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Water Recycle/Reuse Possibilities: Power Plant Boiler and Cooling Systems

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WATER RECYCLE/REUSE POSSIBILITIES:
POWER PLANT BOILER AND COOLING SYSTEMS

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ROAP 21AZU
Task 23

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ABSTRACT

This report contains the methodology to evaluate, in economic terms, potential power plant boiler and cooling system water recycle/reuse programs. Drum type boiler systems and closed cycle cooling systems are used as the basis for the programs' water requirements. The evaluations take into account the variable plant characteristics such as makeup water quality, fuel type, thermal efficiency, capacity factor and fixed charge rate.

The evaluation methodology is applicable to existing and proposed power plants, on an individual plant basis--and can be used to determine the over-all economics of potential recycle/reuse programs.

The report is the first of a series that addresses the water recycle/reuse potentials of typical power plant processes. This report is submitted in fulfillment of Task 23 of ROAP 21AZU of the Environmental Protection Agency. Work was completed as of November, 1974.

CONTENTS

FIGURES

TABLES

SECTION I
CONCLUSIONS

One potential contribution to meeting the overall goal of environmental protection in electric power production is to adopt water recycle and reuse programs within and between power plant systems and processes that use and/or discharge water. Two such systems that are common to both nuclear and fossil-fueled power plants are the boiler and cooling systems. However, before recycle/reuse programs between these two systems can be adopted, at least two questions must be answered:

1. How can the two processes be categorized as to water quality and quantity requirements? Once this question is answered, recycle/reuse programs can be proposed that reduce makeup water requirements and total plant discharges.

2. Given the broad spectrum of power plant operating conditions, how can the recycle/reuse programs be monetarily evaluated?

BOILER SYSTEM RECYCLE/REUSE

The boiler blowdown from the flash tank can be <u>recycled</u> to the pretreatment system and then substituted as a portion of the makeup water to the boiler. The resultant economics on an individual plant basis largely depend upon boiler efficiency, percent condensate return and percent boiler blowdown.

The boiler blowdown can be <u>reused</u> without treatment as a portion of the makeup to the closed cycle cooling system. While this reuse scheme has little impact on the water intake requirements, it does provide a use for a blowdown stream that normally would be discarded, or require treatment prior to discharge.

COOLING SYSTEM RECYCLE/REUSE

There are no currently available techniques that allow cooling system blowdown to be reused as makeup to the boiler system, because:

1. Direct reuse (without treatment) is not possible because of the high water quality requirements of the boiler system.

2. Reuse after treatment by such processes as reverse osmosis, electrodialysis, brine concentration, and demineralization is yet to be demonstrated on power plant cooling system blowdown.

On the other hand there are recycle possibilities for the cooling system that show economic potential. The overall economics for any recycle scheme depends upon the following power plant characteristics:

1. Fuel type (fossil vs. nuclear)
2. Overall plant thermal efficiency
3. Cooling system cycles of concentration - both before and after the installation of the recycle program.
4. Plart capacity factor
5. Fixed charge rate for capital expenditures.
6. Percent waste heat dissipated by evaporation in the cooling system.
7. Capital and O/M costs of the programs.
8. Makeup and discharge water costs

SECTION II
RECOMMENDATIONS

This report documents thermal power plant boiler and cooling system water quality and quantity requirements and the water recycle/reuse potential of the two systems. Similar efforts are required that consider other typical plant systems and processes using and/or discharging water, such as:

1. Ash handling systems
2. Air pollution control devices
3. Coal pile and site drainage systems
4. Water pretreatment processes
5. Condensate treatment systems

With this information in hand, the final task is to refine and optimize all recycle/reuse applications on a total plant basis.

SECTION III
INTRODUCTION

To produce electricity, the thermal power generation industry has significant water quality and quantity requirements. These water requirements depend upon characteristic plant processes, as shown in Table 1. As newer, larger power plants come on line, the process water quantity requirements are increasing. At the same time, however, the water sources are not increasing. This situation -- an increasing demand for a resource whose supply remains constant -- raises potential economic and environmental problems. One possible solution to the problems is the practice of water recycle/reuse between the various power plant processes. The net result of this practice is a reduction in total, plant-wide water quantity requirements.

Webster[1] defines use (n.) as "The act of employing anything..." Water reuse then is the use of water by one system that already has been employed in and discharged from another system. An example of water reuse is boiler blowdown water being used as makeup water to a cooling tower.

Reusing Webster[1], the word, cycle, (not to be confused with cycles of concentration) is defined as, "A completed course of operations..." Water recycle is a reuse of water (by a system) that already has run a complete course through the same system. An example of water recycle is cooling tower blowdown water being treated and used as makeup water to the same cooling tower.

The most efficient recycle/reuse programs interpret each water requiring process as an integral part of the total plant water use system. This total system interpretation considers factors such as:

1. water quantity requirements (including process makeup, blowdown and recirculating water).

2. water quality requirements (including process makeup, blowdown and recirculating water).

3. plant operating characteristics that affect water requirements.

4. plant site conditions that affect water requirements and/or supply.

From this interpretation, a well defined "pecking order" emerges that establishes: firstly, where in the total water use system the recycle/reuse should be applied; secondly, which process gets a given class of water (e.g., "first use," recycled, or reused); and finally, which water streams are to be discharged without further use?

As Table 1 indicates, the number of processes in the "pecking order" is dependent on the fuel type. Furthermore, in fossil-fueled plants, fuel quality affects the number of processes. For example, depending upon ash content, an oil fired plant may or may not have an ash handling system; or depending on sulfur content, a coal-fired plant may or may not have an SO_2 removal device. However, at the very least, all power plants -- nuclear or fossil-fueled -- have a boiler and cooling system.

Two types of boiler systems and three types of cooling systems are used by the industry:

I. Boiler systems
   A. Once through
   B. Drum type
II. Cooling systems
   A. Once through
   B. Closed cycle
   C. Combination

Table 1. POWER PLANT WATER REQUIREMENTS

Fuel Type	Pretreatment	Boiler	Cooling	Condensate Treatment	Ash Handling	Air Pollution Control (including SO_2 removal)	Auxiliary
A. Nuclear*	X	X	X	X			X
B. Fossil							
1. Gas	X	X	X	X			X
2. Coal	X	X	X	X	X	X	X
3. Oil	X	X	X	X	X	X	X

*Water requirements for nuclear plant primary loop and emergency coolant supply are not addressed in this report.

Some of the more modern power plants and many of those proposed are using (or will use) drum type boiler systems and closed cycle cooling systems. The choice of the drum type boiler system is usually one of operational preference and reliability. The closed cycle cooling system is chosen generally because of water supply and/or environmental regulations. This report addresses the water qualities and quantities that are associated with these two specific systems and their recycle/ reuse potentials.

Digressing for a moment, the reader should recognize that, using the total system interpretation, any recycle/reuse program, solely between the boiler and cooling systems, may be altered when fitted into the "pecking order." However, the programs cited herein are useful in most cases because (a) the boiler system's characteristics together with the turbine and condenser design have a significant effect on the overall thermal efficiency (and, therefore, the amount of cooling water required); and (b) over 95 percent of the total plant water usage is used for cooling.[2]

Also, this report is only the first of a series which outlines the water recycle/reuse potentials of typical power plant processes. Throughout the series, an attempt is made to keep a continuity to the total system interpretation.

SECTION IV
APPROACH

This report first discusses each system's water requirements in two separate sections (titled, appropriately, THE BOILER SYSTEM and THE CLOSED CYCLE COOLING SYSTEM). Both sections have two sub-sections.

The first sub-section, WATER QUALITY, details the quality characteristics of the system's water flows...such as makeup, blowdown, and recirculating water.

The second sub-section, WATER QUANTITY, describes the amount of water required for the system's water flows. Also, it identifies the power plant's operational characteristics that affect the water quantity requirements.

The report devotes another two sections in describing how recycle/reuse possibilities can be evaluated.

The first section, TREATMENT TECHNIQUES TO ACHIEVE WATER RECYCLE/REUSE discusses--

a. The "pecking order" for recycle/reuse
b. The treatment requirements to be applied to water flows prior to recycle/reuse, and
c. Recycle/reuse economics.

In the final section, ECONOMIC EVALUATION METHODOLOGY: COOLING SYSTEM WATER RECYCLE POSSIBILITIES, three hypothetical power plant situations are described. In each situation a cooling system water recycle possibility is evaluated.

SECTION V
THE BOILER SYSTEM

Figure 1 is a schematic water flow diagram of a typical power plant boiler system.

WATER QUALITY

Boiler design pressure has the most significant effect on makeup, boiler feedwater, condensate/steam, blowdown, and flash tank effluent water quality. Typical power plant boilers operate at or above 100 Kg/cm^2 (1500 psig). Table 2 contains maximum values for water quality parameters in boiler systems with operating pressures above 100 Kg/cm^2.

WATER QUANTITY

The boiler feedwater stream results from the combination of the condensate return and makeup water flows. The condensate return flow rate is equal to the steam production rate minus any condensate/steam leakage. This leakage rate is typically 0 - 2% of steam production. The steam production rate itself is related directly to power production; its value is about 3180 Kg steam/MWH (7,000 lb. steam/MWH).

The makeup water flow rate (after pretreatment) to the boiler is equal to the total water loss from the system due to blowdown and condensate/steam leaks. It is expressed by the equation

$$M = R[K_B + K_R]$$

where:
- M = makeup water flow rate in Kg/hr
- R = steam production rate in Kg/hr
- K_B = blowdown rate, expressed as a fraction of steam production
- K_R = condensate/steam leakage rate, expressed as a fraction of steam production

Figure 1

Boiler System

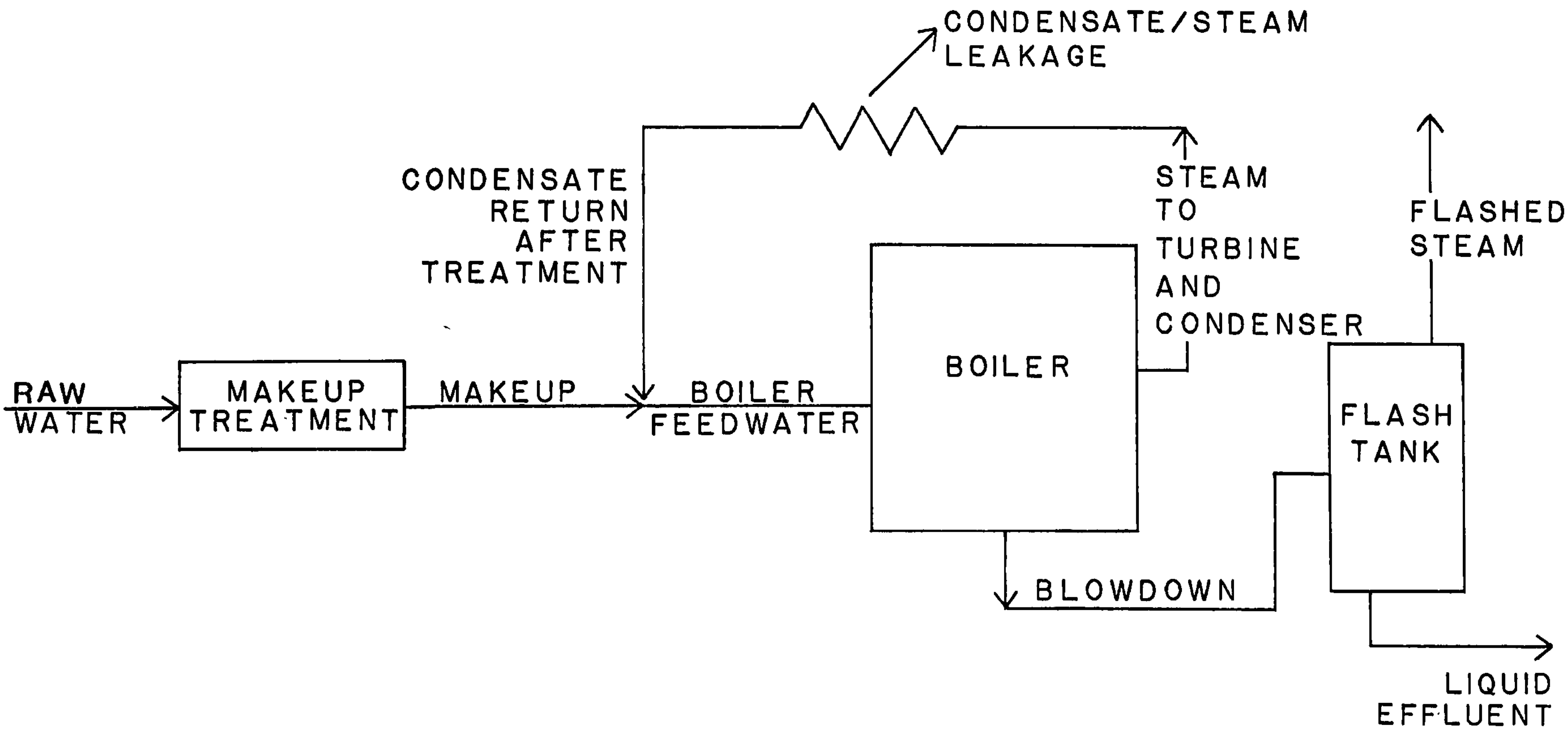


Table 2. BOILER SYSTEM WATER QUALITY[3]

Water Quality Parameter	Streams (Typical values in mg/l)			
	Feedwater (Makeup and Condensate Return)	Steam and Condensate Return	Blowdown[4,5]	Flash Tank Effluent[4,5]
Aluminum	0.01	Essentially		
Alkalinity	absent			
Ammonia	0.7	pure		
Copper	0.01			
Hardness	absent	water		
Iron	0.01			
TDS*	0.5		50	100
Silica	0.02(Wakenhuth[5])		3	6

*Total Dissolved Solids

Typical blowdown rates are 0.1 - 2%, expressed as a percentage of steam production. Equation (1) defines the blowdown rate.

$$B = RK_B \qquad (1)$$

where: B = blowdown flow rate in Kg/hr

R = steam production rate in Kg/hr

K_B = blowdown rate, expressed as a fraction of steam production

After the blowdown leaves the boiler, it passes through a flash tank where part of it is flashed off. The <u>liquid</u> effluent rate from the flask tank is:

$$S = RK_B[1 - \frac{H_B - H_F}{V_F}] \qquad (2)$$

where: S = liquid effluent rate, Kg/hr

H_B = heat of liquid water at boiler pressure, $\frac{\text{Kcal}}{\text{g}}$

H_F = heat of liquid water at flash tank pressure, $\frac{\text{Kcal}}{\text{g}}$

V_F = latent heat of vaporization at flash pressure, $\frac{\text{Kcal}}{\text{g}}$

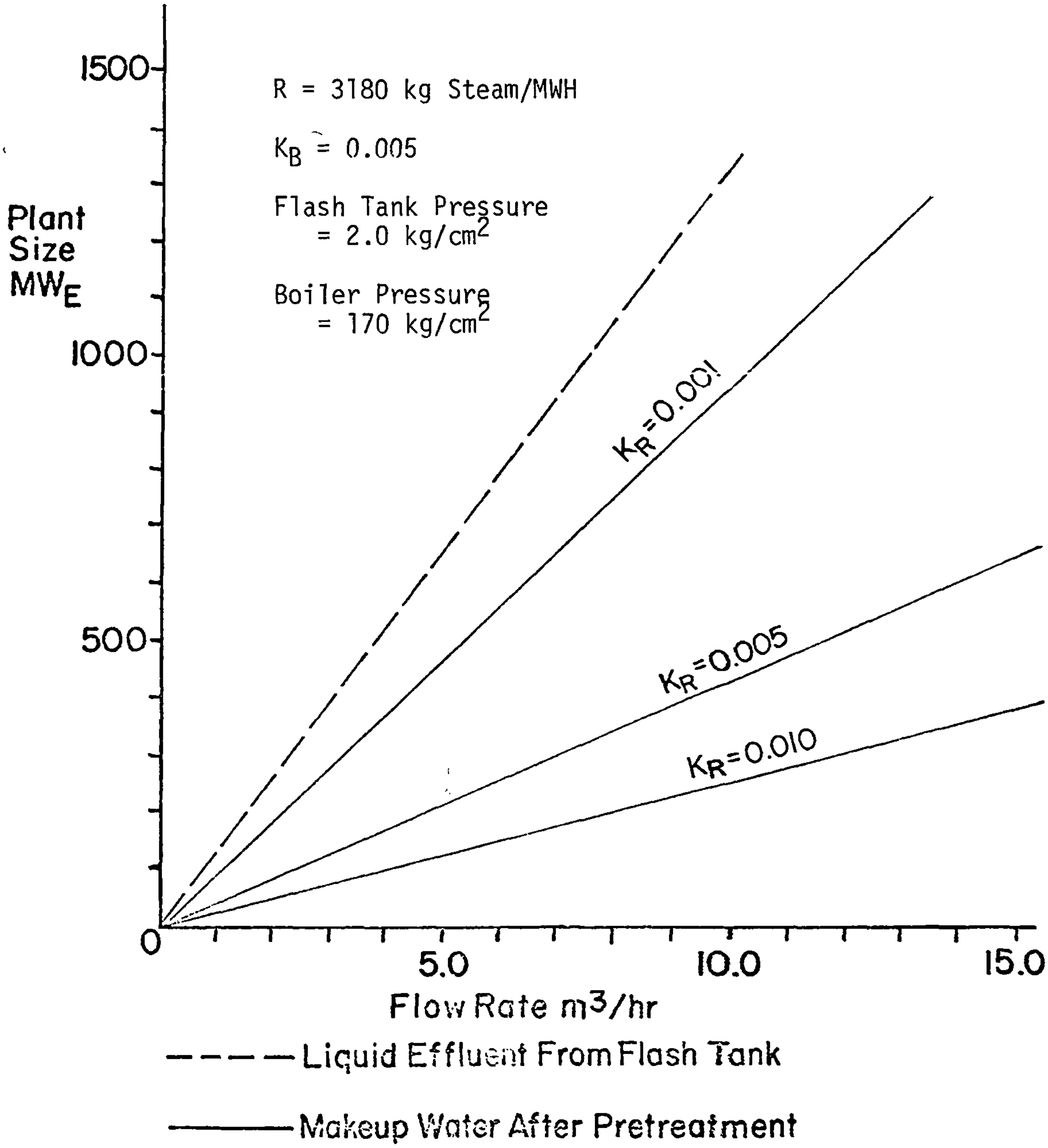
Figure 2 shows examples of the makeup and effluent rates for the boiler system as function of power plant size. The figure is based on the following characteristics:

a. R = 3180 kg Steam/MWH
b. K_B = 0.005
c. Flash tank pressure = 2.0 kg/cm^2
d. Boiler operating pressure = 170 kg/cm^2

Figure 2

Boiler System

Makeup and Discharge Flow Rates



SECTION VI
THE CLOSED CYCLE COOLING SYSTEM

An increasing number of new power plants are using or are planning to use closed cycle cooling systems. The types of closed cycle systems include:

1. Wet Cooling Towers
2. Spray Cooling Systems
3. Wet/Dry Cooling Towers
4. Dry Cooling Towers
5. Cooling Ponds

Of these, only wet cooling towers, contained spray systems, and the wet portion of wet/dry towers are amenable to recycle/reuse evaluations in the context of this report. For this reason, the term cooling system, as used in the remainder of this report, refers to the above three types of cooling systems.

Dry cooling towers use only sensible heat transfer to dissipate the power plant waste heat; thus they have negligible water consumption rates--hence their exclusion.

Cooling ponds are unique in that:

1. Water requirements are affected by all components of the energy budget including long wave back radiation.[6]
2. The pond potentially gains and loses water by precipitation, run-off, and seepage.
3. The pond's large water volume may act as a treatment system that alters water quality characteristics such as suspended solids and BOD.
4. Treatment of the recirculating water, except possibly Cl_2 ahead of the condenser, is not practical.

WATER QUALITY

Figure 3 is a schematic water flow diagram of a typical cooling system.

Drift, Blowdown, and Recirculating Water

In the recirculating water, constituents (originally in the makeup water) are concentrated due to the evaporation of the cooling water. As more evaporation continues, the solubility limits of the constituents are approached. In addition, temperature changes that occur in the system effect the solubility of these constituents. If the solubility limit of one or more of the constituents is exceeded, cooling system fouling may result. Table 3 provides some recirculating water quality limitations that are required to minimize this fouling.[6] The blowdown serves to keep the recirculating water within the limits. It should be noted that water quality characteristics of the blowdown and drift are the same as for recirculating water, which is the source of these system losses.

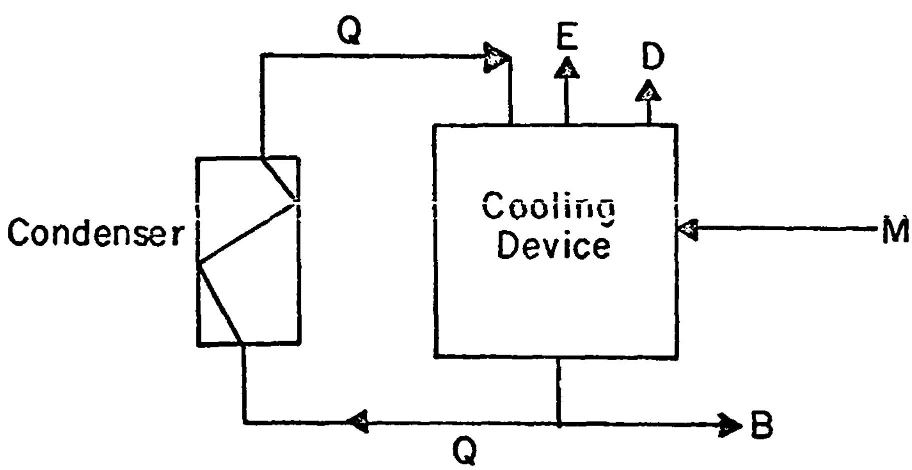
Makeup Water

Typically, the plant supplies water to the system from the most readily available water source with little or no pretreatment. Therefore, no general rule-of-thumb exists for makeup water quality. However, Table 4 contains generally acceptable makeup water quality characteristics that are available from Juvan.[7]

The quality of the makeup water determines the maximum cycles of concentration (cycles) at which the system can operate without water treatment; where cycles is defined as the number of times that conservative constituents in the makeup water are concentrated

Figure 3

Closed Cycle Cooling System



Where Q = Recirculating Rate (m^3/hr.)

B = Blowdown Rate (m^3/hr)

M = Makeup Rate (m^3/hr)

E = Evaporation Rate (m^3/hr)

D = Drift Rate (m^3/hr)

Table 3. RECIRCULATING WATER QUALITY LIMITATIONS[6]

Characteristic	Limitation	Comment
pH and Hardness	Langelier Saturation Index = 1.0	Langelier Saturation Index = pH - pHs where
pH and Hardness with addition of proprietary chemicals for deposit control.	Langelier Saturation Index = 2.5	pH = measured pH pHs = pH at saturation with $CaCO_3$ See Sisson[8] for nomograph solution.
Sulfate and Calcium	$(C_{SO_4}) \times (C_{Ca}) = 500{,}000$	C_{SO_4} = concentration of SO_4 in mg/l C_{Ca} = concentration of Ca in mg/l as $CaCO_3$
Silica	$C_{SiO_2} = 150$	C_{SiO_2} = concentration of SiO_2 in mg/l
Magnesium and Silica	$(C_{Mg}) \times (C_{SiO_2}) = 35{,}000$	C_{Mg} = concentration of Mg in mg/l as $CaCO_3$
Suspended Solids[4]	C_{ss} = 400 mg/l	C_{ss} = concentration of ss in mg/l

Table 4. ACCEPTABLE COOLING SYSTEM MAKEUP WATER QUALITY CHARACTERISTICS

Constituent	Concentration (mg/l)
Calcium, as $CaCO_3$	40 - 200
Magnesium, as $CaCO_3$	10 - 50
M Alkalinity, as $CaCO_3$	5 - 50
Sulfate, as SO_4	20 - 140
Chloride, as Cl	10 - 150
Silica, as SiO_2	2 - 50
Iron, as Fe	0.2 - 10.0
Manganese, as Mn	0.1 - 1.0
Oil	<1 - 5.0
Suspended Solids	10 - 200
pH	5.5 - 7.5 (pH units)
Specific Conductance, µmhos (18°C)	100 - 500

in the recirculating water. For example, it is possible to have a makeup water supply with a silica concentration of 50 mg/l as SiO_2. By definition then, the recirculating water SiO_2 concentration is 50 x (cycles). Referring to Table 3, the maximum cycles of concentration based on silica are: 150/50 = 3.0 cycles. If this same water has a magnesium concentration of 20 mg/l as $CaCO_3$, the magnesium concentration in the recirculating water is 20 x (cycles). The maximum achievable cycles of concentration based on magnesium silicate is:

$$[50 \times (\text{cycles})] \times [20 \times (\text{cycles})] = 35{,}000$$
$$(\text{cycles})^2 = 35$$
$$\text{cycles} = \text{approximately } 6.0$$

After the calculation of the maximum cycles for the other water quality parameters, if the lowest maximum value for the cycles is three; then the cycles of the water supply are said to be silica limited.

It logically follows that -- with the broad spectrum of water quality available for cooling water use across the country -- a given water supply can be limited by any of the water quality parameters in Table 3.

WATER QUANTITY

The recirculating water quantity requirement for a thermal power plant depends upon the plant size, its efficiency, and the temperature rise across the condenser[6]. The governing equation is:

$$Q = \frac{(WH)(P)}{(\Delta T)(Cp)(\rho)} \qquad (3)$$

where Q = Recirculating water flow rate (m^3/hr)
WH = Waste heat to cooling water (KJ/MWH)
P = Plant size MW_e
ΔT = Temperature rise across the condenser (C°)
Cp = Specific heat of water (4.174 KJ/KgC°)
ρ = Density of water (1000 Kg/m^3)

The makeup, evaporation, and blowdown rates are related to the cycles of concentration by equations (4) and (5) if drift is neglected. The symbols for the equations are listed in Figure 3.

$$B = E/(c-1) \qquad (4)$$

$$M = Ec/(c-1) \qquad (5)$$

where c = cycles of concentration

Two approximate methods for estimating the evaporation rate are available.[6] One method applies to equation (6).

$$E = \frac{0.75(P)(WH)}{2.319 \times 10^6 \ KJ/m^3} \qquad (6)$$

Equation (6) is based on 75 percent waste heat dissipation by latent heat transfer and the approximate latent heat of vaporization value for water--2.319×10^6 KJ/m^3 (1000 Btu/lb). Equation (6) can be rewritten:

$$E' = E/P = (WH)(0.323 \times 10^{-6}) \ m^3/KJ \qquad (7)$$

where E', in m^3/hr/MW, is the evaporation requirement per megawatt hour of plant operating capacity. The value of E' is directly proportional to the amount of waste heat rejected to cooling water; therefore, its value depends on fuel type (fossil vs. nuclear) and over-all plant thermal efficiency, as shown in Figure 4.

With the substitution of Equations (3), (4) and (5) into equation (7), the relationships between blowdown/makeup/recirculating water and the evaporation requirements are expressed:

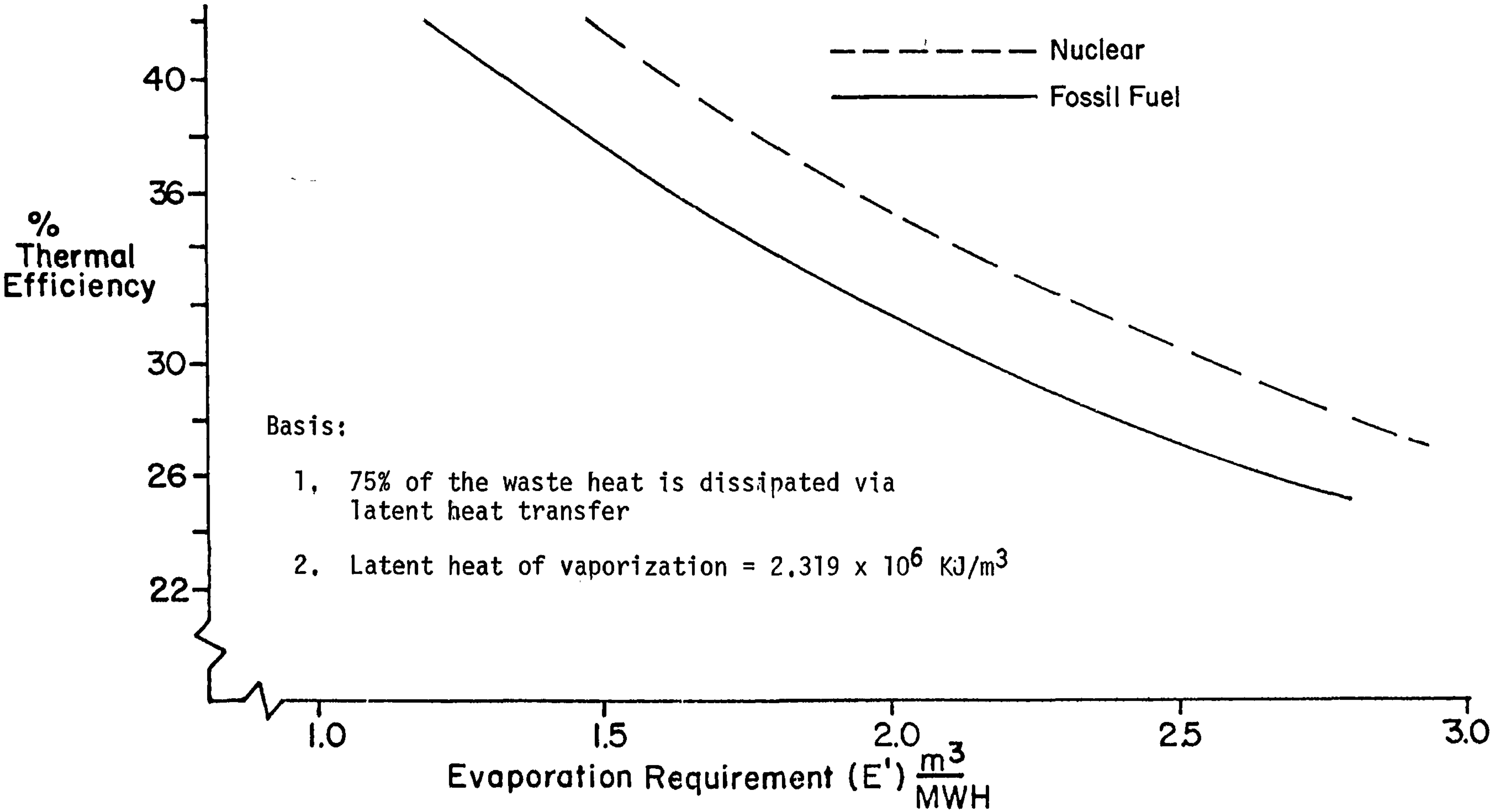
$$B = E'P/(c-1) \qquad (8)$$

$$M = E'Pc/(c-1) \qquad (9)$$

$$Q = E'P(742)/\Delta T \qquad (10)$$

Figure 4

Power Plant Evaporation Requirements



Figures 5, 6, and 7 are graphical representations of the above three relationships. The figures are based on fossil-fueled power plants operating at 38 percent efficiency. The plant size, P, in the figures represents the plant output. For example, a 500 megawatt plant producing at 100 percent capacity and having a cooling system operating at three cycles, has a makeup requirement of 1080 m^3/hr. A 500 megawatt plant producing at 80 percent capacity has a makeup requirement of 870 m^3/hr (corresponding to a makeup requirement of a 400 megawatt plant operating at 100 percent capacity).

The blowdown requirements of Figure 5 also include the drift losses from the system. State-of-the-art design can control drift losses to a few thousandths of a percent. Except for the case of very high cycles of concentration (say above 20 cycles) this drift loss can be neglected in determining the blowdown rate.

With the development and explanation of equations 8-10, the purpose of this subsection is accomplished. The reader should be comfortable with these equations...because they are used in the remainder of the report to evaluate cooling system recycle/reuse possibilities.

Figure 5

Power Plant Blowdown Water Quantity Requirements

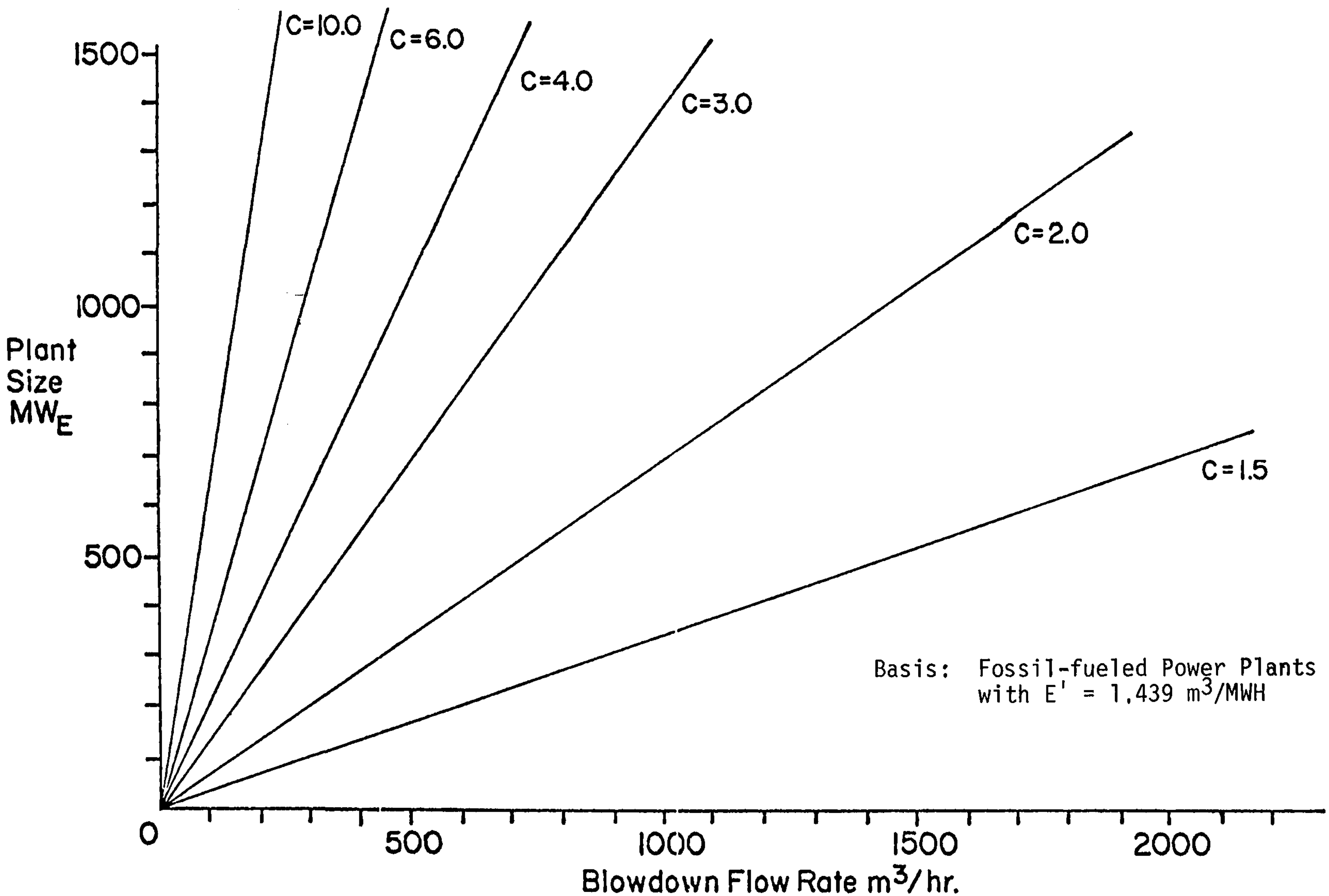


Figure 6

Power Plant Makeup Water Quantity Requirements

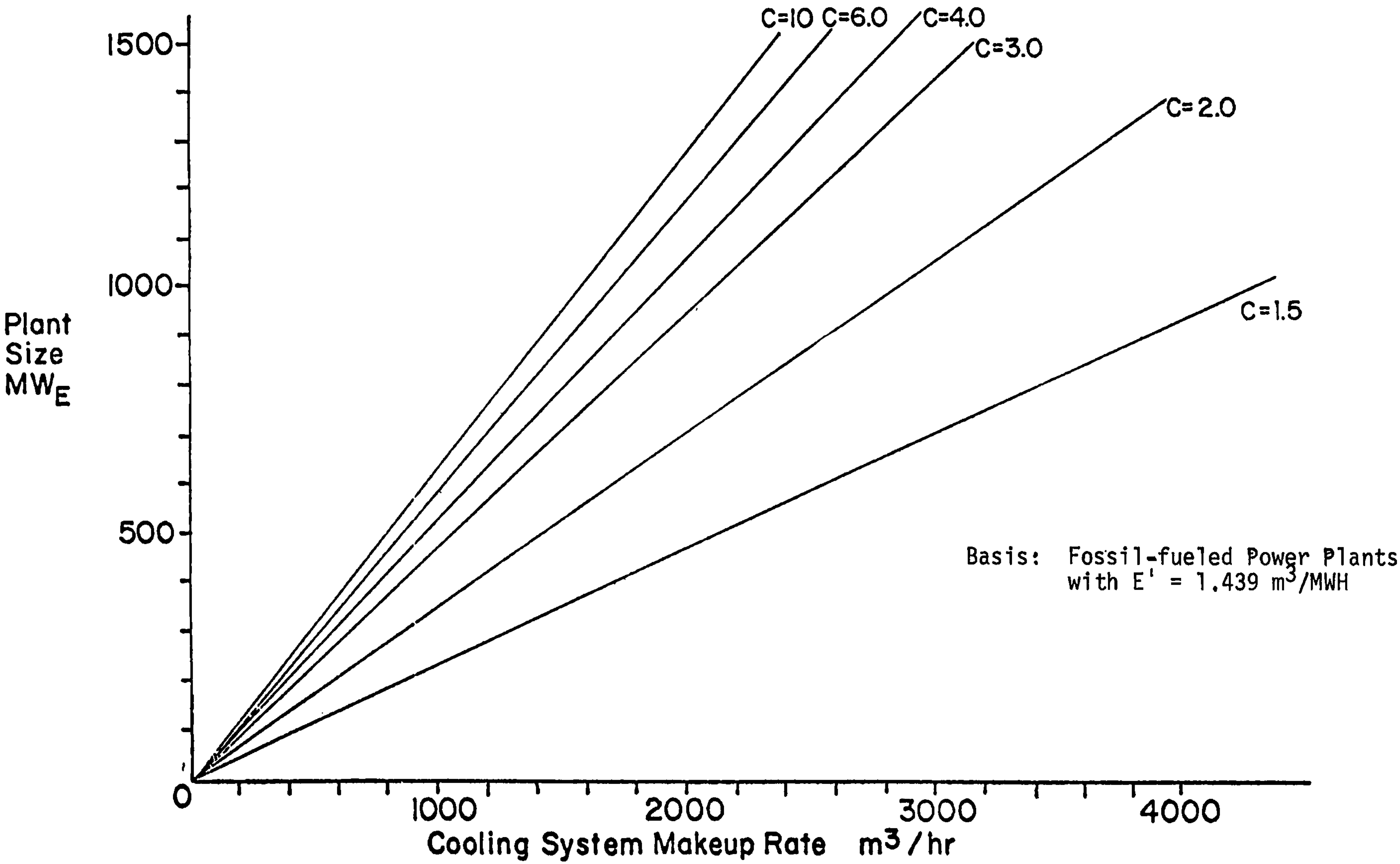
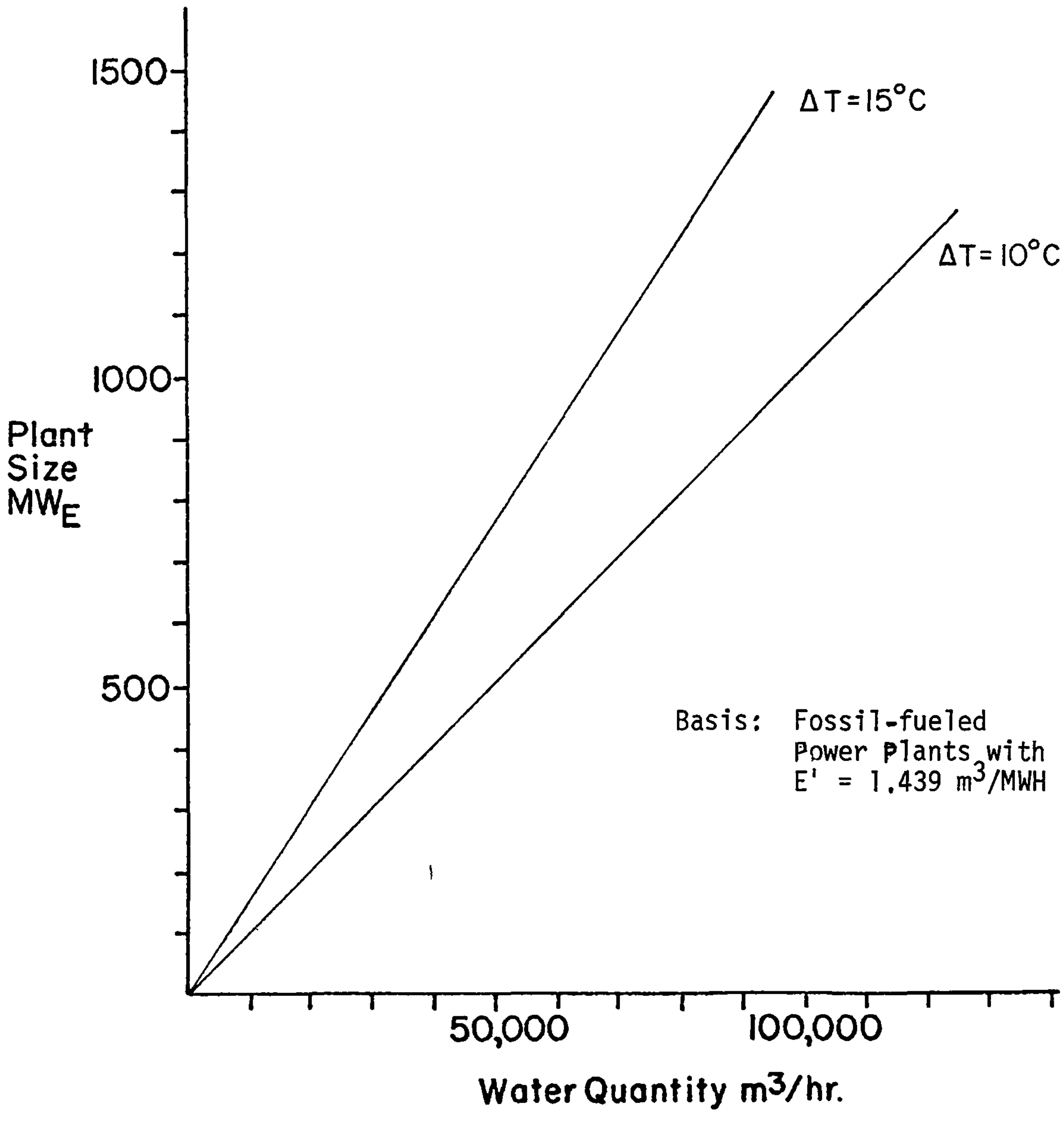


Figure 7

Power Plant Recirculating Water

Quantity Requirements



SECTION VII

TREATMENT TECHNIQUES TO ACHIEVE

WATER RECYCLE/REUSE

BOILER SYSTEM

Recycle Possibilities

From Table 2, the water quality and quantity characteristics of the flash tank effluent indicates that it possibly could be used as makeup water to the boiler. It could be added to the raw water prior to pretreatment*; also, the flash tank steam could supply low grade steam for plant processes. Fuel and water treatment cost savings are available with this recycle program[9,10]. Also, benefits can be realized from the reduction in makeup and discharge water quantity and from potential savings in disposal costs. For example, a thousand megawatt fossil-fueled power plant operating at 80 percent capacity and having the following characteristics, saves nearly $125,000 per year:

1. Overall boiler efficiency - 0.85
2. Fuel cost - $\$0.96/10^6$ KJ (1.00 per 10^6 BTU)
3. Water treatment costs - $\$0.13/m^3$ ($0.50 per thousand gallons)
4. Blowdown rate - 0.5 percent
5. Flash tank operating at 2 Kg/cm^2 (15 PSIG)
6. 15 percent heat and water loss in the recycle program

The calculations for this savings are in Appendix A. The dollar figure above does not take into account:

---

* The flash tank effluent is of higher quality than the raw water. Generally, raw water quality is the same as cooling system makeup water quality (see Table 4).

a. any cost for valves and piping.
b. any flash tank effluent pretreatment costs.
c. any savings in pretreatment systems operation.
d. any savings in waste disposal handling.

<u>Reuse Possibilities</u>

The boiler flash tank water quality is better than the cooling system recirculating water quality (Table 2 vs Table 3); therefore, it can be used as a portion of the makeup water supply to the cooling tower. Although this scheme has little overall impact on the power plant's water supply balance (see example below), it does provide reuse of a water flow that normally would be discarded.

Example - A 500 MW fossil-fueled power plant, operating within the boundary conditions for Figures 2 and 6, has a flash tank effluent rate of 3.7 m^3/hr. The plant's cooling system makeup rate is 2180 m^3/hr @ 2 cycles; 970 m^3/hr @ 4 cycles; and 900 m^3/hr @ 10 cycles.

COOLING SYSTEM

<u>Reuse Possibilities</u>

In comparing the water quality requirements between the boiler system and the cooling system, there is no potential for directly reusing the closed cycle cooling system blowdown as makeup water to the boiler system.

Pretreatment of the cooling system blowdown (prior to reuse) with such processes as brine concentration, reverse osmosis, and demineralization are proposed.[2, 11, 12] These processes can produce an effluent that is near boiler water quality. However, the practical potential of the processes is yet to be demonstrated on large power plant cooling systems.

Recycle Possibilities

All closed cycle cooling systems recirculate (and therefore recycle) water. However, this report's definition of cooling system water recycle goes beyond the operation of a cooling system. Cooling system water recycle involves using water treatment methods to increase the number of times that water recirculates in the system. The result is a net reduction in the makeup and discharge water quantities. There are three methods by which the number of recirculations can be increased:

1. Makeup water treatment programs (makeup programs) - where all or a portion of the makeup is treated prior to entering the system. The treatment results in a net reduction in the makeup and discharge water quantities.
2. Recirculating water treatment programs (recirculating programs) - where all or a portion of the recirculating water is treated and recycled back to the cooling system. The treatment results in a net reduction in the makeup and discharge water quantities.
3. Blowdown water treatment programs (blowdown programs) - where all or a portion of the blowdown is treated and recycled back to the cooling system. Again, the net result is a reduction in the makeup and discharge water quantities.

Typically, makeup or blowdown programs involve treatment of all the makeup or blowdown water flow. On the other hand, recirculating programs usually involve treating a portion of the recirculating water flow.

Table 5 contains the capital and operating/maintenance (O/M) costs for some potential treatment programs. The references contain further information on the efficiencies and physical descriptions of the programs. In some specific cases, the cost data can be affected by one or more economic anomalies, such as extremely high land values, high interest rates (or other factors affecting the fixed charge rate) and above average installation charges. Also some recycle programs have additional water treatment costs or credits associated with the recycled water. To provide guidance for these anomalies, the costs are based on "normal" conditions of:

1. land values - no greater than 1600 \$/hectare (4,000 \$/acre).
2. fixed charge rates - 0.10/yr to 0.20/yr.
3. installed cost of capital equipment - no greater than 2.5 times the basic equipment costs.
4. no water treatment costs/credits given to any recycled water flow.

The following subsection describes the technique that translates the cost data in Table 5 into their most popular and workable form - a mills per kilowatt hour (mills/KWH) basis. Once the costs are in this form, they can be more readily compared with one another and with overall plant costs.

COST CONVERSION TECHNIQUE

Equations 8 through 10 show that blowdown, makeup, and recirculating water quantities are directly related to the power plant's load variation. That is, as power production increases or decreases... yea, verily, so do the water requirements increase or decrease proportionally. The water requirements are expressed as flow rates (water volume/unit time). For cost analyses water requirements can be expressed more conveniently in units of water volume/unit of electricity produced. By the division of the plant size (P) into both sides of equations 8 10, such expressions are achieved as follows:

Table 5. TREATMENT PROGRAM COSTS

Treatment Program	Capital Costs $\$/m^3/hr$ ($/gpm)	O/M Costs $\$/10^3 m^3$ ($\$/10^6$ gal)	Reference
1. Make-up			
Polymer Addition	N/A	$\frac{4.4 - 31}{\text{cycles}}$ $\left(\frac{16.7 - 117}{\text{cycles}}\right)$	from 13
pH Control	N/A	6.6 (2.5)	13
2. Recirculating			
Sidestream filtration/clarification			
Conventional	352 (80)	8 (30)	14
"Rapid Sand"	110 (25)	8 (30)	15
3. Blowdown			
Lime Softening	330 (75)	15 (57)	13
Brine concentration	38000 (8636)	230 (871)	13

$$B/P = E'/(c-1) \qquad (8a)$$
$$M/P = E'c/(c-1) \qquad (9a)$$
$$Q/P = E'(742)/\Delta T \qquad (10a)$$

The ratios (B/P, M/P, Q/P) have the units of m^3/MWH. For individual plants the values of these ratios remain constant, even though load variations occur. With these ratios, the costs in Table 5 can be converted to a mills/KWH basis by applying the following steps, which are based on an annual breakdown of cost and performance:

1. Convert the capital costs into $\$/m^3$ by: multiplying the capital costs (with the units, $\$/m^3/hr$) by the fixed charge rate (with the units $(yr)^{-1}$ and dividing by the capacity factor (with no units) and the number of hours in a year (8760 hr/yr).
2. Add the result of step 1 to the O/M costs. The results of this addition are defined as SUM, with the units $\$/m^3$.
3. Use equations 11, 12 or 13 to determine, respectively, the blowdown, makeup, or recirculating program's costs in \$/MWH or mills/KWH.

Blowdown Costs = (SUM) x B/P
and from Equation (8a)
$$\text{Blowdown Costs} = (SUM) \times E'/(c-1) \qquad (11)$$

Makeup Costs = (SUM) x M/P
and from Equation (9a)
$$\text{Makeup Costs} = (SUM) \times E'c/(c-1) \qquad (12)$$

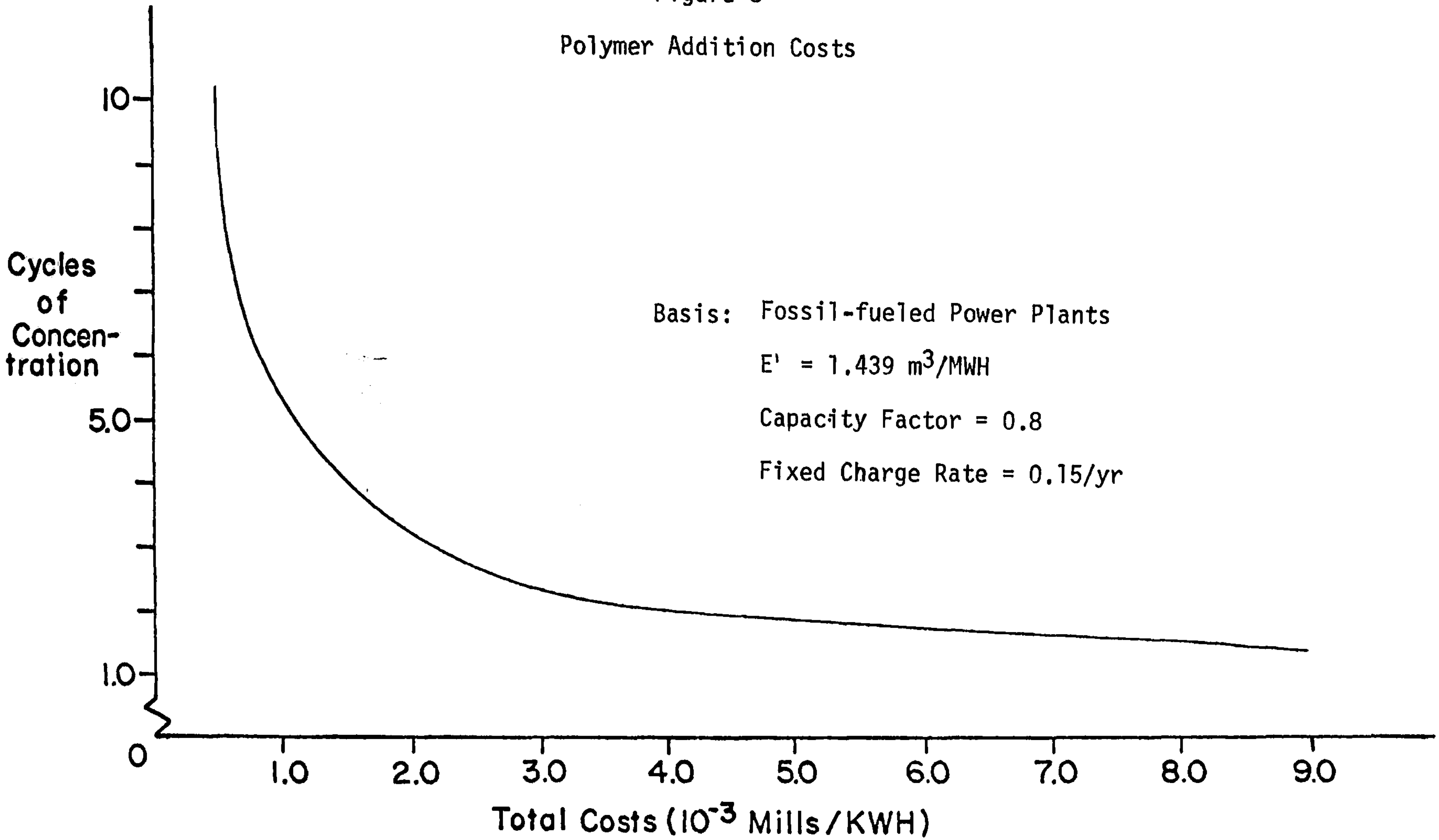
Recirculating Costs = (SUM) x Q%/P (10^2)
and from Equation (10a)
$$\text{Recirculating Costs} = (SUM) \times E'(Q\%)\ (7.42)/\Delta T \qquad (13)$$
where Q% is the percent of the recirculating water being treated.

Figures 8 thru 13 illustrate the recycle program costs on a mills/KWH basis for fossil fueled plants with a 0.15/yr fixed charge rate and an 0.80 capacity factor.

The costs relationships represented by Equations (11), (12), and (13) together with the water quality/quantity relationships already developed, are useful tools for evaluating recycle program economics in both existing and proposed cooling systems. The next section is devoted to describing, via the example format, a general economic evaluation methodology that uses these relationships.

Figure 8

Polymer Addition Costs



based on polymer costs of ($0.0308/$m^3$)

Figure 9

pH Control Costs

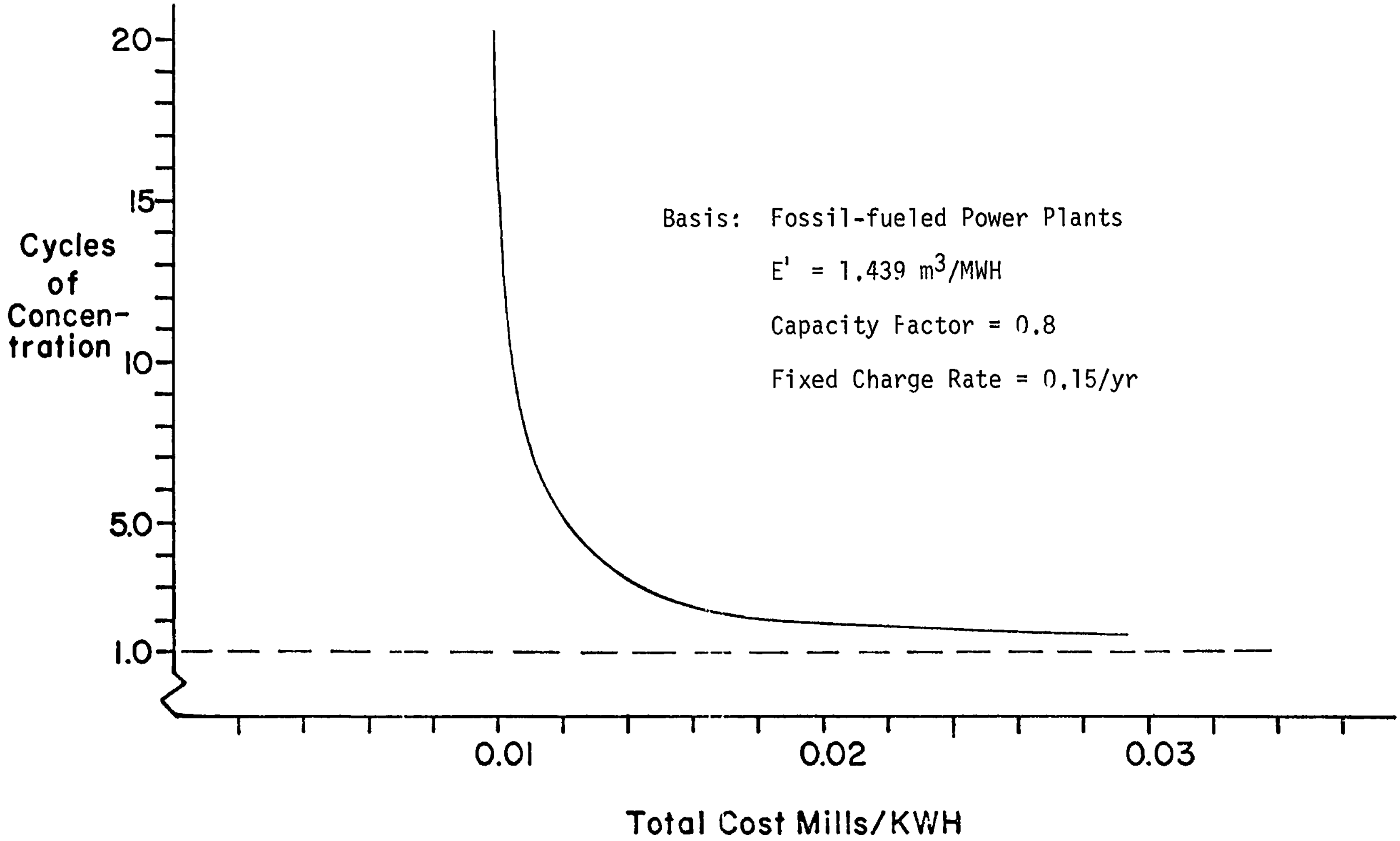


Figure 10

Conventional Side Stream Filtration Costs

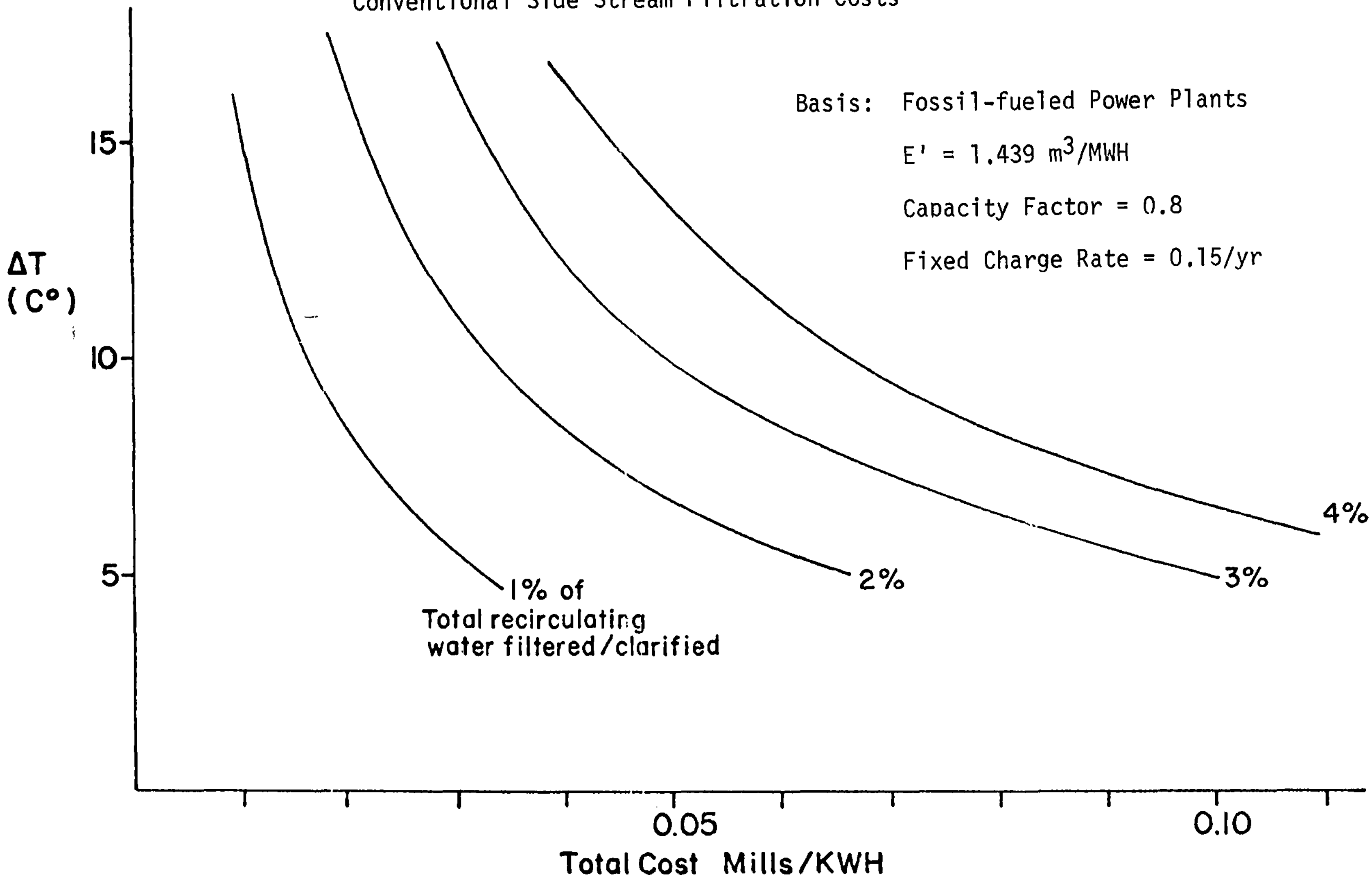


Figure 11

"Rapid Sand" Side Stream Filtration Costs

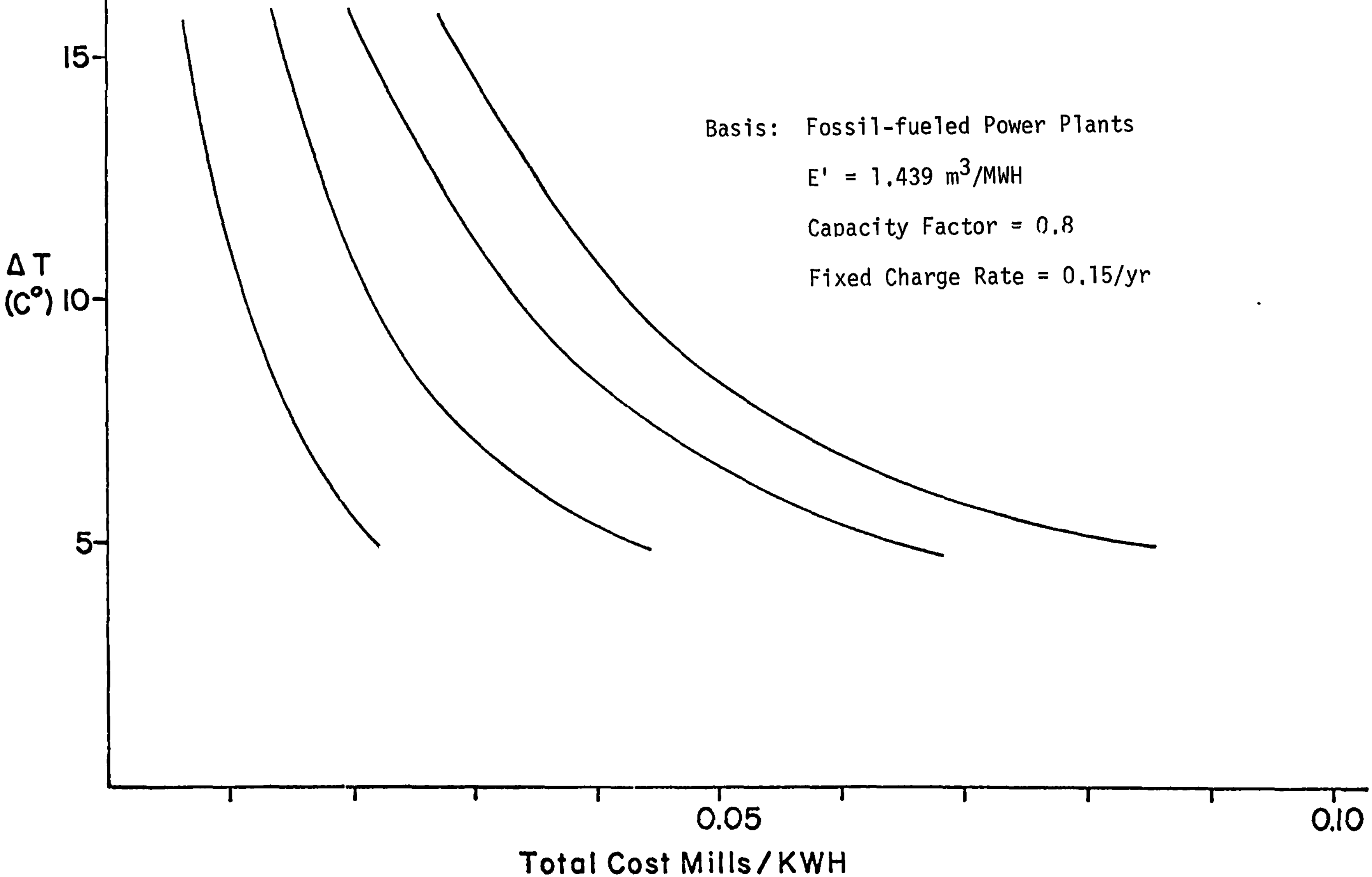


Figure 12

Lime Softening Costs

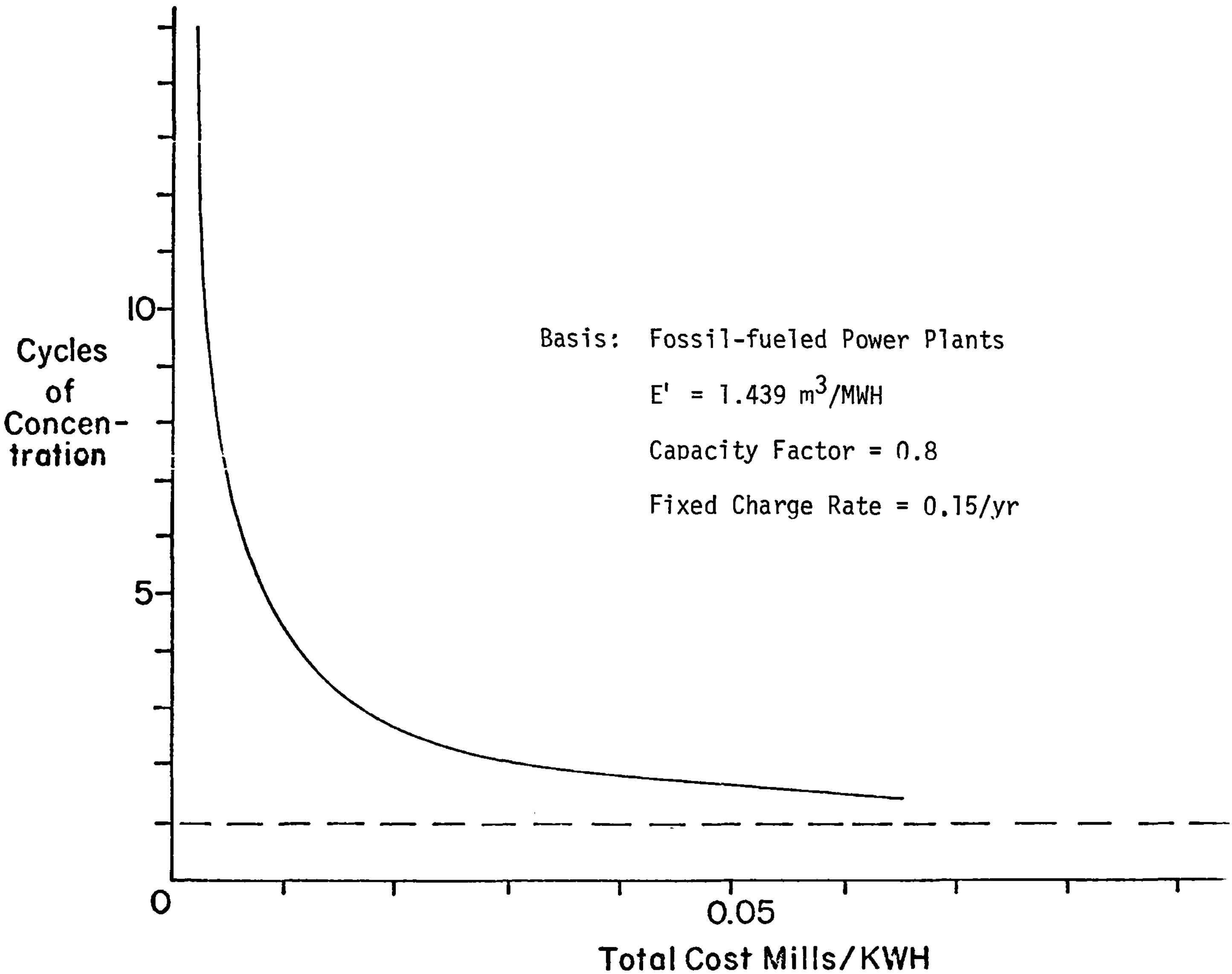
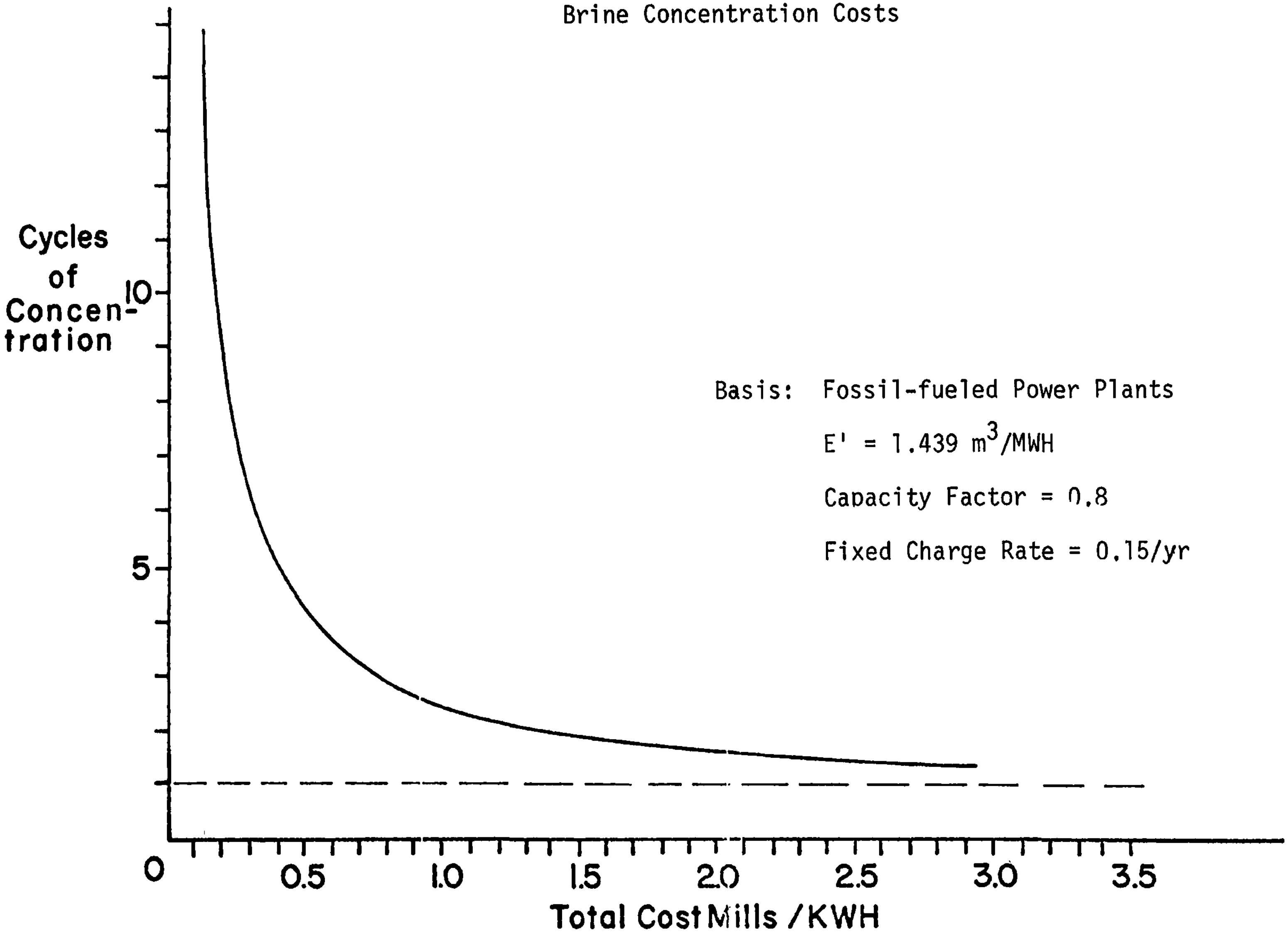


Figure 13

Brine Concentration Costs



SECTION VIII
ECONOMIC EVALUATION METHODOLOGY: COOLING SYSTEM RECYCLE POSSIBILITIES

In order to illustrate the method of economically evaluating cooling system recycle possibilities, three hypothetical power plant situations are presented. Table 6 contains the pertinent power plant characteristics for these situations. The reader should keep in mind three premises that apply to the situation:

1. It is assumed that the biological effects of the total plant discharges are not compromised by the recycle schemes,
2. It is assumed that the discharges from the recycle schemes can be treated by the waste handling systems already available to the plant, and,
3. Boies et al,[13] state that most cooling systems use an acid or base for recirculating water pH adjustment; therefore, it is assumed that the three plants add these chemicals as required to control pH in the cooling system.

There are conditions where one or more of the premises do not apply. Under such conditions, the cost of additional treatment systems or lack of same must be considered in the overall economics.

POWER PLANT #1 - SIDESTREAM FILTRATION AS A RECYCLE POSSIBILITY

This five hundred megawatt plant has a cooling system operating at 1.5 cycles. The system is suspended solids limited (see Table 3). A consultant advises that, if 1 percent of the recirculating water were treated by conventional sidestream filtration/clarification, the system could operate at 3 cycles and be silica limited. What is the cost of this proposed program? What is the net reduction in water quantity requirements?

Table 6. HYPOTHETICAL POWER PLANT CHARACTERISTICS

Characteristic	Power Plant Number		
	1	2	3
A. Operation			
Fuel type	Fossil	Fossil	Nuclear
Overall efficiency (%)	38	35	30
Size (MW_E)	500	750	1000
Capacity factor	0.8	0.6	0.8
Fixed charge rate $(yr)^{-1}$	0.15	0.11	0.13
B. Cooling System			
T (C°)	10.6	N/A	N/A
Cycles	1.5	2.0	2.5
Table 4 limit	S.S.	pH and Hardness	Calcium and Sulfate
Recirculating rate (m^3/hr)	50,000	N/A	N/A
Makeup Costs ($/$m^3$)	N/A	N/A	0.020
Discharge costs ($/$m^3$)	N/A	N/A	0.379
C. Proposed Recycle Program	Side Stream Filtration	Warm Lime Softening	Polymer Addition

The values of the evaporation requirement (E'), the plant capacity factor, and the fixed charge rate allow direct use of Figures 6, 9, and 10. From Figure 10 the sidestream filtration cost is 0.0155 mills per kilowatt hour. From Figure 9 the savings in pH control cost for operating at 3 cycles instead of 1.5 cycles is 0.0142 mills per kilowatt hour. The net cost of the recycle program is therefore:

0.0155 - 0.0142 = 0.0013 mills/KWH

From Figure 6 the reduction in makeup water requirements is 900 m^3/hr (3960 gpm).

POWER PLANT #2 - WARM LIME SOFTENING AS A RECYCLE POSSIBILITY

This 750 megawatt station has a cooling system operating at 2 cycles of concentration. It is pH and hardness limited. The plant manager, one Mr. Buzz Barr, finds that, by treating the blowdown with warm lime softening and recycling to makeup, the system can operate at 5 cycles and be magnesium and silica limited. From the example calculations shown in Appendix B the cost of a lime softener system to treat the entire blowdown is 0.0091 mills per kilowatt hour. The credit in pH control costs for operating at 5 cycles instead of 2 cycles is 0.0082 mills per kilowatt hour. This particular recycle program results in a net cost of

0.0091 - 0.0082 = 0.0009 mills/KWH

The reduction in water requirements is 947 m^3/hr (4170 gpm).
NOTE: This reduction in makeup requirements is not directly attainable from the water quantity relationships described in section VI. In most blowdown programs, such as this one, the blowdown is recycled after treatment and serves as a portion of the makeup requirement (thereby reducing the overall makeup to the system). The amount that is recycled depends on several factors, including makeup water quality, treatment efficiency, and degree of sludge water entrainment. In this example, a figure of 80 percent blowdown recycle is used.

POWER PLANT #3 - POLYMER ADDITION AS A RECYCLE POSSIBILITY

This 1000 megawatt station has a cooling system operating at 2.5 cycles. It is calcium and sulfate limited. It is in a water short area where water costs (influent) are $0.02/m^3 ($25/acre ft). Furthermore, the station is under a contract---signed by the plant manager--to pay a local municipality $0.0264/m^3 ($0.10/1000 gallons) to handle the cooling system blowdown in the city's sewage treatment facility.

The power plant engineer proposes a proven water treatment program calling for the addition of a phosphonate/polymer chemical to the makeup water. This addition allows the cooling system to operate at 15 cycles and be magnesium and silica limited. From the example calculations shown in Appendix B, the cost of the phosphonate/polymer addition is 0.0055 mills per kilowatt hour. The savings in payments to the sewage treatment facility is 0.0396 mills per kilowatt hour. Additionally, the savings in pH control costs are 0.0099 mills/KWH. Also, the savings in makeup water costs are 0.03 mills/KWH. The program actually saves 0.074 mills per kilowatt hour. This translates into an annual savings of $518,592. The reduction in water requirements is 1200 m^3/hr (5282 gpm).

As a result of the above proposal the plant engineer is now the new plant manager. The former plant manager is now a tour guide at the St. Louis Zoo .... working under Marlin Perkins, I think.

SUMMATION

By digesting the information contained in the above examples, the reader can see there are several factors which affect the economic evaluation of the treatment programs. The factors include:

1. Fuel type (fossil vs. nuclear)
2. Overall plant thermal efficiency

3. Cooling system cycles of concentration both before and after the installation of the treatment program.
4. Plant capacity factor.
5. Plant fixed charge rate.
6. Percent of the waste heat dissipated by evaporation in the cooling system.
7. If applicable, influent/effluent surcharges.

The economic evaluation methodology considers these factors on the total recycle program costs.

SECTION IX

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SECTION X

APPENDICES

Page

APPENDIX A
BOILER SYSTEM RECYCLE ECONOMICS

Using the plant data from Table 7, the savings in the recycle program are:

<u>Water from flash tank</u>

$$\text{Savings} = \left[\frac{\$0.13}{m^3} + \frac{\$0.96}{10^6\ \text{KJ}}\left(\frac{4.18\ \text{KJ}}{\text{Kg C°}}\right)(121 - 15.5)\text{C°}\left(\frac{10^3\ \text{Kg}}{m^3}\right)\right]$$

$$\left[1 - \frac{1670 - 508}{2194}\right][0.005]\left[3178\ \frac{\text{Kg}}{\text{MWH}}\right]\left[\frac{m^3}{10^3\ \text{Kg}}\right]$$

$$= 0.00413 \text{ mills/KWH}$$

<u>Vapor from flash tank</u>

$$\text{Savings} = (2194 - 65)\ \frac{\text{KJ}}{\text{Kg}}\left(\frac{1670 - 508}{2194}\right)(0.005)(3178)\frac{\text{Kg}}{\text{MWH}}\left(\frac{\$0.96}{10^6\ \text{KJ}}\right)$$

$$= 0.01720 \text{ mills/KWH}$$

<u>Total savings = 0.02133 mills/KWH</u>

For a thousand megawatt plant with a 0.80 capacity factor, the annual savings are:

$$\text{Savings} = \left(1000\ \frac{\text{MWH}}{\text{hr}}\right)\left(8760\ \frac{\text{hr}}{\text{yr}}\right)\left(0.02133\ \frac{\text{mills}}{\text{KWH}}\right)(0.8)\ \frac{\$}{1000\ \text{mills}}\ \frac{1000\ \text{KWH}}{\text{MWH}}$$

$$= \$149,480$$

A fifteen percent heat and water loss from the recycle scheme results in a savings of about $125,000 per year.

Table 7. BOILER SYSTEM CHARACTERISTICS

A. Boiler	
Steam Production Rate	3178 Kg/MWH (7000 #/MWH)
Operating Pressure	170 Kg/cm^2 (2415 PSIG)
Efficiency	85 percent
Blowdown Rate	0.5 percent
Fuel Costs	\$0.96/10^6 KJ (\$1.00/10^6 BTU)
Flash Tank Pressure	2 Kg/cm^2 (30 PSIG)
Water Treatment Costs	\$0.13/m^3 (\$0.50/10^3 gal)
Makeup Water Temperature	15.5°C (60°F)
Flash Tank Temperature	121°C (250°F)
B. Heat Values (from Betz[9])	
Blowdown Water	1670 KJ/Kg (719 BTU/lb)
Flash Tank Liquid Water	508 KJ/Kg (219 BTU/lb)
Flash Tank Heat of Vaporization	2194 KJ/Kg (945 BTU/lb)
Makeup Water	65 KJ/Kg (28 BTU/lb)
C. Physical Constants	
Heat Capacity of Water	$4.18 \frac{KJ}{Kg C^\circ}$ ($1.0 \frac{BTU}{lb\ F^\circ}$)
Conversion Factor	1000 Kg = 1.0 m^3 (water)

APPENDIX B

COOLING SYSTEM RECYCLE ECONOMICS

POWER PLANT #2 CALCULATIONS (Example)

from Figure 4, E' = 1.662

from Table 5 the cost of the softener is

$$\text{Cost} = \left[\frac{\$.057}{10^3\ \text{gal}}\ \frac{264\ \text{gal}}{\text{m}^3} + \frac{\$75}{\text{gpm}}\ \frac{4.4\ \text{gpm}}{\text{m}^3/\text{hr}}\left(\frac{0.11}{0.6}\right)\frac{\text{yr}}{\text{yr}\ 8760\ \text{hr}}\right]\frac{1.662}{(c-1)}$$

$$= [0.0220]\ \frac{1.662}{4}$$

$$= 0.0091\ \text{mills/KWH}$$

pH control Costs

without softener

$$\text{Costs} = [0.0066]\ \frac{1.662}{(2-1)}\ (2)\ \frac{\text{mills}}{\text{KWH}}$$

$$= 0.0219\ \text{mills/KWH}$$

with softener

$$[0.0066]\ \frac{1.662}{(5-1)}\ (5)$$

$$= 0.0137\ \text{mills/KWH}$$

Net savings in pH control costs

0.0219 - 0.0137 = 0.0082 mills/KWH

Water Requirement Savings

$$\text{Savings} = M_1 - M_2 = 1.662(750)(0.8)\left[\frac{2}{1} - \frac{4.2}{4}\right] = 947\ m^3/hr$$
$$= 4170\ gpm$$

POWER PLANT #3 CALCULATIONS (Example)

from Figure 4, E' = 2.521
@ 2.5 cycles

$$\text{pH Control Costs} = [0.0066]\ \frac{2.521(2.5)}{(1.5)}$$

$$= 0.0277\ \text{mills/KWH}$$

$$\text{Blowdown Costs} = [0.0264]\ \frac{2.521}{1.5}$$

$$= 0.0444\ \text{mills/KWH}$$

$$\text{Makeup Water Costs} = [0.02]\ \frac{2.52.(2.5)}{(1.5)}$$

$$= 0.084\ \text{mills/KWH}$$

@ 15 cycles

pH Control Costs = 0.0178 mills/KWH

Blowdown Costs = 0.0048 mills/KWH

Makeup Water Costs = 0.054 mills/KWH

$$\text{Polymer Addition Costs} = [0.0308]\ \frac{2.521}{14}$$

$$= 0.0055\ \text{mills/KWH}$$

Net Savings = 0.0277 + 0.0444 + 0.084 - 0.0178 - 0.0048 - 0.054 - 0.0055

= 0.074 mills/KWH

= $518,592/yr

Water Requirement Savings

$$\text{Savings} = M_1 - M_2 = 2.521\ [1000](.8)\ [\frac{2.5}{1.5} - \frac{15}{14}]$$

$$= 1200\ m^3/hr \text{ or } 5282 \text{ gpm}$$

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16. Abstract This report contains the methodology to evaluate, in economic terms, potential power plant boiler and cooling system water recycle/reuse programs. Drum type boiler systems and closed cycle cooling systems are used as the basis for the programs' water requirements. The evaluations take into account the variable plant characteristics such as makeup water quality, fuel type, thermal efficiency, capacity factor and fixed charge rate.

The evaluation methodology is applicable to existing and proposed power plants, on an individual plant basis--and can be used to determine the over-all economics of potential recycle/reuse programs.

The report is the first of a series that addresses the water recycle/reuse potentials of typical power plant processes.

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