OPTIMISATION OF MSF TOP BRINE TEMPERATURE AND RECIRCULATION RATE USING FINANCIAL ANALYSIS

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Abstract

This paper studies the impact of two of the key multi stage flash distillation (MSF) design parameters, top brine temperature (TBT) and recycle rate, on the design of the accompanying power plant, and on the overall power desalination project (power/desal) economics. The study uses an integrated system net present value (NPV), which overcomes the problems associated with how to allocate the cost of steam production between the power and desalination plants. The method uses process simulation and bottom up costing of both the power plant and the MSF plant to generate capital costs, finance costs, non energy operating costs and fuel costs. These costs are combined with power and water revenues to give an overall project NPV for the combined power/desal facility.

Increasing TBT reduces the capital cost of MSF, without significantly affecting power or steam consumption. However, the increased TBT also increases the temperature of steam required in the brine heater, which reduces the amount of power that can be generated by the back pressure steam turbine. In addition, the number of "hot" stages is increased, increasing the cost of tube materials.

In a similar manner, MSF capital cost can be reduced by increasing the brine recirculation rate. This has the advantage of not increasing the temperature of any of the flash stages, therefore allowing the same materials to be used. However, it does increase steam demand and power consumption.

This study shows how key MSF design parameters can have a significant impact on the design of the accompanying power plant, and demonstrates why any optimisation of the MSF process cannot be truly effective without considering the knock-on implications on the steam generation system (power plant).

CONTENTS

I. INTRODUCTION

The desalination industry has seen a lot of recent interest in operating MSF plants with increased TBT. This can be achieved through the use of nanofiltration technology[1,2,3], advanced anti-scalant chemicals, or acid scale control. Increasing the TBT increases the quantity of distillate produced for a given brine flow, without significantly affecting the Gain Output Ratio (GOR), or steam consumption per unit of product. However, it does increase the pressure of low pressure (LP) steam required from the power plant.

Increasing the brine recycle rate also increases distillate production. However, there is a corresponding reduction in the GOR, and an increase in the pressure drop across the tubes, which leads to increased power consumption.

Any economic assessment of thermal desalination technology is faced with the key issue of assignment of cost to the steam consumed by the desalination plant. Many methods have been used in the past[4,5,6,7,8], but all of these methods have to contend with the fact that the steam requirement for the desalination plant (flowrate and pressure) can have a very significant effect on the power plant design.

For this reason, this paper considers the combined power and desalination plant as a single, economic facility, which is fed with gas and seawater, and produces two saleable products of power and water. This facility has capital and operating costs, which are combined with the fuel cost, power & water revenues to calculate the overall project NPV. Since the economic analysis only considers the overall facility, there is no need to calculate the cost of supplying steam and electricity to the desalination plant.

This study uses process simulation and costing tools for both the desalination plant and the power plant. The MSF process simulator models the process performance (distillate production, steam consumption, power consumption) of an MSF plant for a given combination of brine recycle rate, TBT, salinity, feed temperature, heat reject section cooling water flow, tube configuration and fouling factors. The model includes the impacts of tube velocity on heat transfer coefficients, brine loading rate on non equilibrium temperature losses, increased brine temperature on boiling point elevation and increased vapour rates on vapour pressure drop. Having simulated the process performance, the model also estimates the MSF capital and operating costs, based on quantity.

The power plant simulator[9] models and costs the power plant. The model accounts for the impact of steam pressure & temperature on the steam turbine and heat recovery steam generator cost.

II. STUDY PARAMETERS

General Parameters 2.1

Table 1 shows the overall parameters used in this study.

Seawater Temperature	33 °C
Seawater Salinity	40 g/kg
Gas Cost	US\$1.50/GJ
Water Tariff	70 US¢/m^3
Power Tariff	2.5 US¢/kW.hr
Water Production	100 MiGD Target
Power Export	1700 MW

Table 1 General Study Parameters

Multi Stage Flash Design Parameters 2.2

The basis for the MSF plant is a 100 MiGD design described by Nada [10], which is used to derive the design information listed in Table 2.

	Brine Heater	Heat Recovery Stages	Heat Reject Stages
Number of Stages	1	18	3
Tube Surface Area	6578 m^2	6348 m^2	Variable
Fouling Factor	0.3 x 10^{-3} m^{2}K/W	0.2 x 10^{-3} m^{2}K/W	0.2 x 10^{-3} m^{2}K/W
Tube Length	19 m	19 m	19 m
Tube Outside Diameter	29 mm	29 mm	29 mm
Tube Thickness	Variable	Variable	0.9 mm
Tube Material	AL6XN or 66/30/2/2 Cu/Ni	AL6XN, 66/30/2/2 Cu/Ni or 90/10 CuNi	66/30/2/2 Cu/Ni
Number of Tubes	3,800	3,668	Variable

Table 2 Assumed and Derived MSF Design Parameters

As indicated above, the tube material and thicknesses in the brine heater and heat recovery stages are variable, depending on the brine temperature leaving the stage, the brine recycle pump pressure and also on the average brine velocity in the tubes.

Table 3 shows the rules used to select tube material based on brine temperature and Table 4 shows the rules used to select tube wall thickness based on brine recycle pump delivery pressure.

Material	Average Brine Velocity in Tubes	Brine Temperature Leaving Stage
AL6XN	Velocity > 3.75 m/s	> 135 °C
66/30/2/2 Cu/Ni	3 m/s < velocity ≤ 3.75 m/s	90 °C < Temperature ≤ 135 °C
90/10 Cu/Ni	Velocity ≤ 3 m/s	≤ 90 °C

Table 3 Tube Material as a Function of Average Brine Velocity

Brine Recycle Pump Pressure	90/10 Cu/Ni	66/30/2/2 Cu/Ni	AL6XN
≤ 15 Bara	0.9 mm	0.9 mm	0.5 mm
15 Bara < Pressure ≤ 20 Bara	1.2 mm	1.2 mm	0.5 mm
> 20 Bara	Use AL6XN	Use AL6XN	0.5 mm

Table 4 Tube Wall Thickness as a Function of Brine Recycle Pump Pressre

For each case in the study, the following procedure was used to design the MSF plant:

1. Select tube material appropriate to the required tube velocity.
2. Adjust brine recirculation rate until average velocity leaving first (hottest) heat recovery stage is as required.
3. Adjust the number of tubes in each heat reject stage until the average velocity leaving the first (hottest) heat reject stage is as required.
4. Adjust the flowrate through the heat reject section (repeating step 2 above for each new value) until the temperature leaving the heat reject section is 40 °C.
5. Check tube material in each stage is appropriate to brine temperature leaving stage. If not, change material and repeat above steps.
6. Check tube wall thickness and material in each stage is appropriate for the brine recycle pump delivery pressure. If not, change wall thickness and repeat above steps.
7. Adjust total number of MSF units to the integer value which gives closest to 100 MiGD total distillate production.
8. Adjust brine heater, recovery & reject section tube number, brine recycle and reject flowrates by 100 / total capacity (in MiGD) so that the total MSF production capacity is a constant 100 MiGD
9. Record cost and operating data for financial analysis.

Power Plant Design Parameters 2.3

The basis of the power plant design is combined cycle blocks, with each block comprising 2 General Electric GE9FA gas turbines, 2 heat recovery steam generators (HRSGs), and a single, backpressure steam turbine, with a single pressure, non re-heat steam cycle. The gas turbine air inlet includes a fogger, to increase the gas turbine output.

Ambient Air Temperature	40 °C
Maximum Steam Temperature	550 °C
Maximum Duct Firing per HRSG	150 MWth LHV
Relative Humidity	40%
Ambient Air Pressure	1.013 Bara
Steam Pressure Leaving Power Plant	0.2 Bara above condensing pressure in brine heater
Condensate Return Temperature	5 °C below condensing temperature in brine heater
Proportion of Condensate Returned	99%
Make-up Water Temperature	40 °C

Table 5 Power Plant Design Parameters

The following procedure is used to design the power plant:

1. Input steam pressure and flowrate requirement from the desal plant.
2. Calculate the net power requirement for the power plant (power export + desal plant power consumption).
3. With full GT fogging, adjust HRSG duct firing until the required steam mass flowrate is achieved, using the maximum high pressure steam temperature and the greatest turbine inlet pressure which results in dry steam leaving the steam turbine.
4. If the net power requirement is not met, increase the number of power blocks.

5. If the net power requirement is exceeded, reduce the degree of fogging until the net power requirement is matched.
6. If the net power requirement is exceeded with no fogging, reduce the steam turbine inlet pressure until the net power requirement is matched, adjusting the steam temperature to maintain dry, saturated steam at the steam turbine outlet.
7. If the net power requirement is exceeded with the minimum steam pressure, turndown the GT.
8. If the maximum duct firing per HRSG is exceeded, increase the number of power blocks.

Financial Parameters 2.4

In this study, all options are assessed using an overall project Net Present Value (NPV), with all costs discounted to the project commencement date. A typical power-desalination project takes 2 or 3 years to build, and for this study, it is assumed that the project takes 3 years from project commencement date to commercial operation, and that the capital cost is spent at a constant rate during these 3 years. Construction interest is paid in each year on half of the capital spent in that year as well as all capital and interest spent in previous years.

It is assumed that annual operating costs, fuel cost, power and water tariffs remain constant (no inflation and no demand growth/decline).

All annual costs (during construction and operation) are discounted to the mid-point of that year.

Based on the above, it is possible to calculate NPV multipliers for both capital, operating costs and revenues. In this manner, the NPV is simply calculated by multiplying the total capital cost (power plant and desal plant) by the capital cost multiplier and taking this away from the total annual net operating revenue (water revenue + power revenue – fuel cost – fixed power & water operating costs – variable power & water operating costs).

Construction Interest Rate	8%
Construction Period	3 Years
Proportion of Equity	30%
Interest Rate Charge on Equity	15%
Proportion of Debt	70%
Interest Rate Charged on Debt	6%
Overall NPV Discount Rate	8.7%
Operating Period	20 Years
Capital Cost Multiplier	0.99
Operating Cost/Revenue Multiplier	7.57

Table 6 Financial Parameters

III. RESULTS AND DISCUSSION

Effect of Brine Recirculation Rate 3.1

Figure 1 shows the results of NPV plotted against recycle rate for tube velocities from 1.5 to 4 m/s, for 90, 110 and 130 °C. Also indicated on the figure are the regions where either 3 or 4 power blocks were required, and the regions of differing tube thickness and material.

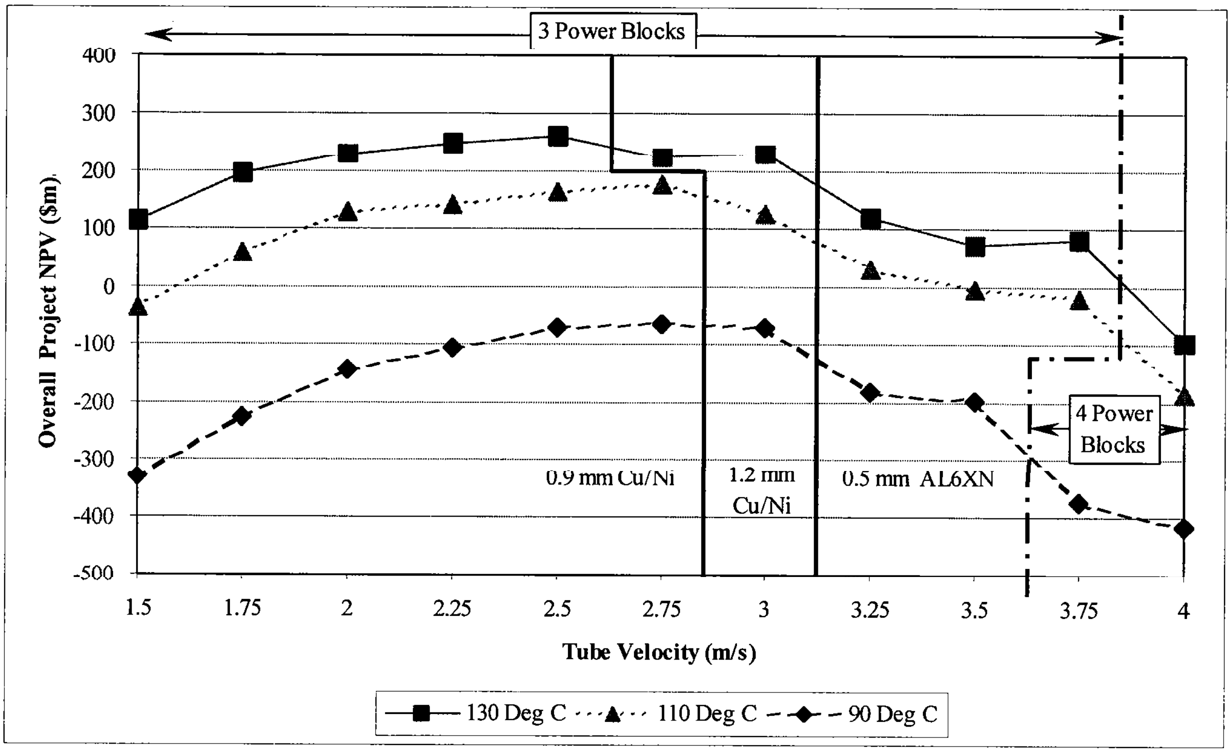

Figure 1 NPV as a Function of Top Brine Temperature

All 3 curves in Figure 1 clearly show that, for low tube velocities, increasing tube velocity increases NPV. This is because the distillate production of an MSF plant is proportional to the tube velocity, hence increasing tube velocity reduces capital cost.

Increasing the tube velocity increases the tube pressure drop, which consequently increases the desal plant power consumption. In addition, the increased pressure in the tubes requires the tube thickness to be increased from 0.9 mm to 1.2 mm, and as tube velocity is further increased, the material and thickness change from 1.2 mm Cu/Ni to 0.5 mm AL6XN. The consequence of increasing tube thickness is that the capital cost of the unit is increased. This can be seen in Figure 1, where there is a step drop in NPV for all 3 curves when the tube thickness increases from 0.9 mm to 1.2 mm, and also, when the tube material changes to the more expensive AL6XN. Figure 2 gives a more detailed breakdown of desal operating parameters for the 90 °C TBT.

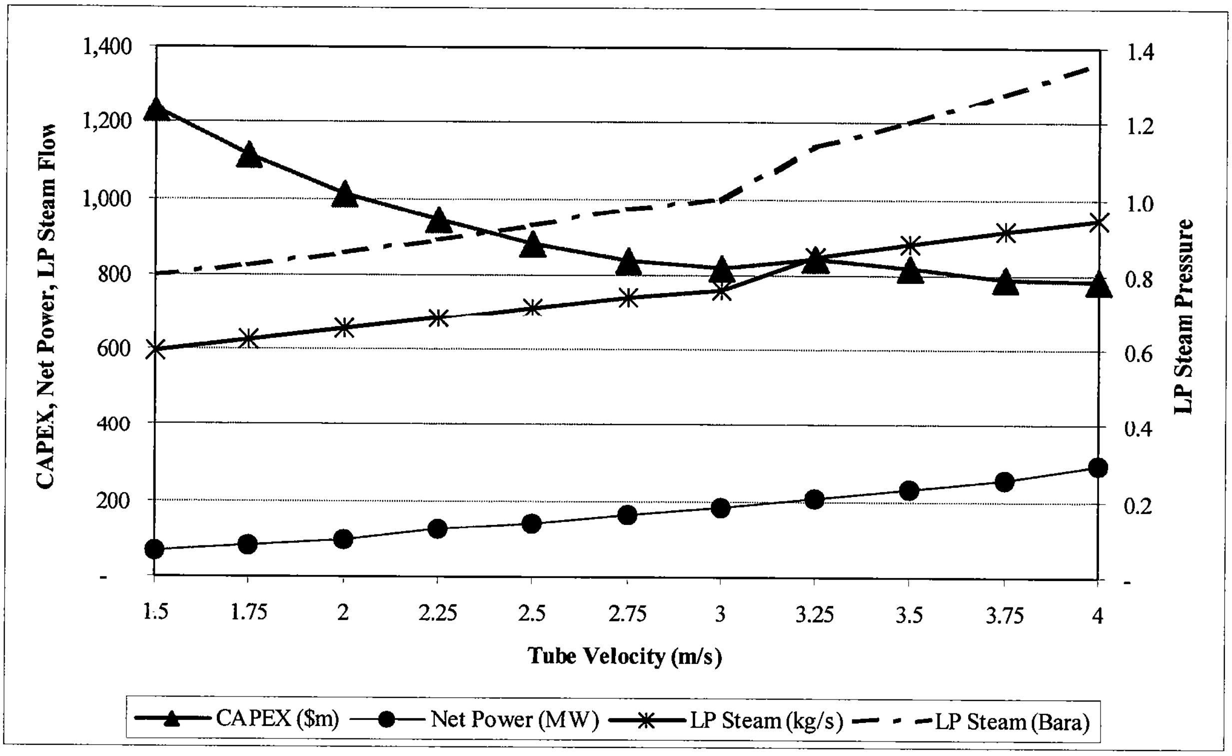

Figure 2 Key Desal Operating Parameters

Increasing the tube velocity increases the heat transfer duty per unit surface area, which reduces thermal efficiency and consequently increases unit steam consumption. In addition, the heat load per unit surface area in the brine heater is also increased, resulting in increased steam temperature and pressure.

These effects have significant implications for the design and performance of the power plant, as indicated in Figure 3 (which is for the 90 °C TBT case), which shows how both the LP steam and the power plant net power (desal plant power demand + power export) increase with increasing tube velocity. This increased demand for both LP steam and power can be met by increasing the level of duct firing in the HRSGs. Between tube velocities of 1.5 and 3 m/s, the power to steam ratio can be conveniently handled by adjusting the level of fogging in the gas turbines, and hence the steam turbine inlet condition is dictated by the maximum temperature constraint of 550 °C. However, in increasing tube velocity from 3 to 3.25 m/s, the tube material changes from Cu/Ni to AL6XN. AL6XN tubes have thinner walls than Cu/Ni tubes, and the thermal conductivity of AL6XN is lower than Cu/Ni. As a result of the thinner walls, the inside tube diameter is increased, and as a result, at fixed tube velocity, the brine recirculation rate is greater for AL6XN than for Cu/Ni. Since the MSF heat load is proportional to the brine recirculation rate, there is a greater heat load on AL6XN tubes than Cu/Ni tubes. As a result of the greater heat load, and poorer thermal conductivity of AL6XN, there is a disproportionate drop in thermal efficiency going from a tube velocity of 3 m/s to 3.25 m/s, which can be seen by the step increase in LP steam consumption.

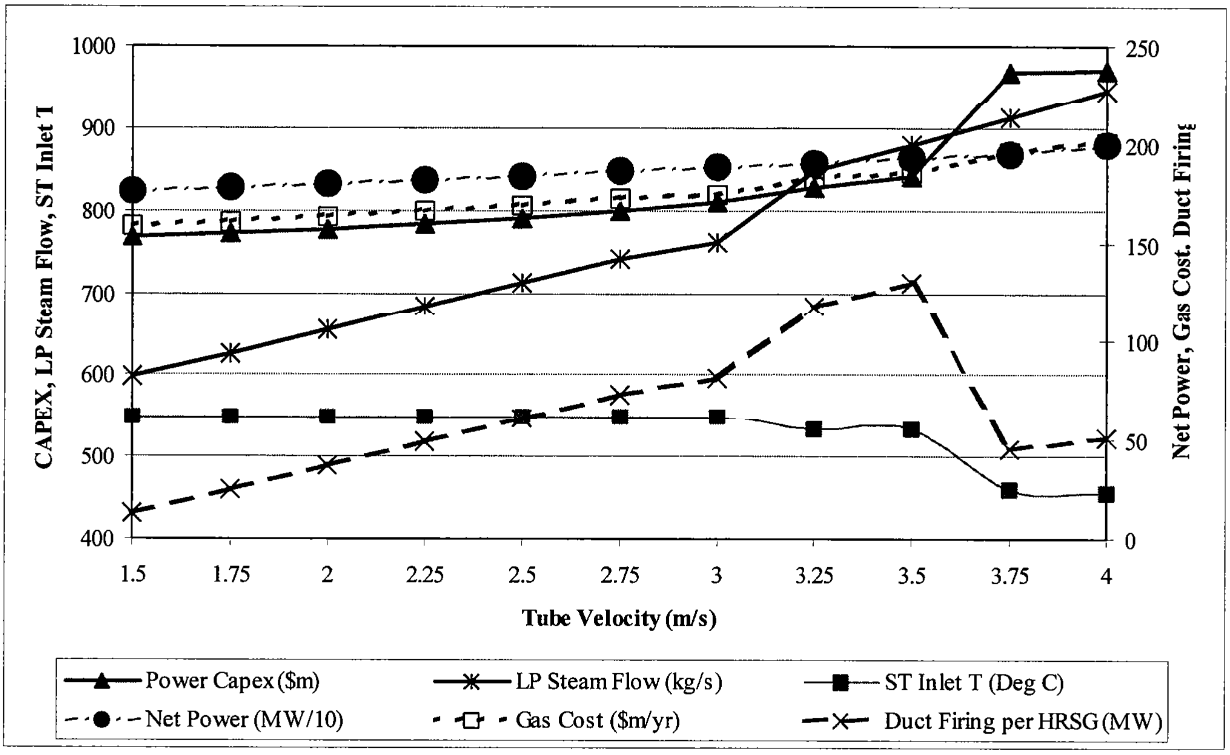

Figure 3 Key Performance Parameters for Power Plant

Because there is a step change in steam flow, but no step change in power demand, the steam to power ratio is greater than can be handled by fogging the GTs, and it is now necessary to reduce the ST inlet temperature.

From Figure 3, it is clear that the increasing power and LP steam demand can be met by increasing HRSG duct firing. However, in going from 3.5 to 3.75 m/s, the duct firing requirement exceeds the maximum limit of 150 MW, and as a result, it is necessary to introduce an additional power block. This introduces a significant step increase in the capital cost of the power block, which is why the NPVs for 3.75 & 4 m/s are so low.

Introducing an additional power block increases the power available from GTs, which greatly reduces the power required from the STs. This means that the ST inlet pressure has to be reduced to its minimum value (as can be seen in Figure 3 by the significant drop in ST inlet temperature) and the GTs have to be turned down. The consequences of this are that there is a loss of cycle efficiency, which can be seen in Figure 3 by the step increase in gas cost going from 3.5 to 3.75 m/s.

In conclusion, increasing tube velocity increases both the capital and operating costs of the power plant, if a constant power export is maintained. These increases are smooth where they can be accommodated by increasing HRSG duct firing with the same number of power blocks, but when the number of power blocks has to be changed, the increases are significant. Therefore, as shown in Figure 1, there is a balance between the capital cost savings for the MSF plant and the capital and operating cost increases of the power plant. This balance leads to the optimum tube velocity.

Effect of Top Brine Temperature 3.2

From above, it is clear that the optimum tube velocity lies in the range 2.25 to 3 m/s. Figure 4 shows plots of NPV against TBT for tube velocities in this range, and

Figure 5 shows a more detailed breakdown of the MSF performance and cost parameters for the 2.5 m/s tube velocity case, plotted against TBT. It should be noted that in this study, the additional costs required to prevent scaling at elevated TBT are not included. These items can be very significant, but it is not the purpose of this paper to evaluate them; rather, its intention is to indicate the potential to improve overall economics by operating with higher TBT. Thus Figure 4 shows that if the NPV of providing scale control, to allow the TBT to be increased from 110 to 130 °C, is less than about $100m, then this could be justified economically. However, there would be no value in providing scale control to allow operation above 150 °C.

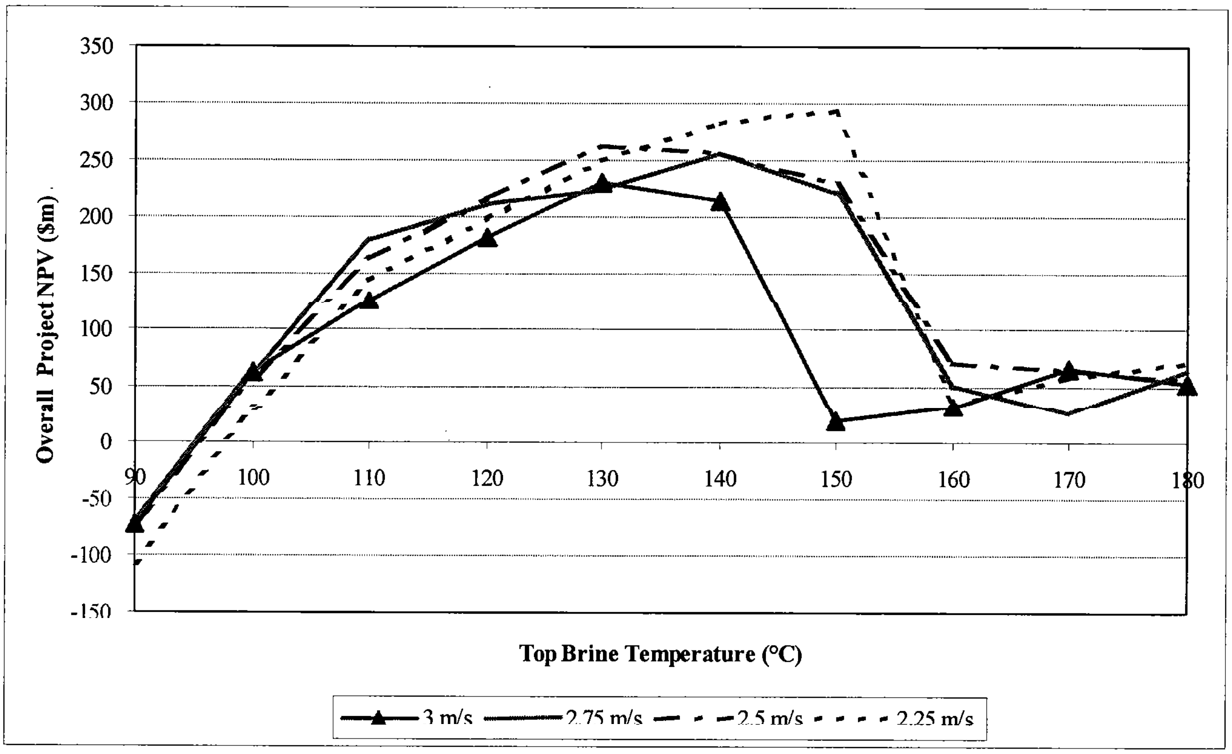

Figure 4 Effect of TBT on NPV

Figure 5 clearly shows that the LP steam pressure increases with TBT, which is because the steam is required to heat the brine at a higher saturation temperature. The figure also shows that the ratio of brine recycle flowrate to distillate production flowrate decreases as TBT increases. This is because the greater flash range allows a greater proportion of the brine flow to be flashed in a single pass. Hence, for a constant quantity of flashed vapour (i.e. distillate production), the brine recirculation rate is reduced. Since the velocity in the tubes is constant, and the brine temperature, and consequently pressure, in the brine heater increases with TBT, the delivered head for the brine recirculation pump also increases. The largest proportion of the MSF power consumption is from the brine recirculation pump, and since the absorbed power of the recirculation pumps is proportional to the product of the delivered head and the flowrate, desal power consumption decreases with increasing TBT for TBTs from 90 °C to about 140 °C (where the reduction in flow is more significant than the increase in pressure) and remains fairly constant above 140 °C (where the reduction in flow matches the increase in pressure).

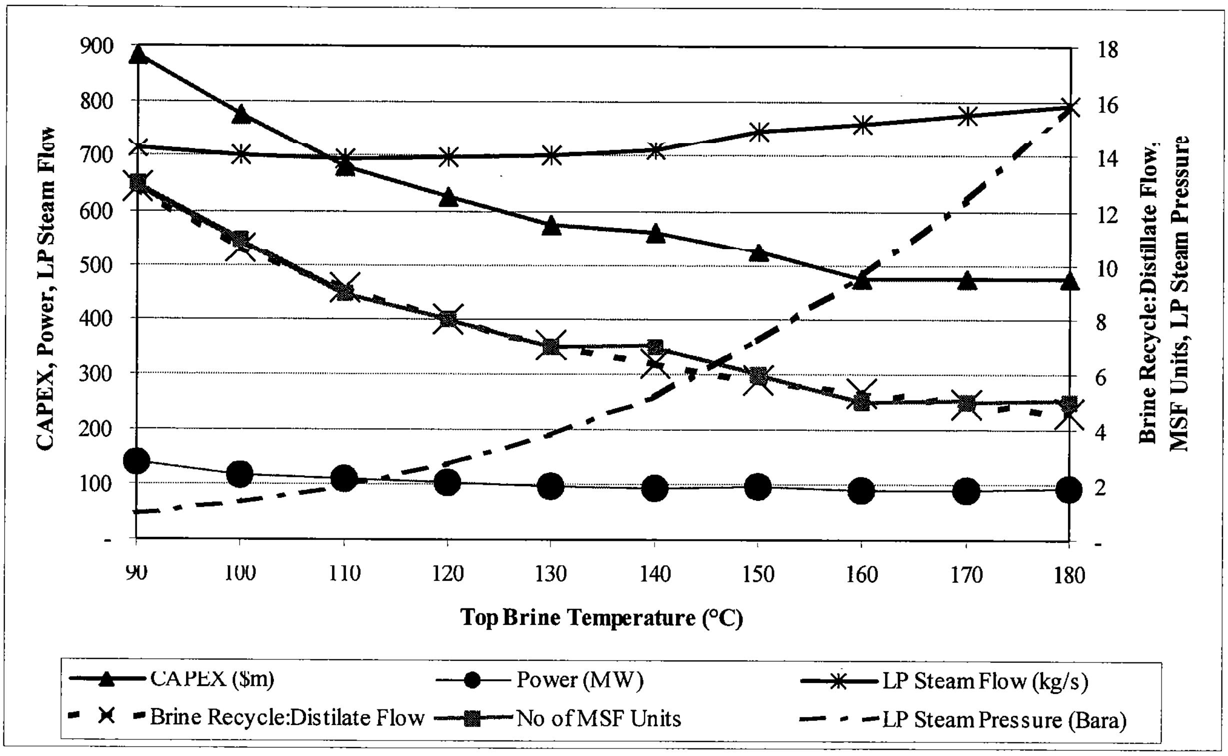

Figure 5 Key Operating and Performance Parameters for Desalination

The LP steam consumption remains virtually constant between TBTs of 90 and 140 °C. This is because the increased flash range provides a greater temperature driving force, which balances the increased heat load due to the greater flash load. However, at 150 °C and above, the brine recirculation pressure increases above 15 Bara because of the elevated brine pressure in the brine heater, and this results in the requirement for thicker Cu/Ni tubes. In addition, because of the high brine temperature, the hottest stages require AL6XN tubes. The effect of this, as discussed above, is to reduce the thermal efficiency of the process, hence the increase in steam consumption between 140 and 150 °C. Also, as TBT is increased above 150 °C, the number of AL6XN stages increases, hence the thermal efficiency continues to decrease, and the LP steam consumption increases.

Figure 5 also shows significant reductions in the number of MSF units, and consequently capital cost with increasing TBT. The capital cost savings going from 160 to 180 °C result from a smaller number of tubes being required in the same number of units, but these savings are much less than those realised by reducing the number of units.

Figure 6 shows plots of the principal steam cycle parameters plotted against TBT. As already explained above, as TBT increases, so does the LP steam pressure, which is effectively the ST exhaust pressure. Since the ST is specified to produce dry, saturated steam at the outlet, increasing the ST exhaust pressure also increases the ST inlet pressure and temperature. In this case, the ST inlet pressure is increased for TBTs from 90 to 140 °C, with the ST inlet condition being constrained by the maximum inlet temperature of 550 °C. As TBT is increased to 150 °C, the ST inlet pressure reaches its maximum constraint of 140 Bara, and there is a slight drop in ST inlet temperature at this point.

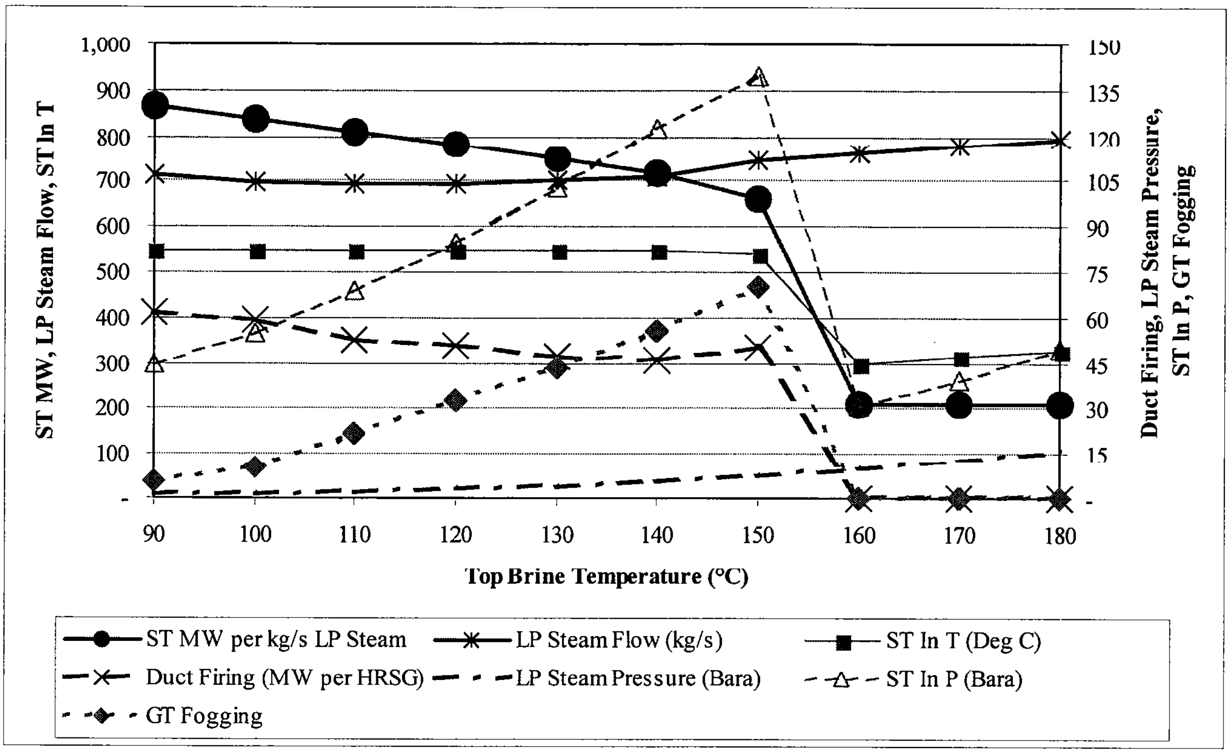

Figure 6 Steam Cycle Parameters as a Function of TBT

Figure 6 also shows that the ST output per unit steam flow decreases as TBT increases from 90 to 150 °C. This is because of the reduced enthalpy difference between the ST inlet and exhaust steam, which results from the elevated exhaust pressure. Because the LP flowrate is dictated by the desal plant, and is fairly constant, this means that as TBT is increased, there is less power available from the STs, and since the total net power production required is fairly constant (desal power demand is nearly constant), this requires more power to be produced by the GTs. This is achieved by increasing the level of fogging in the GT inlet, as indicated in
Figure 6.

Once TBT is increased above 150 °C, the increased power production from the GTs cannot be achieved by increasing fogging, and it is necessary to provide an additional power block. This provides a big step increase in GT power, hence there is a significant reduction in the power required from the STs, but not in the LP steam flowrate. Consequently, the steam temperature and pressure are reduced dramatically at this point.

The overall impact of these factors on the economics of the power plant is shown in Figure 7.

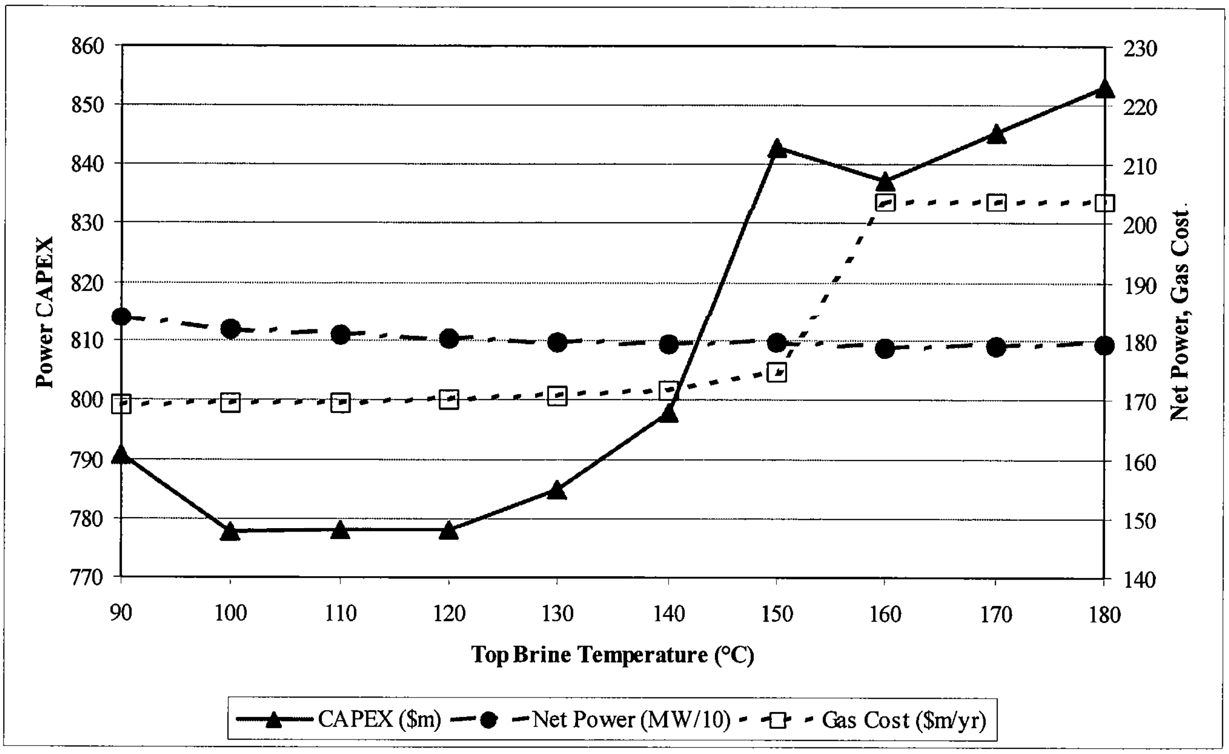

Figure 7 Power Plant Economic Parameters as a Function of TBT

Figure 7 shows that generally, the capital cost of the power plant increases with increasing LP steam pressure. This is because the amount of power extracted per unit of steam generated is reduced and because the increased pressure requires greater structural strength for the ST, HRSG drum and pipework. However, there is an increase in capital cost for the 90 °C TBT point, which shows that at very low steam pressures, the high steam specific volume results in increased duct sizes. This is accentuated by the fact that the desal steam demand at 90 °C TBT is greater than at 100 °C TBT. It should be noted, from Figure 7, that there is a very significant increase in capital cost going to a TBT of 150 °C. At this temperature, the ST inlet pressure is 140 Bara, and it appears that there is a very big increase in power plant cost when going upto this pressure. This is probably due to a step change in the HRSG boiler tube thickness at this point. In fact, the capital cost increase going to 140 Bara is as great as the capital cost increase resulting from going to an additional power block.

In terms of gas consumption, Figure 7 shows that there is a gradual increase in gas cost from 100 to 150 °C, which results in the loss of power extraction per unit steam flow with increasing ST pressure. Gas cost at 90 °C is greater than at 100 °C because the LP steam flow, and desal power demand are both greater at this value. The figure also shows a major step increase in gas cost when the additional power block is introduced. This is because the power extraction per unit steam flow is very much reduced in these cases.

IV. CONCLUSIONS

- Increasing brine recirculation rate (tube velocity) reduces the capital cost of MSF desalination, but increases power and steam consumption.
- Increasing top brine temperature reduces the capital cost of MSF desalination, but increases LP steam pressure.
- There are optimum values for both TBT and tube velocity for any specific application.
- The optimum values are significantly affected by the impact that the steam and power demand have on the accompanying power plant.
- For the economic conditions of this study, the optimum MSF design is either for a TBT of 130 °C with a tube velocity of 2.5 m/s, or for a TBT of 150 °C and a tube velocity of 2.25 m/s.
- For the economic conditions of this study, there is great value in increasing TBT to 130 °C, but the costs of further increases above 130 °C are unlikely to be justified by the savings.
- True optimisation of power-desalination processes can only be achieved by consideration of the overall facility, and not by consideration of the power plant and desalination plant in isolation.

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