763 1390	8		371551107003500	3320	1
361537109460201	1850	899		371552107003700 371555107003700	3183 3300	i a
361542108252801 361545103075101	1320 6987	1 4896		371555111352300	1230	1
361636103471901	1620	4696		371600107010000	3010	i
361659103500101	2070	1		371601107004200 371605111344001	3320 1240	1
3618 03 109 21 5601 362034 109 560001	1510 2180	950 205		371630111341001	1060	i
362037110033901	18 20	191		371630111351501 371655111345001	1530 1100	1 ,
362058107092101 362116109370301	4290 1035	1 29 D		371743107570200	1570	i
362145103316901	1310	8		37 18 47 1 07 48 28 0 0 37 19 06 1 03 03 5 2 0 0	4820 4110	;]
362149109463361 362156109591801	3760 2840	360 1172		372326107505260	3340	1
362222108285501	5110	1		372330107505200 372453111391801	3246 1650	1 I
					.000	1

STATION NUMBER	TLS (FESS)	TO TAL DEFTH (FT)	385100108031100 385102108031500 385122107290301	2770 2750 75 00	1
372656107481700	3880	1	385123110020101	201900	53 10293
372653107482300	3670	1	385127111170201 385138111151801	1230 3454	406 1
372707107432000 372827111472801	3887 1780	1	33 5159 111154501	5100	1
373235103440400	1410	i .	385159111154502 385217110055201	4780 22200	; ;
373609108515200 373811110425801	1860 3380	1	38 5224111142602	3870	150
374021110504401	39 60	8362	385225111130001 385225111152601	388 0 1350	1
374115108014400 374117108014400	2745 2790	1	385230110064401	103800	9568
374119108014400	2745	i	385233111130301	1530	1
374120108014500	2250 2390	1	385235110502101 385238111130201	1673 1140	1200
374135110542800 374238110442400	2790	i	38 5 2 4 9 1 1 1 1 3 0 9 0 1	4200	1
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374448 108 070200 3748 59 110433100	1780	i	385335110585401	7450	î
375342110581800	8830	1 1	38 53601111229 01 38 550611109 5201	2440	i
375449 110561001 375504108 353201	1410 4830	115	385554110074701	3240 394000	1 5896
375525108365801	5290	350	38 56 19 1 1 0 0 8 0 6 0 1	13500	2627
375629108372001 375733108370501	5290 9810	325 901	38 57 14112264701 38 57 15 112271201	1940 1255	78 7
375739110000300	1080	1	38 57 32 1 1 0 0 0 2 2 0 1	165900	11895
375802108362601 380041111015600	3760 2320	1	38 58 01 11 01 329 01 38 58 19 11 026 57 01	29 09 00 308 0	10600
380121110512000	6780	1	38 59 20 1 08 26 4 0 0 1	1570	i
38 0220111015001 38 0250110040001	1060 1406	1	38 59 39 112272303 39 002111009 2301	1 08 0 3 29 0	16
38 0358 108 315 100	5380	57	390044106532600	1910	1
38 0406 1 1027 240 1	2140	5175	39 0045112281201 39 013111108 0501	1520 6450	1
38 043 11 1 04 04 00 1 38 04 5 0 1 1 1 0 0 3 1 0 1	10400 1990	668 3 1	39 0327 1 1 1 0 3 0 4 0 1	5 34 0	i
38 05 16 11 01 50 50 1	14100	5534	39 0334108 351801 39 0354111003401	1630 46800	1
38 05 4 3 1 1 0 5 8 4 1 0 1 38 09 38 1 1 0 2 4 3 3 0 1	1170 1460	1 650	39 04 04 1 1 1 08 0 1 0 1	50566	7299
38 1 3 3 4 1 1 0 2 9 5 8 0 1	48760	6128	39 0406 1 1 1 0 1 4 2 0 1 39 0 4 5 4 1 1 0 0 8 3 2 0 1	6870	1
38 141111039 4201 38 1427 108 304201	7420 1200	4000	39 0535112370001	1310 2070	30
38 143 1 1 1 0 39 2 5 0 1	2140	500	39 0540112370001	1990	1
38 144 [110 3628 0]	8835	6584	39 06 25 1 1 1 0 1 3 8 0 1 39 06 28 1 1 2 2 0 1 4 0 1	10100	1
38 1441110362802 38 1448108 323801	4600 1560	2245 335	39 06 37 1 08 4 0 0 6 0 1	2000	i
38 15 28 11 01 04 20 1	1720	2750	39 0653111005401 39 0708110410801	8120 2250	1 1
38 16 36 1 1 0 1 7 3 4 0 1 38 1 7 4 9 1 1 0 5 1 2 9 0 1	85500 4487	688 6 8 1 7 4	39 07 10 109 37 030 1	68 10	4760
38 1749 1113139 01	1200	500	39 08 22110525101 39 09 33108 405701	3280 5050	!
38 18 16 1 1 1 3 1 0 6 0 1 38 19 16 1 1 0 4 0 38 0 1	3840 6105	1 28 4 7	39 1027 110472101	3550	1 476
38 19 32 108 5 428 0 1	1800	205	39 1049 1102409 01	39995	8431
36 19 34 11 10 32 30 2 38 20 19 11 10 70 8 0 1	1171 1390	1350 800	39 1049 110240902 39 1119 108 405 301	4120C 434C	38 0.0 1
38 2020 1 1 1 0 3 4 6 0 1	2547	1250	39 13 15 1 10 5 7 0 3 0 1	5080	. 1
38 2024 11 104 300 1	1920	764	39 13 17 1 1 0 2 3 4 7 0 1 39 1 3 3 3 1 0 7 1 3 2 8 0 0	42 697 28 04	7083 1
38 2025 108 5 30 40 1 38 2027 1 1 1 0 4 1 6 0 1	1560 3328	1 761	39 13 34 107 13 3000	2780	i
38 2029 11109 0201	1311	2353	39 1350107133600 39 1404111402601	2960 1130	1
38 2058 108 47 5 000 38 2136 1102 2200 1	2570 2390	1	39 14 10 11 139 300 1	1180	i
38 2224110433501	1254	407	39 14 19 1 1 1 39 19 00 39 1556 1 1 0 2 0 4 9 0 1	3120 4170	1 3180
38 2227 08 48 1 01 38 2233 1043220	18 30 1 053	1 39 2	39 1559 1102049 01	4734	30
382238 1044020	1700	503	39 1629 108 540 101 39 2002 108 24440 1	3670	1
38 2304 1 1 1 0 7 5 9 0 1 38 23 5 5 1 1 0 4 4 3 2 0 1	2250 7540	7301	39 2110108 260601	1780 1780	1
38 2424 1 08 5 6 28 0 1	4040	1	39 21 28 108 145701	3780	1
38 2447 1104 1460 1 38 2450 110265 101	29 30 16400	750 68 20	39 2209 108 155600 39 2210108 300300	3760 1490	1
38 25 17 110 100 501	28700	68 6 7	39 22 13 1 08 3 1 48 0 1	1180	1
38 25 18 11017 3201 - 38 26 22 110 32 06 01	30000 11000	8 09 6 7664	39 2228 108 34 37 0 1 39 22 36 1 10 26 23 0 1	1030 2438	ı
38 2649 111142601	1132	1	392242108213701	2180	1
38 27 07 1 1 0 0 0 2 3 0 1	2410	1 07.5	39 2247 108 214500 39 2314108 06 3600	2290	1
38 27 08 11137 1201 38 27 17 111365601	1200 1220	28 5 28 5	39 2328 108 22330 1	1110 1440	1
382717111370101	1165	1	39 23 48 11 105 37 01	1300	i
38 2727 1024570 38 28 22 1 100 50	5380 4660	6523 1	39 23 50 10 7 1 1 1 4 0 0 39 23 52 1 08 0 5 1 4 0 0	1460 9320	1
38 28 23 1 1 1 0 0 1 5 0 1	5500	1	39 24 28 10706 45 00	1840	1
38 28 24 1 1 1 0 0 4 4 0 1	4310	1	39 24 39 11 03 318 01 39 24 47 10 7 09 1 0 0 0	29 68 3 235 0	7132
38 28 39 111123401 38 28 39 111123402	9390 70800	440 950	39 24 49 1 07 09 18 0 0	1130	1
33 28 5 2 1 1 0 3 6 1 3 0 1	9 0 3 0	6430	39 26 17 108 02 39 00 39 26 30 108 03 13 00	1050 1660	1
38 29 43 110 24 54 0 1 38 30 55 110 25 52 0 1	498 0 699 0	59 40 6007	39 27 10 109 27 200 1	104400	8116
38 3145 1103 22501	2150	400	39 27 12 11 05 15 30 1 39 27 27 107 14 23 00	73650	11675
38 315 31 105 312 02 38 32 11 11 05 60 60 1	1160 1810	1	392732108040000	2630 1390	I i
38 3223 1 1 1 1 2 3 2 0 1	5955	6704	392745107142400	2320	1
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38 3424 1 1 0 0 5 0 9 0 1	18050	5750 6498	39 28 28 107 16 130 1	1010	1
33 3503 111050501	2540	767	39 29 20108 001400 39 29 35109 330101	2460 15735	1 5700
38 35 14 11 03 45 10 1 38 36 06 11 01 02 20 1	3500 40600	29 0 6701	39 29 48 11 04 5 38 01	23570	10854
383652110034001	31780	7225	39 30 00 1 08 22 5 0 0 1 39 3 1 0 2 1 1 2 1 9 4 5 0 1	1340 1430	1
38 3724110143001 38 33 29 110143001	26167 210000	639 6 6470	39 310211219 4510	1330	406 1
33 39 21 1 1 0 0 8 0 9 0 1	94700	7393	39 31 07 11 028 59 01 39 31 131 1030 2001	8 4600 108 0	9 1 53
385000107314801 385021107380601	3100 2100	1	39 3147 110 37 28 01	35780	1 8509
385022107383200	2010	i	39 3148 11036 1601	67770	9174
385026110531901 385031110085501	1214 174000	69 0 9 4 5 0	39 3149 11038 1301 39 315411219 29 01	3607 1983	3114 203
385037109440101	6530	535	39 3221112221801	1034	303
38 5045 111 17 18 01 38 5047 107 3323 01	1290 8220	720 66	39 3234110240601 39 3244110251401	1330 1790	1 66
38 5 0 49 1 1 1 1 5 3 1 0 1	2410	1	39 3258 10719 1000	17600	1

STATION NUMBER	TDS (PPM)	TO TAL DEPTH	39 5	226109091202 228109163401	4077	21 5840
39 3259 10719 1700	18 000	I.		229 109 09 120 1 233109 15160 1	4230 1127	70 6569
39 3259 10719 1800 39 3259 10719 1900	20400 19950	1		237103284600	1040	1
39 330010719 2700	18200	i		237109362601	18685 1130	8520
39 330110719 1500	19900	1		238 109 1608 01	1965	1950
39 330210719 0400 39 330510719 0000	18 05 0 18 00 0	1		239 103 1339 00	6400	ı
39 3314107200800	21500	1		251110123001 303108300300	35560 1800	4860 1
39 3314112223301	2580	1		318 109 162 101	1030	59 5 G
39 331610718 5100 39 3316107200800	18 300 21 300	1 39 2		325108271501	1000	1
39 34 12 109 43 06 01	24547	6792		326108374001 327108173500	1850 1830	1
39 3527111541701	1770	120		327108232000	1530	ì
39 3527 11 154 16 01 39 37 00 109 42 500 1	1655 4711	7300		327110070101 328108304300	4719 2840	529 6 1
39 37 30 107 18 0000	18 400	1		328 108 304 301	1350	1
39 37 37 107060000 39 37 39 107062200	9 040 1 028 0	1	39 5	331108271500	1088	1
393745107060000	10500	392		336108291500 338108311900	1 29 2 28 5 4	1
39 39 24 1 09 19 5 4 0 1	4190	1005		345109253001	23400	5445
39 39 29 1 09 18 5 0 0 1 39 39 3 0 1 09 19 3 0 0 1	2913 2720	1295		347108270000	243 0	1
39 39 5 5 1 09 08 37 0 1	1480	1		348 108 2658 00 359 109 09 320 1	4250 3560	1 50
39 4006 1105 1210 1	4040 1240	210 150	39 5	416111590801	1040	1
39 4039 112155301 39 4100111504501	1477	90		6412109142201 6424108174200	20265 5415	69 4 7 1
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39 4126 109 4349 01 39 4135 109 1649 01	1460 4248	129 82	39 5	433109381701	2110	5672
39 4135109 1649 02	3294	42		5439108223302 5443106463400	1157 3150	1715
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39 4221109 202701 39 4221109 202702	6030 27800	119		445108174300	4345	1
39 42 52 1 09 20 1 50 1	5965	Ī		5447108192100 5449109125201	358 0 19 5 4 0	7050
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39 4458 106 39 3201	2370	1		5455111551501	1889	1
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39 45 0 3 1 0 9 2 1 1 2 0 2 39 4 5 0 5 1 0 9 2 1 1 2 0 1	17520 7730	19		507110314401	9674	550C
39 45 05 1 09 2 1 1 2 0 2	16700	i		5508108175700 5510109094901	18 45 25 44	90
39 45 27 109 16 200 1	1649	1402		5512110031901	34390	5250
39 45 3 0 1 0 8 2 7 1 2 0 0 39 4 5 4 0 1 0 8 1 9 1 2 0 1	1100 1680	655		5515109094901	2260	60
39 45 40 103 19 1202	2170	1040		5515109094902 5524108290300	28 1 0	31 1
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39 4617108 514701 39 4627108 224300	3725 1015	1		5530109134901	1418	612
39 46 32 1 09 17 42 0 1	19575	5515		5548 109 04 500 I 5548 109 03 070 I	23900 1022	1 1176
39 47 19 108 17 26 00 39 47 19 108 17 32 00	1180 1120	j 1		5554109172701	3340	38
39 47 19 108 17 5601	1110	i		5554109172702	1852	17
39 4722108 175700	1170	1		5554109172703 5559108260500	3160 1212	20
39 47 35 108 134 300 39 47 47 108 2149 01	10267 1390	1	39 5	600108154600	2058	i
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39 48 15 108 17 3200	1215	1		5617109134401 5617109134402	28 79 1406	31 <i>7</i> 504
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39 48 35 1 08 08 49 0 0	1620	1 40 7		628 109 1629 01	1268	41
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39 48 53 103 14 3600 39 48 57 108 122 100	1500 1413	1	39 5	633109384602	10820	42
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39 5040109 075202 39 5052109 4418 01	38 04 5 4 18	18 90	39 5	710112034000	6610	1
39 5059 106 18 560 1	1210	1		715109272001	6843	6454 1
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39 5 1 5 5 1 08 1 2 3 1 0 0	1210	495		5755108211401 5801109245801	3746 18320	1755 36
39 5215108 17 18 00 39 5215108 17 23 00	1302 1342	l 1	39 5	8 04 109 07 170 1	1626	34
39 52 18 1 08 1 7 2 5 0 0	1428	1		58 04 109 07 17 02 58 14 11 15 52 50 1	1718 1503	22 495
39 5226 109 09 120 1	4203	29	39.5		* w ****	

STATION NUMBER	TES (FPM)	TOTAL DEFTH (FT)	4009 45 11 01 358 01 4009 55 11 226 000 1	1910 2180	250
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39 58 23 1 09 4 4 08 0 1	9 08 0 1 49 0	6679 1	401003109104401 401004112023401	1636 1740	1 225
39 58 40108 222500 39 58 41108 151000	2180	i	401005109151401	7530	1
39 53 50 1 09 3 05 2 0 1	8 38 0	2540	401012110292101 401015110161201	1230 2110	200 36
39 58 52 109 17 28 0 1 39 59 04 108 164600	29940 3425	1	401017109091701	3633	1
39 59 06 1 09 3628 0 1	55300	3234	401017110081702	4480	40
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400245108462600 400301108165000	2050 29 370	665 1	401235110451801 401240110502101	369 0 128 2	340 110
400302108145000	5571	- 1	401244110502602	4430	548
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4005 18 109 40 360 1	2340	125	401619107502901	1250	l
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400736110352601 400748110163801	2820 6743	1 7600	40 19 17 109 2258 01 40 19 55 109 14 140 1	1060 1420	40 1
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STATION NUMBER	TES (PFM)	TOTAL DEPIH (FT) 411608107373701 411749109405901	1236 659 6	1 2400
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402346106590001 402347107351900	1690 1020	1	413142109280201 413149107313501	1210 1650	764 0
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402422109182901 402424110092401	1300 29884	733 11860	413245106430001 413246108425900	1280 1135	49 30 1
402437109420601	2035	69 15	413300108063001	3450	o
402444110010201 402457110045901	10400	109 50	413320110234701	1390	0
402457110045901	13310 29550	11130 10510	413330109 320001 413339 109 18 1401	248 0 116 0	15 150
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4058 40108 222500	1380	1	4153 14109 29 06 01	1 08 0	1029
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411016108490001	2400	145	420605109223401	2550	265
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411445109353001 411506109355001	169 G 169 C	22 18 22 18	421346110152201	2610	200
,550.0.00001	1090	22 15	421501110115001	1660	265

STATION NUMBER	TDS (PRI)	TOTAL DEFTH (FT)	422505109451001	651C	29.0
			422515109551001	1650	300
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421755109552001	7020	49 3	424622110020001	1030	200
421835107272801	4920	120	430116109325001	2390	:
421847109512101	1040	205	431636110005701	1140	;
4219 05109 512001	1030	349	431702110010001	1000	
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422150109554001	1730	420	421551110120701	1510	205
422335109463501	3160	218		1310	55

APPENDIX B

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).

= latitude (north, positive). = declination (north, positive). = hour angle (solar noon, ω =

A.M., positive).

the angle of incidence of beam radiation.

With these angles we can calculate the Zenith angle, $\theta_{\rm Z}$, 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, ts:

$$\omega_{\rm s} = -\cos^{-1} (\tan \phi \tan \delta)$$

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

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

$$q_h = \int_0^{t_s} a \sin \omega t \, dt = 2 a t_s/\pi$$

$$(Btu/ft^2-day)$$

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

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, qhh)

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

$$= \frac{q_{h}}{2} \left[\cos \left(\frac{\pi t_{j+1}}{t_{s}} \right) - \cos \left(\frac{\pi t_{j}}{t_{s}} \right) \right]$$

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

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

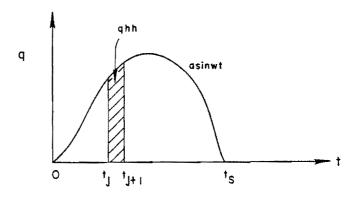


Figure B-1. Total daily and hourly solar

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

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

where

C = sky factor (smaller when cloudy)
$$= \frac{q_h}{I_{se} \cos \theta_z}$$

 I_{se} = solar intensity outside of atmo- $= 428.881 \{1+2 \{0.01673 \text{ sin} \}$

 $[2\pi (day+81)/365]$ } (Btu/ft²)

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

$$\operatorname{Ref} = \frac{1}{2} \left[\frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} + \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \right];$$
when $\theta_1 \neq 0$

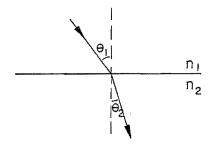


Figure B-2. Transmission of solar radiation.

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

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, I₂, and the absorbed solar energy, I₁, can simply be described as $I_2 = I_0 \text{ Ref}$ $I_1 = I_0 \text{ (1-Ref)}$ where I_0 is the solar incidence.

$$I_2 = I_0 \text{ Ref}$$

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

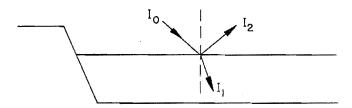


Figure B-3. Transmission and absorption of solar radiation.

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/1), slurry 2 is intermediate (TDS 4,640 mg/1), and slurry 3 is the highest (TDS 13,200 mg/1).

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 $^{\rm CO}_{\rm 3}/^{\rm CO}_{\rm 1}$

	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	а	<0.6	<2.
3	<0.5	<0.6	12.
4	<0.5	<0.6	<2.
The state of the s			

a Insufficient sample to complete analysis.

Table C-4. Barium; µg Ba/liter.

	Slurry 1	Slurry 2	Slurry 3
Saline Transport	***	0.5	E 7
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 l	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.
Ž.	Y 161.	N 315.	y 398.

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

	Slurry l	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-13. Copper; µg Cu/liter.

	Slurry l	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-10. Chromium; µg Cr/liter.

	Slurry l	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-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-11. Cobalt; µg Co/liter.

	Slurry l	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	а	N <2.	N < 2.
4	a	N <2.	N <2.

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-12. Conductivity; µmhos/cm. Table C-16. Lead; µg Pb/liter.

	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.

	Slurry l	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.

 $^{^{\}mathrm{a}}$ Insufficient sample to complete analysis.

 $^{^{\}mathrm{a}}$ Insufficient sample to complete analysis.

Table C-17. Lithium; µg Li/liter.

	Slurry l	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. Table C-22. Nickel; μ g Ni/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.

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

^aThe 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 l	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 8.	y 7.	Y 12.
3	Y 4.	N 3.	Y 5.
4	y 8.	Y 7.	Y 7.

Table C-26. pH; pH units.

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

Table C-27. Phosphate, ortho-; mg P/liter. Table C-31. Silica; mg SiO_2 /liter.

	Slurry l	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-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

 $^{^{\}mathrm{a}}$ Total phosphorus was not run on the samples from slurry 1.

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-30 Selenium; µg Se/liter.

	Slurry l	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.

	Slurry l	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-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.

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

Slurry l	Slurry 2	Slurry 3
461.	613.	3400.
Y 512.	Y 676.	N 3320.
Y 707.	Y 873.	N 3680.
N 483.	Y 697.	N 3400.
Y 406.	N 606.	Y 3100.
	461. Y 512. Y 707. N 483.	461. 613. Y 512. Y 676. Y 707. Y 873. N 483. Y 697.

Table C-34. Strontium; mg Sr/liter. Table C-37. Zinc; μ g Zn/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-35. Sulfate; mg $SO_4/liter$.

	S.	lurry 1	S.	lurry 2	S	lurry 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.

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

	C11	C1	<u> </u>
	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.

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, CO3.	Table D-6. Barium, Ba.
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 *	SALINE TRANS MEDIA 1 COAL MINE TWO 1 + COAL MINE ONF 1 + COAL MINE THREF 1 + COAL MINE FOUR 1 +
Table D-2. Alkalinity, CO ₃ .	Table D-7. Barium, Ba.
Sample Slurry No.	Sample Slurry No.
COAL MINE FOUR 3 * COAL MINE THPFF 3 ** COAL MINE ONF 3 * COAL MINE TWO 3 * SALINE TRANS MEDIA 3 *	SALINE TRANS MEDIA 2 + COAL MINE FOUR 2 + COAL MINE THREE 2 + COAL MINE TWO 2 + COAL MINE ONE 2 +
Table D-3. Aluminum, A1.	Table D-8. Barium, Ba.
Sample Slurry No.	Sample Slurry No.
SALINE TRANS MEDIA 1 * COAL MINE THREE 1 * * COAL MINE TWO 1 * * COAL MINE FOUR 1 * COAL MINE ONF 1 *	COAL MINE THREE 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 * COAL MINE ONF 3 * COAL MINE FOUR 3 *
Table D-4. Aluminum, Al.	Table D-9. Boron, B.
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 +	SALINE TRANS MEDIA 1 COAL MINE THREE 1 * COAL MINE OMF 1 * COAL MINE FOUR 1 * COAL MINE TWO 1 *
Table D-5. Aluminum, Al.	Table D-10. Boron, B.
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 +	SALINE TRANS MEDIA 2 COAL MINE ONE 2 + COAL MINE THREF 2 + COAL MINE FOUR 2 + COAL MINE TWO 2 +

Table D-11. Boron, B. Sample Slurry No. SALINE TRANS MFDIA 3 COAL MINE ONF 3 * COAL MINE FOUR 3 * COAL MINE TWO 3 * COAL MINE THREE 3 *	Table D-16. Chloride, Cl. Sample Slurry No. SALINE TRANS MEDIA 2 COAL MINE FOUR 2 COAL MINE THREE 2 COAL MINE THREE 2 COAL MINE ONE 2 COAL MINE TWO 2
Table D-12. Calcium, Ca. Sample Slurry No. COAL MINE TWO 1 COAL MINE THREF 1 COAL MINE ONF 1 SALINE TRANS MEDIA 1 COAL MINE FOUR 1	Table D-17. Chloride, Cl. Sample Slurry No. COAL MINE THREE 3 * COAL MINE ONF 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 * COAL MINE TWO 3 * COAL MINE FOUR 3 *
Table D-13. Calcium, Ca. Sample Slurry No. COAL MINE ONF 2 * COAL MINE THO 2 * COAL MINE THREF 2 * COAL MINE FOUR 2 * SALINE TRANS MEDIA 2 *	Table D-18. Cobalt, Co. Sample Slurry No. COAL MINE THREE ? * COAL MINE FOUR ? * SALINE TRANS MEDIA ? * COAL MINE ONE ? * COAL MINE ONE ? *
Table D-14. Calcium, Ca. Sample Slurry No. COAL MINE DNF 3 COAL MINE THRFF 3 COAL MINE THRFF 3 COAL MINE TRANS MFDIA 3 COAL MINE FOUR 3 *	Table D-19. Cobalt, Co. Sample Slurry No. COAL MINE ONF 3 * COAL MINE TWO 3 * SALINE TRANS MEDIA 3 * COAL MINE FOUR 3 * COAL MINE THREF 3 *
Table D-15. Chloride, Cl. Sample Slurry No. SALINE TRANS MEDIA 1 * COAL MINE FOUR 1 * COAL MINE THREF 1 * COAL MINE ONF 1 * COAL MINE TWO 1 *	Table D-20. Copper, Cu. Sample Slurry No. SALINE TRANS MEDIA 1 * COAL MINE ONF 1 * COAL MINE THREE 1 *

Table D-21. Copper, Cu.	Table D-26. Iron, Fe.
Sample Slurry No.	Sample Slurry No.
COAL MINE THREE 2 * COAL MINE FOUR 2 * SALINE TRANS MEDIA 2 * * COAL MINE ONE 2 * * COAL MINE TWO ? *	SALINE TRANS MEDIA 3 COAL MINE FOUR 3 COAL MINE TWO 3 * COAL MINE ONE 3 * COAL MINE THREE 3 *
Table D-22. Copper, Cu.	Table D-27. Lead, Pb.
Sample Slurry No.	Sample Slurry No.
COAL MINE THREE 3 * COAL MINE TWO 3 * COAL MINE ONF 3 * COAL MINE FOUR 3 * SALINE TRANS MEDIA 3 *	COAL MINE THREE ? * COAL MINE FOUR ? * SALINE TRANS MEDIA ? * COAL MINE ONF ? * COAL MINE TWO ? *
Table D-23. Fluoride, F.	Table D-28. Lead, Pb.
Sample Slurry No.	Sample Slurry No.
COAL MINF FOUR 3 COAL MINE THREF 3 * COAL MINE TWO 3 * COAL MINE ONF 3 * SALINE TRANS MEDIA 3 *	COAL MINE THREE 3 COAL MINE ONE 3 SALINE TRANS MEDIA 3 COAL MINE TWO 3 4 4 COAL MINE FOUR 3 +
Table D-24. Iron, Fe.	Table D-29. Lithium, Li.
Sample Slurry No.	Sample Slurry No.
COAL MINE THREE 1 + COAL MINE TWO 1 + SALINE TRANS MEDIA 1 + COAL MINE FOUR 1 + COAL MINE ONE 1 +	SALINE TRANS MEDIA 1 COAL MINE ONE 1 * COAL MINE THREE 1 * COAL MINE TWO 1 * COAL MINE FOUR 1 *
Table D-25. Iron, Fe.	Table D-30. Lithium, Li.
Sample Slurry No.	Sample Slurry No.
SALINE TRANS MEDIA 2 * COAL MINE TWO 2 * COAL MINE FOUR 2 * COAL MINE THREE 2 * COAL MINE ONE 2 *	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.	Table D-36. Molybdenum, Mo.
Sample Slurry No.	Sample Slurry No.
COAL MINE ONE 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 * COAL MINE FOUR 3 * COAL MINE THREE 3 *	SALINE TRANS MEDIA 2 COAL MINE FOUR 2 * COAL MINE ONE 2 * COAL MINE THREE 2 * COAL MINE TWO 2 *
Table D-32. Manganese, Mn.	Table D-37. Molybdenum, Mo.
Sample Slurry No.	Sample Slurry No.
SALINE TRANS MEDIA 1 COAL MINE TWO t * COAL MINE FOUP 1 * COAL MINE THREE 1 * COAL MINE ONE 1 *	COAL MINE FOUR 3 * COAL MINE ONF 3 * SALINE TRANS MEDIA 3 * COAL MINE THREF 3 * COAL MINE TWO 3 *
Table D-33. Manganese, Mn.	Table D-38. Nitrate, N.
Sample Slurry No.	Sample Slurry No.
COAL MINE TWO 2 COAL MINE FOUR 2 * COAL MINE THREE 2 * SALINE TRANS MEDIA 2 * COAL MINE ONE 2 *	COAL MINE THREF 3 * COAL MINE ONF 3 * COAL MINE FOUR 3 * COAL MINE TWO 3 * SALINE TRANS MEDIA 3 *
Table D-34. Manganese, Mn.	Table D-39. Nitrite, N.
Sample Slurry No.	Sample Slurry No.
COAL MINE FOUR 3 + COAL MINE THREE 3 + SALINE TRANS MEDIA 3 + COAL MINE ONE 3 +	COAL MINE THREF 3 COAL MINE FOUP 3 * COAL MINE ONF 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 *
Table D-35. Molybdenum, Mo.	Table D-40. Organic carbon, C.
Sample Slurry No.	Sample Slurry No.
SALINE TRANS MEDIA 1 COAL MINE THREF 1 + COAL MINE TWO 1 + COAL MINE ONF 1 + COAL MINE FOUR 1 +	SALINE TRANS MEDIA 1 COAL MINE THREF 1 * COAL MINE TWO 1 * COAL MINE FOUR 1 * COAL MINE ONF 1 *

Table D-41. Organic carbon, C.	Table D-46. Potassium, K.
Sample Slurry No.	Sample Slurry No.
SALINF TRANS MEDIA 2 + COAL MINE THREE 2 + COAL MINE TWO 2 + COAL MINE FOUR 2 + COAL MINE ONE 2 +	COAL MINE TWO 2 * COAL MINE FOUR 2 * COAL MINE THREF 2 * SALINF TRANS MEDIA 2 * COAL MINE ONF 2 *
Table D-42. Organic carbon, C	Table D-47. Potassium, K.
Sample Slurry No.	Sample Slurry No.
SALINF TRANS MFDIA 3 COAL MINE THPEF 3 * COAL MINE FOUR 3 * COAL MINE TWO 3 * COAL MINE ONE 3 *	COAL MINE TWO 3 COAL MINE FOUR 3 COAL MINE THREE 3 SALINE TRANS MEDIA 3 COAL MINE ONE 3 *
Table D-43. Phosphate, ortho-, P.	Table D-48. Silica, SiO ₂ .
Sample Slurry No.	Sample Slurry No.
COAL MINE ONE 3 * COAL MINE THREE 3 * COAL MINE FOUR 3 * COAL MINE TWO 3 * SALINE TRANS MEDIA 3 *	COAL MINE TWO 1 * SALINE TRANS MEDIA 1 * COAL MINE THREE 1 * COAL MINE FOUR 1 * COAL MINE ONE 1 *
Table D-44. Phosphorus, total, P. Sample Slurry No.	Table D-49. Silica, SiO ₂ . Sample Slurry No.
COAL MINE FOUR 3 * COAL MINE TWO 3 * * COAL MINE THREF 3 * COAL MINE ONE 3 * SALINE TRANS MEDIA 3 *	COAL MINE ONF 3 COAL MINE THREF 3 * COAL MINE TWO 3 * COAL MINE FOUR 3 * SALINE TRANS MEDIA 3 *
Table D-45. Potassium, K. Sample Slurry No.	Table D-50. Silver, Ag. Sample Slurry No.
SALINE TRANS MEDIA 1 COAL MINE TWO 1 * COAL MINE THREF 1 * COAL MINE FOUR 1 * COAL MINE ONF 1 *	COAL MINE THREF 1 + SALINE TRANS MEDIA 1 + + COAL MINE ONF 1 + + + COAL MINE FOUR 1 + + COAL MINE TWO 1 +

Table D-51. Silver, Ag.	Table D-56. Strontium, Sr.
Sample Slurry No.	Sample Slurry No.
COAL MINE THREE 2 + COAL MINE ONE 2 + SALINE TRANS MEDIA 2 + COAL MINE FOUR 2 + COAL MINE TWO 2 +	SALINE TRANS MEDIA 1 COAL MINE ONE 1 * COAL MINE THREE 1 * COAL MINE FOUR 1 * COAL MINE TWO 1 *
Table D-52. Silver, Ag.	Table D-57. Strontium, Sr.
Sample Slurry No.	Sample Slurry No.
COAL MINE FOUR 3 * COAL MINE THREE 3 * COAL MINE ONE 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 *	SALINE TRANS MEDIA 2 * COAL MINE ONE 2 * COAL MINE THREE 2 * COAL MINE FOUR 2 * COAL MINE TWO 2 *
Table D-53. Sodium, Na.	Table D-58. Strontium, Sr.
Sample Slurry No.	Sample Slurry No.
COAL MINE FOUR 1 SALINE TRANS MEDIA 1 * COAL MINE THREE 1 * * COAL MINE OHF 1 * COAL MINE TWO 1 *	SALINE TRANS MEDIA 3 COAL MINE ONE 3 COAL MINE THREE 3 COAL MINE FOUR 3 COAL MINE TWO 3
Table D-54. Sodium, Na. Sample Slurry No.	Table D-59. Sulfate, SO ₄ . Sample Slurry No.
COAL MINE FOUR 2 * SALINE TRANS MEDIA 2 * COAL MINE ONE 2 * COAL MINE THREE 2 * COAL MINE TWO 2 *	BALINF TRANS MEDIA 1 COAL MINE ONF 1 * COAL MINE THREF 1 * COAL MINE FOUR 1 * COAL MINE TWO 1 *
Table D-55. Sodium, Na. Sample Slurry No.	Table D-60. Sulfate, SO ₄ . <u>Sample</u> <u>Slurry No.</u>
COAL MINE FOUR 3 * COAL MINE ONF 3 ** SALINE TRANS MEDIA 3 ** COAL MINE THREE 3 ** COAL MINE THREE 3 **	COAL MINE THREE 2 * SALINE TRANS MEDIA 2 * * COAL MINE FOUR 2 * * COAL MINE ONF 2 * COAL MINE TWO 2 *

Table D-61. Sulfate, SO ₄ .	Table D-63. Zinc, Zn.
Sample Slurry No.	Sample Slurry No.
SALINE TRANS MEDIA 3 COAL MINE FOUR 3 + COAL MINE ONE 3 + COAL MINE THREE 3 + COAL MINE TWO 3 +	COAL MINE ONF 1 * COAL MINE TWO 1 * COAL MINE THREE 1 * SALINE TRANS MEDIA 1 * COAL MINE FOUR 1 *
Table D-62. Total dissolved solids, TDS.	Table D-64. Zinc, Zn.
Sample Slurry No.	Sample Slurry No.
COAL MINE POUR 3 * COAL MINE ONE 3 * COAL MINE THREE 3 * SALINE TRANS MEDIA 3 * COAL MINE TWO 3 *	COAL MINE ONF 2 COAL MINE FOUR 2 * COAL MINE TWO 2 * * COAL MINE THREE 2 * * SALINE TRANS MEDIA 2 *

Table D-65. Zinc, Zn.

Sample	Slur	<u>.</u>			
COAL MINE	ONF	3			*
COAL MINE	TWO	3		*	*
COAL MINE	THREE	3		*	
COAL MINE	FOUR	3	*		
SALINF TR	ANS MEDIA	3	*		