Long Term Analysis & Effect of Acid Cleaning Tests on the Performance of Multi Stage Flash (MSF) Desalination Units

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Abstract

This paper presents the long term monitoring and analysis of the performance of large (5.5 MIGD) Multi Stage Flash (MSF) desalination units. The units performance measures include; Performance Ratio (PR), Gained Output Ratio (GOR), Capacity & Availability factors (CF & AF). Despite of the continuos ball cleaning and anti-scalent regular dosing, the long term analysis shows that the units PR deteriorates with time, due to scale deposits. The effect acid cleaning tests is presented in details and shows a marked increase in the units' performance. Pre and post cleaning analysis shows an increase in GOR of up to 34.8 %, and an increase in the recirculation flow rate, due to surfaces cleaning, of up to 4.8%, which leads to 20 % increase in water production rate.

Nomenclature

A = Heat Transfer Area (m^2)

BH = Brine Heater

C = Brine Specific Heat (kJ/kg. °C)

F = Fouling Factor

GOR = Gained Output Ratio

Hc = Condensate Enthalpy (kJ/kg)

Hs = Steam Enthalpy (kJ/kg)

M_{cond} = Condensate Flow (kg/hr)

M_{mkup} = Make-up Flow Rate (kg/hr)

M_{pw} = Product Water Flow Rate (kg/hr)

M_{rec} = Brine Recycle Flow (kg/hr)

PR = Performance Ratio

PW = Product Water

T_{log} = Log Mean Temp. Difference (°C)

T_{st} = Steam Temperature (°C)

TBT = Top Brine Temperature (°C)

Tb_{in} = Brine Inlet Temp. To BH (°C)

Tb_{ls} = Last Stage Brine Temp. (°C)

Tb_{fs} = First Stage Brine Temp. (°C)

Tv_{ls} = Last Stage Vapor Temp. (°C)

Tv_{fs} = First Stage Vapor Temp. (°C)

Uc = Clean Tube HTC (W/m^2 °C)

Uo = Observed HTC (W/m^2 °C)

1- Introduction

Multi Stage Flash (MSF) desalination technology is widely used for water producing world wide. Desalinated water production using MSF units presents more than 50% of desalination technologies. Most of large MSF desalination units operate in association with power producing units, thus together forming cogeneration systems for power and desalted water production. Large MSF units design incorporates the most recent field proven innovations in MSF technology. In addition, a certain degree of flexibility are usually included in the design to accommodate future improvements (as in the method of scale control). The design parameters and materials of construction are also selected to provide the optimum design for the specified requirements of plants facility.

In most of desalination units, the MSF evaporator utilizes brine recirculation with polyphosphate treatment to control scale formation on the heat transfer surfaces (of Brine Heaters (BH), Heat Recovery (HRec) section, and Heat Rejection (HRej) section. Provision is made for alternative use of high temperature additives for scale control. The evaporators are designed as the cross tube type arrangement. A separate vacuum deaerator is provided to remove dissolved oxygen in the make-up seawater to acceptable levels. The major components of the MSF desalination unit are shown in the process flow diagram, Figure (1).

Table (1) shows a typical design criterion of Al-Jubail plant (the world largest water producing plant) made to satisfy the plant objectives, [1]. The designed performance ratio (PR) of 3.44 kg/1000 kJ is the optimum value for a 22-stage MSF plant operating with polyphosphate treatment. The maximum temperature achievable (known as Top Brine Temperature -TBT- is 90.6 °C. The development and application of high temperature scale control additives will increase performance to 4.17 kg/ 1000 kJ for the same desalination unit. The anticipated maximum operating temperature (TBT) is 112.8 °C at the outlet of the brine heater when using these additives. The specified fouling factor of 0.00176 m^2 K/W applies to heat recovery and heat rejection section and to the brine heater. The use of on line ball cleaning system for scale removal and specified fouling factor are inherent requirements to provide the required minimum unit availability. The common minimum acceptable unit availability is specified as 85 %. The maximum number of stages defines a minimum acceptable temperature drop per stage considering the available flashdown temperature range (Tb_{ls} - Tb_{fs}). For 22-stage evaporator, the average temperature drop per stage is about 2.2 °C (4.0 °F). The material for the desalination plant has been chosen on the basis of the specified 20-years plant life. In addition, the variation in seawater quality for an industrial sector of Arabian Gulf was considered. The resultant evaporator material selection is presented in Table (2). Table (3) shows additional power - desal design data. Material selection, as presented, is influenced by several factors. Primary consideration are brine mass flow, method of scale control, extend of desalination, and seawater quality for the specific requirements of the plant. The materials selected reflect the optimum economic and technical choice, [1].

As an extension of the research paper, by the author Ref. [2], this paper presents the detailed monitoring and analysis of typical five units of large MSF plant (5.5 MIGD). The long term monitoring and the effect acid cleaning on the unit performance are presented.

2- Long Term Monitoring of MSF Units

2.1 Introduction

The long term monitoring objective was to closely follow-up the MSF units main performance parameters. The used instruments were calibrated and checked before being used in the performance monitoring computer program. Non-accurate instruments were recalibrated or replaced if necessary.

2.2 Monitoring Procedure

In order to monitor and analyze the long term performance, the following procedure was adopted to ensure accurate and consistent results;

a- Review ASME Performance Test Codes (PTC) for heat exchanges and pumps. The PTC provides techniques and procedure to obtain the most accurate indication of each components performance. They provide consistent standards and guidelines for various procedures, based on proven and acceptable methods b- Review and list the important drawings, the design and guaranteed values, and/or previous acceptable performance test results.

c- Perform site visits to allocate and calibrate instruments & data monitoring devices to be used (Prepare list of instrumentation needed to be calibrated, then calibrate them and replace un-acceptable instrument(s) or added new ones).

d- Prepare test sheets, test conditions, test method, performance criterion, and tolerated errors, based on the acceptable test codes.

e- Perform a preliminary and, then, the final test run(s) using all calibrated instrumentation.

f- Perform an overall unit and equipment heat & mass balance to allocate areas of major errors, and repeat the test (if needed) after correcting the error.

g- Analyze results, compare with design and guaranteed values and/or the previous acceptable tests and report the analysis results with the recommendation(s).

In order to monitor and calculate these performance parameters, a monitoring sheets for data collection have been designed, distributed to the desal units operation staff for data collection. The collected data were checked before being used in the performance calculation program. The data were then be used to monitor the unit's performance ratio (PR), gained output ration (GOR), and the heat transfer coefficient of brine heater, heat recovery and heat rejection sections.

2-3 Performance Equations and Calculation Program

The main equations used for this calculation sheet are:

Performance Ratio (PR)

PR (kg/1000 kJ) $= M_{pw} * (1000) / (\text{Heat Consumption})$

Heat Consumption (in BH) $= M_{cond} * (Hs\text{-}Hc) = M_{rec} * C * (TBT - T_{bin})$

Gain Output Ratio (GOR)

The performance of the desalination unit is also expressed as the Gain Output Ratio (GOR) which is defined as :

GOR $= (\text{Product Water Rate}) / \text{Steam Consumption Rate To BH}$

$= M_{pw} / M_{cond}$

Capacity Factor (CF)

CF = Actual Water Production / Designed Production

Availability Factor (AF)

AF = Number of hours the unit in service / Test period hours

Heat Transfer Coefficient (HTC) & Fouling Factor (F)

a) Brine Heater

U_o = Heat Consumption (in BH) / $(A * T_{log})_{BH}$

F = $1/U_o - 1/U_c$

T_{log} = Log Mean Temp. Difference (°C)

= $(T_{st} - TBT) - (T_{st} - T_{bin}) / \log \{(T_{st} - TBT)/(T_{st} - T_{bin})\}$

b) Heat Recovery Section

U_o = $M_{rec} * C * (T_{out} - T_{in})_{rec} / (A * T_{log})_{rec}$

T_{log} = Log Mean Temp. Difference (C)

= $(Tv_{ls} - Tb_{ls}) - (Tv_{fs} - Tb_{fs}) / \text{Log} \{(Tv_{ls} - Tb_{ls})/(Tv_{fs} - Tb_{fs})\}$

A simple computer program was developed using MS EXCEL Version 5.0 to calculate the performance parameters including, PR, Flash Range, Heat transfer coefficient (HTC) of BH, HTC of H. Recovery section, .. etc.. Figure (2) shows a sample of the developed calculation sheet with typical data and performance results.

3- Long Term Desal Units Performance

Figures (3) to (7) illustrate the long term (four years) performance parameters for five large MSF units. The upper part of the Figure illustrates the unit production and its associated performance parameters of capacity factor (C.F. %), Gained Output Ratio (GOR) and Performance Ratio (PR). The lower graph illustrates the unit operating hours (100 % operation mode, 70 % operation mode, Hot recirculation/Dump operation mode, and the unit outage hours) and the associated performance parameter; availability factor (AF %). From these Figures the deducted observations are:

1- Unit performance ratio (PR) deteriorates with time from the first available documented data. The jump increase in PR near the end of year four is due to the unit acid cleaning after which the unit PR starts again to drop, due to the restarting of scale accumulation. The detailed analysis of the unit pre and post acid cleaning will be discussed later.

2- GOR follows almost the same trend as PR. GOR decreases with time. The jump increase in GOR near the end of year four is due to the unit acid cleaning, after which the unit GOR starts again to drop.

3- The production and capacity factor follow also the same trend as PR and GOR. However they are affected also by the availability of the unit and the mode of operation. The production (and therefore the capacity factor) drops when the unit is not in service (is not available for maintenance or other wise - see outage hours) or it is not on 100 % mode of operation (see also total hours, or 100 % and 70 % modes of operation).

4- The total outage hours represents 5.2 % of the total running hours. This indicates the high unit availability which varied, from 88.5 % to 100 %. The outage hours are mainly due to unit annual maintenance.

5- The total dump hours represents 2.5 % of the total operating hours which is relatively high and represent a major loss in water production, [3].

6- The full drop of all performance measures (PR, GOR, and CF) is only due to the unit (forced or planned) outage for maintenance (AF = 0).

4- Effect of Acid Cleaning Tests

4.1 Cleaning Procedure

In order to remove scale from evaporators tubes, modified acid cleaning method using recycle brine pump for the circulation of acidified and inhibited low pH brine (1.5 ~ 2.0) was adopted. Prior to acid cleaning of the evaporator, the unit was off loaded and put in cold circulation under vacuum condition. Make-up and blow down pumps were off and stand by to be put in service for: i) stage level adjustment, if required, and, ii) flushing the evaporator after completing the cleaning process. During acidified brine circulation and flushing, single recycle pump at approx. 5000 ~ 6000 m^3/hr was used.

Acid injection to the circulating brine was carried-out through the stage 18 flash chamber drain valve connected to the acid tanker by flexible reinforced none metallic pipe. Acid tanker was fully vented to atmosphere during acid charging to the evaporator. The circulating acidified brine temperature was maintained between 47 °C ~ 49 °C at brine heater outlet. LP steam through normal heating system was used when required. Samples of circulating acidified brine at heat recovery inlet (discharge of the R.B. Pump) and at the brine heater outlet was collected and analyzed at regular intervals. The procedure of acid cleaning of the first tested unit took more than three days due to: i) delays in acid delivery to the site, and ii) extended flushing period.

The evaporator in each area of Desal plants was to be inspected before acid cleaning. Scale samples from brine heater and other locations were to be collected and detailed condition of scale existence was to be recorded before and after cleaning of the evaporator. The heavily scaled evaporator was chosen for this purpose. Pictures of tubes, tube sheet and water box condition of brine heater and heat recovery stage before and after cleaning were taken for comparison. During the pre acid cleaning inspection of scale debris found accumulated in the water boxes were removed before the evaporator was boxed up for acid cleaning. Typical procedure for one desal-unit cleaning activities can be summarized follows:

1- Evaporator was off loaded. Shutdown and drained to open brine heater and heat recovery water box manholes for pre cleaning inspection.
2- Both side water box manholes were opened.
3- Inspection sample collection and picture taking were done, loose debris from water boxes were removed.
4- Evaporator was boxed up for acid cleaning.
5- Acid injection started from the tanker. Acid injection completed after three hours. Circulation continued.
6- Flushing started and stopped when the 2nd acid tanker arrived.
7- Acid charging form the tanker completed. Circulation continued.
8- Flushing started again and continued for up to 10 hr. and Flushing stopped when 3rd tanker arrived.
9- Acid injection started, and continued for about three hr. Acid injection completed. Circulation continued.
10- Flushing started and continued for about 10 hr.

11- Evaporator drained and water boxes opened for inspection. Cleaning of water boxes and boxing up of the evaporator.

12- Evaporator was ready for start-up, Start-up of the evaporator.

13- P.W. on dump at 70 %, then on dump at 100 %.

14- Checked P.W. conductivity (Lab analysis).

4.2 Post Cleaning Performance

Acid cleaning removes scale from heat transfer surfaces, and should, therefore, increase the heat transfer surface effectiveness. This leads to an increase in the rate of heat transferred and therefore, both PR & GOR and, in addition, decreases the steam requirement to reach the specified TBT. On the other hand, the tubes surface cleaning reduces the pressure losses of the brine recirculation (BR) system and increases the BR flow. Improvement in cleaning effectiveness depends, however, on the amount acid used and the time allowed for cleaning.

Figure (8) illustrates typical pre & post acid cleaning trend on the units' performance ratio (PR). There is a remarkable improvement in PR of the cleaned units. Table (4) shows also typical operating values of the pre & post acid cleaning. These values indicated the improvements in the product water which varies between 87 m^3/hr (8.9 %) in unit # 5 to 173 m^3/hr (19.6%) in unit # 3. Similarly, the improvement in the unit GOR varies from 1.0 to 2.16. On the other hand, the tube cleaning reduces the system pressure drop which is indicated from the increase in the brine recycle flow rate from 1.7 % to 4.8 % as shown in Table (4). Table (5) summarizes the post cleaning inspection and observations of these units.

5- Concluding Remarks

1- Evaporator tubes acid cleaning has been carried out for large MSF units according to scheduled program. Cleaning has been carried out with modified procedure using brine recycle pump procedure.

2- There is a remarkable improvement in PR of the cleaned units. Typical operating values of the pre & post acid cleaning shows the improvements in the product water varies from 8.9 % to 19.6 %. Similarly, the improvement in the GOR varies from 1.0 to 2.16. On the other hand, the tube cleaning reduces the system pressure drop which is indicated from the increase in the brine recycle flow rate from 1.7 % to 4.8 %.

3- Inspection and observations of these units show the following:
   - Some brine heater tubes, tube sheet & tube ends had scale film deposits. Some are blocked by sponge rubber balls and scale debris
   - Some recovery stages tubes were found blocked by sponge balls and scale debris.
   - Water box wall had thick deposits of salt that peeled on pulling
   - Some tube leakage were found

4- On the basis of pre and post acid cleaning data analysis, it is to be conducted that a satisfactory improvement in the evaporator performance was achieved.

REFERENCES

1- Consultants & Contractors "Al-Jubail Phase II Power/Desalination Plant: Al-Jubail, Saudi Arabia", Bahrain 1981 Congress, Bahrain (1981).

2- Hassan E. S. Fath "Al- Jubail Desalination & Power Plant Performance - Review of the Last Five Years Statistical Data", 2nd Acquired Experience Symposium, RDTC, SWCC- Jubail, Sept. (1997).

3- Hassan E. S. Fath "Improving The Performance of Multi Stage Flash (MSF) Desalination Plants", Proceedings of the Third Int. Water Technology Conf., p 321, Alex., Egypt, March 20-23 (1998). Also, First Arab Water Conf., Vol. 1, Cairo, April 26-28 (1998).

Table 1 Design Criteria

Design Parameter	Specified Value
unit capacity	986 m^3/hr (6.25 mgd)
type of plant	single effect, multistage flash, brine recirculation type, cross tube arrangement
chemical addition	scale control • polyphosphate • high temperature additive oxygen scavenging • sodium sulfite antifoam agent
performance ratio	3.44 kg product/l000 kJoule (8.0 pound product/1000 Btu)
maximum brine temperature	90.6 °C — polyphosphate 112.8 °C — high temperature additive
sea water conditions (Arabian Gulf)	46,500 ppm IDS salinity 35°C
distillate purity	25 ppm IDS
scale removal	on-line: sponge ball tube cleaning system off-line: sulfamic acid
brine concentration	65.000 ppm TDS — brine heater 70.245 ppm TDS — blowdown
blowdown temperature	43.3°C
fouling resistance	0.00176 m^2 K/W
maximum number of stages	22
minimum tube size	19 mm (3/4 in.)
deaeration	separate deaerator O_2 in makeup: 20 ppb maximum

Table 2 Evaporator Materials of Fabrication

item	material
flash chambers	
• stages 1 and 2	• 316L stainless steel clad carbon steel
• stages 3 through 22	• carbon steel
condenser tubing	
• brine heater	• 70/30 copper nickel (18 BWG)
• heat recovery section	• 90/10 copper nickel (18 BWG)
• heat reject section	• titanium (22 BWG)
waterboxes	
• heat recovery section	• 90/10 copper nickel clad carbon steel
• heat reject section	• nickel aluminum bronze
tube plates	
• heat recovery section	• 90/10 copper nickel clad carbon steel
• heat reject section	• nickel aluminum bronze
distillate trough	• 316L stainless steel
mist eliminators	• 316L stainless steel
brine (low control devices	• 316L stainless steel
flash hoods and splash plates	• 316L stainless steel
baffle plates in condensing section	• 316L stainless steel
piping	
• brine	• 90/10 copper nickel clad carbon steel and reinforced thermosetting resin pipe (RTRP}
• seawater	• RTRP
• distillate	• RTRP
• vents	• 316L stainless steel and RTRP
pumps	
• brine recycle	• 316L stainless steel ana1 Ni-Resist
• brine blowdown	• 316L stainless steel and Ni-Resist

Table 3. Basic Data: Power Plant Design

heat required in the desalination plant	2362.5 X 10^6 Kcal/hr
steam pressure at turbine outlet for desalination plant	1.41 kg/cm^2
enthalpy of condensate at brine heater outlet	99.05 Kcal/kg
efficiency of the turbine	80%
efficiency of the generator	98%
auxiliary power consumed internally	10% gross power output
cost of fuel oil	0.28 SR/litre, i.e. 27.81 SR/10^6 Kcal with higher caloric value of 10.277 Kcal/kg
annual load factor for power generation	0.75
annual load factor for water production	0.9
efficiency of boiler	90%

Table 4. Acid Cleaning Parameters & Effect on Evaporators Performance

Unit No.	**Acid* Used** (tons)	**Evaporator Off Prod.** (Hrs)	**Pre Cleaning Values**				**Post Cleaning Values**				**Improvements**	
			P.W. m^3/hr	Condes m^3/hr	R.B.** m^3/hr	GOR	P.W. m^3/hr	Condes m^3/hr	R.B.** m^3/hr	GOR	P.W. m^3/hr	GOR
21	87	84	874	141	11,300	6.2	1037	124	11,700	8.36	163	2.16
22	58	70	913	125	11,000	7.3	1050	120	11,300	8.75	137	1.45
23	58	91	881	134	11,300	6.57	1054	120	11,800	8.11	173	1.54
24	47	80	1000	135	11,900	7.4	1112	132	12,300	8.4	112	1.0
25	29	75	973	127	11,600	7.7	1060	119	11,800	8.9	87	1.2

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* Sulfuric Acid ** R.B. Recirculating Brine

Table 5. Post Cleaning Inspection & Observations

Unit No.	Inspection & Observation
1	- Brine heater (BH) inlet tube and tube sheet were clean. - BH outlet top right few upper row tubes had scale film deposit. Tube sheet & tube ends still had hard scale deposits. - Recovery stages were mostly clean. However, some tubes were found blocked by spongy rubber balls and scale debris - Water box wall in low temperature recovery section still had thick deposits of salt that peeled on pulling. - Few tubes at the bottom rows of low temp. recovery stages were found blocked by scale debris.
2	- Brine heater (BH) tubes were mostly clean. Some tubes were partially or fully blocked. - Heat recovery tubes in the high temp. Stages were mostly clean. - Heat recovery tubes in the low temp. Stages still has some scale film present. - Water box wall in low temperature recovery section had heavy salt deposits - Scale debris detached from the water box was found blocking some lower rows of tubes.
3	- Brine heater (BH) tubes were satisfactory clean. However some tubes were partially or fully blocked by spongy rubber balls and scale debris. - Heat recovery tubes, tube sheet and water box were same as unit-2.
4	- Brine heater (BH) tubes & tube sheets, water box walls on both inlet and outlet side were clean. - Heat recovery tubes through out the recovery section were satisfactory clean. However, some tubes were found blocked by debris in different stages. - Water box wall in cold stages had some salt deposits. In most of the places, debris had peeled off and blocked some tubes in the lower section of the tube bundle.
5	- Brine heater (BH) tubes had considerable deposits. Some tubes particularly upper few rows having scale. - Most of the heat recovery tubes were only partially cleaned. - Heavy deposits of salt was found all around the water box wall - Many tubes were found blocked by scale and balls.

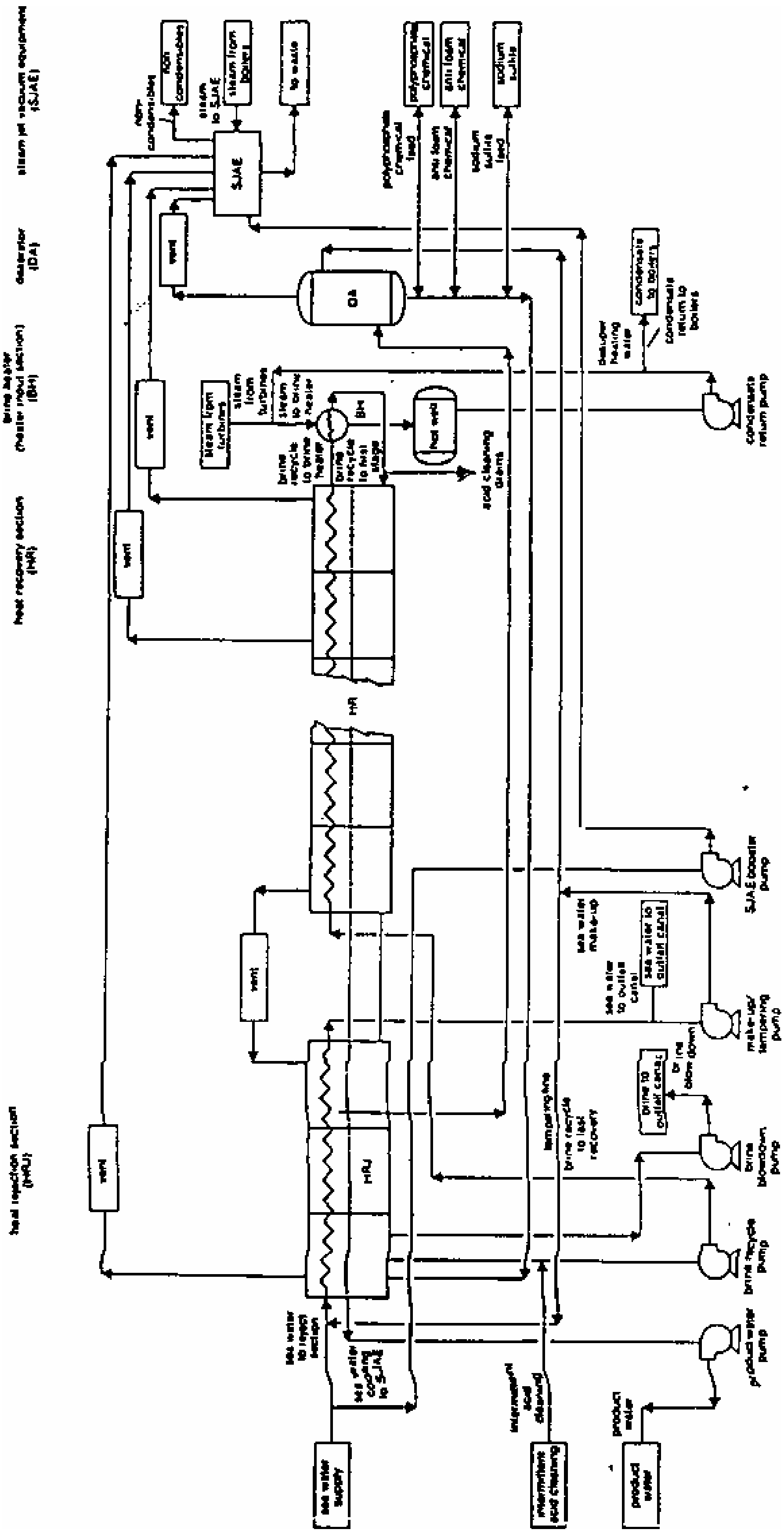
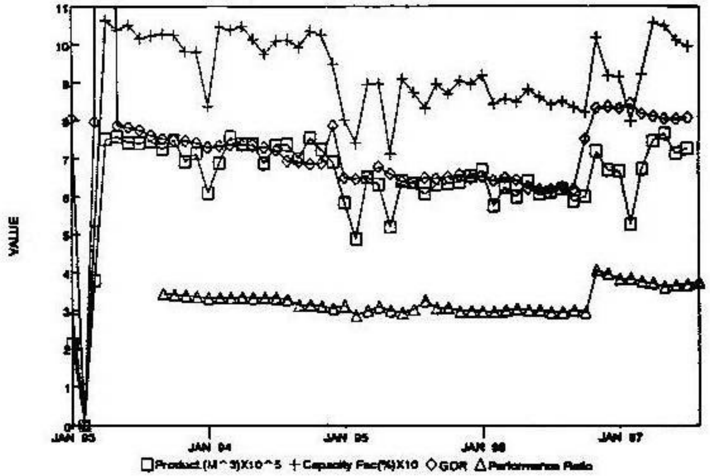


Figure (1) MSF Desalination Process Diagram

UNIT GENERAL DATA							
PHASE		UNIT		OPN MODE		ACD CLEAN	
DESIGN DATA							
		B/H		H/REC		H/REJ	
SURFACE AREA		3,225.7		77,314.8		7919.1	
UNCLEAN							
FLOW & TEMPERATURE DATA ENTRY							
		FLOW M3	TEMP C	Sp. Vol.	LATENT HEAT OF STEAM		
DISTILLATE		986	41.5	1.0084	2259.9		
CONDENSATE		130	98.9	1.04282	COOLING WATER CIRC.		8144.25
BRINE RECYCLE		12.594					
TEMPERATURE FOR BRINE AND VAPOR						LMTD	
				ST 1 V T	87	B/H	10.86
B/H IN T	85.0	ST 19 Br T	43.3	ST 20 V T	47.2	HREC	13.33
B/O TEMP	90.6	ST 22 Br T	35	ST 22 V T	41.5	HREJ	5.45
			Sp HEAT		TOTAL HEAT TRANSFER		
	BRINE HEATER		3.960		281826987		
	H. RECOVERY		3.936		4213676492		
	H. REJECTION		3.911		264353631		
PERFORMANCE PARAMETERS & CALCULATIONS							
G.O.R. (KG OF WATER/KG OF STEAM)			7.84	P.R. (KG OF WATER/1000 KJ OF HEAT)			3.47
		B/H		HREC		HREJ	
HTC (W/M^{2}C)		2 234.6		4 089.4		6120.4	
FOULING RESISTANCE							

Figure (2) Desalination Unit Performance Calculation Sheet



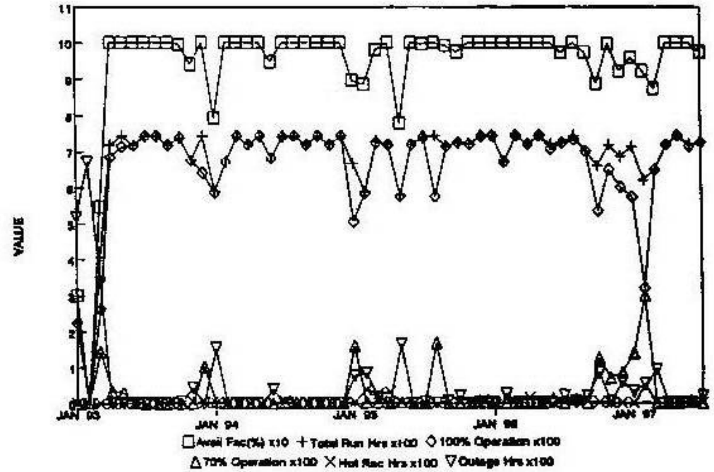


Figure (3) Long Term Performance (Unit #1)

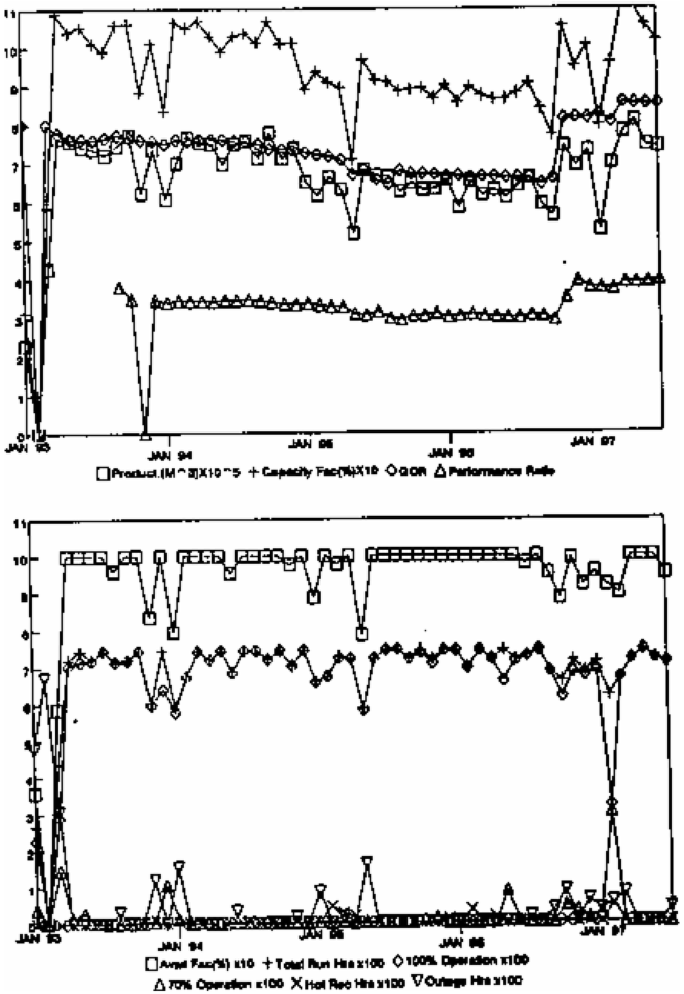


Figure (5) Long Term Performance (Unit #3)

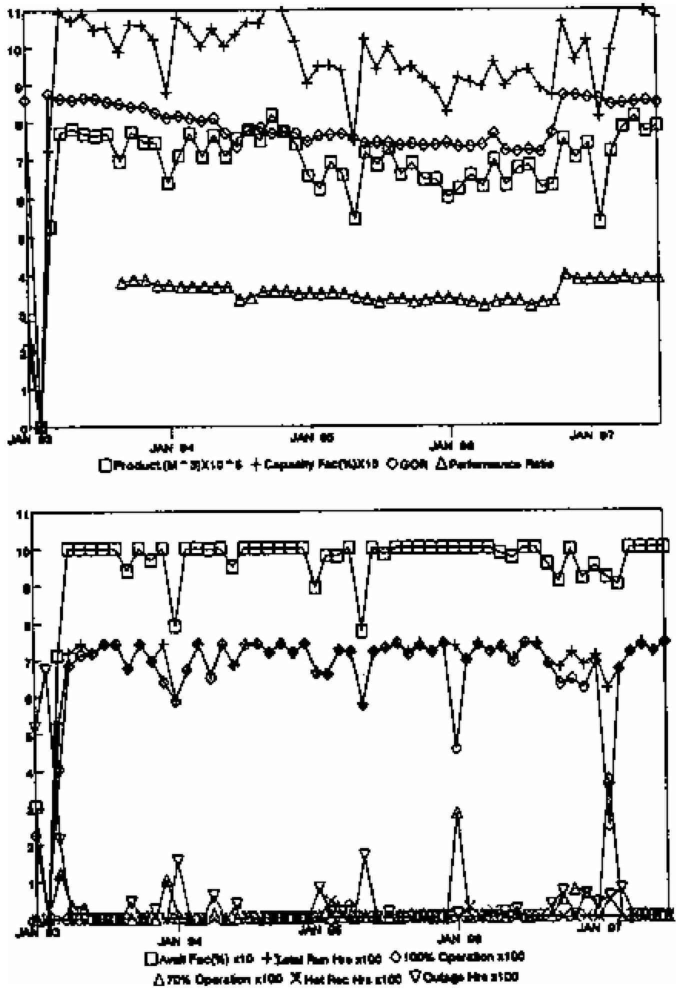


Figure (4) Long Term Performance (Unit #2)

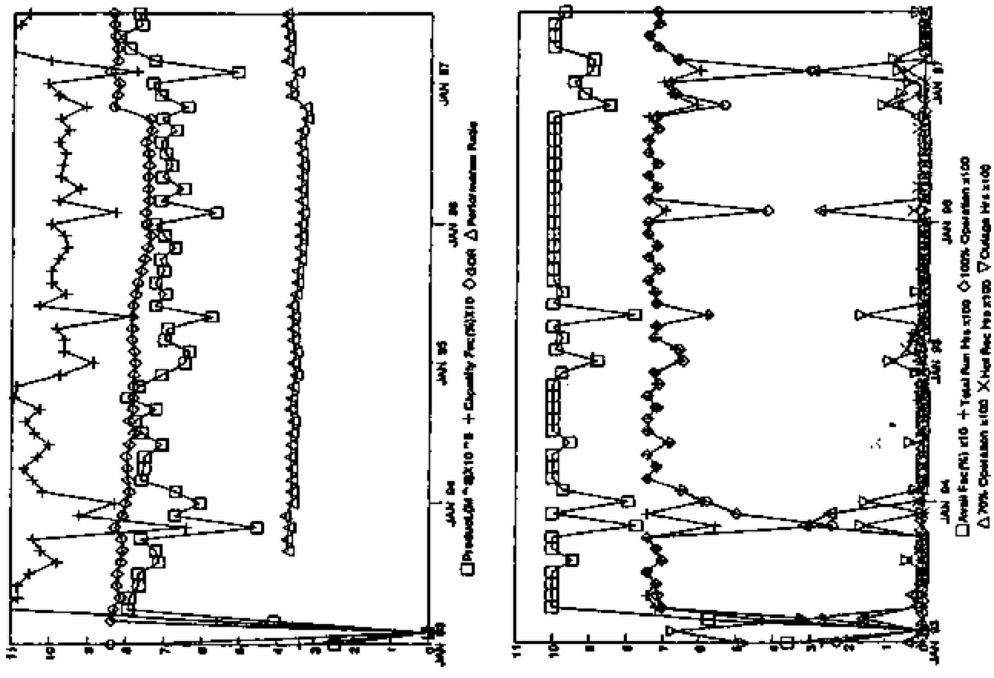


Figure (6) Long Term Performance (Unit #4)

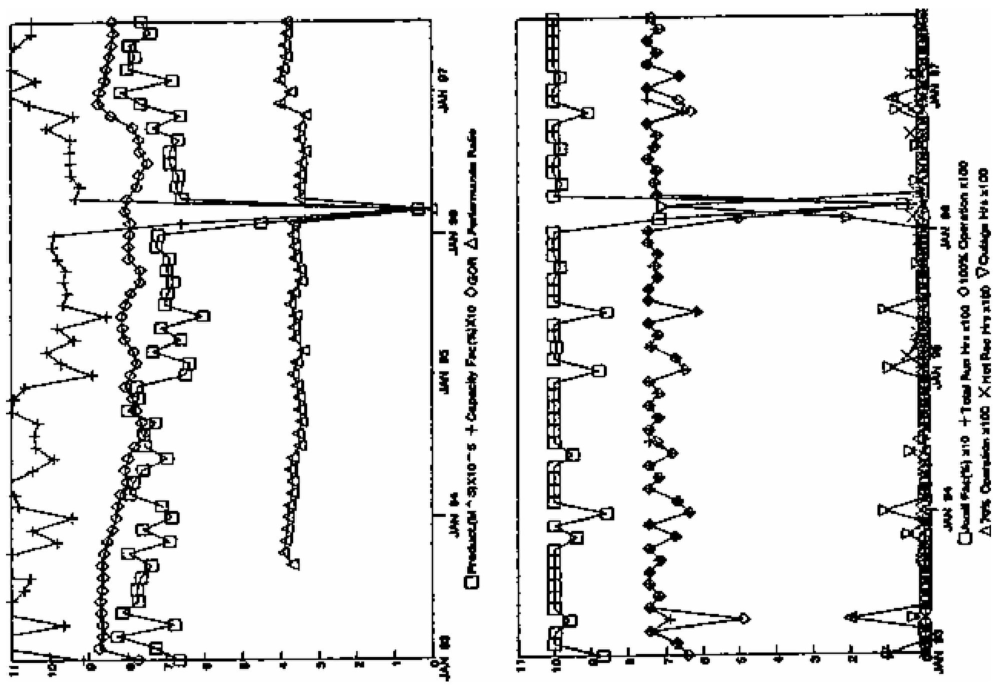


Figure (7) Long Term Performance (Unit #5)

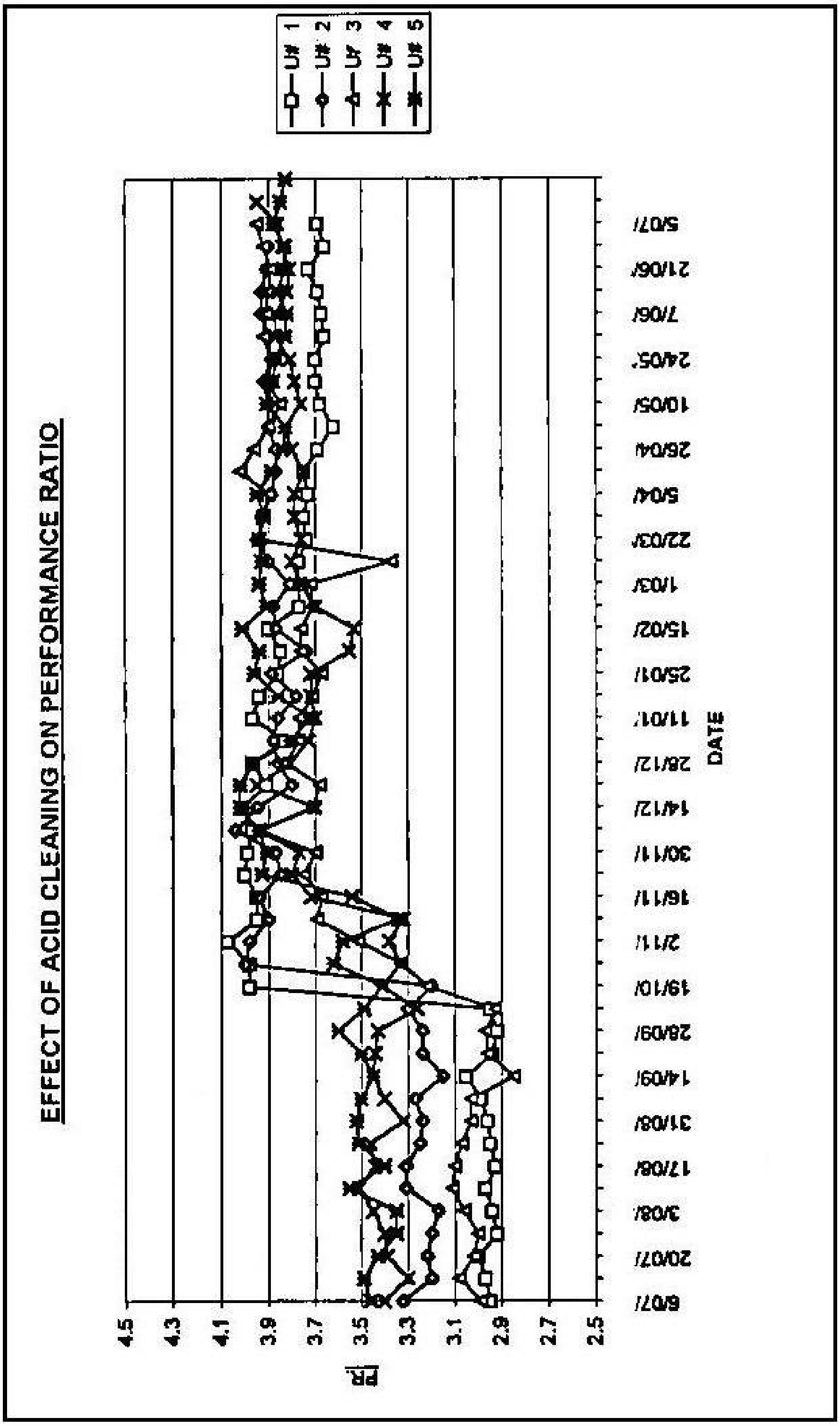


Figure (8) MSF Pre & Post Acid Cleaning Performance Ratio (Unit s#1 to # 5)