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Energy consumption by multi-stage flash and reverse osmosis desalters

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Abstract

Kuwait and most of the Gulf countries, depend mainly on desalted water from the sea for satisfying their fresh water needs. These countries are using the multi-stage flash (MSF) desalting system, as the 'work horse' for their water production. This system is less efficient in energy consumption as compared to the reverse osmosis (RO) system. Moreover, large units based on the MSF system have to be combined with steam or gas turbines power plants for better utilization of steam supplied to the MSF units at moderately low temperature and pressure (as compared to steam produced by large steam generators). The value and the cost of the thermal energy supplied to the MSF desalting system depends on the method of supplying this energy. This steam can be supplied directly from a fuel operated boiler or heat recovery steam generator associated with a gas turbine. It can also be supplied from the exhaust of a steam back pressure turbine or bled from condensed extraction steam turbine at a pressure suitable for the desalting process. Any energy comparison should be based on simple criteria, either how much fuel energy is consumed to produce this energy or how much mechanical energy is needed per unit product. The energy consumed in the light of the practice used in most Gulf countries are discussed here. In this study, reference desalting and power plants are used for comparison purposes. This study shows that shifting from MSF desalting system to the RO system can save up to 66% of the fuel energy used to desalt seawater. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Muti-stage flash; Reverse osmosis; Cogenerartion; Energy consupmtion

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Nomenclature

A	available energy rate, kJ/s
D	distillate product flow rate in kg/s or MGDMGD million imperial gallons per day (4550 m^3/day)
m_s	mass flow rate of steam leaving the boiler
m_r	mass flow rate leaving the reheater
Q	heat flow rate in MW, or volumetric flow rate is m^3/s
Q_F	feed flow to the RO desalting plant
O_f	fuel supplied to dual purpose (power-desalting) plant producing
Q_d	heat supplied to a desalting plant
Q_{fp}	fuel supplied to single purpose power plant
Q_b	boiler heat supply
S	rate of steam supplied to a desalter, kg/s
s	specific entropy, kJ/kg K
s	second
TBT	top brine temperature, maximum temperature of the brine, T_0 in °C (before entering the first stage of the MSF)
T_0	environmental temperature
W_d	work consumed by an MSF plant
η_b	boiler efficiency
η_{CY}	first law efficiency of the cycle
ε_{CY}	second law efficiency of the cycle

Subscripts

b boiler

d desalting unit

1. Introduction

In recent years, the Electricity and Water Ministry (MEW) in Kuwait has been satisfying the country desalted water needs by building Multi-Stage Flash (MSF) desalination units of 5 or 6 million imperial gallons per day (MGD) each and, of gain ratio (distillate product to steam supply ratio) of 8 (Statistical Year Book 1997, State of Kuwait [4]). Examples are: 16 units × 6 MGD in Doha West, 7 units × 6 MGD in Doha East, 4 units × 6 MGD in Azzour South, and 4 units × 5 MGD in Shuaiba South. Another 4 × 6 MGD in Azzour, and 4 × 6 MGD in Sabiyaare are planned. Each pair of desalting units, of 6 MGD each, are combined with a steam turbine of 300 MW (or the 2 × 5 MGD units are combined with one 240 MW power unit in Shuaiba South). It is estimated that the specific thermal energy required by an MSF unit is in the range of 300 kJ/kg distillate and thus a unit of 6 MGD consumes about 90 MW thermal energy in the form of steam at a relatively low pressure (of 2–3 bar), compared to the pressure produced by large steam generators used in power plants. So, the steam generated in

Table 1
Examples of dual purpose power desalting plant

Plant	Desalter capacity (10^3 m^3/day)	Power unit(s) capacity (MWe)	Power water ratio (MWe/10 m^3)	Desalter plant characteristics							
				TBT	Treatment method[a]	Tube arrangement	TTD brine heater	PR S/D	Number of units	R/D	Year
Doha West	12 × 27.3	6 × 300	5.5	90.56	P	CT	6.98	8	24	12.67	’84
Phase II	12 × 32.7		4.6	110	HT	CT	5.97	8.8	24	9.25	’85
Doha West Phase I	4 × 27.3	2 × 300	5.5	90.56	P	CT	5.8	8	24	12.5	’84
Doha East	7 × 27.3	7 × 150	5.5	90.56	P	CT	5.7	8	26	12.6	’78
Shuaiba S	6 × 22.7	6 × 134	5.9	90.56	P	CT	5.5	8	25	12.8	’79
Jeddah 4[b]	10 × 22	5 × 100	2.27	112	A/HT	LT	9.0	7	24	8.7	’80
Jeddah 3	4 × 22	4 × 62	2.87	107.7	A	CT	8.85	7	16	9.24	’79
Jubail I	6 × 23	6 × 50	2.18	90.6		CT	NA	8	22	NA	’83
Jubail II[c]	40 × 23.5	1295	1.63	112.8	HT	CT	NA	8	22	NA	’84
			90.6	90.6	P						

[a] A: Acid additive; P: Polyphosphate additive; HT: high temperature additive; Arrangement of tubes in the flashing chamber CT: cross tube; LT: long tube.

[b] Experience with Jeddah plants calls for a maximum TBT of 116° for acid treatment, a maximum heating steam saturation temperature of 121°C, and a recircualtion brine of total dissolved solids (TDS) less than 59,000 ppm.

[c] The only back pressure turbine arrangement in this list. Others are extraction condensing turbines.

power plants is usually expanded in a steam turbine from the throttling condition to the conditions required by the desalting units, and thus doing work before it is bled to the desalting units. This is usually done from the cross-over tube between the intermediate and low-pressure turbines. Moreover, each 6 MGD unit consumes about 5 MW of mechanical work (about 4.4 kWh/m^3 of desalted water) to drive its pumps.

It is known that most of the Gulf countries are using MSF desalination, as the 'work horse' to produce their potable water needs. This system is excellent in many aspects such as:

1. The distillate water capacity per single unit is very high as compared to other working systems. El Taweela plant in the UAE is using MSF units of 10–12 MGD capacity per unit.
2. The system is simple and highly reliable. No moving parts exist except the pumps, and there is long and excellent experience in choosing materials, leading to a high reliability and high load factor. Extensive experience has been gained in the Gulf area for operating and maintaining the units of this system.
3. The big users of desalting plants in the Gulf area have the tendency of avoiding the slightest technological risk in choosing any new system.
4. The pretreatment of the RO system is not well developed. It changes from one area to another depending on the seawater constituents. The RO should be introduced in slow pace while gaining more experience with this problem. Saudi Arabia and other Gulf countries are gradually building more large capacity of RO plants. Most of the new desalination contracts in the world are for RO system.

However, this system has some major disadvantages such as:

1. The MSF system consumes much more energy than other systems, such as RO.
2. Large MSF units should be combined with power plants in order to use steam extracted from steam turbines or from heat recovery steam generators, see Table 1. The use of fuel-fired boilers to produce relatively low-pressure and temperature steam to drive this desalting system is a wasteful process from the thermodynamics point of view. The second law of thermodynamics efficiency of modern boilers of power plants producing steam of high temperature and pressure is in the range of 50%, while boilers producing saturated steam at atmospheric temperature is in the range of 15%. When power demand is low, and the turbine cannot supply all the steam needed for the desalting unit, the extracted steam can be supplemented to this unit from the boiler through throttling station. Also, when the steam turbine is not operating and there is a need for desalting water, the steam required for the desalting unit is fully supplied from the boiler through the throttling station. It becomes a case of fully or partially boiler driven desalting unit with real loss of available energy.
3. The MSF desalting system can only operate at full capacity, so it should be supplied with its full steam need whenever it is under operation. The system becomes unstable at part load, i.e., partial supply of steam.

It is appropriate to consider other developed desalting systems for future installation or for substituting any failing MSF unit.

2. Energy consumed by multi-stage flash desalting systems

The comparison of energies consumed by the MSF desalting system with those of a desalting system consuming only mechanical energy such as RO is not straightforward. The purpose of this paper is to present a simple and realistic comparison of the energy consumption of MSF and its RO systems.

The thermal energy supplied to operate an MSF unit is in the form of relatively low-pressure steam to the brine heater (heat input section, HIS). The saturation temperature of this steam should be only few degrees (5–10°C) above the top brine temperature (TBT). The TBT temperature depends on the method applied for treatment of seawater. It is 90.6°C for polyphosphate, about 100°C for high temperature additives, and 120°C for acid treatment methods. It was noticed that the design for all Kuwaiti plants working at a TBT of 90.6°C, the saturation temperature of the heating steam is 97°C.

The value and the cost of the thermal energy supplied to the MSF desalting system depends on the method of supplying this energy. This steam can be supplied directly from a fuel operated boiler or heat recovery steam generator associated with a gas turbine. It can also be supplied from the exhaust of a steam back pressure turbine or bled from condensed extraction steam turbine at a pressure suitable for the desalting process. The basis of any energy comparison should be based on simple criteria, either how much fuel energy is consumed to produce this energy or how much mechanical energy is needed per unit product. The energy

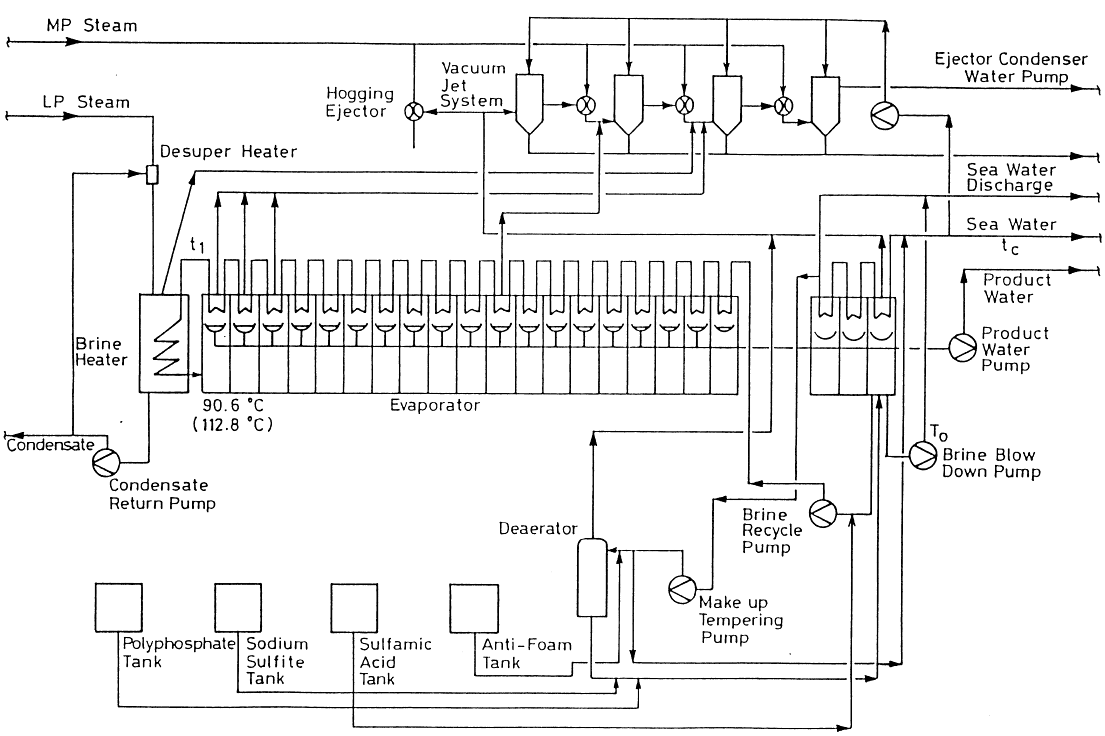

Fig. 1. Reference multi-sage flash desalination unit.

consumed in the light of the practice used in most Gulf countries is discussed here. In this study, reference desalting and power plants are used for comparison purposes.

2.1. Reference desalting plants

To study the energy consumption of an MSF system in some details, consider an MSF desalting unit as shown in Fig. 1, designed to operate at either 90°C (case A) or 100°C (case B) TBT as a reference unit for this study. The operating steam has a saturation temperature of 10°C higher than TBT. The unit design and operating parameters are given in Table 2. The specific thermal energy input to the unit (Q_d/D) at a TBT of 90 and 100°C are 310 and 260 kJ/kg, respectively. The mechanical energy consumption to drive the pumps of this reference MSF plant is 5 MW (equivalent to 15.84 kJ/kg product or 4.4 kWh/m^3) when the unit is operated at TBT of 90°C.

Table 2
Characteristics of a reference desalting plant (case A: TBT = 90°C, T_s = 100°C; case B: TBT = 100°C, T_s = 120°C)

Main data	Case A		Case B	
Distillate output D kg/s (10^3 m^3/day)	313.25 (47)		381.4 (57.17)	
Specific steam consumption S/D (when steam is saturated)	8		8.77	
Recirculation to distillate ratio R/D	12.67		9.545	
Feed (make up) to distillate ratio F/D	2.6		2.434	
Brine blowdown to distillate ratio B/D	1.6		1.434	
Cooling water to rejection section D	8.54		6.18	
Power consumption of recirculation pump, kW	3824		3645	
Brine recirculation pump, flow, m^3/h × head, m	15.127 × 72.8			
Number of stages (recovery + rejection)	21 + 3			
Heat transfer surface areas, m^2				
Brine heater	3544 (1378 tubes of 44 mm O.D. and 18.6 m length)			
Recovery heater	21 × [3676.5 m^2, each]			
Rejection stages	3 × [3676.5 m^2, each]			
U × LMTD (clean/design), (kW/m^2 K) × K	Clean	Design	Clean	Design
Brine heater	4.6 × 4.3	2.1 × 12.1	4.7 × 3.6	2.1 × 13
Stages 1, 2 (recovery, Cu–Ni)	3.6 × 2.2	2.3 × 3.4	4.8 × 2.3	2.8 × 4.0
Stages 3–21 (recovery, brass)	4.3 × 1.8	2.8 × 3.2	4.9 × 2.3	2.8 × 3.9
Stage 22–24 (rejection, brass)	4.0 × 1.8	2.6 × 4.0	1.9 × 3.3	1.4 × 7.0
Water velocity (m/s)				
Brine heater		2.13		1.98
Recovery stage		1.98		1.83
Rejection stage		2.08		1.83
Fouling factor (K m^2)/kW				
Brine heater	12.86 × 10^{-3}			
Recovery stages	3.59 × 10^{-3}			
Rejection stages	9.47 × 10^{-3}			

2.2. Reference single purpose power plant

The reference power plant is a regenerative steam power plant cycle with one reheat, six feed water heaters (including one open feed heater), motor driven boiler feed water pump (BFP), and nominal electric power production of 300 MW at the generator terminal. The cycle design flow sheet is given in Fig. 2. The cycle has high pressure (HP), intermediate pressure (IP) and low pressure (LP) turbines with tandem arrangement. The main parameters are: throttling conditions 140 bar, and 535°C, reheat temperatures 535°C, reheat pressure around 40 bar with pressure drop 7.5%, boiler feed water pump enthalpy rise 23.78 kJ/kg. The pressure, temperature and flow rates are shown in the flow sheet. The heat supplied by the boiler of this single purpose plant is

$$Q_{bp} = m_s(h_s - h_f) + m(h_{rh} - h_{rc}) = 261.037(3420 - 1067) + 239.637(3529 - 3108)$$

$$= 715.10724 \text{ MW}.$$

The fuel energy supplied to the boiler is $Q_{fp} = 715.10724/0.92 = 777.29$ MW, where 0.92 is the first law efficiency of the boiler Q_{bp}/Q_{fp}, based on the fuel low heating value.

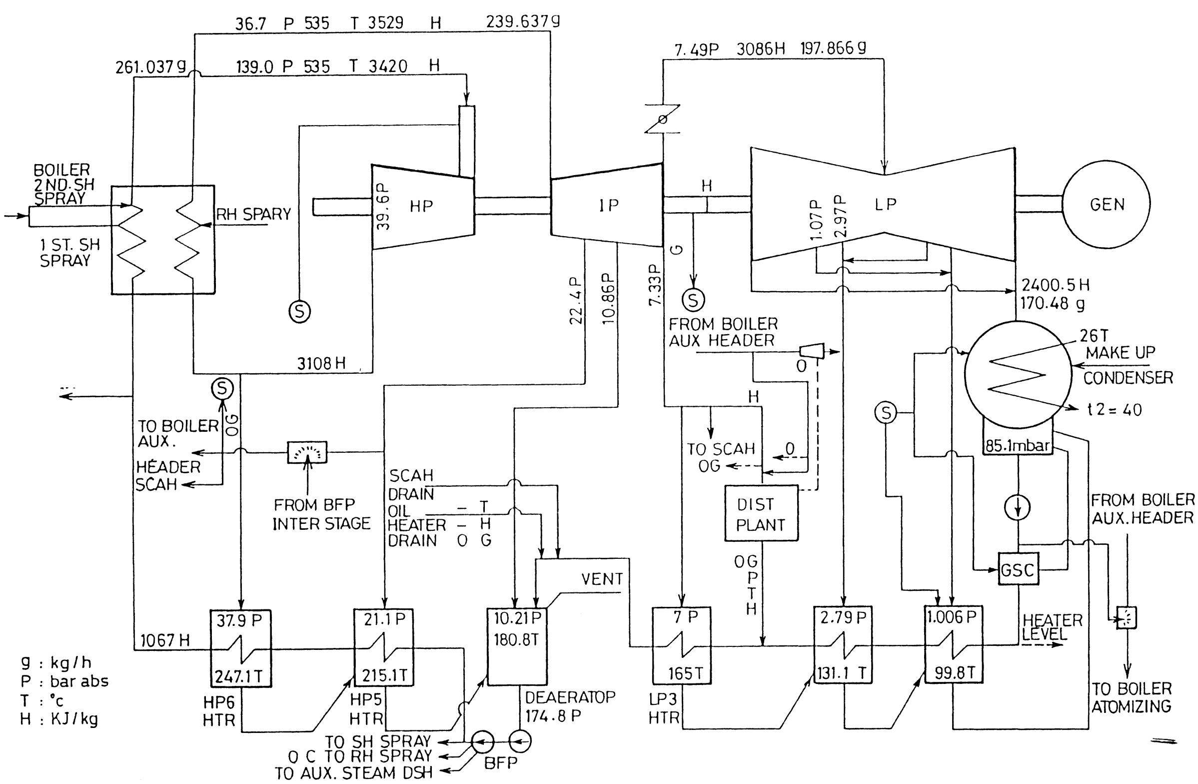

Fig. 2. Single purpose steam power plant.

The calculated power plant efficiency (W/Q_{fp}) is equal to 0.386. By assuming 3.5% auxilary power loss and 2.5% end losses, the net efficiency is $0.386 \times 0.975 \times 0.965 = 0.363$.

2.3. Reference dual purpose (DP) plant

The same single purpose power (PP) plant was used as dual purpose plant, but with the steam extracted from the cross over tube joining the exhaust of the IP turbine with the inlet LP turbine. The throttling and reheat conditions and other main data applied before for the PP plant are same for the DP plant case except the plant efficiency. However, to compensate for the heat supplied and steam extracted to the desalination units, the following changes took place (see Fig. 3).

Steam is extracted to the desalination plant at a rate of 77.27 kg/s and enthalpy of 2942.7 kJ/kg from the cross over pipe. Also a steam at a rate of 3.72 kg/s is extracted from the boiler header at an enthalpy of 3071 kJ/kg to operate the desalination plant steam ejector. The main steam flow rate at MSV is increased from 261.04 kg/s for the PP plant to 297.84 kg/s for the DP plant to compensate for the steam bled to the desalters. The steam flow rate to the condenser decreases from 175.44 kg/s for the PP plant to 119.17 kg/s for the DP plant. The fuel heat added to the boiler increases from 777.29 MW for PP plant to 868.88 MW for DP

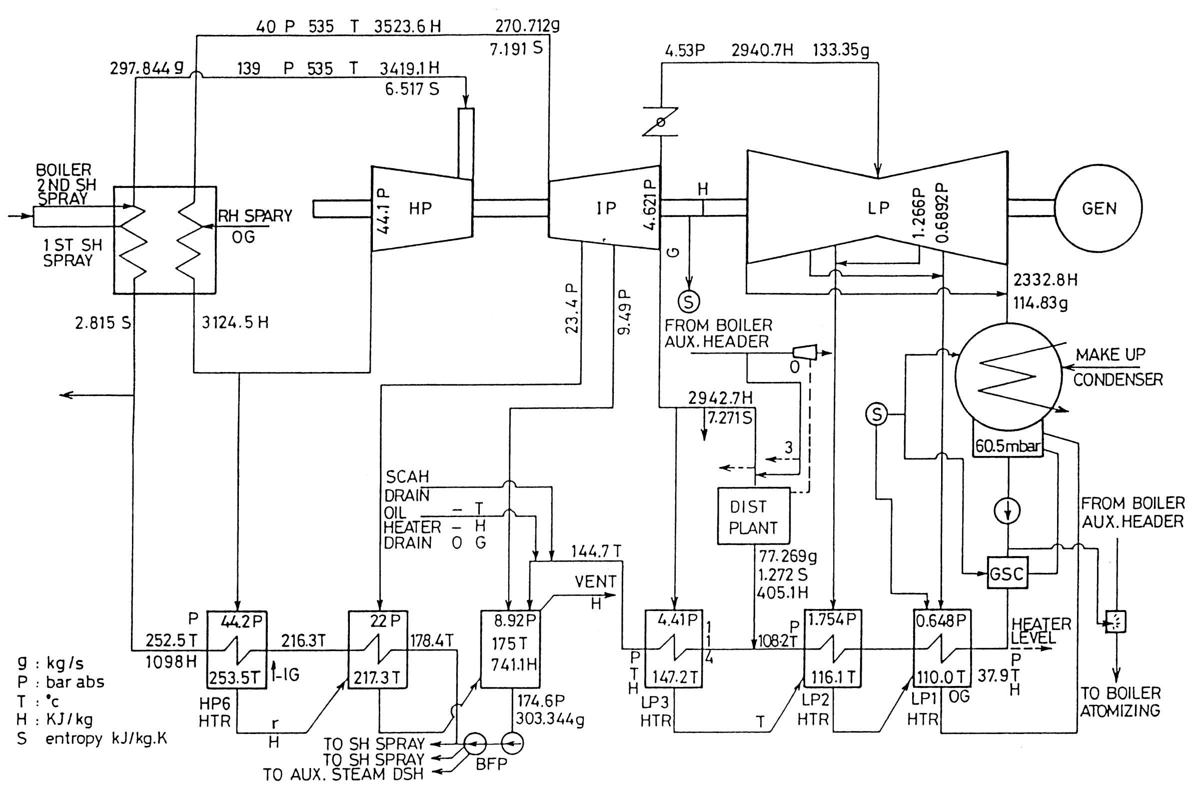

Fig. 3. Dual purpose (power-desalting) steam plant.

plant. It may be noticed here that the increase of steam flow rate in the HP turbine (the case of DP plant) increases the efficiency of that turbine. Also the decrease of the steam flow rate to the LP turbine (again the case of the DP plant) increases the efficiency of the LP turbine. The efficiency of the DP plant cycle (W/Q_f) is equal to 0.345. The net plant efficiency including 2.5% of power due to the end losses, and 3.5% due to auxillary losses is 0.325. The utilization factor $(W+Q_d)/Q_f = 0.57$. It may be noticed here that the efficiency 0.325 does not include the benefits given by the desalter; while the utilization factor UF overestimates the gain by desalter by equalizing the quality of W with Q_d.

2.4. Boiler driven desalting plant

The firing of high availability fuel to produce relatively low-pressure steam is a wasteful process from the thermodynamics point of view. So the practice of using boilers to directly operate a desalting systems is limited to low capacity systems. Another situation exists if the desalting system is to be supplied with steam extracted from a turbine, and this turbine is out of operation while desalted water is needed. The desalting unit, then, has to be supplied with steam directly from the boiler. The fuel energy supplied to produce a unit mass of distillate product would be simply the specific energy consumed per unit distillate divided by the first law efficiency of the boiler. The efficiency of the boiler used in the reference power plant is 0.92. However, it is noticed here that the mid size relatively low-pressure steam boilers usually have efficiencies in the range of 0.8, i.e., lower than 0.92 assumed for high pressure power plant boilers.

Consider a boiler producing steam to be supplied to the reference MSF desalting unit of 6 MGD. The energy consumed by the 6 MGD desalting unit is 98 MW thermal. The fuel energy required to produce this 98 MW is $98/0.92 = 106.52$ MW. Since 6 MGD is $6 \times 4550/(24 \times 3600) = 0.316$ m^3/s = 316 kg/s, then the specific fuel thermal energy is equal to 106.52/0.316 = 337 MJ/m^3 = 337 kJ/kg product.

The reference-desalting unit is consuming 5 MW mechanical energy to run its pumps. Then, the specific mechanical energy consumed is equal to

$$W_d = 5000\ (\text{kJ/s})/316\ (\text{kg/s})$$

$$= 15.823\ \text{kJ mechanical work/kg product}$$

$$= 15.823 \times 1000/3600 = 4.395\ \text{kWh/m}^3$$

The efficiency of the reference power plant is 0.363.

So, the fuel required to produce the 5 MW mechanical work is 5/0.363 (= 13.774 MW fuel energy). The total fuel energy consumed to produce the 6 MGD is $13.774 + 106.52 = 120.294$ MW, and the specific fuel energy is $120.294/0.316 = 380.677$ MJ/m^3 or 380.677 kJ/kg product. Now if this fuel energy was used to produce work in the reference power plant, it would produce net work of $120.294 \times 0.363 = 43.667$ MW work or $43.667/0.316 = 138$ MJ/m^3 = 138 kJ/kg = 38.385 kWh/m^3 mechanical work. This would be equal to the specific work to be charged by the desalting process.

These calculations show that it is very costly to operate the desalting plant directly by the boiler. Even in a co-generation plant, it is important to avoid throttling the high-pressure steam produced by the boiler to feed the desalting unit when the turbine is not working.

2.5. Extracted steam from a condensing extraction turbine

This is the practice used by Kuwait and most Gulf countries. In this arrangement, high availability steam is produced by a steam generator, expanded in high- and low-pressure turbines, and partly extracted to the desalting unit; and the rest is expanded to the condenser. The reference dual purpose (called co-generation) power desalting plant is given in Fig. 3. This plant is producing 300 MW electrical work and supplies about 196 MW thermal energy to 2 units of 6 MGD each desalting plants. The heat supplied by the boiler Q_b to the cycle, and the heat supplied by the fuel to the boiler Q_f, are calculated by

$$Q_b = m_s(h_{be} - h_f) + m_r(h_{rh} - h_{rc}) = 297.844(3419.1 - 1098) + 270.712(3523.6 - 3124.5)$$

$$= 799.370 \text{ MW.}$$

$$Q_f = Q_b/\eta_b = 799.37/0.92 = 868.88 \text{ MW}$$

There are many methods to allocate the consumed fuel energy to the power and desalting processes [2], i.e., dividing Q_f between the electric generation and the desalted water generation. These methods are explained in the following sections and the fuel charged to the desalting process, the specific fuel energy, and the specific mechanical energy according to each of these methods are calculated.

3. Energy consumption by different methods

3.1. Method 1: all benefits go to the desalting process

In this method the energy consumed by the power producing process in the DP plant is considered as the same energy consumed to produce the same power in the reference single purpose power producing plant. The difference of the fuel energy supplied to the single and dual-purpose plants (both producing the same power output 300 MW), is charged to the desalting process. The difference between the fuel energy supplied by the boiler of the reference 300 MW single producing plant Q_{fp}, and the fuel supplied to the boiler of the DP plant Q_f to produce 12 MGD beside the 300 MW work is calculated by

$$Q_{fd} = Q_f - Q_{fp} = 868.88 - 777.29 = 91.59 \text{ MW.}$$

The fuel energy charged for thermal energy per m^3 is equal to 91.59/(2 × 0.316) = 144.92 MJ/m^3 = 144.92 kJ/kg.

As calculated before, the mechanical energy for the reference desalting unit is 15.823 kJ/kg and its equivalent fuel energy required to produce it by the reference single purpose power plant is $15.823/0.363 = 43.59$ kJ/kg. The total fuel energy charged for both thermal and mechanical energy consumption is $144.92 + 43.59 = 188.51$ kJ/kg product. If this fuel energy is supplied to the single power producing plant, it would produce a mechanical energy equal to $188.51 \times 0.363 = 68.43$ kJ/kg = 19 kWh/m^3. For the reference 6 MGD desalting unit:

The fuel energy charged for thermal energy is 144.92 (MJ/m^3) $\times$ 0.316(m^3/s) = 45.795 MW
The fuel energy charged to mechanical energy is $43.59 \times 0.316 = 13.774$ MW
The total fuel energy charged to produce 6 MGD is $13.774 + 45.795 = 59.569$ MW

The total equivalent mechanical energy charged to produce 6 MGD is $68.43 \times 0.316 = 21.624$ MW

It is noticed here that the case of boiler driven desalting system, the desalting plant is charged with the highest fuel energy consumption, i.e., 380.7 MW/m^3 fuel energy and 38.4 kWh/m^3 total mechanical energy. At the same time, in this method (Method 1), all benefits of the dual-purpose plant given to the desalting process, the desalting system charged the minimum energy, i.e., 188.5 MJ/m^3 fuel energy, or 19 kWh/m^3 total equivalent mechanical energy. This clearly shows that using dual-purpose arrangement saves up to 50% of fuel or mechanical energy in producing desalted water, as compared to boiler-driven desalting system.

3.2. Method 2: all benefits go to the power production process

In this method, all the energy consumed by the desalting is considered equal to the case of boiler driven desalting system, mentioned earlier, while all the benefits of dual purpose generation is given to the power production process. The fuel energy supplied to the dual purpose plant $Q_f = 868.88$ MW to produce 300 MW electric energy and 12 MGD desalted water is divided as follows:

1. $2 \times 106.52 = 213.04$ MW to be charged to the desalting system (same as this energy was supplied by separate boiler), and
2. The balance $868.88 - 213.04 = 655.56$ MW fuel energy is charged to the power production.

This gives an artificial high efficiency to the power production process equal to: $\eta = 300/655.56 = 0.4574$ and low heat rate equal to heat rate of 7866.7 kJ/kWh.

3.3. Method 3: the work loss due to steam bleeding is charged to the desalting process

If the steam extracted from the turbine to feed the desalting plant was allowed to proceed to the low-pressure turbine and expands to the condenser, it will produce extra work. This extra work or the work loss due to the extraction of steam to the desalting system is logically should be charged to the desalting system. As shown in the flow sheet, the steam is extracted to the 12 MGD two units desalting system at a flow rate of 77.269 kJ/kg, and enthalpy of 2942.8, and leaves at temperature of 97°C (enthalpy of 405.1). If part of this steam is allowed to expand in the LP turbine to the enthalpy of 2332.8 kJ/kg, condensed in the condenser at temperature of 42.4°C, then it is heated to the same condition of steam leaving the desalter at 97°C, the work produced by the steam is 43.24 MW. This amount of work is equivalent to the thermal energy consumed by the desalter. The fuel energy required to produce this amount of work in the single purpose plant is $43.242/0.363 = 119.12$ MW. By adding 10 MW mechanical work consumed by these 2×6 MGD units, the total equivalent energy consumption is 53.24 MW mechanical work. Again this is equivalent to fuel energy of $53.24/0.363 = 146.67$ MW. This would give specific mechanical energy of $53.24/(2 \times 0.316) = 84.24$ MJ/m^3 or 84.24 kJ/kg ($= 23.4$ kWh/m^3). To produce this work from the reference single purpose power plant, the amount of fuel supplied is $84.24/0.363 = 232.07$ kJ/kg. This is certainly more reasonable method than the two previous calculating methods. The philosophy behind this method that the value of the steam supplied to the desalter lies in its ability to produce work. This method takes into account the quantity as well as the availability of the steam supplied to the desalting units.

3.4. Method 4: the availability energy method

The fuel energy supplied to the steam generator in the dual purpose power plant produces available energy given by the boiler A_b which is equal to:

$$A_b = m_s[(h_{be} - h_f) - T_0(S_{be} - S_f)] + m_r[(h_{rh} - h_{rc}) - T_0(s_{rh} - s_{rc})]$$

$$= 297.844[(3419.1 - 1098) - 300(6.517 - 2.815)] + 270.712[(3523.6 - 3124.5) - 300(7.191 - 6.587)]$$

$$= 419{,}528.3 \text{ kW} = 419.52831 \text{ MW}$$

The boiler available energy is used to produce the electric power energy and to supply the available energy required to (or consumed by) the desalting units. The available energy consumed by the desalters A_d to produce the 12 MGD is given by

$$A_d = m_d[(h_{di} - h_{de}) - T_0(S_{di} - S_{de})]$$

$$= 77.269[(2942.7 - 405.1) - 300(7.271 - 1.272)]$$

$$= 57016.8 \text{ kW} = 57.017 \text{ MW}$$

So, the fuel energy supplied to the steam generator can be divided according to the sharing of the steam generator available energy in supplying the available energy to each product (power and desalted water), i.e.

$$\text{Fuel charged to the desalter} = Q_{fd} = Q_f \times \frac{A_d}{A_b}$$

$$Q_{fd} = 868.88 \times \frac{57.017}{419.528.3} = 118.087 \text{ MW.}$$

So the fuel energy charged to the desalter to produce 12 MGD is equal to 118.087 MW (compared to 119.12 MW in the previous method). This gives specific fuel energy consumption equal to 118.087/(2 × 0.316) MJ/m^3 (=186.847 kJ/kg). If this fuel energy is supplied to the reference power plant to produce work, it would give equivalent mechanical energy equal to 118.0869 × 0.363 = 42.86 MW to produce 12 MGD. By adding the 10 MW mechanical energy consumed by the two desalting units, the total equivalent work is 52.866 MW. This gives specific mechanical work consumption of 52.866/(2 × 0.316) = 83.65 MJ/m^3 = (83.65 kJ/kg or 23.236 kWh/m^3 and specific fuel energy of 230.44 MJ/m^3.

It is noticed here that this method charged the desalting process with almost the same values given by Method 3 (Section 3.3). The reason is that these methods followed almost the same philosophy. This is the value of the steam given to the desalting system which should be accounted to its ability to produce work and this work should be calculated and charged to the desalting process. This is more acceptable thermodynamics approach since its takes into account besides the quantity of the consumed thermal energy the availability of the consumed steam.

The analysis was extended to find the extra fuel heat added to the power and heat produced by boiler plant in order to produce desalted water at different power production are shown in Figs. 4 and 5. It was clear from the analysis that the available energy produced by the boiler increases with the power output, while the available energy consumed by the desalting units is almost constant, see Figs. 6 and 7. However, it was noticed that the pressure of the steam extracted to the desalting units decreases with the decrease of the power output. This was expected to decrease the desalting available energy consumption, but the decrease is not noticeable.

The second law efficiency of the dual purpose plant cycle defined by $(W + A_d)/A_b$ is higher than that for single purpose plant, and increases with the power plant output (see Fig. 7). Fig.

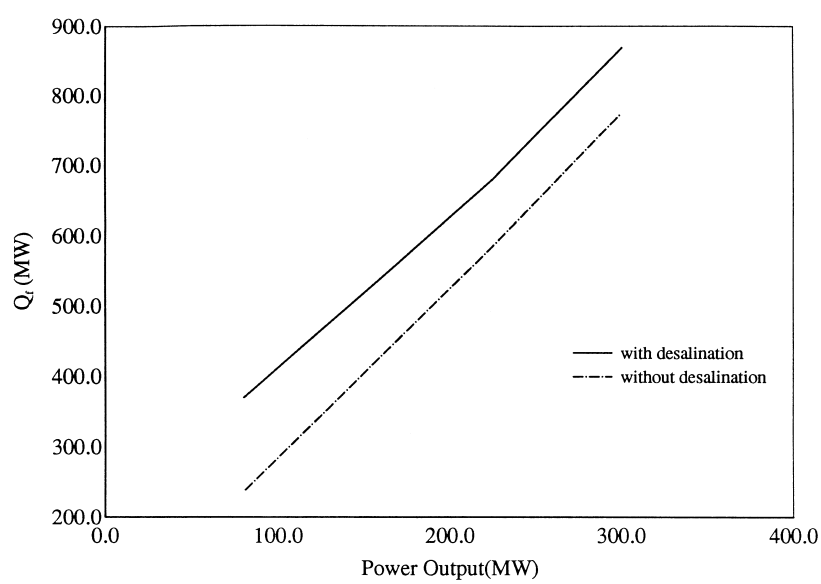

Fig. 4. Fuel energy vs. power output.

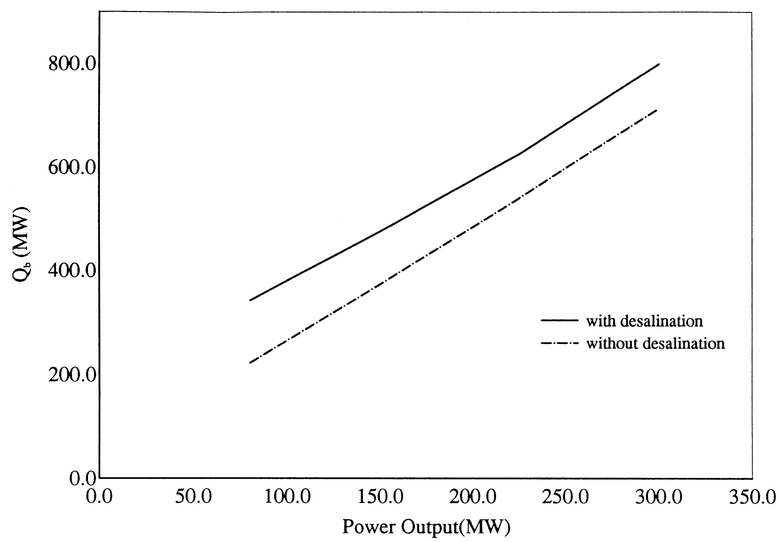

Fig. 5. Boiler heat output vs. power output.

8 shows that the cycle efficiency of dual purpose power plant is less than that of single purpose power plant.

4. Energy consumed by reverse osmosis

Reverse osmosis (RO) desalting system is the main competitor of the MSF desalting system.

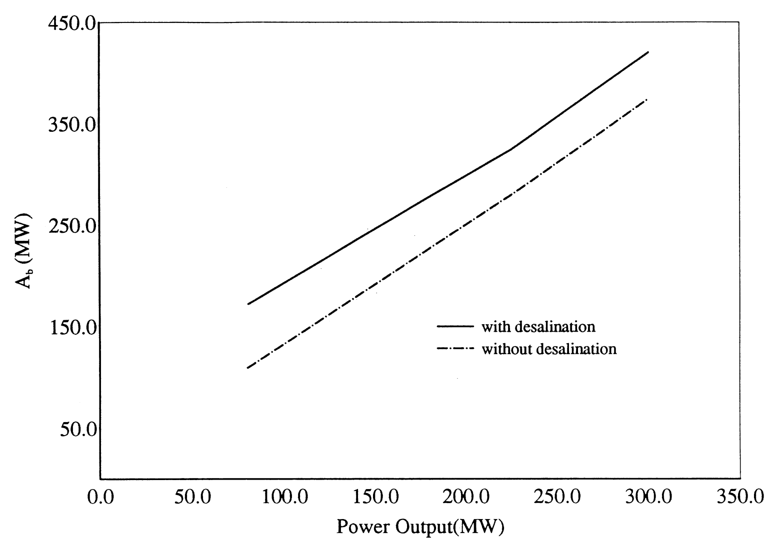

Fig. 6. Available energy given by the boiler vs. power output.

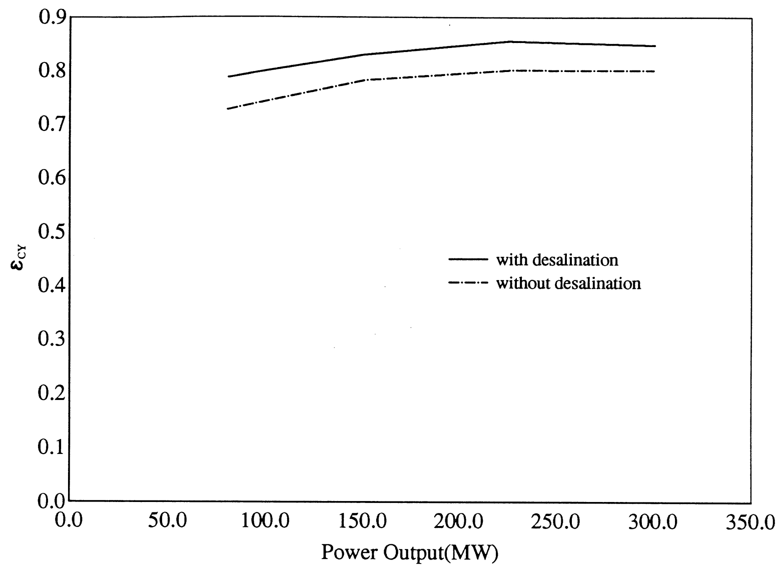

Fig. 7. ε_{CY} vs. power output.

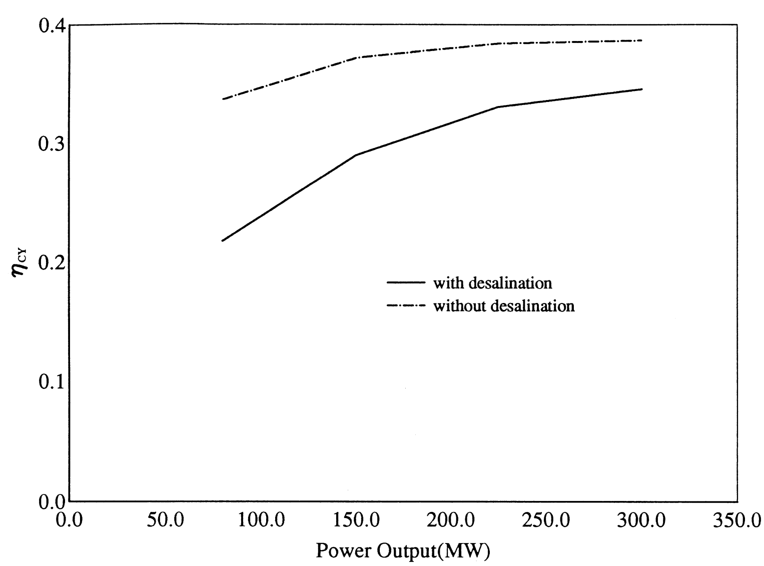

Fig. 8. η_{CY} vs. power output.

The RO system became more attractive by the continuous improvements in membrane materials, the raising of both feed pressure and temperature limits, and production of potable water from high salinity water in the Gulf area in single stage. The main advantages of the RO system, over the MSF system are:

1. It consumes less energy, and only in the form of mechanical energy delivered by motor(s).
2. No need to be combined by a power plant or to interfere with its operation. In fact, it can be operated only during non-peak power demand period. It has simple start/stop operation.
3. It is delivered and operated in modules, so no need to shut off the whole plant for emergency or routine maintenance.

Our objective here is to compare the energy consumption of the RO system and compares it with that of the MSF system. Consider a practical case similar to Jeddah I RO plant phase II of 12.5 MGD reported by Al-Badawi et al. [1], with the plant specifications given in Table 3. The plant consists of 10 trains and each train gives a product rate of 5680 m^3/day (65.74 kg/s). The procedure to calculate the power consumption is outlined here for one train of this Jeddah plant.

Since the recovery ratio (product/feed) is 0.35, then the feed flow rate (=65.74/0.35) is 187.83 kg/s. The plant actual feed pressure is around 60 bar (the membranes maximum allowable pressure is 70 bar). Assuming an efficiency of the feed pump equal to 0.75, and its driving motor efficiency is 0.92, then the feed pump power consumption is

$$Q_F\left(m^3/s\right) \times \Delta P\,(kPa)/\eta_p \times \eta_m = (187.83/1000) \times (6000)/(0.75 \times 0.92) = 1633.3\,kW.$$

By considering 20% more energy is consumed by other pumps (e.g., seawater supply, seawater boost and chemical dosing pumps) the power consumption is $1.2 \times 1633.3 = 1959.96$ kW.

To calculate the energy recovered in a turbine from the brine blow-down:

the brine flow rate = 187.3 − 65.74 = 122.09 kg/s.
The brine pressure = feed pressure − pressure loss in the feed-brine side = 60 − 3 = 57 bar.
Recovered energy = brine flow rate (m^3/s) × P (kPa) × η_t = (122.09/1000) × 570 × 0.65 = 444.41 kW

Table 3
Jeddah 1 RO plant specification

	Jeddah 1 RO plant phase II
Plant	
Number of trains	10
Capacity	1.25 MGD × 10 trains (5680 m^3/day (10 trains)
Permeate quality $C1^-$	Less than 625 mg/l
Operation condition	
Seawater TDS	43,300 mg/l
Temperature	24–35°C
Recovery ratio	35%
Maximum feed pressure	70.42 kg/cm^2
SDI (15)	Less than 3
Module	
Model	TOYOBO HOLLOSEP
Number of modules	HM10255FI
Membrane guarantee	148 pcs × 10 trains 5 years with 10% annual replacement

where η_t is the efficiency of the recovery turbine and is assumed equal to 0.65 here. This is a typical value for reversed centrifugal pump working as a turbine. Pelton wheel turbine can be used with efficiency up to 90%.

Net energy consumption is $1959.96 - 444.41 = 1515.55$ kW
Specific work done is $1515.55/65.74 = 23.05$ kJ/kg $= 6.4$ kWh/m^3.

The fuel energy required to produce this amount of work in our referenced single purpose power plant is $23.05/0.363 = 63.5$ MJ/m^3.

It should be pointed out that Al-Fujaira plant actual measured power consumption is 6.54 kWh/m^3 [3] but the guaranteed power consumption (represents the maximum) is 7.5 kWh/m^3. This plant is in operation since 1991.

Comparison of the specific energy consumptions by different methods are given later in Table 4 after estimating the energy consumption by RO.

Table 4 presents the specific energy consumption of the MSF by different methods and the energy consumption of RO. Clearly, the energy conumed by the RO is much less than that consumed by the MSF plants. The guaranteed specific mechanical consumption by RO is 7.5 kWh/m^3 (27 kJ/kg) and its equivalent fuel energy is 74.6 kJ/kg. This is to be compared to 23 kWh/m^3 (83 kJ/kg) equivalent specific mechanical energy consumption for MSF units in Kuwait and its equivalent mechanical energy of 230 kJ/kg. This is clearly in the range of three time the energy consumption by the RO method.

It was estimated that the desalted water production in Kuwait in 1996 was 63562 MGD. The fuel energy consumed to produce this amount by MSF units in a dual purpose according to the fair method of availability analysis is 63562×4550 (m^3/MGD) $\times 230.4$ (MJ/m^3) $= 6.7 \times 10^{10}$ MJ. This is equivalent to $(6.7 \times 10^{10})/(42 \times 1000) = 15.95 \times 10^5$ ton of fuel. Here, the 42 MJ/kg is the high heating value (HHV) of the fuel used in the combustion. If this amount of water was produced by RO system, the equivalent fuel consumed would be equal to 4.4×10^5 ton of fuel or 72.4% saving in the fuel.

5. Conclusion

The fuel energy supplied to the boiler should be allocated fairly between the two products. Combining both power and desalting water production processes came up with certain

Table 4
Fuel and mechanical energy consumption per unit desalted product

	Method	Fuel energy (MJ/m^3)	Work consumed kJ/kg (kWh/m^3)
MSF	Boiler driven MSF, all benefits go to power production process	380.677	138 (38.385)
MSF	All benefit go to desalting water production	188.51	68.43 (19)
MSF	Work loss due to steam extraction method	232.07	84.24 (23.4)
MSF	Availability analysis	230.44	83.65 (23.24)
RO		63.5	23.05 (6.4)

advantages. These should be shared according to acceptable, and reasonable rules. The methods of availability and loss of work due to extraction of steam to the desalting system are the most reasonable methods to adopt. These methods give the following fuel energy and work to account for both thermal and pumping energy consumption:

1. In Method 3 (work loss due to steam extraction), the fuel energy is 232.07 kJ/kg product and the work energy is 84.24 kJ/kg product (= 23.4 kWh/m^3)
2. In Method 4 (availability analysis), the fuel energy is 230.44 kJ/kg and mechanical work of 83.65 kJ/kg (= 23.24 kWh/m^3)

This work shows that the fuel energy consumed in the RO plant is less than 30% of the energy consumed in the MSF desalting plants.

References

[1] A. Albadawi, et al., Operation and analysis of Jeddah 1-Phase II plant, in: IDA World Congress of Desalination and Water Sciences, Abu Dhabi, Vol. 3, 1995, pp. 41–53.
[2] M.A. Darwish, et al., Development of the multi-stage flash desalting system, Desalination 100 (1995) 35–64.
[3] M. Schierachi, Seawater reverse osmosis plant in Fujairah—United Arab Emirates, in: IDA World Congress of Desalination and Water Sciences, Abu Dhabi, Vol. 3, 1995, pp. 99–107.
[4] Statistical Year Book, Ministry of Electricity and Water, State of Kuwait, 1997.