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USE OF HIGH TDS WATER FOR COOLING AT THERMAL ELECTRIC GENERATING PLANTS

Trevor C. Hughes[1], J. Clair Batty[2], and C. Earl Israelsen[3]

[1]Research Scientist at the International Institute for Applied Systems Analysis, Laxenburg, Austria.

[2]Professor of Mechanical Engineering at Utah State University, Logan, Utah.

[3]Research Scientist at the Utah Water Research Laboratory, Logan, Utah.

SYNOPSIS

Major increases in the fraction of water resources allocated to cooling of thermal electric plants is presently occurring and this trend is projected to accelerate during the next few decades. As the freshwater resources in energy rich regions become fully allocated, additional cooling water is being acquired by transfer from other sectors, principally agriculture.

One possibility for extending regional water resource bases is to use brackish or saline water in place of fresh water. Increases in cost of operating thermal electric recirculating cooling systems as salinity of make-up water increases are modeled. The example used is a hypothetical 1000 MW power plant located in the Upper Colorado River Basin in Western US. The parameters modeled include changes in input and output quantities of cooling water and resulting increases in the size of zero-discharge effluent disposal ponds. The increased treatment costs for three operating modes are calculated. Specifically, the options modeled include: (1) no treatment other than biocide (causing large waste streams and related disposal costs); (2) water softening to prevent scaling; and (3) a combination of softening, desalination, and brine concentration.

In addition to the increased treatment and disposal costs (as functions of salinity) a relative value scale for saline water is presented. The concept involves calculation of costs one should be willing to pay for water of any level of salinity given an assumed delivery cost for water of lower (higher) salinity.

Conclusions are that it is technically feasible to operate recirculating tower type cooling systems with high salinity water (examples already exist) and indeed innovative cooling tower designs allow salinities as high as 150,000 mg/ℓ of total dissolved solids. The economic feasibility of using low quality make-up water depends upon relative costs of saline and fresh water and/or quantification of social benefits resulting from maintaining fresh water allocations to agricultural and environmental uses.

RESUMÉ

Utilisation des eaux saumâtres pour la refrigeration des centrales thermiques

Actuellement, on assiste à une forte augmentation de la part des ressources hydrauliques consacres à la réfrigération des centrales thermiques et ou prévoit que cette tendance va encore s'accéler au cours des prochaines décennies. Une possibilité pour accroitre les ressources hydrauliques environnantes disponibles est d'utilizer des eaux saumâtres ou salies à la place d'eau douce. L'augmentation des coûts opératoires des systèmes de réfrigeration en circuit ferme en fonction de la salinité de l'eau est modelisé. Les parametres modelisés comprennent les variations des quantités d'eau captées et rejetées par le système de réfrigeration ce qui se traduit par une modification de la taille des installations d'épuration des eaux rejetées. Les calculs de l'augmentation des coûts de traitement a été fait pour les modes opératoires suivants: (1) traitement exclusivement chimique (ou chlore, ce qui entraine des pertes et des couts importants); (2) adoucissement de l'eau pour éviter la formation de tartre; (3) une combination d'adoucissement, de desalement et de concentration de saumure. En conclusion, on montre qu'il est techniquement possible d'utiliser des eaux fortement salies dans des systèmes de réfrigeration en circuit fermé (des exemples existent déjà) de plus des nouvelles conception de systemes de refroidissement autorisent des concentrations de l'ordre de 150,000 mg/ℓ de matières dissoutes. La faisabilité économique de l'utilisation des eaux de mediocre composition dépend du cout relatif entre eau salie et eau douce et/ou de la quantification du gain social obtenu en reservant l'eau douce a l'agriculture et l'environement.

RESUMEN

Un mayor aumento en la proporción de recursos hidráulicos para enfriamiento de plantas de generación electrica esta actualmente occurriendo y esta tendencia es proyectada aumentor decrante las próximas decadas. Una posibilidad para extender las bases regional de recursos hidráulicos es utilizando salolre o aguas salinas en lugar de agua dulce. Los aumentos en los gastos de operación de un sistema de enfriamiento de reciclo de generación electrica conforme la salinidad de abastecimiento de agua es modelado. Las entradas y resultados de los parametros modelados incluyen cambios en las cantidades de agua para enfriamiento, resultando aumentos en el tamaño de descargo-zero de las aguas residales. El aumento de costos de los seguientes modos son calculados: (1) Ningun tratamiento fuera del de biocido (causando grande corriente de desperdicion y causando grandes gustos de disposición. Llegamos a la conclusión que es posible recircular tecnicamente el sistema de enfriamiento con aguas de alto porcentage de salinidad (ejemplos ja existen) y en realidad diseños de torres de enfriamiento permiten que salinidades tan altas como 150,000 mg/ℓ a un total de solidos desueltos. La posibilidad economica de usar bajo calidad de abastecimientos de agua depende de los costo relativos de aguas dulce y salinas y/o los beneficios sociales resultando del mantenimiento de aguas dulces con distribución para uso de agricultura y de ambiente.

INTRODUCTION

During the shift from oil based energy to renewable energy sources in the next few decades, there will inevtiably be a period of heavy reliance upon coal and synfuels. This transition period will be associated with very large increases in water resource inputs to energy development and various environmental impact outputs within the regions where the fossil fuels are extracted, and converted to a useable energy form. Unfortunately, much of these fossil fuel resources are located in areas which are semi-arid and where high quality water resources are already completely allocated. There are, however, in many such regions, very significant quantities of water which are so high in total dissolved solids (TDS) as to be unuseable for municipal or agricultural purposes. Sources of such water can include pumped groundwater from shale and other soluble formations, artesian flow from oil and gas exploration testholes, return flows from agricultural land, effluent from coal mines, geothermal development wastewater, and even seawater. Usually the actual quantities of high TDS water are unknown because most surface and groundwater data gathering efforts have ignored this water (it is usually classified as a potential contaminant rather than a resource). In this paper high TDS water will be considered to include brackish water (1-10 thousand mg/ℓ) and saline water (10 to 35 thousand mg/ℓ).

The occurrence of large quantities of high TDS water is of course not limited to semi-arid regions. For example, in Poland (certainly a non-arid region), serious coal related saline water disposal problems exist in at least 3 river basins; and the opening of additional coal mines in the Vistula River Basin depends upon protecting the Vistula and its tributaries against additional drainage of saline groundwater from coal mines (BOJARSKI and SKINDEROWICZ, 1980; and Stone et al, forthcoming).

There appear to be two possible approaches to increasing the water supply available to water-short regions, thereby meeting demands for energy without eliminating or greatly decreasing irrigated agriculture. One solution is to import the water needed from other water-rich regions. Major importation projects are new being discussed in Canada, the USA, Mexico, Australia, India and the USSR (VOROPAEV, 1979). Importation projects usually are associated with significant negative environmental impacts in the exporting basins and therefore should not be implemented before exhausting all possible management concepts for local water resources.

This brings us to the second approach for increasing the supply of water available for energy demands, which is the use of high TDS water. This concept is not feasible for irrigation users since it would require treatment costs which greatly exceed the value of irrigation water except in very unusual circumstances (very high valued crops). However, the energy industry experiences no such constraint. Even if the additional treatment costs due to using high TDS water were \$0.40 per m^3, the marginal increase in cost of operating a thermal electric power plant would be only 2.6% (Israelsen et al, 1980). If the plants were designed specifically for use of such water, the cost increase should be considerably less.

The remainder of this paper will summarize research on the economic feasibility of using high TDS water for cooling of thermal electric power plants which has been done at Utah State University and will outline continued work on this topic which is being undertaken at both USU and the International Institute for Applied Systems Analysis (IIASA).

UPPER COLORADO CASE STUDY

The research project at USU focused upon use of high TDS water for energy development within the Upper Colorado River basin. This basin has several characteristics which make the TDS water use concept attractive as follows: (1) Total water demand is rapidly approaching total supply. (2) Very large energy related water demands are projected for the near future. (3) The Colorado river already has a serious salinity problem. Its magnitude is suggested by the fact that various studies which attempted to quantify the value of reducing its salinity (actually the measure of damages to downstream water users) have calculated it as US $ 230,000 to $ 320,000 for each mg/ℓ of change (Narayanan et al, 1979).

A thermal electric power plant with multiple circulation through cooling towers can be conceptualized for our purposes as a black box which requires water and fossil fuel as inputs and which outputs a much smaller quantity of water (having evaporated some 90% of the make-up water). Once through cooling will not be considered because of the immense water diversion quantities required. Of particular interest is the fact that essentially the entire quantity of input minerals is returned in the concentrated blowdown (cooling tower waste) stream. Consider a hypothetical 1,000 MW power plant operating at 35% thermal efficiency and an 80% load factor which has average cooling water cycle flows (using high quality water) as shown in Figure 1. The actual Rankine power cycle water system is not shown since its make-up water requirement is extremely small and it has essentially no effluent. We will be concerned only with the cooling cycle which rejects the hugh quantities waste heat to the atmosphere. The number of cycles through cooling towers and the water treatment and disposal costs are all functions of salinity of the make-up water. Therefore, the focus of the following cooling water system modeling discussion will be upon calculating changes on these costs, as salinity is varied.

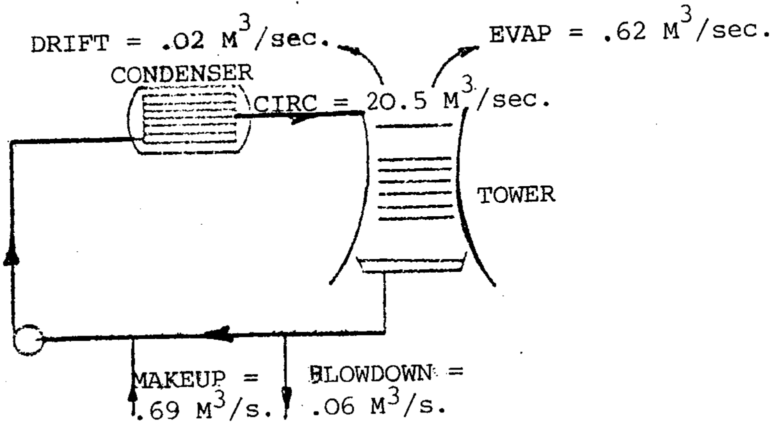

Figure 1 . Typical Water Flow Rates in the Conventional Cooling Water Loop of a 1000 MW Power Plant.

The added costs for operating a cooling system as salinity increases depend in part on the particular ions 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 1. The broad implications of using these kinds of waters in conventional power plant cooling are examined.

Mass Balance Equations

The flow mass balance equations necessary to calculate the cooling tower system input/output relationships are the following:

Make-up Water = drift loss + Evap. Loss + Blowdown (1)

Make-up Salt = drift salt + Blowdown salt (2)

Table 1. Concentration of Constituents in Cooling Tower Make-up Waters

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

An energy balance for the cooling tower is:

$$\dot{Q} = \dot{M}_1 h_1 - \dot{M}_2 h_2 \quad (3)$$

where the $\dot{M}_i$ and h_i terms are mass flow rates and specific enthalpy respectively of the water entering and leaving the tower and $\dot{Q}$ is the rate of heat rejection from the 1000 MW plant as shown in Figure 2. The bd and mu notation refers to blowdown and make-up.

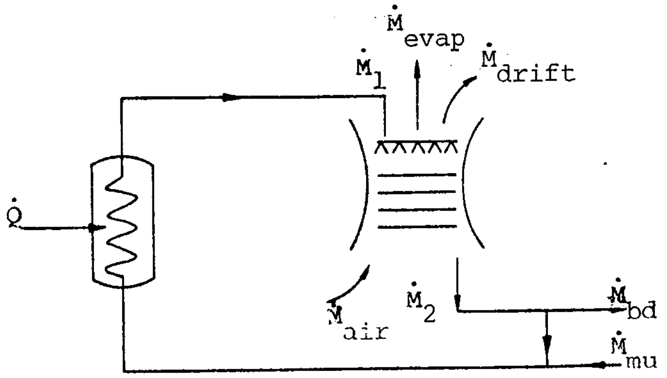

Figure 2. Basic Elements of the Cooling Tower

$\dot{Q}$ can be calculated as (note that waste heat from a plant with 35% efficiency and 80% load factor can be approximated as 40% efficiency at 100% load):

$$\dot{Q} = 1000\ (1.0 - .4)/.4 = 1500\ \text{MW} = 5.12(10^9)\text{BTU/hr}. \quad (4)$$

By assuming temperatures entering and leaving the tower of 43.3°C and 26.7°C and an evaporation rate of 1% of the circulating water per 5.5°C (10°F) reduction in temperature, we have:

$$\dot{M}_{evap} = .01\ \dot{M}_1\ (\Delta T)/5.5 = .03\ \dot{M}_1 \quad (5)$$

Also drift will be estimated at 0.1% of $\dot{M}_1$. From these simple equations the make-up and blowdown water flow rates can be calculated as a function of their salt concentrations if no water treatment (other than a biocide to prevent organic growth on surfaces) is used. The results of such calculations are displayed as Figure 3 for a single upper limit of circulating water salinity.

The actual upper limit on salinity (and more importantly the type of salinity) that is permitted is a function of the design and type of materials used in the cooling system and/or the extent and type of water treatment provided. The additional investment costs for corrosion and deposition prevention materials in the cooling system are not modeled in this paper. However, water treatment costs will be included and treatment such as softening is to a large extent an alternative to more expensive materials. As Figure 3 shows, the quantity of both make-up and blowdown water increase with salinity of make-up and as the make-up salinity approaches the circulating water limit, the quantity of blowdown approaches the quantity of make-up (thereby approaching the unfeasible domain of once-through cooling).

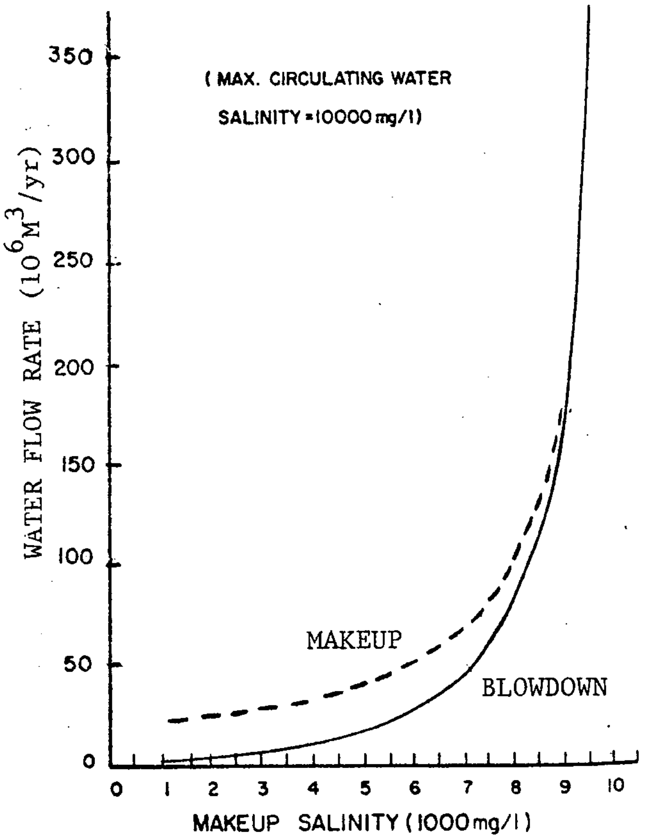

Figure 3. The Impact of Make-up Salinity on the Annual Volume of Make-up and Blowdown Water necessary for cooling a 1000 MW Power Plant without Water Treatment.

Water Treatment and Disposal Costs

From the large array of possible make-up and/or recirculating water treatment methods only 3 will be evaluated here.

Option 1. No treatment--Disposal in Evaporation Ponds:

The mass balance equations already presented provide a means of calculating water and salt inflows and outflows from the cooling loop. The only treatment cost assumed will be the relatively minor cost of biocide.

The disposal costs are essentially those for constructing an evaporation pond designed for zero discharge during a critical (high precipitation/low evaporation) year. The calculation of required pond volume and area as a function salinity and therefore volume of inflow (blowdown) is difficult since evaporation rate depends upon wind, radiation, temperature of water and air, precipitation, relative humidity, salinity, and most important - the pond area itself. Therefore, an iterative computer program was developed to calculate pond sizes given climatic data for an average and a critical year in the case study area. The related construction costs were then estimated by assuming flat topography, a plastic lining and allowance for mineral deposition at the bottom for 40 years plus 1 meter of brine depth. The cost per unit of pond area is somewhat size dependent but generally in the $85,000 - $100,000/hectare range. The pond size model and cost functions are detailed in Israelsen et al, (1980).

Option 2. Softening of Make-up Water plus Sidestream Treatment (& Disposal):

This option requires cold process softening (addition of lime to precipitate Mg^{++}, Ca_a^{++}, and S_iO_2) for both the make-up water and recirculation side stream to keep hardness below 400 mg/ℓ and prevent scaling (Figure 4). Lime quantities were calculated as a function of Ca and Mg in the make-up water. Capital costs and cost of lime were estimated at 1980 US levels. Disposal costs were calculated as described for Option 1.

Option 3. Make-up Water Softening plus Desalination and Brine Concentration of Blowdown (& Disposal):

This option replaces side stream softening with both reverse osmosis (r.o.) and brine concentration of the r.o. waste stream. The assumed brine concentration (b.c.) design has been used in several recently constructed plants in the Colorado Basin. It has a waste stream of only 7% of inflow and the only external energy required is that to drive compressor (24 Kwh/M^3 of feed). The tandem operation of the r.o. and b.c. units (Figure 6) appears to be efficient since the r.o. unit produces a large reject stream of about 48% of feed. The costs and details of operation are given in Israelsen et al, (1980). Disposal costs were calculated as described previously.

Results

The water treatment and disposal costs for the 3 options and a range of make-up water and circulating water salinity are given in Figures 6, 7, and 8.

Option 1 is not realistic both because of scaling problems (no softening is provided) and because of the large evaporation ponds required. It is included here only to show the reduction in disposal costs which results from proper treatment (it consists of only disposal costs plus a small biocide cost).

Disposal costs are greatly reduced as the circulating salinity is allowed to increase as indicated by Figure 6. However, some increase in capital cost of the cooling system would also occur as allowable circulating salinity is increased (due to changes in materials for corrosion protection) and these costs are not included. Figures 7 and 8 show a clear advantage for option 3 (softening, desalination and brine concentration) as compared to option 2 (softening only).

Relative Value of Water as a Function of Salinity

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 \$.08/M^3 and better quality of water (for example, TDS = 1,000 mg/ℓ) is available but the cost delivered to the plant is \$.40/M^3. 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 5,000 mg/ℓ make-up water consider the following equations:

$$MU_i \times VALUE_i + COST_i = MU_5 \times VALUE_5 + COST_5 \qquad (6)$$

where the MU_i and MU_5 are quantities of make-up water of salinity i and 5,000 mg/ℓ respectively, $VALUE_i$ and $VALUE_5$ are the value (in the case of MU_i) and the price (in the case of MU_5) of make-up water delivered to the plant. $COST_i$ and $COST_5$ are the water treatment and disposal costs as described previously. By assuming a price for 5,000 mg/ℓ water and calculating the costs and quantities via equations already given one could calculate $VALUE_i$ which should be interpreted as the highest cost one should pay for water of salinity i. The results of such calculations for assumed allowable circulating salinities of 10,000 and 24,000 respectively are displayed graphically in Figures 9 and 10. For example, if circulating water at 10,000 mg/ℓ is allowed in a system using option 2 treatment and make-up water of 5,000 mg/ℓ is deliverable at $\$.08/M^3$ one should pay as much as $\$.80/M^3$ for water of 1,000 mg/ℓ. If however, the circulating limit is relaxed to 24,000 mg/ℓ then no more than $\$.32/M^3$ should be paid for the better quality water.

DISCUSSION

The potential for utilizing high TDS water in energy related uses includes other applications such as transport media for coal slurry lines (with recycling as cooling water at the destination), cooling for coal gasification and other synfuel conversion processes, materials handling and dust control at mines. The summary of the economic modeling effort reported here was limited to only a single application--cooling of thermal electric generating plants. The equations allow calculation of variations in both input and output quantities of water and treatment and disposal costs as a function of make-up water TDS. Some of the costs and the evaporation pond sizes are specific to the Upper Colorado River Basin but the methodology should be useful in other climates and economies.

There is no question that cooling systems can be designed for successful operation with highly saline water. Examples of existing plants which use circulating water varying from brackish to seawater (7,800 to 45,000 mg/ℓ TDS) are Chalk Point (Washington, D.C.), Turkey Point (Florida), and Forked River (New Jersey). Also, there is considerable current activity related to developing innovative cooling tower designs specifically for operating at very high salinities. An example which appears very promising is the Binary Cooling Tower (BCT) concept which is being proposed in the US. The BCT approach uses a closed loop of high quality water with heat exchange to a secondary fluid through a thin membrane in the cooling tower. The secondary fluid (which rejects the heat by evaporation) can be at salinities as high as 150,000 TDS.

The economic aspects of make-up water quality selection can be reduced to questions of: (1) cost of delivering low quality water relative to the cost of higher quality alternatives (by using the methods presented here for calculating treatment and disposal costs); and (2) increases in cooling system investment cost as a function of circulating water salinity and the tradeoffs between treatment and investment costs which are possible (which are not included in this paper but will be the subject of future research). As demonstrated here increasing the make-up water salinity causes significant increases in both the quantities of required supply and waste streams and treatment and disposal costs. This implies

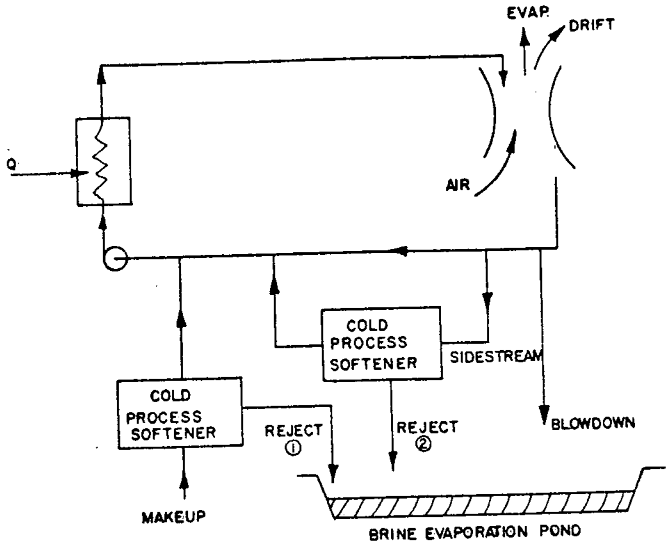

Figure 4. Simplified Schematic of Water Treatment Option 2 in which Mg, Ca, and SiO_2 are controlled within Specified Limits.

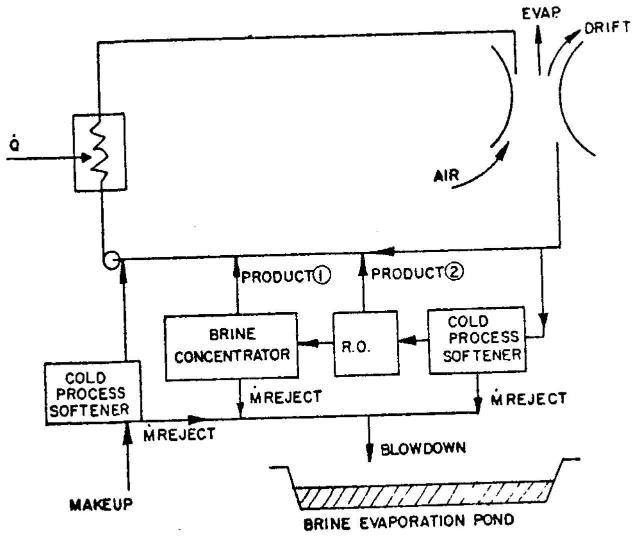

Figure 5. Schematic of Option 3 in which Makeup Water is softened and Blowdown Concentration is provided.

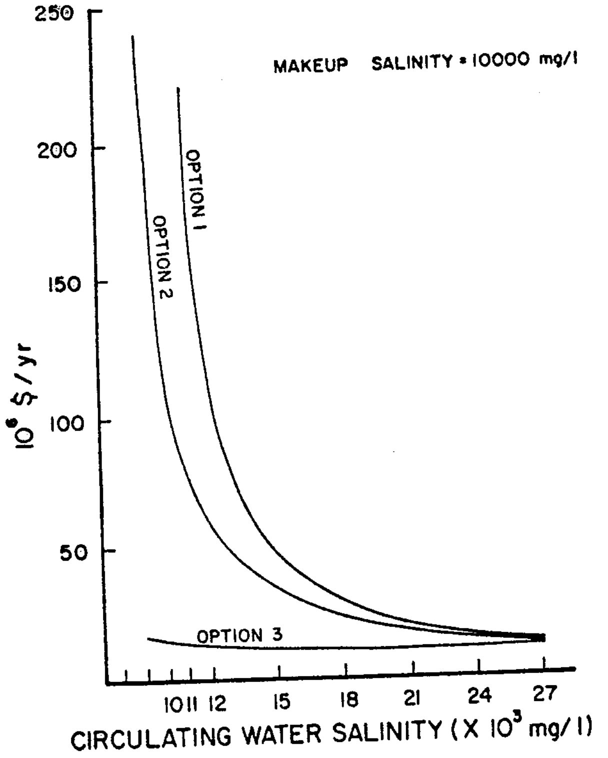

Figure 6. Water Treatment and Disposal Costs as a Function of the allowable TDS of circulating Loop Water assuming the Salinity of the Make-up Water is 10,000 mg/ℓ.

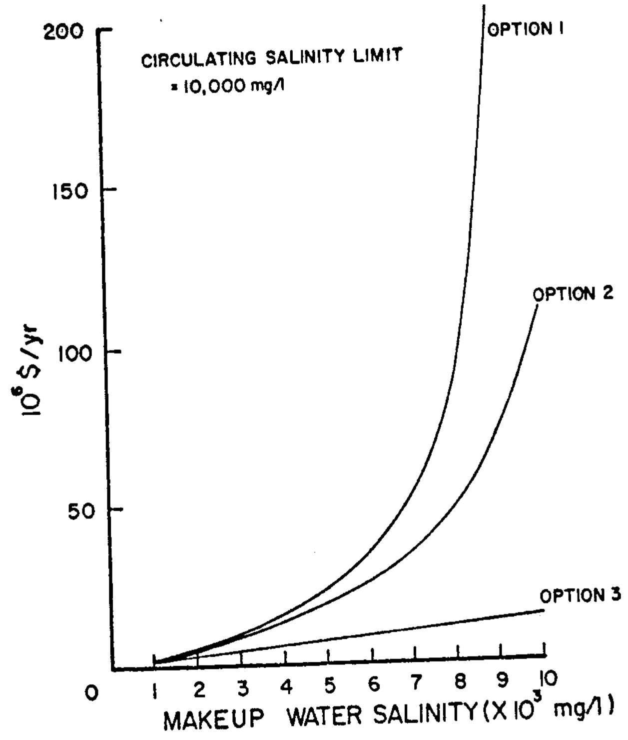

Figure 7. Water Treatment and Disposal Costs as a Function of Make-up Water Salinity assuming the TDS Limit of the circulating Water is 10,000 mg/ℓ.

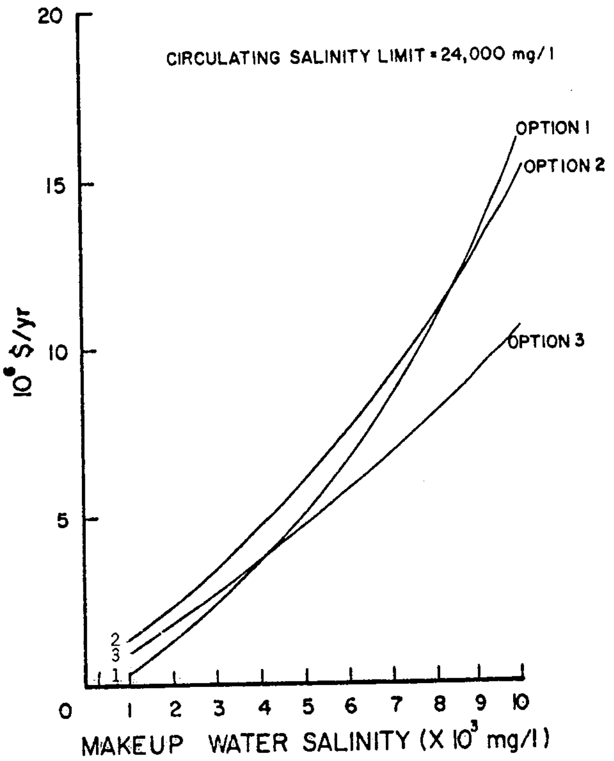

Figure 8. Water Treatment and Disposal Costs as a Function of Make-up Water Salinity assuming the TDS Limit of the circulating Water is 24,000 mg/ℓ.

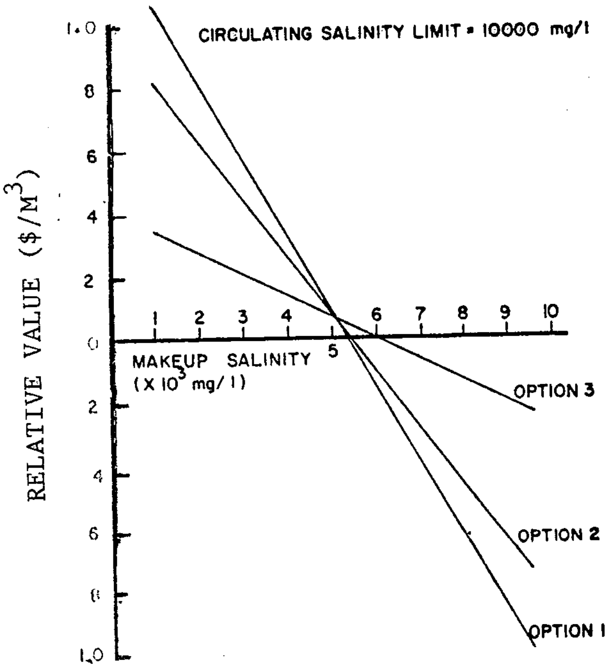

Figure 9. Relative Value of Make-up Water assuming 5000 mg/ℓ water is available at \$.08/M^3 and Circulating Water Salinity Limit is 10,000 mg/ℓ.

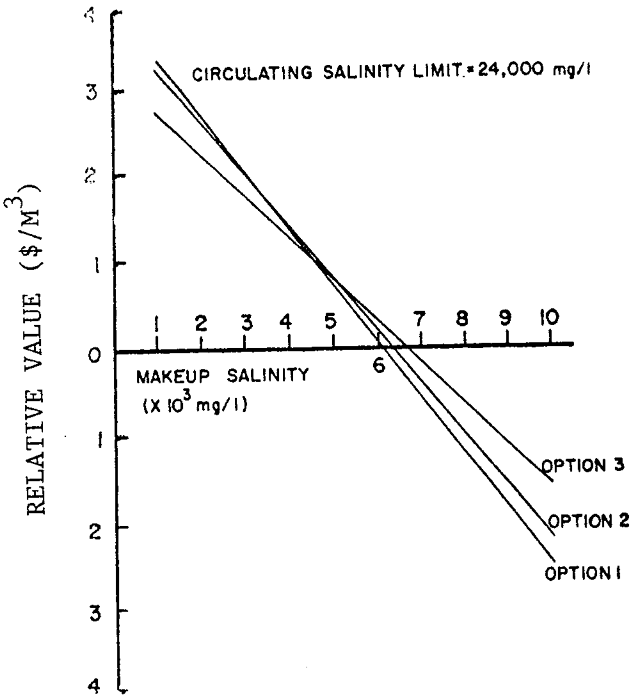

Figure 10. Relative Value of Make-up Water assuming 5,000 mg/ℓ water is available at \$.08/M^3 and Circulating Water Salinity Limit is 24,000 mg/ℓ.

that so long as fresh water is available at a cost less than the positive value levels indicated by Figures 9 and 10 (and adjusted for other climates) the power producers will continue to seek high quality water (usually by purchases from agriculture). If sufficient social and/or environmental benefits can be identified for maintaining the high quality water either in a stream or for diversion by users which cannot use the available low quality sources, then governmental incentives such as tax allowances for using the low quality water for cooling may be appropriate.

Space limitations prevent a discussion of possible environmental benefits which such low quality water use could create. The basic notion, however, is that it is possible to convert a power plant from a salt concentrator to a salt remover by both evaporating saline rather than good quality water and by disposing of minerals on pond bottoms rather than returning them to the river. In this context pond life (based upon mineral storage volume) equal to the life of the power plant becomes important unless commercial recovery of minerals is feasible--which is currently doubtful.

Another topic which is not addressed here but is of importance is the problem of mineral disposal in climates where zero discharge holding ponds are not feasible. In that situation one can envision small brine pipelines to deliver water to large rivers, seas, or to more arid regions.

The International Institute for Applied Systems Analysis at Laxenburg, Austria, is currently planning research on this topic as part of their ongoing regional water management task. The objectives will include extending the modeling effort begun at Utah State University, addressing the question of disposal in non-arid climates, identifying case studies in both planned and market economies, and assessing the potential benefits of desalinating municipal water supply with waste heat from thermal generating plants. IIASA collaborators will include but certainly not be limited to USU, where research is also continuing. A current topic of interest at USU is use of the inverse thermal gradient in solar ponds (ponds created for power plant effluent waste disposal) for supplementing energy production.

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