**A Comparative Investigation of the
Economics of Seawater Desalting
Based on Current and Advanced
Distillation Concepts**

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MASTER

OAK RIDGE NATIONAL LABORATORY

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A COMPARATIVE INVESTIGATION OF THE ECONOMICS OF SEAWATER DESALTING
BASED ON CURRENT AND ADVANCED DISTILLATION CONCEPTS

Pinhas Glueckstern*   Sherman A. Reed

ABSTRACT

A reassessment of desalting plant design and product water cost based on current technology and energy and equipment costs has been made. Plant sizes in the range of 1 to 200 Mgd utilizing the multistage flash (MSF) and the vertical tube evaporator (VTE) were investigated. Process steam was assumed to be supplied by large nuclear dual-purpose plants or from fossil-fired low-pressure boilers. Plants applying the pH control method versus the threshold pretreatment method were compared. The potential benefits of applying low cost aluminum tubing in low-temperature VTE plants were also investigated.

1. INTRODUCTION

This document summarizes the recent work performed at Oak Ridge National Laboratory (ORNL) to reevaluate the cost of desalting seawater by applying current technology and cost data as of mid 1975.

For the two most common desalting processes — the multistage flash evaporator (MSF) and the vertical tube multieffect evaporator (VTE) — various tubing materials have been investigated.

For the MSF process, the investigation included a comparison between plants applying the pH control feedwater pretreatment method and plants operating at lower temperatures applying threshold scale control method by adding to the feedwater makeup small amounts of polyphosphates.

For the VTE process, copper alloy-tubed plants operating at high temperature of 121°C (250°F) were compared with low temperature plants 77°C (170°F) utilizing aluminum alloy tubes either smooth or fluted on the condensing (outside) side. We assumed pH control water pretreatment for plants employing double fluted tubes and polyphosphate pretreatment for plants with semifluted (outside only) tubes.

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All desalting plant designs investigated in the size range of 5 to 200 Mgd were optimized with the aid of the computer programs previously developed at ORNL. This was done after making some changes to the latest versions of the MSF and VTE computer programs. These programs, termed MSF-21 and VTE-21, were modified to apply current technology, instead of the more advanced — and not yet proven — technology adapted in the conceptual designs defined by the initial programs.

In addition to the design modifications, all cost functions have been updated; some of them were escalated to mid-1975 prices and other changes incorporated even more recent cost data (fourth quarter 1975). The section of the computer program dealing with the evaluation of indirect cost was also modified to include escalation during construction.

2. SUMMARY AND CONCLUSIONS

The main objectives of the present study were: (1) to reassess the capital cost and unit water cost of desalting plants applying current technology and cost data, (2) to compare high-temperature plants versus low temperature plants applying threshold feedwater treatment instead of acid, and/or low cost materials, such as aluminum for VTE effect tubing, and (3) to classify potential technological improvements and their effect on capital and unit water costs.

The study considered the following plant types:

1. High temperature, 121°C (250°F), acid-treated MSF plants.
2. Low temperature, 88–93°C (190–200°F), polyphosphate treated MSF plants.
3. High temperature, 121°C (250°F), acid-treated VTE plants.
4. Low temperature, 77°C (~170°F), VTE plants applying aluminum tubing. This concept could not be based on proven technology and was therefore evaluated for two different sub-concepts:
  - (a) Plants employing doubly-fluted tubes and an acid feed-water pretreatment.
  - (b) Plants employing tubes fluted only on the condensing side and a threshold feedwater pretreatment.

The threshold pretreatment method currently uses mainly polyphosphates or polyelectrolytes (recently other additives reported to be more effective have been introduced) at various locations, but mainly for small cross tube MSF plants. As no definite assumption concerning the possible cost savings due to less expensive materials, maintenance, and other cost factors can presently be based on experience, two different sets of assumptions were made, an optimistic and a pessimistic. These sets of assumptions also include different values for the degree of fouling and the corresponding degradation in heat transfer coefficients.

All plant types in sizes ranging between 1 and 200 Mgd, using train sizes not larger than 12.5 Mgd, were optimized on the basis of the following economic ground rules:

1. Interest rate: 10%
2. Plant operating factor; 85%
3. Plant lifetime: 30 years
4. Energy cost: four price levels based upon:
  - (a) Process steam and electrical power obtained from large nuclear power reactors. For this nuclear dual-purpose plant version, the estimated energy costs were as follows:
    - Process steam at 131°C (268°F) = \$0.50/10⁶ Btu
 at 81°C (178°F) = \$0.17/10⁶ Btu
    - Ejector steam at 100 psi and 166°C (330°F) =
 \$0.70/10⁶ Btu
    - Electrical power = \$0.02/kWhr.
  - (b) Process and ejector steam were assumed to be at a price level 150% higher than in (a). The corresponding electrical power was set 75% higher, or \$0.035/kWhr. This price level is representative for small nuclear or fossil-fired dual-purpose plants, and/or for the case of a large increase in nuclear fuel and nuclear reactor equipment cost.
  - (c) Process and ejector steam produced in fossil-fired low-pressure boilers using fuel-oil at a price level

of \$70 to \$75/tonne (\$11 to \$12/barrel) and electrical power bought at a price of \$0.025/kWhr. The corresponding process and ejector steam for this single-purpose plant version at this fuel-oil price was estimated to be \$2/10⁶ Btu.

- (d) Process and ejector steam costs at \$3/10⁶ Btu [50% higher than in (c)].

For the above detailed set of economic ground rules and the prevailing equipment and materials costs in mid-1975, the capital cost per gallon per day and the unit water cost from the optimized desalting plant were as follows:

For dual-purpose plants in the 100-Mgd range:*

<u>Plant type</u>	<u>Performance ratio lb/1000 Btu</u>	<u>Capital cost \$/gpd</u>	<u>Water cost \$/1000 gal</u>
High-temperature MSF	10.8-13.6	1.79-2.05	1.33-1.93
High-temperature VTE	11.0-13.8	1.54-1.80	1.21-1.79
Low-temperature MSF			
- threshold optimistic	7.4-9.4	1.84-2.12	1.34-1.92
- threshold pessimistic	6.2-7.9	2.00-2.30	1.46-2.06
Low-temperature VTE (aluminum tubing)			
- acid treated	6.2-7.8	1.54-1.73	1.09-1.51
- threshold optimistic	5.4-6.3	1.70-1.80	1.23-1.71
- threshold pessimistic	5.3-6.2	1.77-1.89	1.28-1.78

For single-purpose plants in the 100-Mgd range:

<u>Plant type</u>	<u>Performance ratio lb/1000 Btu</u>	<u>Capital cost \$/gpd</u>	<u>Water cost \$/1000 gal</u>
High-temperature MSF	15.6-16.0	2.33-2.39	2.31-2.92
High-temperature VTE	14.4	1.87	2.20-2.85
Low-temperature MSF			
- threshold optimistic	12.2-14.2	2.65-3.16	2.80-3.56
- threshold pessimistic	10.8-12.1	2.98-3.38	3.16-4.02
Low-temperature VTE (aluminum tubing)			
- acid treated	11.8-12.7	2.46-2.65	2.75-3.53
- threshold optimistic	11.1-11.9	2.84-3.08	3.09-3.93
- threshold pessimistic	10.9-11.6	2.96-3.22	3.20-4.12

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* Plants with low performance ratios were optimized using energy costs from large nuclear dual-purpose plants. (Refer to pp. 4 and 24.)

From the results obtained, the following can be concluded regarding desalting costs based upon current technology:

1. For large nuclear dual-purpose plants the optimum performance ratio is in the range of approximately 11 to 14 lb/1000 Btu. The corresponding capital cost is in the range of \$1.50 to \$2.00 per gpd while the unit water cost will range between a low of \$1.20 per 1000 gallons, for low energy cost, up to approximately \$2.00 per 1000 gallons for a high energy cost. High-temperature VTE desalting plants have an approximately 15% lower capital cost and an approximately 10% lower unit water cost than high-temperature MSF plants. Low-temperature MSF plants applying threshold pretreatment would, at the best, be equal in capital cost and unit water cost to the high temperature MSF plants.
2. For large single-purpose plants the optimum performance ratio for the high temperature plants was set to the assumed limit of 16 lb/1000 Btu for the MSF, and 14.4 lb/1000 Btu for the VTE for a design utilizing 20 effects with up to 40 preheater stages. The corresponding capital costs ranged from \$1.85 per gpd for the VTE up to approximately \$2.40 for the MSF. The unit water costs range from \$2.20 up to \$2.90 per 1000 gallons, the VTE having approximately the same economic advantage as the dual-purpose plant. Low temperature MSF plants using threshold pretreatment are less attractive economically for large single-purpose plants.
3. For small dual-purpose plants (which use bleed steam), in the 1-Mgd range, VTE high temperature plants have no economic advantage over MSF plants. The capital costs for current technology plants ranged between \$3.98 to \$4.40 per gpd (see Table 6) and the unit water costs between \$2.85 to \$4.85 per 1000 gallons (Table 9). Low temperature MSF plants applying threshold pretreatment were equal in cost or had a small advantage in comparison to the high temperature MSF and VTE plants.

4. For small single-purpose plants the required capital is very high and might reach \$6.00 per gpd for low temperature MSF plants. Even for high temperature plants the capital cost is as high as \$5.00 per gpd and the corresponding unit water cost between \$4.20 to \$5.00 per 1000 gallons.

The prevailing high energy and equipment costs point now — more than ever before — to the need for a desalting concept which can apply cheaper construction materials and low-grade energy, such as low-temperature process steam. Multieffect distillation plants, applying vertical or horizontal tubing, are the nearest approaches to those basic requirements. In the present study only the vertical version of this concept has been considered. The potential reduction in unit water cost by applying low-temperature VTE plants might be as high as 15 to 20% compared to the best high temperature concept. From the sensitivity analysis performed on a 100-Mgd MSF design, it was found that the total development potential of the MSF process, if fully realized, might reduce unit water costs by about 20%. It was, however, concluded that the assumption of a potential 10% cost reduction, due to future technological developments, is probably a more realistic figure.

3. SCOPE AND OBJECTIVES OF INVESTIGATION

3.1 Objectives

The objectives of the present investigation were as follows:

1. Reassessment of seawater desalting cost by applying the current prevailing technology, equipment, and material cost, at several energy price levels.
2. Appraisal of current applied or proposed desalting plant design concepts in light of the recent changes in energy and equipment costs.
3. Study of pH control (acid) versus threshold (polyphosphate or other additives) feed treatment for the compared plant types and energy price levels.

3.2 Scope of Investigation

All desalting plants investigated were in the range between 1 and 200 Mgd. In this range the following sizes were selected: 1, 2.5, 5, 12.5, 25, 50, 100, and 200 Mgd. For more detailed analysis only four plant sizes: 1, 2.5, 12.5, and 100 Mgd were evaluated.

These plant sizes were optimized for reference heat costs (at 131°C, 268°F) ranging between \$0.50 and \$1.25 per million Btu for dual-purpose plants and two additional heat costs of \$2.00 and \$3.00 per million Btu for single-purpose plants.

4. EVALUATION METHOD

All desalting plant concepts considered (see Sect. 5) were optimized with the aid of ORNL's computer programs MSF21¹ and VTE21.² These programs, originally developed for rapid optimization of advanced MSF and VTE concepts based upon ORNL's 250 Mgd conceptual designs,^{3,4} were modified to allow the evaluation of current technology designs based on prevailing cost and economic criteria.⁵ The adopted design criteria and economic ground rules are detailed in Sects. 6 and 7, respectively.

Each investigated design concept was optimized for four (or more) plant capacities and four different energy cost levels. Although the computer programs are capable of optimizing 8 to 10 of the most important design parameters in the majority of the evaluated designs, only the performance ratio and the number of evaporator stages (MSF) or effects (VTE) were optimized. Other design parameters, such as MSF tube velocities, blowdown to feed concentration ratio and VTE tube length were found to have optimum values beyond the limits set by the adopted design criteria and were therefore set at those limiting design values (see Sect. 6). Several additional design parameters, such as the blowdown temperature and the VTE final condenser approach temperature, were optimized for several plant designs, only. In a reasonable range of design values these design parameters have only a minor effect on the capital and unit water cost. On the other hand, different design values for the blowdown temperature would yield plant designs with different product water temperatures. Some of them would have to apply product water coolers. For sake of simplicity and easy comparison between the different plant designs, these parameters were kept constant (see Sect. 6).

Because of the above mentioned restrictions in optimizing the design parameters and the obviously limited accuracy of the design and cost models, the results of the designs evaluated should not be considered as fully optimized but rather as reasonable system design configurations. Thus cost estimates are adequate to the scope and objectives of the present study.

5. DESALTING PLANT CONCEPTS INVESTIGATED

5.1 General Classification of Current Applied or Proposed Seawater Desalination Design Concepts

5.1.1 Introduction

It is generally accepted that for large seawater desalination plant capacities, especially dual-purpose plants, all possible economical contenders are some version, or subconcepts, of the two basic desalting processes; the multistage flash (MSF) and the multieffect distillation (MED) processes.

The most pronounced differences in the various applied or proposed concepts based on the basic process principles of the MSF and MED are related to the geometric and structural design of the evaporator tube-bundle, the process temperature level, the materials of construction (especially the heat transfer tubing), and the feedwater pretreatment method. Some of these differences are not strictly independent, one from the other. Thus, concepts applying a high process temperature level are restricted to materials of construction having adequate strength and corrosion properties at elevated temperatures. The same holds also for the pretreatment method which must be effective at the applied temperature level.

Generally, the current applied desalting concepts based on the MSF and MED processes may be classified as follows:

5.1.2 Multistage flash (MSF) design concepts

The two structural design concepts are the cross-tube (short tubes) and the long-tube design. Both have advantages and disadvantages at specific conditions. For large capacities the long-tube design was considered to be more economic, especially when applying advanced technology features, such as very long tubes running through a large number of evaporator stages; nearly all conceptual design concepts applied the long-tube design. Although this assumption is probably not generally true for plant designs based on current technology, especially for small plant capacities, the present evaluation was restricted to the long-tube concept.

because the available computer programs are based on this structural concept.

The two current applied pretreatment methods are the pH control (mainly applied for high temperature plants) and the threshold, restricted to low temperature plants only.

5.1.3 Multieffect distillation (MED) design concepts

The two main structural subconcepts of this process are: the vertical tube evaporator (VTE) and the horizontal tube evaporator (HTE). The main basic differences between these two concepts are related to the characteristics of the heat-transfer mechanism, feed pretreatment and distribution, and the current applied heat-transfer tubing material and geometric shape. The VTE, developed to take full advantage of a high temperature process, has undergone a number of development stages regarding especially the heat-transfer tubing and the feed preheating. The latest version of this development, applying doubly fluted effect tubing and a MSF evaporator serving as a preheater, was found to be the most economic design concept of the basic MED process applying vertical tubes. The HTE design concept was not found to be competitive with the VTE concept at high process temperature but might have some advantages at lower process temperature where low cost aluminum tubing and the threshold pretreatment can be applied. This concept was extensively developed in Israel where a 1-Mgd demonstration plant, built by Israel Desalination Engineering, Ltd., has operated successfully for approximately two years. Presently, a scaled-up version of this concept, having a capacity of 8 to 10 Mgd, is in the stages of final design and its construction will start shortly. This desalting plant will be connected to an existing power plant. This project, aimed at developing a prototype of a promising desalting concept, is conducted under a joint development agreement between the United States and the State of Israel and is financed equally by the two countries.

The present study did not consider the HTE concept, especially because of the lack of an appropriate design and cost model of this concept. The potential advantages of a low-temperature MED process, applying aluminum tubing, could however be evaluated for application in a VTE

design concept, recently proposed and preliminary evaluated by ORNL.⁶ This proposed concept was evaluated and compared to the current technology design concepts. A more detailed discussion of the current technology MSF and VTE concepts which were investigated, as well as that of proposed low temperature VTE utilizing aluminum tubing, is given below.

5.2 Multistage Flash (MSF) Plants

5.2.1 High temperature acid treated plants

Due to the thermodynamic advantage of high-temperature distillation plants, almost all large desalting plant designs were assumed to operate at the highest possible temperature level, set by the calcium sulphate solubility limit. This maximum temperature is usually set to 121°C (250°F). At this relative high temperature the only proven feedwater pretreatment method is that of pH control, obtained by acid addition and readjustment (if required) by some neutralizing agent such as NaOH. The other currently applied pretreatment method — the threshold method — based on the addition of some sequestering agents such as polyphosphates and polyelectrolytes, are only effective to an upper temperature limit of about 87 to 93°C (190 to 200°F). Although, as will be discussed later, some recent developed additives were reported to be effective at higher temperatures, the option of applying these additives is still pending more extensive experimental verification.

5.2.2 Low temperature-nonacid treated (threshold) plants

Due to the decreased corrosion and operating problems encountered in plants applying this pretreatment method, this concept is usually preferred for plants operating in remote locations short of skilled operating and maintenance staff.

This concept was however not widely considered, until now, for application in large plant capacities because of the already discussed thermodynamic disadvantages. Three recently occurring factors may, however require reconsideration of this concept. These factors were: (a) sharp increase in energy costs, (b) large cost increase in corrosion resistant cladding materials, and (c) development of more efficient

sequestering agents. The combined effect of using low grade energy in the form of considerable lower turbine extraction steam pressure than required for high temperature processes, and the possible application of cheaper construction materials, may therefore outweigh the inherent thermodynamic disadvantage of the low-temperature process.

Several uncertainties concerning the economic evaluation of the low temperature threshold pretreatment concept made it necessary, however, to apply various assumptions. These uncertainties are related to design, operational, and costing factors. The most important factor regarding the design is the prediction of the fouling factors. Another design and operational uncertainty is whether the applied threshold pretreatment will require periodic chemical cleaning of the heat transfer tubing. This might affect the investment cost as well as the operating cost. Finally, the potential construction cost saving, compared to an acid pretreatment plant, cannot be estimated accurately without performing a detailed design study of a threshold pretreatment desalting plant.

In order to overcome the above mentioned difficulties occurring in the evaluation of threshold pretreatment plants, the evaluation was made for two sets of assumptions, an optimistic and a pessimistic. The differences in design and operating criteria, in cost assumptions between these two approaches, and in relation to a reference acid pretreatment design, are detailed in Sects. 6 and 7.

5.3 Vertical Tube Evaporator (VTE) Plants

5.3.1 High temperature plants

The basic advantages of the VTE process, especially applying doubly fluted effect tubes and a MSF preheater, are most pronounced at elevated temperatures. By applying the forward feed method so that the high temperature effects evaporate the less concentrated feed, the problem of calcium sulphate solubility is less than in the MSF process. Thus higher maximum temperatures and/or blowdown concentrations can be applied. However, due to the higher cost of the required construction materials and of the process steam (in dual-purpose plants) at elevated temperatures, most VTE designs do not utilize top brine temperatures higher than

121 to 127°C (250 to 260°F), or almost equal to that applied in high temperature MSF designs.

As for the MSF plant designs, the only practical pretreatment method for high temperature VTE designs was found to be the current applied pH control method.

VTE technology has much less operational experience than the more common MSF technology. Moreover, the recent developed concept applying doubly fluted tubes has even less operational experience; and it was therefore difficult to compare VTE versus MSF plants, based on current technology. In order to achieve a reasonable objective and economical comparison between these two basic technologies, a higher contingency allowance was applied in the cost evaluation of the VTE design concepts (see Sect. 7).

5.3.2 Low-temperature plants applying the pH control method

Low-temperature VTE designs were found to be competitive with high temperature plants, or even more economical, when applying low-cost aluminum tubing and a modified pH control method, termed the "partial-acid" pretreatment method.⁶

This proposed pretreatment method requires only about 20% of the stoichiometric quantity of acid required to reduce the alkalinity to a minimum. This amount of acid, or approximately 20 to 25 ppm, would be sufficient to keep the pH below the threshold at which precipitation would occur.

As the effectiveness of the partial acid feed treatment has yet not been tested, the present study used a more conservative approach in evaluating the potential benefits of aluminum-alloy tubing low-temperature VTE concept, assuming a conventional acid pretreatment by including full neutralization of the alkalinity to elevate the pH after decarbonation.

5.3.3 Low-temperature plants applying the threshold pretreatment method

The threshold pretreatment method has not been tested on vertical tube evaporators with enhanced tubing surfaces. It will be probably much more difficult to remove the "soft" scale or sludge buildup associated with this method from fluted tubes than from smooth surfaces.

It was therefore concluded that the possible application of semifluted tubes, having enhanced surfaces only on the condensing side, would be a more realistic approach for low-temperature VTE plants applying the threshold method.

Although some experimental tests have been performed to evaluate the overall heat transfer coefficient ($\bar{U}$) of semifluted vertical tubes,⁷ these tests did not include strictly identical conditions of downflow aluminum tubes enhanced on the outside diameter.

From the limited available data only some estimates could be made. The observed $\bar{U}$ for a feed rate of 0.8 gpm [fresh water at $\sim 100^{\circ}\text{C}$ ($\sim 212^{\circ}\text{F}$)] and a temperature difference (ΔT) of 6.7°C (12°F), obtained from tests on both semifluted (outside diameter) and doubly fluted 2-in. OD - 8-ft-long aluminum tubes, were 920 and 1480 Btu/hr·ft²·°F, respectively. The corresponding ratio between $\bar{U}$ of OD fluted and a doubly fluted tube was therefore approximately 0.62. This result can, obviously, be taken only as a rough indication or estimate.

The present evaluation of VTE design concepts, applying threshold pretreatment, was based on this rough estimate of $\bar{U}$ by multiplying the calculated $\bar{U}$ for doubly fluted tubes by a factor of 0.6.

Despite the much lower heat transfer coefficients, it was found still interesting to evaluate VTE design concepts, applying semifluted aluminum alloy tubes, because the results may indicate the economic potential of low-temperature VTE designs, even if an acid pretreatment method cannot be considered compatible with aluminum alloy tubing. Another factor making the evaluation of this design interesting is the fact that the characteristics of this design, such as the average value of the heat transfer coefficient, are very close to those of the aforementioned aluminum alloy horizontal tube evaporator (HTE) design concept.

As for the MSF designs applying the threshold pretreatment, these designs were also evaluated for two sets of assumptions (optimistic and pessimistic). The relevant design and cost assumptions are detailed in Sects. 6 and 7, respectively.

6. BASIC DESIGN CRITERIA

6.1 General

The main objective of this study was to make a reassessment of desalting costs based on current technology. An attempt has therefore been made to use, as far as possible, the same basic design criteria as applied in the recently constructed, or currently designed large desalting plants. These criteria are related mainly to the selection of construction materials and to the feed pretreatment and noncondensable gas removal. The current designed desalting plant designs are usually a much more conservative approach than the various conceptual designs of "advanced" concepts. This approach is probably the result of accumulated operating experience which has indicated the need of a much more corrosion preventative design to reduce the large plant downtimes and high maintenance costs which have been experienced.

As for the thermal-hydraulic design criteria, the values applied in current designs were quite similar to those applied in ORNL's conceptual design. These criteria were tested comprehensively and verified (especially for the MSF) at the San Diego Test Facility.

One of the most important design assumptions was, however, not strictly in accordance with current operating plants. This refers to the applied train and evaporator tube bundle size for large capacity MSF and VTE design. The assumed train sizes of 12.5 Mgd represent a small upscale from current operating large capacity MSF plants (8 Mgd at Hong Kong) but a scale down from the MSF prototype tested at the San Diego Test Facility. For the VTE the scale-up, compared to current operating plants (~3 Mgd at Orange County), is considerably larger but it should be noted that the Orange County plant is a test module employing only 4 effects of a 12-Mgd train. This module could be considered directly applicable to a VTE plant of 12.5-Mgd capacity.

6.2 Summary of Applied Design Criteria

The data for all design concepts are summarized in Table 1.

Table 1. Summary of main basic design criteria

Process type	MSF		VTE			
Pretreatment	Acid	Threshold	Acid	Acid	Threshold	
Top brine temperature, °F	250	190-200	250	170	170	
1. Materials of construction						
1. Tubing						
a. MSF recovery or VTE preheater						
Material	90-10 Cu-Ni		Aluminum-5052			
Surface	Smooth		Smooth			
Tube OD, in.	3/4		3/4			
Wall thickness, in.	0.035		0.049			
Maximum length, ft	70		70			
b. Brine heater						
Material	90-10 Cu-Ni		Aluminum-5052			
Tube OD, in.	3/4		3/4			
Wall thickness, in.	0.049		0.049			
c. Reject section or final condenser						
Material	90-10 Cu-Ni		Aluminum-5052			
Tube OD, in.	3/4		3/4			
Wall thickness, in.	0.049		0.049			
d. VTE effects						
Material	90-10 Cu-Ni		Aluminum-5052			
Surface	Doubly fluted		Doubly fluted		OD fluted	
Tube OD, in.	2		2		2	
Wall thickness, in.	0.035		0.050		0.050	
Tube length, ft	10		10		10	
2. Evaporators shell and internals						
Shell material	Carbon steel					
Lining or coating						
Brine chambers	SS sheets Cu-Ni sheets	Epoxy or phenolic	SS sheets Cu-Ni sheets	Epoxy or phenolic		
Water boxes						
Product trays	316 SS					
Weirs	316 SS					
Demisters	316 SS					
3. Seawater intake & outfall						
Same as in ORNL's conceptual designs						
4. Pumps & drivers						
Same as in ORNL's conceptual designs						

Table 1 (continued)

Process type	MSF			VTE		
Pretreatment	Acid	Threshold		Acid	Acid	Threshold
Top brine temperature, °F	250	190-200		250	170	170
3. Pumps efficiency and pumping heads						
Overall pump and driver efficiency, %				82.7		
Pumping heads, ft						
Feed to plant site				35		
Plant to brine heater				25		
Blowdown pump				40		
Product pump				92		
4. Brine flow characteristics						
Maximum tray flow, lb/hr-ft of width						
Hot end				1,000,000		
Cold end				800,000		
Depth of flashing brine, ft				1.25		
5. Fouling factors, (Btu/hr·ft ² ·°F) ⁻¹						
		Optimistic	Pessimistic			Optimistic Pessimistic
Brine heater	0.0005	0.0005	0.0008	0.0005	0.0005	0.0005 0.0008
Recovery or preheater stages	0.0005	0.0005	0.0008	0.0005	0.0005	0.0005 0.0008
Reject stages or final condenser	0.0007	0.0007	0.0007	0.0007	0.0007	0.0007 0.0007
6. Vacuum system						
NCG in pretreated feed released in evaporator, ppm	30		100		30	
Air inleakage per train, lb/hr				350		
Ejector steam pressure, psig				100		
Ejector steam consumption, lb steam/lb NCG				11.1		

Table 1 (continued)

Process type	MSF		VTE		
	Acid	Threshold	Acid	Acid	Threshold
Top brine temperature, °F	250	190-200	250	170	170
5. Decarbonator and deaerator					
Decarbonator type	Atmospheric	*	Atmospheric		*
Deaerator type			Packed bed - external vessel (vacuum)		
Shell material			Carbon steel		
Lining			Fiberglass		
Packing			Polypropylene		
Nozzles			316 stainless steel		
6. Steam-jet air ejectors		Two-stages + hogging; precondenser, inter-condenser, and after-condenser			
Ejector steam chest and air chamber			Carbon steel or cast iron		
Diffusers and nozzles			316 stainless steel		
Condensers type and material		Shell and tube; * shell - 316 stainless steel; tubes - titanium			
II. Design parameters					
1. Raw seawater					
Temperature, °F			65		
Salinity, ppm TDS			33,600		
Alkalinity, ppm			120		
2. Design constraints					
a. Upper limit for performance ratio, lb/10 ³ Btu	16	14		Limited by number of effects	
b. Upper limit for number of MSF stages or VTE effects	50	40	20	15	15
c. Upper limit for blow-down concentration ratio	2.0	2.0	2.4	2.4	2.0
d. Lower limit for tube velocities, ft/s					
MSF recovery or VTE preheater			5.0		
MSF reject or VTE condenser			5.5		
Brine heater			5.0		

Table 1 (continued)

Process type	MSF		VTE		
	Acid	Threshold	Acid	Acid	Threshold
Top brine temperature, °F	250	190-200	250	170	170
III. Specific consumption of chemicals		Optimistic Pessimistic		Optimistic Pessimistic	
1. Acid (93% H ₂ SO ₄), ppm	126	- **	126	- **	
2. Caustic (NaOH), ppm	10	-	10	-	
3. Sodium sulfite, ppm	2	-	2	-	
4. Antifoam, ppm	0.5	***	0.5	***	
5. Polyphosphate (or equivalent), ppm	-	3	-	3	
6. Chlorine, ppm in raw seawater	← 3 →				

*Fiberglass reinforced polyester made barometric inter- and after-condensers would probably be more economic but no cost data were available.

**Chemical cleaning only.

***Included in polyphosphate.

7. BASES FOR COST ESTIMATES

7.1 General and Bases for Direct Capital Cost

The costs of all design concepts investigated were evaluated with the aid of ORNI's MSF21 and VTE21 computer programs,^{1,2} modified and updated to mid-1975 prices.⁵ All direct equipment costs, except for heat transfer tubing prices for which current quotations have been used, were escalated to mid-1975 prices by applying the following cost escalation indices:

- a. For general construction cost, such as site development, sea-water intake and outfall, buildings, and pump pits — the index (construction cost trends) published by the Bureau of Reclamation was used.
- b. For process equipment, such as pumps and drivers, piping, valves, instrumentation, vacuum equipment and chemical equipment — the index published by *Chemical Engineering* (CE plant cost index) was used.
- c. For skilled labor cost, such as for installation of tubes and tubesheets, the index published by *Engineering News-Record* (ENR index) was used.

For nonacid plants (threshold pretreatment) the unit costs for valves, piping, and instrumentation were assumed to be 10% lower than for acid treated plant. The reduction in evaporator shell cost was assumed to be 20% lower for the designs based on optimistic assumption and 10% lower for the designs based on pessimistic assumptions. The indirect capital costs, such as engineering and supervision, escalation and interest during construction, owner's costs and contingency, and the total annual capital costs were evaluated in accordance with the applied economic ground rules discussed in Sect. 7.2. All operating costs were estimated on the basis of prevailing manpower and material costs, discussed in Sect. 7.3.

7.2 Bases for Estimating Indirect Capital, Contingency and Total Annual Capital Costs

7.2.1 Indirect capital costs

The indirect capital costs were composed of the following components:

a. Engineering, Design, and Supervision (AJSD)

This component was calculated as a function of the direct capital cost, according to the following formula:⁸

$$AJSD = 1.05 + .17582 \exp (-2.089 \times 10^{-8} CD),$$

where CD is the total direct cost.

b. Escalation during Construction

This component was evaluated as a function of the estimated construction time, an assumed escalation rate, predicted to be in effect during the construction time period, and an "S-curve" construction fund expenditure.⁵

The construction time, in months, evaluated by ORNL's computer programs⁸ was evaluated according to the following formula:

$$TIME = 54.1 \times [1 - (1.1 + 6 \times 10^{-9} CD)^{-2.632}] .$$

An annual escalation rate of 8% was assumed to be in effect during the construction period.

c. Interest during Construction

This component was evaluated, similar to the previous cost item, as a function of construction time and the assumed interest rate. The present evaluation applied an annual interest rate of 10%.

d. Owners Cost for Training and Startup

A value of 1.9% of all direct and indirect capital costs was assumed for this component.

7.2.2 Contingency

This cost component is probably the most disputed, and widely different assumptions have been made in the past by different cost estimators. Obviously, for an accurate cost estimate, without any uncertainties, or for a turnkey project without any owners cost, no contingency would have to be applied. It is generally accepted, however, that the

assumed allowance for contingency should reflect two main factors, the state of the applied technology (new or proven concept) and the engineering status of the project, i.e. preliminary or detailed design, first or additional identical unit.

In most desalting plant cost estimates, based on preliminary or conceptual designs, a value of 10 to 15% has been allocated for contingency. These values might have been adequate at financial conditions prevailing several years ago. At the prevailing rate of inflation of equipment cost and high interest rate, it was concluded that a higher contingency allowance should be applied. Thus a value of 25% was allocated for the MSF design concepts and a value of 30% for the VTE design concepts based on less extensively proven technology.

7.2.3 Total annual capital costs

The total annual capital expenses on the total investment (direct + indirect capital costs + contingency) were calculated by applying the annual fixed charge rate based on the following economic ground rules:

- interest rate: 10%
- sinking fund depreciation rate based on a 30-year plant life (0.6%)
- insurances and taxes: 1%.

This is equivalent to an annual fixed charge rate of 11.6%.

Because of the lack of long-term experience with fluted tubing (especially of aluminum alloys), the VTE effect tubes were conservatively assumed to have a lifetime of 15 years* with a retubing cost, prorated over the total plant lifetime, calculated with the aid of an appropriate costing procedure applied in ORNL's computer programs.⁸

7.3 Bases for Estimating the Operating Costs

7.3.1 Energy cost

The energy costs include those for process steam, ejector steam and electrical-power. Reference energy costs were derived by using current

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*This has been the assumed life in all previous ORNL (and other) studies.

costs for a 1000-MW(e) dual-purpose pressurized water reactor. Fuel cycle costs were based on WASH-1174. The resulting costs for steam at 131°C (268°F) and electricity were \$0.50/10⁶ Btu and \$0.020/kWhr. For the steam-jet ejector operating at 100 psig, the resulting steam cost was \$0.70/10⁶ Btu. The resulting steam costs (SC) for lower steam temperature (T_s), as a function of T_s , were fitted by the following polynomial

$$SC(T_s) = -78.5331 + 0.644544 T_s - 0.000608477 T_s^2 \text{ (cents/10}^6 \text{ Btu)}$$

Besides the aforementioned reference energy costs, three additional sets of energy cost were applied, one representing a dual-purpose plant with a 150% higher extraction steam cost, and two energy price levels corresponding to fossil-fuel-fired single-purpose desalting plants.

The case of high energy cost in a dual-purpose plant was assumed to represent energy price levels prevailing for small nuclear or fossil-fired plants, and/or a sharp energy cost increase in large nuclear plants. The corresponding electricity cost was estimated to be \$0.035/kWhr.

The lower energy price level for a single-purpose plant was set to \$2/10⁶ Btu for low-pressure steam. This cost corresponds to a fuel-oil price of \$70 to \$75/tonne (\$11 to \$12/barrel). The electric cost at this energy price level was assumed to be \$0.025/kWhr.

The higher energy price level for single-purpose plants was assumed to be 50% higher for low-pressure steam and 40% higher for the electricity cost. The resulting costs for low-pressure steam and electricity were, therefore, \$3/10⁶ Btu and \$0.035/kWhr.

7.3.2 Operation and maintenance labor cost

The O&M labor costs were based on an average man-year cost of \$16,000 and a 40% overhead on manpower cost. For a 100-Mgd capacity plant, the total O&M staff was set to 56 (38 operational and 18 maintenance). For all plant capacities other than 100 Mgd, the O&M labor cost was assumed to have a scale factor of 0.5. The resulting annual O&M labor cost (AOMC) in \$10³/year as a function of plant capacity (Mgd) was therefore fitted by:

$$AOMC \text{ (Mgd)} = 1250 \text{ (Mgd/100)}^{.5}$$

For nonacid treated plants the O&M cost was set to 10% less for the optimistic assumption and the same as for the acid treated plants for the design cases based on pessimistic assumptions.

7.3.3 Supplies and maintenance materials

The annual costs for this item was set to .7% of the total capital cost for the acid treated plants and 20% lower (.56%) for nonacid treated plants.

7.3.4 Chemicals

The annual costs for chemicals were based on the specific consumptions listed in Table 1 and the unit costs of chemicals listed in Table 2.

7.4 Summary of Economic Ground Rules and Evaluation of Unit Water Cost

All annual operating costs and the unit water costs were based on a plant operating factor of 85%. A summary of the applied economic ground rules is presented in Table 2.

Table 2. Summary of economic ground rules and parameters

General:

Interest rate, 10%
 Insurances and taxes, 1%
 Plant operating factor, 85%
 Equipment cost basis, mid 1975
 Plant life, 30 years
 Tubing life:
     VTE effect tubes, 15 years
     Other tubing, 30 years
 Annual escalation of costs during construction, 8%
 Contingency, 25% for MSF and 30% for VTE designs
 O&M labor cost, \$16,000/man-year (average)
 General and administration cost, 40% of O&M labor cost
 Annual costs for supplies and maintenance materials:
     Acid-treated plants, 0.7% of total capital cost
     Nonacid plants, 0.56% of total capital cost

Unit prices of chemicals:

Sulfuric acid, \$31/ton*
 Caustic (NaOH), \$170/ton
 Chlorine, \$176/ton
 Antifoam, \$1600/ton
 Sodium sulfite, \$305/ton
 Polyphosphate, \$3000/ton

Energy costs:

	Dual-purpose		Single-purpose	
	<u>Low**</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Process steam cost, \$10 ⁶ Btu				
At 100 psig (for ejectors)	0.70	1.75	2.0	3.0
At 268°F	0.50	1.25	2.0	3.0
At 178°F	0.17	0.425	2.0	3.0
Electricity, \$/kWhr	0.020	0.035	0.025	0.035

*Bulk, 100% basis.

**Reference for large nuclear plants.

8. DESIGN AND ECONOMIC DATA OF THE OPTIMIZED DESALTING PLANTS

8.1 Optimum Performance Ratio and Typical Design Data

The optimum performance ratios for the various desalting plant concepts investigated, optimized at four energy price levels for small plant capacities (1 and 2.5 Mgd) and large plant capacities (12.5 and 100 Mgd), are summarized in Tables 3 and 4, respectively.

Typical design data for 100 Mgd (12.5 Mgd train sizes) desalting plants, optimized at the reference energy costs of all design concepts investigated, are listed in Table 5.

8.2 Capital Costs of the Optimized Desalting Plant Designs

The specific investments (\$/gpd) for all optimized plant designs, corresponding to the optimum performance ratios listed in Tables 3 and 4, are summarized in Table 6 (small plant capacities) and Table 7 (large plant capacities).

The capital costs for the high-temperature (acid) and low-temperature (threshold) MSF designs versus desalting plant capacity and performance ratio are illustrated in Fig. 1.

The capital costs of the various VTE concepts investigated versus the number of VTE effects (N_{eff}) are illustrated in Fig. 2. The corresponding performance ratio versus N_{eff} is also shown on the same figure.

Detailed capital cost breakdowns of the optimized 100 Mgd desalting plant designs listed in Table 5 are presented in Table 8.

8.3 Unit Water Costs from the Optimized Desalting Plant Designs

The unit water costs obtained at the reference energy costs from the optimized MSF and VTE desalting plant concepts versus desalting plant capacity are illustrated in Figs. 3 and 4, respectively.

The unit water costs versus energy costs are listed in Tables 9 and 10, for small and large plant capacities, respectively. The effect of energy cost is also plotted in Fig. 5 (100 Mgd plants) and Fig. 6 (1.0 Mgd plants).

Table 3. Optimum performance ratio (lb/10³ Btu) versus heat cost — small plants
(number in brackets = MSF or VTE effects)

No.	Process	Desalting plant capacity, Mgd	1.0				2.5			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$/10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	MSF	High temperature (acid)	(26) 8.29	(34) 11.11	(40) 13.38	(42) 13.82	(29) 9.63	(38) 12.75	(45) 13.69	(46) 16.00
2.		Low temperature (threshold — optimistic)	(20) 6.18	(24) 7.82	(31) 10.81	(33) 12.08	(20) 6.92	(25) 8.83	(32) 12.06	(34) 13.36
3.		Low temperature (threshold — pessimistic)	(17) 5.46	(21) 6.90	(27) 9.88	(30) 11.08	(18) 5.88	(22) 7.43	(28) 10.62	(31) 11.83
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	(15) 8.95	(17) 9.91	(20) 11.55	(20) 11.55	(15) 9.43	(19) 12.20	(20) 12.76	(20) 12.76
5.		Low temperature (acid) (doubly fluted aluminum tubes)	(7) 5.36	(8) 5.94	(13) 9.82	(15) 10.88	(7) 5.63	(9) 7.17	(14) 10.89	(15) 11.67
6.		Low temperature (threshold) (OD fluted aluminum tubes — optimistic)	(6) 4.66	(7) 5.44	(13) 9.58	(14) 10.25	(6) 4.93	(7) 5.63	(13) 10.04	(14) 10.74
7.		Low temperature (threshold) (OD fluted aluminum tubes — pessimistic)	(6) 4.49	(7) 5.24	(13) 9.19	(14) 9.84	(6) 4.79	(7) 5.45	(13) 9.68	(14) 10.35

*For dual-purpose plants reference steam temperature = 268°F.

Table 4. Optimum performance (lb/10³ Btu) versus heat cost — large plants
(numbers in brackets = MSF stages or VTE effects)

No.	Process	Desalting plant capacity, Mgd	12.5				100.0			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$/10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	MSF	High temperature (acid)	(31) 10.66	(38) 13.53	(44) 15.69	(44) 16.00	(31) 10.71	(39) 13.52	(44) 15.62	(44) 16.00
2.		Low temperature (threshold — optimistic)	(21) 7.39	(26) 9.42	(33) 12.15	(34) 13.51	(21) 7.38	(26) 9.44	(35) 12.17	(35) 14.17
3.		Low temperature (threshold — pessimistic)	(18) 6.21	(22) 7.87	(28) 10.80	(31) 12.08	(18) 6.20	(22) 7.89	(28) 10.80	(31) 12.08
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	(15) 11.00	(19) 13.75	(20) 14.38	(20) 14.38	(15) 11.00	(19) 13.75	(20) 14.38	(20) 14.38
5.		Low temperature (acid) (doubly fluted aluminum tubes)	(7) 6.18	(9) 7.83	(14) 11.84	(15) 12.67	(7) 6.18	(9) 7.83	(14) 11.84	(15) 12.67
6.		Low temperature (threshold) (OD fluted aluminum tubes— optimistic)	(6) 5.43	(7) 6.28	(13) 11.14	(14) 11.90	(6) 5.43	(7) 6.28	(13) 11.14	(14) 11.90
7.		Low temperature (threshold) (OD fluted aluminum tubes — pessimistic)	(6) 5.33	(7) 6.16	(13) 10.87	(14) 11.62	(6) 5.33	(7) 6.16	(13) 10.87	(14) 11.62

*For dual-purpose plants reference steam temperature = 268°F.

Table 5. Design data of optimized* 100 Mgd (12.5 Mgd trains) desalting plants

Process type	MSF			VTE			
Pretreatment	Acid	Threshold		Acid	Threshold		
Design & operational assumptions	Reference	Optimistic	Pessimistic	Reference	Reference for aluminum tubing	Optimistic	Pessimistic
Input steam temperature, °F	258	208	198	258	178	178	178
Top brine temperature, °F	250	200	190	250	169	167	167
Performance ratio, lb/1000 Btu	10.72	7.39	6.20	11.00	6.18	5.43	5.33
Number of MSF (or VTE preheater) stages	31	21	18	30	14	12	12
Number of VTE effects				15	7	6	6
Total plant length, ft	557	433	397	222	148	158	158
Total evaporator volume, 10 ³ ft ³	2175	2865	3016	1512	2209	3507	3507
Average heat transfer coefficient (U), ** Btu/hr-ft ² -°F	600	575	486	1001	1046	656	656
Tubing surface, *** 10 ³ ft ²	8027	8689	9097	4533	4633	5841	5867
Seawater intake, 10 ⁶ lb/hr	128.8	179.5	210.8	128.8	232.1	264.2	269.2
Total pumping power, MW	27.70	30.64	34.33	19.48	21.50	25.91	25.91

*At reference energy cost.

**In MSF recovery section or VTE effects.

***Including brine heater and final condenser (VTE).

Table 6. Capital cost of optimized plants versus heat cost — small plants (\$/gpd)

No.	Process	Desalting plant capacity, Mgd	1.0				2.5			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$/10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	MSF	High temperature (acid)	4.40	4.86	5.39	5.48	3.00	3.42	3.56	3.98
2.		Low temperature (threshold — optimistic)	4.05	4.56	5.51	5.99	2.98	3.31	4.08	4.48
3.		Low temperature (threshold — pessimistic)	4.37	4.72	5.78	6.35	3.24	3.54	4.50	4.97
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	4.11	4.39	4.76	4.76	2.76	3.13	3.23	3.23
5.		Low temperature (acid) (doubly fluted aluminum tubes)	3.78	3.99	4.95	5.45	2.72	2.93	3.81	4.04
6.		Low temperature (threshold) (OD fluted aluminum tubes — optimistic)	3.73	3.89	5.35	5.68	2.75	2.91	4.09	4.36
7.		Low temperature (threshold) (OD fluted aluminum tubes — pessimistic)	3.88	4.05	5.60	5.94	2.85	3.10	4.27	4.56

*For dual-purpose plants reference steam temperature = 268°F.

Table 7. Capital cost of optimized plants versus heat cost — large plants (\$/gpd)

No.	Process	Desalting plant capacity, Mgd	12.5				100.0			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$/10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	MSF	High temperature (acid)	2.02	2.32	2.48	2.64	1.79	2.08	2.33	2.39
2.		Low temperature (threshold — optimistic)	2.08	2.36	2.90	3.23	1.84	2.12	2.65	3.16
3.		Low temperature (threshold — pessimistic)	2.26	2.55	3.26	3.66	2.00	2.30	2.98	3.38
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	1.75	2.00	2.07	2.07	1.55	1.80	2.07	2.07
5.		Low temperature (acid) (doubly fluted aluminum tubes)	1.30	1.98	2.72	2.91	1.55	1.73	2.46	2.65
6.		Low temperature (threshold) (OD fluted aluminum tubes — optimistic)	1.97	2.07	3.11	3.35	1.70	1.80	2.84	3.08
7.		Low temperature (threshold) (OE fluted aluminum tubes — pessimistic)	2.05	2.16	3.25	3.51	1.77	1.89	2.97	3.23

*For dual-purpose plants reference steam temperature = 268°F.

Table 8. Capital cost breakdown of optimized (at reference energy cost) 100 Mgd desalting plants

Process type	MSF						VTE							
	Pretreatment		Acid				Threshold				Acid			
			Reference		Optimistic		Pessimistic				Reference		Reference for aluminum tubes	
	Design & operational assumptions		Threshold		Optimistic		Pessimistic				Reference		Reference for aluminum tubes	
			\$10 ⁶	%	\$10 ⁶	%	\$10 ⁶	%	\$10 ⁶	%	\$10 ⁶	%	\$10 ⁶	%
I. Direct capital components														
Condensing surface			24.42	24.67	26.27	25.92	26.59	24.21	19.85	24.04	11.78	14.25	14.48	15.97
Shell and foundation			31.19	31.49	28.33	27.94	31.43	28.62	18.73	22.67	21.71	26.26	24.39	26.89
Brine heater			4.23	4.27	5.22	5.15	7.34	6.68	1.76	2.13	1.40	1.69	1.28	1.41
Final condenser									1.28	1.55	2.05	2.48	2.33	2.57
Pumps and motors			8.97	9.06	10.55	10.40	11.49	10.46	8.51	10.31	8.95	10.83	10.68	11.77
Valves and piping			4.82	4.87	4.37	4.31	4.46	4.06	5.95	7.20	5.87	7.10	5.77	6.36
Instrumentation			3.43	3.47	3.09	3.05	3.09	2.81	5.23	6.33	4.28	5.18	3.81	4.20
Electrical equipment			3.31	3.35	3.59	3.54	3.93	3.58	3.02	3.66	3.19	3.86	3.76	4.15
NCG* removal system			4.16	4.17	3.48	3.43	3.48	3.18	3.84	4.65	3.84	4.65	3.48	3.84
Pre- and posttreatment system			2.51	2.53	1.94	1.91	1.98	1.80	2.47	2.99	2.60	3.15	2.04	2.25
Seawater intake			8.19	8.27	10.63	10.48	12.07	10.99	8.19	9.91	13.03	15.76	14.46	15.94
Site and buildings			3.81	3.85	3.93	3.87	3.96	3.61	3.77	4.56	3.96	4.79	4.22	4.65
Total direct			99.04	100.00	101.40	100.00	109.82	100.00	82.61	100.00	82.66	100.00	90.71	100.00
II. Indirect capital components														
Engineering, design and supervision			7.15	7.22	7.21	7.11	7.43	6.77	6.72	8.13	6.72	8.13	6.93	7.64
Escalation during construction			14.98	15.13	15.41	15.20	17.03	15.51	11.87	14.37	11.88	14.37	13.39	14.76
Interest during construction			19.63	19.82	20.23	19.95	22.43	20.42	15.46	18.72	15.47	18.72	17.49	19.28
Owner's cost (training and startup)			2.68	2.70	2.76	2.72	3.00	2.73	2.22	2.68	2.22	2.68	2.44	2.69
Total indirect			44.44	44.87	45.61	44.98	49.89	45.43	36.27	43.90	36.29	43.90	40.25	44.37
Total before contingency			143.48	144.87	147.01	144.98	159.71	145.43	118.88	143.90	118.96	143.90	130.96	144.37
III. Contingency			35.87	36.22	36.75	36.24	39.93	36.36	35.66	43.17	35.69	43.17	39.29	43.31
Total investment			179.35	181.09	183.76	181.22	199.64	181.79	154.54	187.07	154.65	187.07	170.25	187.68

*Noncondensable gas including decarbonator for acid plants.

Fig. 1. MSF capital cost vs desalting plant capacity and performance ratio (PR).

Fig. 2. Performance ratio and capital cost vs number of VTE effects and desalting plant capacity.

Fig. 3. Unit water cost vs desalting plant capacity (dual-purpose MSF - reference energy cost).

Fig. 4. Unit water cost vs desalting plant capacity (dual-purpose VTE - reference energy cost).

Table 9. Unit water cost from optimized plants versus heat cost — small plants (\$/1000 gal)

No.	Process	Desalting plant capacity, Mgd	1.0				2.5			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	NSF	High temperature (acid)	2.85	3.68	4.20	4.85	2.08	2.79	3.20	3.84
2.		Low temperature (threshold — optimistic)	2.64	3.46	4.57	5.50	2.02	2.66	3.61	4.41
3.		Low temperature (threshold — pessimistic)	2.84	3.58	4.99	6.00	2.19	2.84	4.04	4.95
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	2.72	3.58	4.14	5.00	1.98	2.65	3.14	3.89
5.		Low temperature (acid) (doubly fluted aluminum tubes)	2.43	3.04	4.51	5.52	1.80	2.27	3.66	4.53
6.		Low temperature (threshold) (OD fluted aluminum tubes — optimistic)	2.44	3.06	4.78	5.84	1.87	2.45	3.98	4.96
7.		Low temperature (threshold) (OD fluted aluminum tubes — pessimistic)	2.52	3.16	5.01	6.11	1.93	2.59	4.15	5.16

*For dual-purpose plants reference steam temperature = 268°F.

Table 10. Unit water cost from optimized plants versus heat cost — large plants (\$/1000 gal)

No.	Process	Desalting plant capacity, Mgd	12.5				100.0			
		Plant type	Dual-purpose		Single-purpose		Dual-purpose		Single-purpose	
		Heat cost, \$/10 ⁶ Btu	0.50*	1.25*	2.00	3.00	0.50*	1.25*	2.00	3.00
1.	MSF	High temperature (acid)	1.50	2.10	2.49	3.10	1.33	1.93	2.31	2.93
2.		Low temperature (threshold — optimistic)	1.51	2.08	2.96	3.73	1.34	1.92	2.80	3.56
3.		Low temperature (threshold — pessimistic)	1.63	2.24	3.34	4.20	1.45	2.06	3.16	4.02
4.	VTE	High temperature (acid) (doubly fluted Cu-Ni tubes)	1.36	1.93	2.35	3.00	1.20	1.78	2.20	2.85
5.		Low temperature (acid) (doubly fluted aluminum tubes)	1.26	1.68	2.93	3.80	1.09	1.50	2.75	3.53
6.		Low temperature (threshold) (OD fluted aluminum tubes — optimistic)	1.40	1.88	3.27	4.16	1.23	1.71	3.09	3.99
7.		Low temperature (threshold) (OD fluted aluminum tubes — pessimistic)	1.47	1.96	3.39	4.30	1.28	1.78	3.20	4.12

*For dual-purpose plants reference steam temperature = 268°F.

Fig. 5. Unit water cost vs heat cost. Comparison of 100 Mgd MSF and VTE dual-purpose plants.

Fig. 6. Unit water cost vs heat cost. Comparison of 1 Mgd MSF and VTE dual-purpose plants.

A detailed unit water cost breakdown of the optimized 100-Mgd desalting plants at reference energy costs is shown in Table 11.

Unit water costs versus performance ratio (MSF plant) and number of effects (VTE plant) are plotted in Figs. 7 and 8 for MSF and VTE plants, respectively.

Table 11. Unit water cost breakdown of optimized (at reference energy cost) 100 Mgd desalting plants

Process type	MSF						VTE							
Pretreatment	Acid		Threshold				Acid				Threshold			
Design & operational assumptions	Reference		Optimistic		Pessimistic		Reference		Reference for aluminum tubes		Optimistic		Pessimistic	
	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%
Cost components:														
1. Capital cost	0.671	50.34	0.688	51.23	0.747	51.37	0.579	48.29	0.579	53.31	0.637	51.83	0.661	51.52
2. Retubing							0.014	1.17	0.012	1.11	0.014	1.14	0.014	1.09
3. Energy cost														
Process heat	0.365	27.38	0.327	24.35	0.337	23.18	0.356	29.69	0.228	20.99	0.258	21.00	0.263	20.50
Ejector steam	0.008	0.63	0.016	1.19	0.016	1.10	0.007	0.58	0.007	0.65	0.016	1.30	0.016	1.25
Electrical power	0.132	9.93	0.147	10.94	0.165	11.35	0.110	9.18	0.121	11.14	0.146	11.87	0.150	11.69
Total energy	0.505	37.83	0.490	36.48	0.518	35.63	0.473	39.45	0.356	32.78	0.420	34.17	0.429	33.44
4. Operation & maintenance														
Staff	0.040	3.00	0.036	2.68	0.040	2.75	0.040	3.34	0.040	3.68	0.036	2.93	0.040	3.12
Supply & materials	0.040	3.00	0.033	2.46	0.036	2.48	0.034	2.83	0.034	3.13	0.030	2.44	0.031	2.41
Chemicals	0.077	5.78	0.096	7.15	0.113	7.77	0.059	4.92	0.065	5.99	0.092	7.49	0.108	8.42
Total O&M	0.157	11.78	0.165	12.29	0.189	13.00	0.133	11.09	0.139	12.80	0.158	12.86	0.179	13.95
Total unit water cost	1.333	100.00	1.343	100.00	1.454	100.00	1.199	100.00	1.086	100.00	1.229	100.00	1.283	100.00

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Fig. 7. Unit water cost vs performance ratio and heat cost from high temperature (acid) MSF plants.

Fig. 8. Unit water cost vs number of VTE effects and heat cost from high (acid) and low (aluminum tubes - acid) temperature VTE plants.

9. ANALYSIS OF RESULTS

9.1 Range of Capital and Unit Water Costs

The resulting capital costs for large desalting plants, based on current technology and optimized on the basis of relative low energy cost, obtained from large nuclear plants, range from \$1.50 to \$2.00 per gpd. These costs are about three times higher than the capital costs estimated 7 to 8 years ago for plants having similar performance ratios (11 to 14 lb/10³ Btu). In this time period plant equipment (except heat transfer tubing) and construction cost increased about 100%, on the average. As heat transfer tubing costs were less affected, the average cost increase, caused by inflation of equipment cost, would have to be less than 100%. The additional 100%, or more, of increase in the total capital cost of large desalting plants is caused by two major factors: (a) the prevailing high cost of money and the continuous inflation which strongly affect the indirect capital costs; and, (b) the current observed tendency of the desalting plant manufacturers to apply more conservative design criteria regarding process equipment and construction materials. By far the larger of these two factors is due to (a). From Table 8, it can be seen that the total investment of 100-Mgd MSF plants is approximately 180% of the direct capital cost. This additional 80% is almost three times as much as the percentage for indirect cost plus contingency, applied in the cost estimation of ORNL's 250-Mgd MSF Conceptual Design³ in January 1969.

The resulting capital cost of small desalting plants in the 1-Mgd capacity range varied between \$4 to \$6 per gpd. The lower figure is representative for plants having low performance ratios and the higher figure for plants optimized for high energy costs. At a process steam cost of \$3/10⁶ Btu, optimum performance ratios were found to be approximately 14 to 12 lb/1000 Btu for high-temperature (acid) and low-temperature (threshold) MSF plants (see Table 3).

The resulting unit water costs ranged from ~\$1.20 to \$2.90/kgal and ~\$2.60 to \$6.00/kgal for large (100 Mgd) and small (1 to 2.5 Mgd) desalting plants, respectively. These wide ranges in costs emphasize the

strong impact of energy prices on desalted water cost. From comparison of unit water cost breakdown illustrated in Fig. 9, it can be concluded that a sixfold increase in process steam cost increases the unit water cost by approximately 70 to 120%. It can also be concluded that the threefold to fourfold increase in desalted water cost occurring in the last 2 to 3 years is only partially caused by the sharp rise in energy prices. The other factor contributing to the sharp cost increase, having almost the same impact as the rising energy prices, is obviously continuously rising capital cost and the prevailing high interest rates.

Fig. 9. Unit water cost breakdown vs energy cost and plant size.

9.2 Comparison Between High-Temperature MSF and VTE Plants

For large plants the resulting capital costs of the optimized VTE plants (see Tables 7 and 8) were 13 to 15% lower than the MSF plants operating at the same temperature level. The corresponding performance ratios of the VTE and MSF plants were only slightly different so that the costs reflected the actual basic differences between these two concepts. These differences are well known and have been analyzed comprehensively in the past in numerous studies. For the design concepts based on current technology, the main characteristics of the optimized MSF and VTE designs can be seen from the resulting design data shown in Table 5. By comparing the breakdown of the capital costs, given in Table 8, it can be seen that the greatest differences were obtained in the shell and foundation costs. This difference fully reflects the substantial lower required evaporator volume for the VTE. The other major basic difference — that of the much lower total heat transfer surface — is partially offset by the higher unit surface cost of the enhanced surfaces and the higher tubesheet and tubing installation cost. The somewhat more complicated system of the VTE is reflected by the resulting higher cost of the valves and piping and the instrumentation cost components. The higher unit costs of the pumping units and the electrical equipment for the VTE is offset by the lower total pumping power.

The resulting unit water cost from large high-temperature VTE plants is approximately 10% lower than from the high-temperature acid-treated MSF plants (see Tables 10 and 11). This reduction in cost is obtained mainly due to the lower capital costs, the lower pumping power cost, and the lower chemical consumption cost.

For plants having small capacities (1.0 and 2.5 Mgd), the economic advantage of the VTE is considerably reduced, especially for plants optimized for high energy price levels (see Table 9). For very high energy cost (\$3/10⁶ Btu) the resulting cost from the VTE design was even slightly higher than for the MSF design. It is, however, emphasized that the VTE structural design concept adopted, where the MSF preheater was integrally located in the same vessel under the VTE effects, is probably not well suited to the design requirements of plants having small

capacities and operating with high performance ratios. This is mainly due to the relative short length of the vessel required to house the VTE effects and results in too small a preheater which affects the combined overall performance ratio of the VTE-MSF preheater system. However, the long-tube design adopted for the MSF plants is probably also not the best design concept for small plant sizes for which the cross-tube design might be considerably more economical. The results of the present investigation can therefore not be applied for the comparison between small MSF and VTE units.

9.3 Comparison Between High- and Low-Temperature MSF Designs

By comparing the unit water costs in Tables 9, 10, and 11, it was concluded that low temperature plants, applying the threshold pretreatment method, might be economically attractive for small dual-purpose electric power-MSF desalting plants. For single-purpose plants the assumed potential cost savings could not outweigh the thermodynamic disadvantage of the low-temperature process, and the resulting unit water costs were considerably higher. The effect of energy cost and desalting plant size on the comparison between high- and low-temperature MSF plants, operating in a single or dual-purpose system, are shown in Fig. 10. From the comparison shown in Fig. 10, it can be seen that low-temperature nonacid treated plants could eventually be competitive for continuous rising energy cost, even for large plant capacities.

9.4 Comparison Between High- and Low-Temperature VTE Designs

As expected, the low-temperature aluminum tubing VTE design is only economically attractive for application in dual-purpose plants. The potential reduction in unit water costs (see Tables 9, 10, and 11), when applying doubly fluted aluminum tubing, amounts to 10 to 15%. The larger cost saving was obtained at the higher energy price level. The effect of reference heat cost and plant capacity on the comparison of high- and low-temperature designs are also illustrated in Fig. 11.

Fig. 10. Unit water cost from MSF plants vs heat cost and plant size.

The optimized doubly-fluted aluminum-tubed VTE designs have approximately the same capital costs (except for small capacities) as the high temperature designs, but, of course, for much lower performance ratio (PR). From the design data shown in Table 5, it can be seen that the low-temperature design, for a 100-Mgd plant optimized at the reference energy price level, resulted in only seven effects (PR = 6.18), compared to 15 effects (PR = 11.00) for the high-temperature design. Even at that much lower performance ratio, the reduced heat cost at a temperature of

Fig. 11. Unit water cost from VTE plant vs heat cost and plant size.

178°F more than outweighs the larger heat consumption, and the net effect is reduced process heat cost by about one third (see Table 11). The total energy cost was, however, less affected because of a somewhat higher electrical power cost.

The nonacid treated low-temperature designs have, obviously, considerably less potential benefits because of the basic assumption that a

threshold pretreatment method could not be applied for doubly-fluted tubing. The much lower heat transfer coefficient of tubes fluted on the condensing surface only also affects other design characteristics, such as plant dimensions (see Table 5), and therefore, increases the capital cost substantially.

For large capacity plants and the reference energy cost level, the low-temperature designs applying threshold pretreatment were not found to be competitive with the high-temperature designs. Smaller plants are, however, much less affected by the reduced heat transfer coefficients and benefit more from the potential advantages of the threshold pretreatment. From the comparison shown in Fig. 11, it can be seen that for 1-Mgd plants, potential cost savings of the threshold low-temperature designs are not much lower than those from acid-treated low-temperature design. It can therefore be concluded that even for the case where an acid treatment might not be compatible with aluminum alloy tubing, the low-temperature VTE would still be economically attractive for small capacity plants. For larger capacities this design would eventually be competitive for the case of high energy costs (see Fig. 11).

10. SENSITIVITY ANALYSIS

10.1 Introduction

As far as possible, the present investigation was based on current technology and prevailing economic conditions, except for the low temperature VTE designs. The selection of construction materials, module and train sizes, and other technological design parameters, as well as the economic ground rules, was therefore set accordingly. The only economic parameter varied, in the evaluation of the design concepts investigated, was the energy cost. Other economic or operational parameters, such as the interest rate or the plant operating factor, may vary with time and/or plant location. The effect of these parameters, as well as the effect of technological parameters, which might be eventually varied after some technological and/or materials market developments, were investigated with the aid of a brief sensitivity analysis.

10.2 Effect of Technological Parameters

The major technological design parameters affecting the capital and unit water costs were found to be, as expected, the evaporator shell and tubing material, and, for large capacity plants, the largest applicable independently operating train size, consisting of a multiple number of modules. Several other much less significant design parameters include the tubing diameter and length, the brine flow per tray width (MSF), and the freeboard between the brine level and tube bundle (MSF).

The effect of the aforementioned technological design parameters was made on a 100-Mgd acid-treated MSF design optimized on the basis of the reference energy cost. The effects of module and train size on capital and unit water costs are shown in Fig. 12. From the results in Fig. 12, it is evident that module sizes larger than 12.5-Mgd would not be economic in cases where a small number of trains is utilized for a 100-Mgd design. Thus, in case of two 50-Mgd trains, four 12.5-Mgd modules per train are more economic than two 25-Mgd modules or one 50-Mgd module. The effect of the other major design parameters, each varied independently

Fig. 12. Capital and unit water cost of a 100 Mgd MSF plant vs number of evaporator trains.

while all others were kept at their reference design values, are summarized in Table 12.

In the sensitivity analysis, aluminum-brass tubing was assumed to be 20% cheaper than 90-10 Cu-Ni, and 5/8-in. tubing was assumed to be 5% more costly (per ft²) than 3/4-in. tubing.

The fouling factor, which is mostly dependent on the pretreatment method and some operational factors, such as the tube cleaning frequency, may also be considered as a technological design parameter. Moreover, a low fouling factor yields a high heat transfer coefficient and therefore has a similar effect to that which could be obtained, eventually, by applying some kind of enhanced horizontal tubing, such as spirally indented tubing. Thus, by assuming a theoretical zero fouling factor, the heat transfer coefficient was increased by approximately 40% above the value obtained with the reference fouling factor of 0.0005. The resulting saving (see Table 12) in unit water cost was 6%.

The combined effect of varying several design parameters simultaneously and that of a set of extreme optimistic assumptions was also evaluated and shown in Table 12. The result of this evaluation may give some indication of the inherent development potential of the MSF desalting process.

The effect of a reduced fouling factor was also evaluated, mainly because its effect is equivalent to a higher heat transfer coefficient, which might eventually be obtained by applying some kind of enhanced horizontal tubing, such as spirally indented tubing.

From the results shown in Table 12 it is evident that the total development potential of the MSF process is an approximate 20% cost saving. It is, however, doubtful if all of the listed cost savings could be realized; and it is therefore more realistic to assume a potential cost saving of about 10%.

10.3 Effect of Economic Parameters

The effect of changing the economic ground rules was investigated on four 100-Mgd design concepts optimized on the basis of the reference energy cost. The parameters changed were the interest rate, the plant

Table 12. Effect of technological parameters on the unit water cost from a 100 Mgd high-temperature acid treated MSF plant (unit water cost from reference design = \$1.33/kgal)

Technological design parameters varied	Cost increase		Cost saving	
	\$/1000 gal	%	\$/1000 gal	%
1. Train and module size:				
a. 12 trains and modules (instead 8)	0.06	4.5		
b. 4 trains and 8 modules			0.05	3.8
c. 2 trains and 8 modules			0.08	6.0
2. Aluminum-brass tubing (instead 90-10 Cu-Ni)			0.03	2.3
3. 5/8 in. diameter tubing (instead 3/4 in.)			0.02	1.5
4. Tubing length:				
a. ~200 ft (instead ~70 ft)			0.02	1.5
b. ~100 ft			0.01	0.8
c. ~50 ft	0.01	0.8		
5. Brine tray flow at the cold end:				
a. 4×10^6 lb/hr·ft (width) (instead $.8 \times 10^6$)	0.12	9.0		
b. 1.2×10^6 lb/hr·ft (width)			0.04	3.0
6. Freeboard between brine level and tube bundle:				
a. 7.5 ft (instead 5.75 ft)	0.01	0.8		
b. 4.0 ft			0.01	0.8
7. Fouling factor (recovery section):				
a. .0008 (instead .0005)	0.05	3.8		
b. .0002			0.04	3.0
c. Zero fouling			0.08	6.0
8. Combined effect of 1c and 2			0.13	19.8
9. Combined effect of 1c, 5, 6b, 7b and 8b			0.19	14.3
10. Combined effect of 1c, 3, 4, 5a, 6b, 7b and 8b			0.22	16.5
11. Combined effect of 1c, 2, 3, 4, 5a, 6b, 7b and 8c			0.28	21.1

operating factor, the total capital cost, the total energy cost, and the total operating and maintenance cost (less energy cost). The effect of changing the reference values of these parameters on the unit water cost is summarized in Table 13.

The results of the sensitivity analysis shown in Table 13 indicate that at more favorable economic conditions, including a 20% decrease in interest rate, total investment and operating (excluding energy) cost, and a higher plant operating factor (90% instead of 85%), a cost saving of about 20 to 25% could be realized. On the other hand, less favorable economic conditions, including a 20% increase in interest rate, total investment and operating cost, a lower plant operating factor (75% instead of 85%), and a 50% increase in energy cost would affect the unit water cost by about 50 to 55%.

Table 13. Effect of economic parameters on the unit water cost from 100 Mgd desalting plants

Process type	MSF				VTE			
Design concept	High-temperature Acid treated		Low-temperature Threshold*		High-temperature Acid; Cu-Ni tubes		Low-temperature Acid; aluminum tubes	
Reference unit water cost	1.33	100.0	1.34	100.0	1.20	100.0	1.09	100.0
	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%	\$/1000 gal	%
1. Interest rate:								
Increased from 10% to 12%	+0.13	+9.8	+0.13	+9.7	+0.12	+10.0	+0.12	+11.0
Decreased from 10% to 8%	-0.12	-9.0	-0.12	-9.0	-0.11	-9.2	-0.11	-10.1
2. Plant operating factor:								
Increased from 85% to 90%	-0.04	-3.0	-0.04	-3.0	-0.04	-3.3	-0.04	-3.7
Decreased from 85% to 75%	+0.10	+7.5	+0.10	+7.5	+0.09	+7.5	+0.09	+8.3
3. 20% change in capital cost	+0.13	+9.8	+0.14	+10.4	+0.12	+10.0	+0.12	+11.0
4. 50% increase in total energy cost	+0.25	+18.8	+0.25	+18.7	+0.24	+20.0	+0.18	+16.5
5. 20% change in operation and maintenance cost**	+0.03	+2.3	+0.03	+2.2	+0.03	+2.5	+0.03	+2.8
6. Combined effect of all increasing cost factors	+0.73	+55.0	+0.71	+52.9	+0.63	+52.5	+0.57	+52.3
7. Combined effect of all decreasing cost factors	-0.29	-21.8	-0.30	-22.4	-0.27	-22.5	-0.27	-24.8

*Optimistic assumptions.

**Excluding energy cost.

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