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DRINKING WATER FROM THE SEA: REVERSE OSMOSIS, THE MODERN ALTERNATIVE

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Drinking Water from the Sea: Reverse Osmosis, the Modern Alternative

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SYNOPSIS

The process of reverse osmosis (RO) has been extensively developed over the past 15 to 20 years and is now a commercially proven process. In practice, RO may be used for the desalination of numerous types of water including sea water. The authors outline the principles of RO and its development and explain the design of RO plants for shipboard applications. Different types of membranes are described together with how these fit into the various arrangements of plant. Associated subjects such as pretreatment, control and operation and maintenance are also discussed. Cost comparisons and power consumption figures are given for RO and the more conventional shipboard desalination systems such as multi-stage flash and vapour compression. These show that RO is now economically attractive compared to the other systems and has the added attractions of simplicity and low maintenance.

INTRODUCTION

The process of reverse osmosis (RO) has undergone extensive development over the past 15 to 20 years,[1] turning what had previously been a laboratory curiosity into a commercially proven process. This process may be used for the desalination of numerous types of water, including sea water, and the concentration of industrial effluents for precious metal recovery. It also has applications in the electronics and food industries. Since RO is a new technology, areas of possible application are still being discovered and new types of membrane are being developed to meet specific requirements. The main purpose of this paper is to discuss the application of RO to the desalination of sea water for ship- and shore-based units.

The following section gives a very brief review of the basic theory of RO and the type of membranes available.

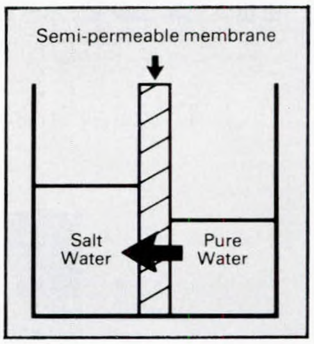


FIG. 1 Osmosis

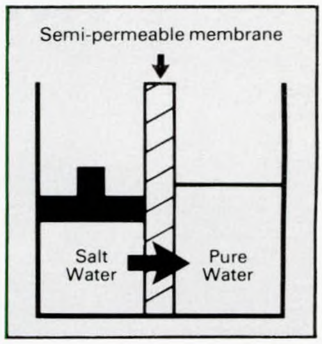


FIG. 2 Reverse osmosis

PRINCIPLES OF RO

When a solution, which has a chemical potential, is separated from pure water, which has a lower chemical potential, by a semipermeable membrane, i.e. a membrane which will allow the passage of water but not salt, then pure water will flow through the membrane so as to reduce the potential of the salt solution (Fig. 1). This process will continue until all the pure water has passed through the membrane or until the hydrostatic head of the salt solution is sufficiently high to arrest the process. At this latter point the hydrostatic pressure is known as the osmotic pressure of the salt solution at its particular concentration.

Reverse osmosis, as the name implies, is the use of this phenomenon in the reverse direction, resulting in water being forced through the membrane from the concentrated solution to the more dilute. This reverse flow is achieved by applying a pressure, higher than the osmotic pressure of the concentrated solution, to the concentrate side of the membrane (Fig. 2).

Table I gives typical values of the osmotic pressure for different concentrations of sodium chloride solutions at 25°C. A widely used rule of thumb, which relates the increase in osmotic pressure to an increase in salt concentration of the solution, is 0·01 lbf/in^2 for each mg/l.

The rate of flow of pure water through the membrane depends on the temperature of the water and the 'net driving pressure'. In a real system the 'net driving pressure' is less than the applied, owing to a number of factors:

(i) For RO to take place the osmotic pressure of the solution must be overcome.

(ii) To avoid a concentration of salt in the boundary layer next to the membrane surface, the solution must flow over the membrane and therefore pressure must be applied to overcome the frictional pressure losses.

Table I: Variation of osmotic pressure with salt concentration

SALT CONCENTRATION (mg/l)	OSMOTIC PRESSURE (bar)
1000	0.7
15 000	11.6
35 000	27.8
50 000	40.4

J. T. Allanson is an Honours graduate in Chemical Engineering from UMIST. In his early career he was involved in the development of freeze desalination and aspects of sand filtration. Three years ago he took up the position of Development Manager with Ames Crosta Babcock and became involved in the development of reverse osmosis, a major aspect of which has been reverse osmosis for marine application.

R. Charnley is a Chartered Mechanical Engineer who has worked for many years on the mechanical design of sewage and water treatment equipment and has been responsible for a wide range of research and development projects. In his present position of Senior Mechanical Engineer he has lately been working on the design of special marine reverse osmosis units for the Ministry of Defence.

(iii) As pure water is removed from the original solution the salt concentration increases and therefore the osmotic pressure increases. The initial net driving pressure must be high enough to account for these. For most applications, and from past experience, the net driving pressure will be around 25 bar. The osmotic pressure of brackish water is typically 4 bar and for sea water 28 bar; allowing for plant pressure drops, a typical applied pressure for a brackish plant is 35 bar and for a sea water plant 65 bar.

These relationships are clearly illustrated by Fig. 3. Here sea water is pumped at pressure P_1 into a membrane tube. The value of P_1 takes into account three factors: an allowance for the pressure drop due to the liquid flowing down the tube, the osmotic pressure of the sea water and the net driving pressure. As the sea water passes down the membrane tube, permeate passes through the membrane and the remaining sea water becomes more concentrated: hence the osmotic pressure increases, thus decreasing the net driving pressure. This process continues down the tube with the net driving pressure progressively decreasing and, hence, the flow rate of permeate through the membrane decreasing (the rate of permeate flow depends on the net driving pressure).

If the tube were infinitely long, the osmotic pressure could continue to increase, the net driving pressure continually decreasing until it becomes zero, at which point the permeate flow would cease. In practice, however, this situation is avoided owing to a limiting concentration of a precipitating salt or the uneconomic use of membranes.

Although the membrane is considered semipermeable, in practice there is a small transfer of salt across the membrane, the rate of which is proportional to the difference in salt concentration across the membrane.[2–4] Therefore, as the sea water travels down the membrane and becomes more concentrated, the transfer of salt through the membrane increases and hence the salt concentration of the product increases.

In practice the designer chooses an operating pressure and recovery for a system so that precipitation of chemicals does occur; efficient use is made of the membrane area, and the quality of the product water is within WHO standards. Figure 4 illustrates the effect found in practice of a change in applied pressure on permeate flow and product salinity at different temperatures.

The designer must have an understanding of how the process of RO occurs and the numerical relationship of the variables. A number of theories have been proposed to explain the transport of salt and water through a semipermeable membrane. Generally, however, the practical equations used in RO design are based on the membrane being a non-porous diffusion barrier in which the molecules dissolve, and the transport of the molecules being governed by the equivalent of diffusion control.

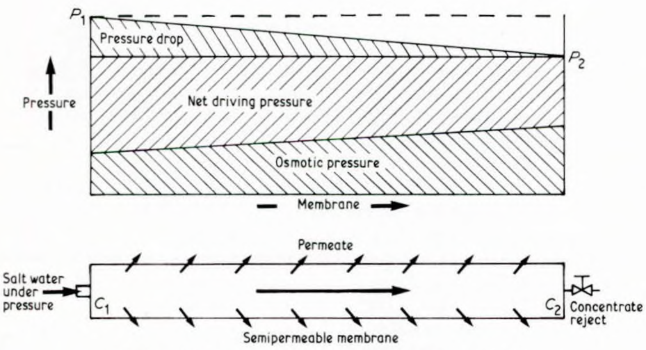


FIG. 3 Pressure changes in a RO system

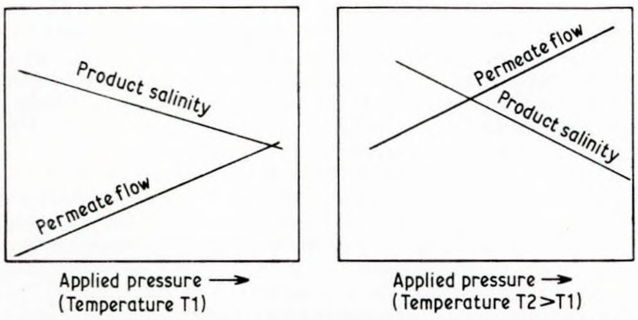


FIG. 4 Effect of change in applied pressure on permeate flow and product salinity at different temperatures

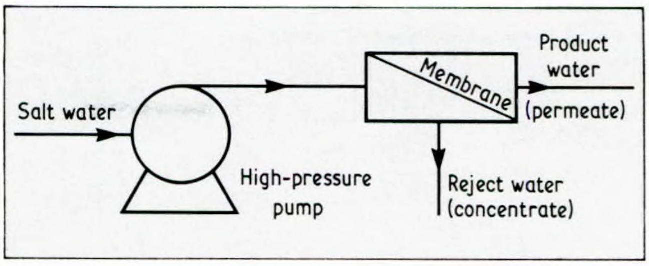


FIG. 5 Practical application of RO

Two simplified practical equations can be derived which govern the transfer of water and salt across the membrane:

$$F_w = -A\,(DP - DTT) \qquad (1)$$

and

$$F_s = -B\,(DC) \qquad (2)$$

where

- F_w = Water flux (g/cm²/s) through the membrane
- A = Membrane constant (g/cm²/s atm)
- DP = Pressure differential applied across the membrane (atm)
- DTT = Osmotic pressure differential across the membrane (atm)
- F_s = Salt flux (g/cm²/s) through the membrane
- B = Salt permeation constant (cm/s)
- DC = Concentration differential across the membrane (g/cm³).

Equation (1) shows that the mass flow of water depends on the 'net driving pressure' available. Equation (2) shows that the mass salt flux is independent of pressure but dependent on the difference in salt concentration across the membrane. In both equations temperature is assumed to be constant. The effect of temperature on constants A and B varies according to the membrane materials used. With a knowledge of all these variables, the designer uses computer techniques to reach a final design.

How is RO achieved in practice? Figure 5 shows a HP pump which continuously feeds sea water under pressure into a membrane. Purified water (permeate) passes through the membrane and rejected salts remain in the concentrated solution, which is continuously discharged to waste.

MEMBRANE TYPES

There are several types of membrane commercially available in a variety of materials. The two predominant types are hollow fine fibre and spirally wound.

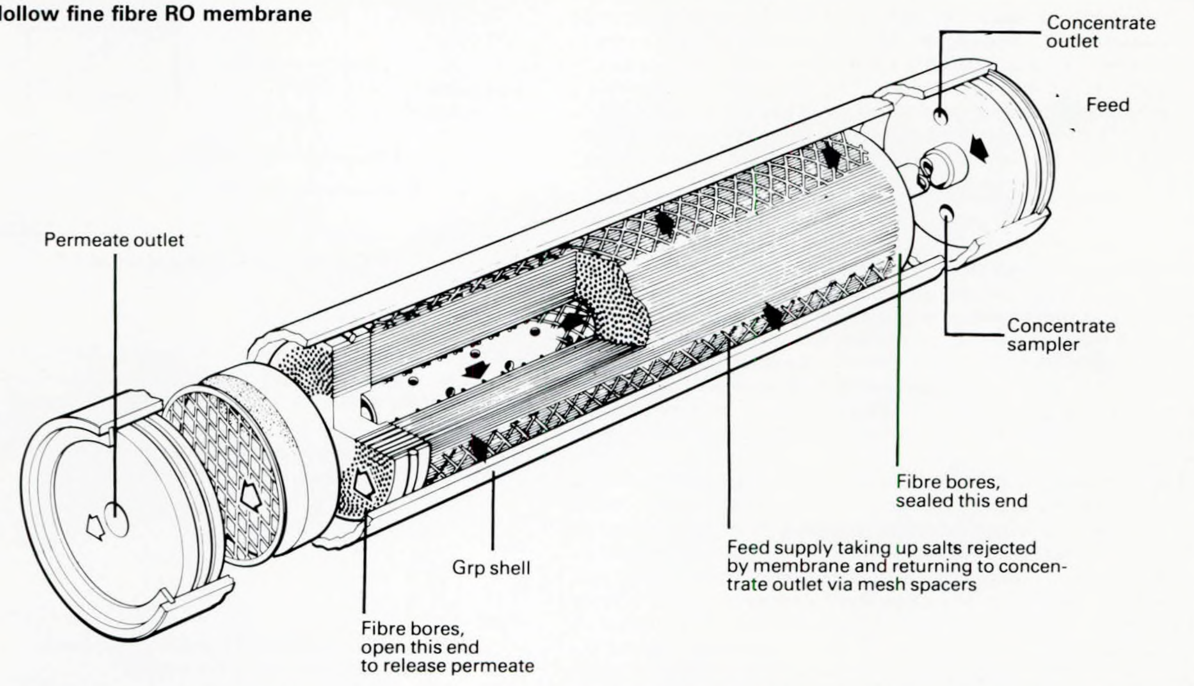
The hollow fine fibre membrane is made of an aromatic polyamide or cellulose acetate material which is spun to form hollow fibres having an i.d. of approximately 42 microns and an o.d. of 85–100 microns. Several thousand of these fibres are formed into a U-shape, the closed end of which is sealed whilst the open ends are formed into a resin pot (Fig. 6). The assembly is then mounted in a pressure vessel made of glass fibre, used for its good corrosion resistance.

Feed water is fed under pressure to the outside of the hollow fibre; water then passes through the tube wall and is collected in the centre of the tube as permeate (product water).

The chief advantage of this type of membrane is its very high surface area/volume ratio, which helps to minimize the space envelope required. In practice, this benefit is largely cancelled out by the fact that the output per unit surface area is only about one-tenth of that achieved by spiral wound configurations. In addition, the fibre bundle is very susceptible to permanent blockage by fouling or precipitation, which increases the pretreatment required for many applications. This is a distinct disadvantage for shipboard use, where space is at a premium.

The second type of membrane—spirally wound—is normally constructed from cellulose acetate for brackish water applications and from polyamide or polysulphonate for sea water applications. The membrane is constructed as a multiple layer sandwich, consisting of a

FIG. 6 Hollow fine fibre RO membrane



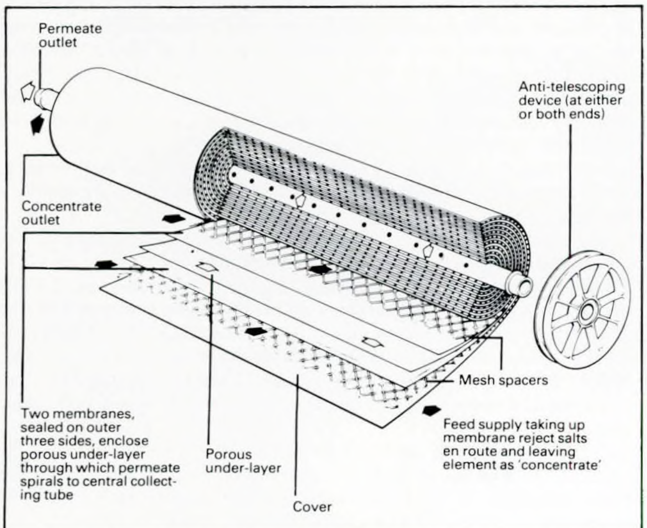
central permeate carrier covered on both sides by the semipermeable membrane with porous layer support.

This sandwich is glued around three edges to prevent feed water contacting the permeate. The RO element is formed by attaching the fourth edge of several sandwiches to a central perforated permeate collection tube; placing a coarse mesh spacer outside each sandwich to enable the raw water to flow across the membrane surface; rolling up the whole assembly around the permeate collection tube, and finally covering with a glass fibre outer wrap (Fig. 7). The completed elements are then fitted into a glass fibre pressure vessel.

Water is pumped under pressure into one end of the module and flows over the membrane surface. Permeate passes through the membrane, flows through the inner section of the membrane and is collected in the central tube. The concentrate leaves the module via the opposite end to the feed.

The spiral wound membrane is less susceptible to irrevocable blockage than the hollow fine fibre, owing to the more turbulent flow. This makes it more attractive in applications where space or economic considerations make substantial pretreatment processes unattractive.

FIG. 7 Spiral wound membrane module



In particular, the polyamide membrane can tolerate a wide pH range, which can alleviate the requirement for pH-correction for sea water applications. It is also attractive because of its stable long-term rejection characteristic, which is the key to a good sea water membrane.

The other types of membranes available are tubular membranes, which consist of 5 mm diameter (or greater) rods, and 'plate and frame' type units consisting of flat sheets of membranes supported on flat plates in a pile. These two types of membranes are generally found in industrial applications, e.g. food concentrating processes, where the capability for mechanical cleaning of the membrane is a priority. They are not generally economical for brackish or sea water applications.

RO PLANT DESIGN

RO plant design is based upon a specified feedwater analysis, product flow and product quality. Apart from pretreatment considerations (which are discussed in the following section), plant performance is mainly influenced by feedwater quality in terms of its total dissolved solids (TDS). Changes in TDS result in a change in the osmotic pressure of the feedwater, which directly affects the plant output and quality. As previously discussed, temperature also affects output but the plant can be designed to cope with wide fluctuations in TDS and temperature. The approach of designing a plant to cope with the worst case will be reflected in the cost; i.e. a larger and more expensive plant to produce the required output at lower feed temperatures.

There are a number of design constraints associated with RO plants. Two particular limitations are compaction and concentration polarization. In a well-designed plant, both these factors would only have a limited (and anticipated) effect.

Essentially, compaction is the forced increase in density of the membrane layer due to operation at higher temperatures and pressure. This results in a tighter membrane with improved rejection characteristics but with a permanent and significantly reduced flux (output). The extent of compaction is directly related to the feedwater temperature and pressure, with an increase in either resulting in an acceleration of the rate of compaction.

Concentration polarization is a term used to express the effect of an increased concentration of solute at the membrane surface due to the formation of a stagnant boundary layer. Essentially, the net driving pressure available for performing RO is related to the boundary layer and not the bulk concentration. Hence, significant concentration polarization can markedly reduce the membrane output and lead to precipitation problems. This problem is generally contained by maintaining a minimum brine side flow, which promotes sufficient turbulence to restrict the effect to an acceptable level.

It should be emphasized that a correctly designed plant will not suffer significantly from chemical or physical damage when operated and maintained within the appropriate guidelines.

For all types of semipermeable membranes there is a relationship between water flux and feedwater temperature, which approximates very roughly to a 3% increase in water flux per °C rise in temperature.

Referring back to Equation (1) it can be seen that, by maintaining a constant applied pressure at an elevated temperature, a higher output from the plant could be expected. There are, however, limitations concerning the extent to which this increase in temperature and/or increase in applied pressure may be utilized, due to the effects of compaction and polarization. As a guide, feedwater temperatures should not exceed 40°C.

The effect of temperature on output is particularly relevant to ship-based units, which can be subject to wide temperature variations. General practice is to specify the plant output at a lower temperature and allow adequate control (normally using hand-operated throttle valves) to compensate for temperature changes. By careful design, it is possible to supply a RO plant which will give a constant rated output over a temperature range of 1 to 40°C. It should be noted, however, that the effect of such a wide temperature range is to increase the cost of the plant because the membrane requirement will be based on a low temperature.

Another approach is to specify a design temperature and also specify minimum plant output requirements at lower temperatures. This approach may prove more attractive since, for shipboard applications, potable water consumption decreases in colder climates.

Once the membrane design parameters have been established together with the degree of feed pretreatment (discussed in detail later), the client must choose between a single- or two-stage system.

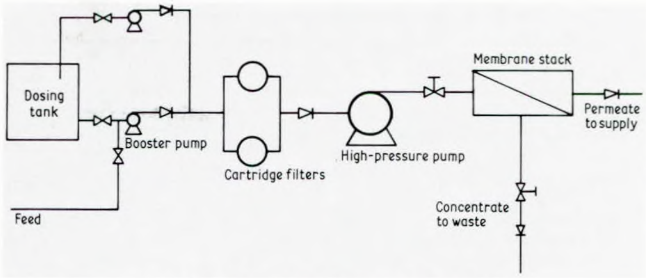


FIG. 8 Single-pass arrangement

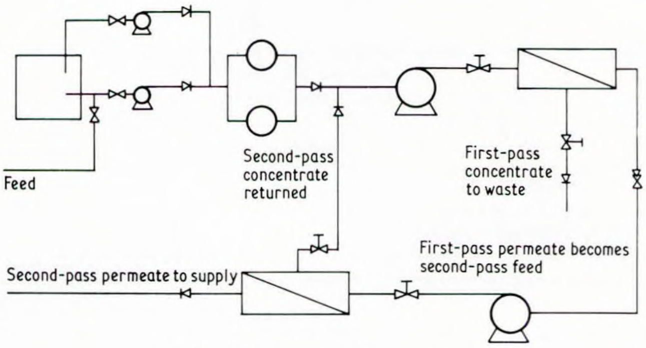


FIG. 9 Two-pass arrangement

The single-pass system

In this system (Fig. 8), the sea water feed supply is presented to the duplicated cartridge filter system by a booster pump, with chemical dosing en route from a small dosing tank. On leaving the filter, the flow passes to the HP pump and thence to the membrane stack. The concentrate is discharged to waste and the permeate is immediately available for use.

The two-pass system

The first part of a two-pass system (Fig. 9) is identical to the single-pass arrangement except that the permeate is not released for use. Instead, it becomes the feed supply to a second HP pump and second membrane stack.

Since in most cases the feed supply from the first pass is already of potable standard, further salt rejection in the second-pass membrane stack usually produces a final permeate having a TDS concentration of less than 50 mg/l.

The second-pass concentrate is still of very high quality and advantage is taken of this by returning it to the suction of the first-pass HP pump, where it substantially dilutes the original seawater feed supply.

The various factors concerning the two systems are given in Table II. These factors can be used as a guide but each case must be treated on its merits.

Many of the factors determining the choice really lie with the user. Two-stage sea water units have proved capable, over many thousands of hours running time, of producing final product water quality of less than 10 mg/l TDS from an initial concentration in sea water of 35 000 mg/l. In addition, they are more self-compensating in terms of feedwater quality (or temperature) fluctuations. The ability of two-stage units to continue to produce potable water in the event of failure of either of the stages may be particularly attractive to a user.

In comparison, a single-stage unit is considerably cheaper and requires a smaller space envelope. It uses less energy but is more susceptible to feedwater changes and has less redundancy. There are applications where two single-stage units have been used in parallel to produce the required output. However, it is likely that the use of a comparatively sized two-stage unit would be more attractive in these applications owing to its increased flexibility.

Pretreatment

An important consideration when designing a RO plant is the degree of pretreatment. There has evolved, from operating experience with pilot and full-scale RO plant, a set of guidelines which relate to both the operation of the membrane and the quality of the feedwater supplied to the membrane. These guidelines are aimed to maximize the membrane life by reducing the fouling and precipitation tendencies of the feedwater.

Fouling by precipitation can be avoided by the addition of up to 5 mg/l of sodium hexametaphosphate (or equivalent); and, depending upon the requirements of the membrane material, the addition of acid to reduce the pH to 5.0.

The extent of pretreatment varies considerably according to the application. However, a 10 micron cartridge filter will almost certainly be required to prevent substantial build-up of suspended solids on the membrane. Full chemical pretreatment with slow sand filtration can double the volume of space required and add 50% to the capital costs. The detailed design and application of additional pretreatment units to cope with specific problems is beyond the scope of this paper. It should, however, be stressed that it is this area of the design which determines the long-term performance of the RO unit.

In small installations (and particularly those with space limitations), ideal feedwater conditions are frequently not attainable. In these

Table II: Considerations in selecting a single-pass or two-pass system

	SINGLE-PASS SYSTEM	TWO-PASS SYSTEM
Temperature effect	Significant	Self-compensating
Water salinity effect	Significant	Self-compensating
Capital cost	1	1.75
Basic redundancy facility	None	Up to 100%
Power consumption per m^3 of product water (kWh)	12	17
Product water yield under adverse conditions	Lower	Maintained
Product water quality from sea water (TDS, mg/l) (approx.)	500	50 or less if required
Overall size/weight	1.0	1.5
Installation	Single skid	Single skid
Operation and maintenance	1.0	1.5

Table III: Routine operational requirements

ACTION	FREQUENCY
Make up dosing chemicals	2 days
Check dosing pump operation	Per watch
Log flow rates	Per watch
Log product salinity	Per watch
Log filter pressure differential	Per watch
Log RO element pressure differential	Per watch
Check valve setting	Per watch

Table IV: Main routine maintenance requirements for commercial marine RO plant

ACTION	FREQUENCY
Change HP pump oil	500 h
Top up booster pump bearing oil	500 h
Replace cartridge filter elements	As necessary
Check drive belt tension	500 h
Clean RO elements chemically	As necessary

circumstances, it must be accepted that periodic cleaning of the membranes will be required. This increases the need for a chemically resilient membrane, to allow more aggressive (and hence more effective) cleaning solutions to be used.

While the RO membrane has, effectively, a 100% rejection towards bacteria and virus, it is standard practice to chlorinate (i.e. sterilize) the product water to prevent bacterial growth. In applications with pH-adjustment of the feedwater (such as is required with cellulose acetate membranes), then pH-adjustment and degassing of the product may be required in addition to chlorination.

Post-treatment

The major post-treatment of the permeate is sterilization by chlorination. To overcome the somewhat flat taste of the permeate compared with normal tap water, soda ash is sometimes dosed; this also reduces the corrosive nature of the water.

Control

RO readily lends itself to automatic control and monitoring. The control, on simple sea water plants, consists of HP pump protection (via pressure switches) and membrane protection on shut-down (via a LP flush routine). This control can then be supplemented to meet operational requirements. For instance, automatic starting of the plant can be achieved by means of product tank level probes, and automatic dumping of out-of-specification product water can be provided via conductivity measurement.

The types of control are determined by the particular application along with the specifications for the quality and quantity of product water. Where there is greater emphasis on reliability, it is possible to install standby units with automatic changeover; or, for sea water applications, to adopt a design which utilizes two stages, with either stage able to operate independently if necessary.

Generally, for small shipboard units, the trend is towards keeping the control and monitoring systems as simple as possible commensurate with adequate protection, relying to an extent on manual surveillance. If required, total automatic operation with sophisticated controls can be implemented but this increased complexity invariably leads to higher maintenance requirements and less reliability, as well as very much increased capital costs.

While there is scope for automatic remote control and computerized data-logging systems for operation and control of RO plants, the normal ship-based plant does not require or indeed benefit from these.

Commercial plants must have an automatic product dumping system incorporated to comply with DoT regulations. Usually this would be a solenoid valve, controlled by contacts in the conductivity meter, which diverts the product to waste if the TDS becomes too high.

The instrumentation and control, in its most basic form, consists of product water quality monitoring (conductivity), product flow measurement and membrane pressure indication. Control is manual, via feed and concentrate valves, and protection devices are limited to a LP switch on the suction of the HP pump, a HP relief valve and switch and motor interlocks. This has proved to be a simple and very effective system.

Mechanical equipment

Normally, a commercial shipboard RO plant would be a single-pass unit as shown in Fig. 8. The booster pump is required to maintain an inlet pressure to the HP pump of 20 to 60 lbf/in^2. The pump is also used as a flushing pump, for cleaning the elements. One type used with particular success is a centrifugal pump having all the wetted components made from glass-reinforced plastic.

The cartridge filter is usually a single full-flow unit having a 316 stainless steel body containing up to fifteen 10-micron cartridges made of wool or phenolic resin. Special duplex back-washable filters with porous sintered metal elements are sometimes used when the feedwater may be of low quality and sand filters cannot be fitted.

Triplex plunger pumps are currently used to provide the high pressure required at the membranes. These have proved to be reliable when suitable materials have been used. Ceramic pistons, polyacetal valves and aluminium-bronze or chromium-plated brass heads have proved satisfactory. Plunger pumps inherently produce pulsations, which can have a destructive effect on the pipework. Even a triplex pump can produce flow variations of more than 20% and a pressure variation of 50%, and these must be nullified by fitting an accumulator to the system. Normally, the accumulator is fitted directly on to the pump head on the discharge side. Careful consideration must also be given to the design of the HP pump inlet piping to ensure that the friction losses and acceleration head are limited to values which prevent destructive cavitations behind the pump plungers. Soft flexible hoses are fitted to both the inlet and outlet of the pump to isolate vibration and further dampen pulsations.

The pressure vessels housing the RO membranes are usually manufactured from glass-reinforced plastic using the filament winding process. Because of the inherent variations in the quality of the material, stringent test standards are used. Typically, the test vessel is subjected to a fatigue test of 100 000 cycles from zero to working pressure, followed by a static test of six times working pressure which, for sea water vessels, is 6000 lbf/in^2. End enclosures are either made of a metal/PVC composite or are formed from resin casting.

Pipework and valves for commercial units are usually supplied in 316 or 316L (low carbon) stainless steel. Experience has shown that, providing the sea water flow rate is over 1 m/s, corrosion of 316L is minimal. Where conditions are quiescent, 316L is subject to crevice corrosion and pitting, therefore crevices must be avoided; for example, the use of socket welded fittings is not recommended. Low carbon grades of stainless steel are used to minimize the risk of intergranular corrosion at welds. Copper/nickel pipework is used on warships and offshore plants and studies are currently being made into the use of high alloy steels and titanium.

OPERATION AND MAINTENANCE

A vital area of a properly organized O & M programme is the logging of data. This is particularly relevant to RO plants, as many of the problems are progressive in nature and can be best rectified by early recognition. It is beyond the scope of this paper to discuss membrane problems and their associated remedies but, essentially, RO technology and experience have now developed to the stage where most potential problems can either be designed out or reduced to acceptable levels. The prerequisite still remains, however, that there must be adequate monitoring of the plant.

Table III shows the basic routine operational requirements for a typical shipboard unit. Additionally, if a sand filter is fitted, it would need back-washing at intervals, depending on conditions; the pressure differential across the filter also needs logging.

On a small ship-based unit, probably the single most likely malfunction is a RO membrane blockage due to suspended solids or possibly precipitation. The effect on the plant is to reduce the output (at constant applied pressure) and ultimately to block the membrane completely.

Membrane deterioration is monitored by using the flow, differential pressure and conductivity readings to calculate a temperature-compensated 'standard flux'. When this has declined by 10% then chemical cleaning is required, although it should be noted that at this stage performance will still be adequate.

The measurement of small differential pressures at high pressures is notoriously difficult and expensive. A cheaper system is to measure the membrane inlet and outlet pressure on two separate directly applied pressure gauges and log the difference. Logs must be religiously kept up to date and reviewed to determine trends.

Although not essential, the additional measurement of concentrate flow can be beneficial, in that pump problems can then be detected at an early stage.

The chemical dosing on package marine plants would normally be limited to the injection into the feed of 5 mg/l of sodium hexametaphosphate (Calgon) to inhibit the precipitation of calcium carbonate on the concentrate side of the membrane. Calgon is usually stored in powder form and is mixed with water in a small dosing tank fitted to the RO skid. Normally the tank would be sized to give 2 days' supply of dosing fluid. Calgon is a non-toxic chemical and does not require special precautions for handling. An alternative sequestering agent sometimes used is in concentrated liquid form and is easier to handle.

Maintenance of the mechanical equipment on commercial units is basically simple. The main routine maintenance requirements are listed in Table IV.

Account has to be taken in the plant layout and positioning to enable pump heads and RO membranes to be removed when necessary for major overhauls. Under normal circumstances, membranes could be expected to last at least 3 years, although this is very dependent on the inlet conditions. The membranes can be removed from the pressure vessels simply by disconnecting the pipe unions, removing the end cap's retaining circlip and sliding the end cap and membrane out of the vessel. Replacement of an individual membrane is normally completed within 15 minutes.

ENERGY REQUIREMENTS

The graphs shown in Figs 10 and 11 show specific power usage against water recovery, with and without energy recovery. The graphs were generated using a very simplified model and it should be noted that no account was taken of the effect of recovery on product quality and of any membrane constraints which may apply when working at higher recoveries, e.g. pressure limitations; however, with modern sea water membranes, recoveries of up to 30% can be achieved with adequate product quality.

It should also be borne in mind that RO modules are only available in standard sizes and in practice it is not always possible to fit actual plant parameters to the theoretical curves, particularly on very small plants where the options are limited. Referring to Figs 10 and 11:

$$\text{Specific power (kWh/m}^3) = (Q_f \times P)/Q_p \times \eta_p \times \eta_m$$
$$\text{Recovery (\%)} = (Q_p/Q_f) \times 100$$

where Q_f is the feed flow; P is the working pressure; η_p is the efficiency of the pump; η_m is the efficiency of the motor, and Q_p is the product flow.

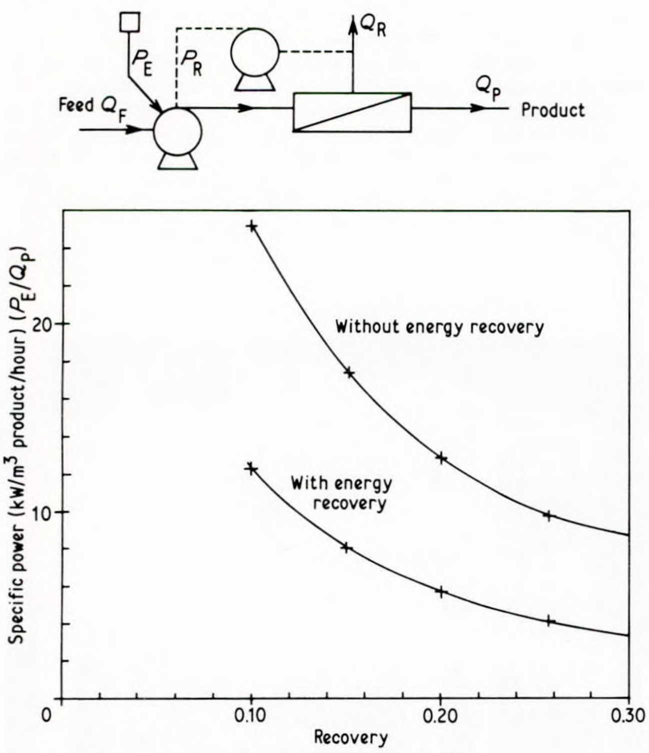
Figure 11 shows the characteristics for two-stage plants. Note that it has been assumed that the second stage would operate at 75% recovery and that energy would only be recovered from the first stage.

On a single-stage plant, up to 90% of the feed flow goes to waste as the concentrate. This stream is still at high pressure and normally the energy would be dissipated through a control valve. However, this waste energy can be utilized to help drive the feed pump and power savings of over 50% can be achieved. Suitable energy-recovery plunger pumps are now available for small plants but their current cost is approximately 20 times that of the standard pump.

Recent studies have shown that energy recovery on larger plants using centrifugal pumps and turbines is economically viable and can result in considerable savings.

COMPARISON OF RO WITH CONVENTIONAL DESALINATION

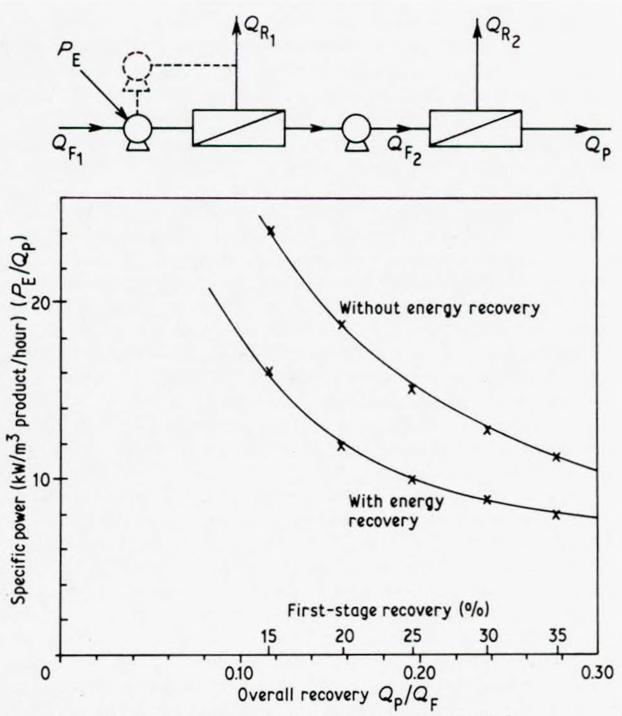
The devastating effects of the rise in oil prices over the past decade has resulted in RO becoming a most attractive proposition, particularly for the desalination of sea water.[1,5]



Assumptions: RO inlet pressure 1000 lbf/in^2
RO outlet pressure 900 lbf/in^2
Feed pump efficiency 25%
Recovery turbine efficiency 70%
Motor efficiency 90%

FIG. 10 Energy consumption of single-stage RO plant

FIG. 11 Energy consumption of two-stage RO plant



Assumptions: First-stage inlet pressure 1000 lbf/in^2
Second-stage inlet pressure 400 lbf/in^2
Feed pump efficiency 85%
Recovery turbine efficiency 70%
Electric motor efficiency 90%
Second-stage recovery (Q_p/Q_{f2}) 0.75
First-stage outlet pressure 900 lbf/in^2

Table V: RO vs. other desalination methods

PLANT	RELATIVE ENERGY CONSUMPTION[a]	RELATIVE COST[b]	RELATIVE SIZE[b]	REMARKS
Submerged-element distiller single effect	10.0	2.0	1.0	1. Feed treatment essential. 2. High energy consumption.
Waste-heat distiller	1.0[c]	1.4	1.0	1. Feed treatment advised. 2. Complicated pipe systems required in warships.
Two-stage flash plant	6.5	2.1	1.9	1. Feed treatment essential.
Four-stage flash plant	4.9	2.3	2.1	
Vapour compression distiller	2.4	1.0	1.9	1. Tendency to be noisy. 2. Feed treatment essential. 3. Simple to install.
RO single-stage	1.0	1.3	1.3	1. Careful prefiltration required. 2. Water quality suitable for drinking only from single stage. 3. Very simple to install.

[a] Referred to fuel oil.

[b] For distiller only. Costs and sizes are based on the basic units only, i.e. no allowance is made for sand filters.

[c] This assumes all heat is free and the only energy required is that for pumps and compressors.

Numerous comparisons that have been made of relative power consumption show that RO needs only between 10 and 50% of the energy required by the commercially available alternative. Generally RO is quoted as requiring 9.5 kW to produce 1 m^3 of potable water from sea water (without energy recovery), as opposed to 16 kWh/m^3 for large-scale multi-stage flash distillation and around 24 kWh/m^3 for a vapour compression distiller. However, there are so many factors to take into account that direct comparison figures are difficult to quantify accurately; but all studies done to date show that RO is considerably less energy-intensive than other methods.

In operational comparisons, the reliability, low maintenance requirements and low labour costs/operator involvement when compared with other forms of desalination are particularly attractive. Units specially designed for shipboard use can normally reach full operational performance within 5 minutes of start-up; they require 5 minutes of data-logging on a periodic basis (say, every 4 hours) and chemical tank make-up once every 2 days, involving perhaps 20 minutes labour.

In addition, the number of items of equipment requiring routine maintenance is limited. This is in line with the philosophy to reduce maintenance requirements for non-steam auxiliaries.

The capital costs of a RO system are significantly influenced by a number of factors, including the degree of instrumentation and control, the use of a single- or two-stage system and the capacity of the unit. The influence of the unit capacity is not quite so clear-cut because of the effect of temperature but, generally, the basic design capacity can be taken for cost-comparison purposes.

Operating costs also depend on the nature of the plant and the chemical costs in particular are obviously significantly influenced by the degree of pretreatment.

One of the major running costs is membrane replacement. A standard membrane life has generally been taken as 3 years but experience indicates that lives in excess of 5 years are possible. The length of life is not always clear-cut since the drop in performance towards the end of life may be acceptable, depending on the user or process requirement. The other reason why membrane life predictions are tentative at best is that the operation and maintenance of the plant has by far the most significant effect on the membrane life. Regular fouling of the membrane, by suspended solids or precipitation; incorrect storage, and operation outside recommended design limitations will all inevitably reduce the membrane life. These factors must be offset against the capital and running costs of providing ideal pretreatment and control.

Normally, for small plants, ideal pretreatment and control are not economically viable. The Ministry of Defence have been evaluating RO units for shipboard installation and have determined that the cost of producing 1 tonne of potable water from sea water by RO is about £1.65. This compares with around £9 per tonne for a flash distiller (based on fuel at £150 per tonne). Table V gives a guide to relative costs of a typical RO plant and other processes.

APPLICATIONS

Figure 12 illustrates a two-stage plant designed and manufactured for warship use. The plant was designed to MOD requirements and copper nickel piping is used throughout. Full automatic fail-safe features are incorporated and chemical dosing facilities are fitted within the skid, which was designed to strict space and weight limitations.

Figure 13 shows a single-pass plant which can produce 22 tonnes of potable water per day at 5°C and 54 tonnes/day at 25°C. It has a maximum power consumption of 25 kW, a weight of 1.75 tonnes and dimensions of 2.1 m (height) × 2.0 m (width) × 1.5 m (length). Either as a replacement for an existing system or in a completely new vessel, the compactness of an RO system is one of its many advantages.

FIG. 12 Two-stage plant for warship use

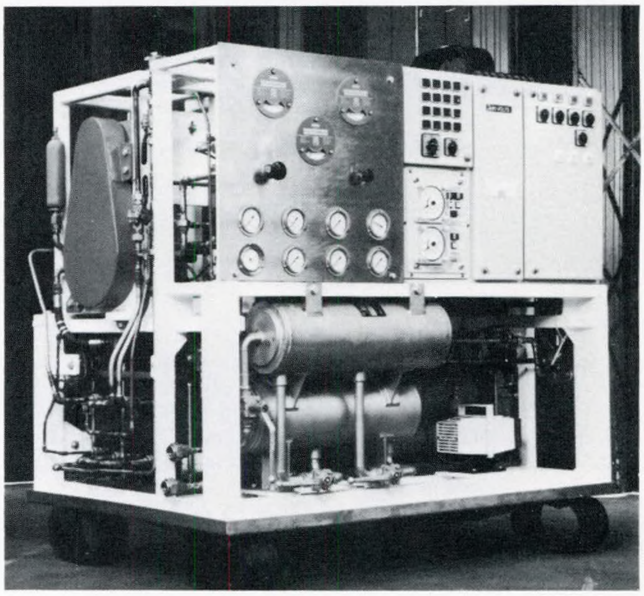


Figure 14 shows a single-stage commercial unit which is rated at 20 tonne/day output at 20°C or 6.4 tonne/day at 5°C. This plant was designed specifically for shipboard use and has overall dimensions of 1000 × 900 × 1425 mm high. It weighs approximately 420 kg.

Department of Trade approval

All plants for installation on UK-registered ships must have Department of Trade approval. The standards which must be met ensure the plants are of an internationally acceptable engineering standard and that the drinking water produced is chemically and bacteriologically fit for human consumption.

All DOT-approved plants must have a salinometer on the product water to indicate the quality of the water and the product water must be automatically sterilized. Operation of the plants within 20 miles of a coastline is not allowed, hence pretreatment is not required. It is interesting to note that under the DOT, a committee was formed to study the requirements for operation of plants close to the Falkland Islands. The guidelines of the study detailed pretreatment.

SUMMARY

The development of RO membranes has reached the stage where drinking water can reliably be produced from sea water in a single stage and very high quality water can be produced in two stages. Sufficient experience has now been gained to enable optimum pretreatment systems to be designed. Compact, skid-mounted units, ideal for mounting in ships, are being produced which have low operational, maintenance and power requirements, with the added advantage of quick and easy start-up. RO systems are therefore now a viable and attractive alternative to the traditional shipboard methods of producing high-quality water.

The potential for RO is by no means fully realized at present. Apart from its application in the desalination of both brackish and sea water, it can be used in a variety of situations where a reduction in dissolved salts (or indeed an increase in valuable metal ions such as silver) is desired.[6] The development of new membrane material is continually widening the applications of RO. For example, in the foreseeable future it will be possible to produce boiler feedwater from a two-stage plant.

ACKNOWLEDGEMENTS

The authors wish to thank Ames Crosta Babcock Ltd for allowing the time and facilities for this paper to be produced. They also wish to thank Mr R. J. Maloney and Mr M. R. Owen, MOD(N), for their valuable assistance.

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FIG. 13 Single-pass 22 t/day-plant installed in engine room of *Myrmidon*

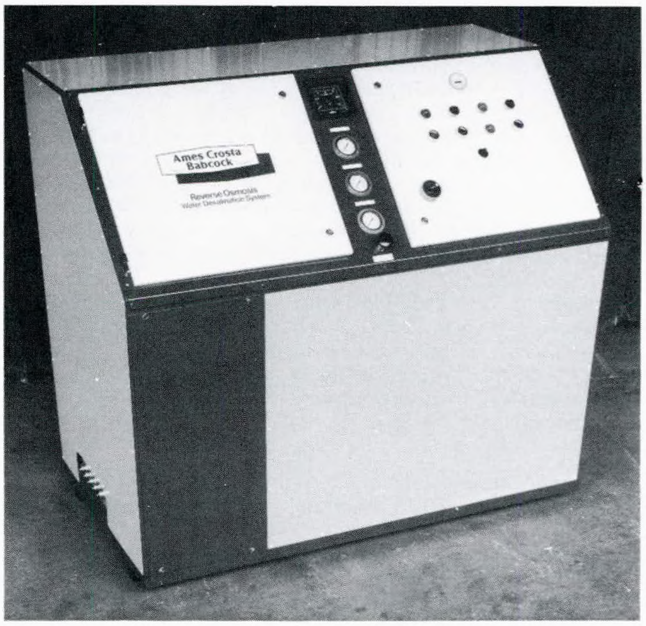

FIG. 14 Single-stage 20 t/day shipboard unit

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Discussion

CDR R. A. A. DEAN CEng, FIMarE (Ministry of Defence): The word osmosis is strange to those of us who have been trained as Mechanical Engineers and I must admit that, when people first started talking about reverse osmosis desalination plants in the early 1970s, I had to ask my wife with her 'O' level in Biology to explain exactly what it meant.

We are grateful this evening to Messrs Allanson and Charnley for their very clear explanation of the process and of its practical application in the marine field.

Trials on RO desalination were carried out at the AMTE, Portland, during the 1970s. The main problems were unreliable membranes; the difficulties of pressurizing sea water to 60 bar, and sea water filtration. By 1979 the filtration problem had been solved and a reliable high-pressure pump developed. But the membranes tested, which were of the cellulose acetate rod and tubular types, remained unreliable, the first type being too bulky and the second too fragile and susceptible to fouling for practical shipboard use.

Some 4 years ago a different type of membrane became available: a thin fibre composite (TFC), made of polyamide material rather than cellulose acetate, in a spiral-wound (or swiss roll) configuration. A test plant was supplied by Ames Crosta Babcock and installed at Portland late in 1980. The results were so successful that in early 1982 it was decided in principle to fit RO desalination plants into the new conventional submarine to be built by Vickers and the new Type 23 frigate to be built by Yarrows.

Shortly after this decision the Falklands crisis broke. Merchant ships were taken from trade in large numbers to assist the Fleet. Necessary modifications included the fitting of extra fuel tanks; flight decks; gear for replenishment at sea, and desalination plant.

The speed with which RO plants could be manufactured and installed made them the obvious candidate to meet the water requirement. Twenty merchant ships and six warships were thus fitted with RO plants during the next 3 months. Fortunately there were two firms who could respond to the need: Ames Crosta Babcock, who had already been involved in the trials at Portland, and Clarks of Hull, who had supplied an RO plant to *QE2*. Both firms put in a tremendous effort and RO plants were never the critical factor in the ships' sailing dates for the Falklands.

A wealth of operating experience has been gained from these installations. Most of the technical problems were a direct result of the haste with which the plants had been manufactured, e.g. with materials not to MOD standards and inadequate bracketing.

The lessons learnt concern four areas; vibration and resilient mountings; membrane performance; filtration, and system design.

Vibration

There were extensive fractures to welded joints in the pipework, particularly in stainless steel, and a number of pressure gauges suffered vibration damage. These failures were caused by ship-induced vibration and, in some cases, by vibration from the reciprocating pump—the larger the pump, the greater the problem. The problem can be overcome by mounting the pump separately on special mounts with flexible pipework connections, the complete plant being on a flexibly mounted skid.

Membranes

Two types of membranes were used, the TFC spiral-wound type being fitted in all but three ships, where the cellulose triacetate hollow-fibre type was used. Both worked well over the relatively short period of operation but experience at Portland over 5 years shows that the TFC type is more reliable. The TFC membranes in HMS *Leeds Castle* have been in operation for 7000 hours (equivalent to 18 months). They have been cleaned four times but have not needed to be changed.

Another important advantage of using TFC spiral-wound membranes at sea is that no acid dosing is required. SS *Uganda* was fitted out with cellulose triacetate membranes and containers of hydrochloric acid had to be air-freighted out; this was not popular. Also, acid dosing is an additional and, possibly, hazardous task at sea.

Filters

During the trials at Portland some sand filters had been installed which, throughout the varying sea and weather conditions over 12 months, had removed enough dirt and marine growth to provide sufficiently clean sea water for the membranes. The disadvantage of such filters is their size, space being at a premium in warships.

Some work was carried out in 1981 to assess the cleanliness of sea water at Portsmouth, Plymouth and Portland by measuring the fouling index and turbidity. The results showed that no filtration was required beyond 10 miles from the shore; good filtration was needed inside 3 miles; and between 3 and 10 miles it depended on sea and weather conditions.

Instructions were therefore given to ships that RO plants could be freely operated outside the 10 mile limit; intelligently operated in the 3–10 mile range, but shut down inside the 3 mile limit. In the event these were not adhered to and ships operated their plants within half a mile of the shore. All were equipped with 5–10 μm prefiltration cartridges which operated satisfactorily in the deep clear waters close inshore at Ascension Island but which clogged up in the murky waters of Port Stanley.

The authors mention in their paper the possibility of fitting sand filters. Do the figures given in Table V, showing the relative cost and size of RO plants, include sand filters for continual operation? If not, what would the figures be? I should also like to know the authors' experience with sand filters in terms of protecting the 10 μm cartridge filters.

It is unrealistic to expect RN ships to adhere to even a 3 mile limit when operating RO plants and clearly filtration standards will have to be improved. Some experience will be gained from SS *Rangatira* and other ships that have been retrofitted with sand filters.

System design

The trials in 1981 at Portland were carried out with a two-stage plant because it had previously been considered that the purity of water from a single-stage plant was marginal for drinking purposes and inadequate for gas turbine and helicopter washing.

The quality of water from the first stage of a TFC membrane, however, turned out to be satisfactory for drinking purposes. All plants fitted for the Falklands operation were therefore single stage and no one complained about the quality of the water.

The optimum design for surface warships would appear to be two single-stage plants, with a small, separate second stage to produce high-quality water. Some redundancy is lost with a single-stage unit so, if these are fitted, it is essential to have more than one plant in a ship to ensure the availability of fresh water.

Preheating

The ships of the Task Force had to operate their machinery over a wide range of sea water temperatures: from the tropics, with sea water temperatures of 30°C, to the South Atlantic itself where the temperature could be as low as −1°C.

If, as the authors state in their paper, the output of potable water rises by 3% per °C rise in sea water feed temperature, is it not obvious to include in the design of the plant some provision for preheating, either by waste heat or direct heat?

Are there any technical disadvantages of such a solution; and would the authors comment on the economic viability of including a preheater in the design?

CDR M. B. F. RANKEN (Aquamarine International (Fisheries and Ocean Development) Limited, London): I found this an interesting paper and one which may be timely during a water strike! The subject of RO is an unfamiliar one; this is the latest of very few papers on desalination plants presented to this Institute.

Having been responsible for distilling plant in the Admiralty soon after the War, the comments which follow may be of interest.

Many of us were brought up on single, double and triple-stage evaporators, of main interest and importance in HM Ships. Merchant ships mostly carried enough in their tanks for drinking water, with perhaps an evaporator for boiler feedwater which was sometimes integrated into the steam and feedwater system as a whole.

After the Second World War, much work was done to improve the performance of existing plant and to develop new types. We had the incentive of almost incessant trouble and difficulty with the normal British plants, and the example of the US submerged-coil and Soloshell compound low-pressure plants, together with considerable experience with the scale-inhibiting injection of starch and boiler compound (though it appeared afterwards that the starch largely cancelled out the boiler compound, or vice versa!); over 200 sets of injection equipment were supplied under AFO 3981/44. There was also some experience from enemy sources: the Umlauf flexing-element in destroyers and the vapour-compression plants in submarines. Caird & Rayner improved the latter for the *T* and *A*-class submarines, including making them stable in operation whilst snorting. The Aiton forced-circulation unit in *Vanguard* and the Worthington Simpson plant in *Glasgow* were never successful; hydrochloric acid was needed for cleaning the *Vanguard* plant's tube nest and caused some anxiety when the storage tank's lead lining leaked and the acid started boiling, which led to hasty ditching of the whole tank overboard.

Much work was done on scale-inhibiting methods and agents and led to low-pressure/low-temperature operation (where the scale formed is different and more brittle), ferric chloride and other chemicals, eventually leading to Belloid TD and others, developed by teams at G & J Weir Ltd and the Admiralty Materials Laboratory, Holton Heath.

Until then the outputs of plants supplied to Admiralty requirements were those attainable with clean coils; even with optimum operation under very careful watchkeeping, the best that could be obtained on a continuous basis was no more than 70% of the clean coil output; and then only for up to 10–14 days continuous output, usually on live steam. Not only was low-pressure operation specified for new plant, using exhaust steam (which itself had to be provided with new constant-pressure automatic control valves), but it was arranged that all new Statements of Requirements stipulated that the specified output was to be attainable after 500 hours continuous running, i.e. scaled-up. In the Type 15 frigate conversions and other destroyer modernizations this led to the new 25 ton/day evaporator being larger in physical size than the existing wartime so-called 40 ton/day plant, which of course never produced more than 25–28 tons/day when it was run.

Other improvements were the introduction of flexing heating elements, such as the Maxim, and separate pumps to replace the old combined pump which had been such a continuous anxiety and trouble in every size of ship.

Diesel-driven ships were being built and this led to the development of the 25 ton/day vapour-compression plants, using rotary compressors like the Rootes and the Lysholm (Howden); centrifugal and axial-flow alternatives were discarded at that time because of their instability outside a narrow range of operating conditions.

In 1950 the Admiralty Distilling Experimental Station was set up at Portland. One of its original purposes was to test vapour-compression plants for diesel frigates and the like. We had to find and scrounge scrap *Bangor* class boilers, an R-class battleship's turbo-generator and various other items to equip the station as cheaply as possible.

The breakthrough came in the early 1950s with the Hillier/Silver/Weir multi-stage flash evaporator. In the Middle East oilfields there was a major demand for fresh water and this provided great incentives to develop these systems for a region where there was free energy, in the form of gas, for power and heat, and plenty of sea water. Today, plants are mostly installed in conjunction with banks of large gas turbo-driven electric generators; typical units produce 10–12 million gallons (45 000–55 000 tons) of water per day.

Smaller versions of this type of system are also used in merchant ships, usually utilizing heat from main and auxiliary diesel engine jacket cooling water systems, with exhaust heat boilers as well when needed. For example, the Royal Caribbean Cruise Line's *Song of America* built by Wärtsilä carries 1575 passengers and around 500 crew; about 370 ton/day of drinking water is required. The usable mechanical output available from the main engines and generators all at full power is 25 580 kW, so that about 50 000 kW is theoretically available as waste heat from the jackets and exhausts. Various freezing cycles have also been tried experimentally ashore.

The vapour-compression plants for the Royal Navy's surface ships were superseded by multi-stage flash-type units.

In 1969 the International Marine and Shipping Conference (IMAS 69) was held in London. The paper by A. Wallace on 'Distilling plant in the Royal Navy' concluded: 'Just over the horizon is the strong possibility of steamless ships in which water production must either depend on using low-grade diesel jacket heat for distillation or the techniques of reverse osmosis.'

Reverse osmosis, as the present paper shows, really had no place (and we did not even consider it) as long as the requirement for the quality of boiler feedwater was below 2.5 ppm of total dissolved solids (TDS); even the requirement for drinking water used to be 7.5–15 ppm TDS.

Also, the requirement for sterility meant that the water had to be heated above 162°F (72°C), although 120°F (49°C) for a minimum time was believed to be enough. It was therefore clearly better not to operate plants in harbour. Will the authors please say what standards have to be met today, and how this is achieved with RO units?

Reverse osmosis obviously has attractions for application in non-steam-driven surface ships and in diesel (but not nuclear) submarines. Its place seems doubtful, however, in most merchant ships, which have a regular, constant source of waste heat from cooling water jackets and engine exhausts.

I should like to ask the authors the following questions:

1. What types and powers of pump are used in view of the very high operating pressures involved, i.e. 1000 lbf/in^2?
2. What is the maximum membrane operating pressure which can be used continuously?
3. What proportion of the feedwater is discarded as brine concentrate, in both single and two-stage units?
4. Surely it is easy to provide a feed heater (using waste heat) to ensure a minimum design temperature of, say, 10 or 15°C? What would be a reasonable maximum temperature? (Sea water in the Arabian Gulf reaches 35 to 37°C.)
5. What frequency of cleaning is normal for operation only on clean sea water; and what care is needed in feed dosage and filtration?

A. BURNETT (Offshore and Marine International Services): We are product business development consultants to the international offshore industry. My company's interest lies in the commercial, technical applications of RO within the industry.

One slide shown by the authors listed seven advantages of RO. Surely these are requirements rather than 'advantages' and would be expected in any case. Can the authors elaborate, especially regarding disadvantages?

In the offshore industry, where it costs several hundreds of pounds per day for one man to be present offshore, economy is a factor at the forefront of the equation. With this in mind, I would like to comment on particular aspects, as follows.

Membranes

These obviously form the heart of the system. Is it possible to guarantee consistency of manufacture between membranes?

One recent development covering new technology is the plate-type membrane. Can the authors give any further information or experience on their use, possibly for offshore, and whether their use results in increased maintainability?

What happens, for instance, if one is stuck with one membrane: for example, in a ship that has been at sea for some time and does not carry any spares. What is the longest time that one membrane will run with reasonable efficiency without spare back-up?

Additives

Pretreatment plant, it was mentioned, was fitted in some installations. Most of the RO plant appears relatively simple to be automated. Can the additive side of the system be automated satisfactorily to give reduced man-hours (and therefore, greater economy)?

Noise

An earlier speaker pre-empted my question on vibration, but what are the noise levels to be expected from an average RO plant? This is of particular interest to the offshore industry, where we are soon to be faced with new noise regulations, to be implemented world-wide.

Volume/weight

What are the volume and weight of a typical complete RO unit including all accessory equipment, i.e. spares, automation systems etc.: all the bits and pieces needed for an extended run?

N. M. WADE and R. HEATON (Preece Ewbank Consulting Limited): With regard to energy considerations, the authors refer to comparative energy consumptions of sea water RO at 9.5 kWh/m^3, 16 kWh/m^3 for MSF distillation and 24 kWh/m^3 for vapour compression. Figures of 12 and 17 kWh/m^3 are also quoted in the paper for single and double-pass RO.

In making such comparisons it is important to realize that the form in which energy is used differs with the process. RO and vapour compression require mechanical/electrical power; and MSF requires some power plus heat, generally in the form of steam at about 1.0–2.0 bar pressure. Direct comparisons of energy consumption in kWh/m^3 can thus be misleading.

We have attempted to analyse this question by referring energy consumption to the fuel source required (see Fig. D1) and have examined the effect on costs. The results are summarized in Table D1. Due to the cost of power generation the overall cost of energy for the processes become closer than indicated by the fuel consumptions, typical figures being given in the final column.

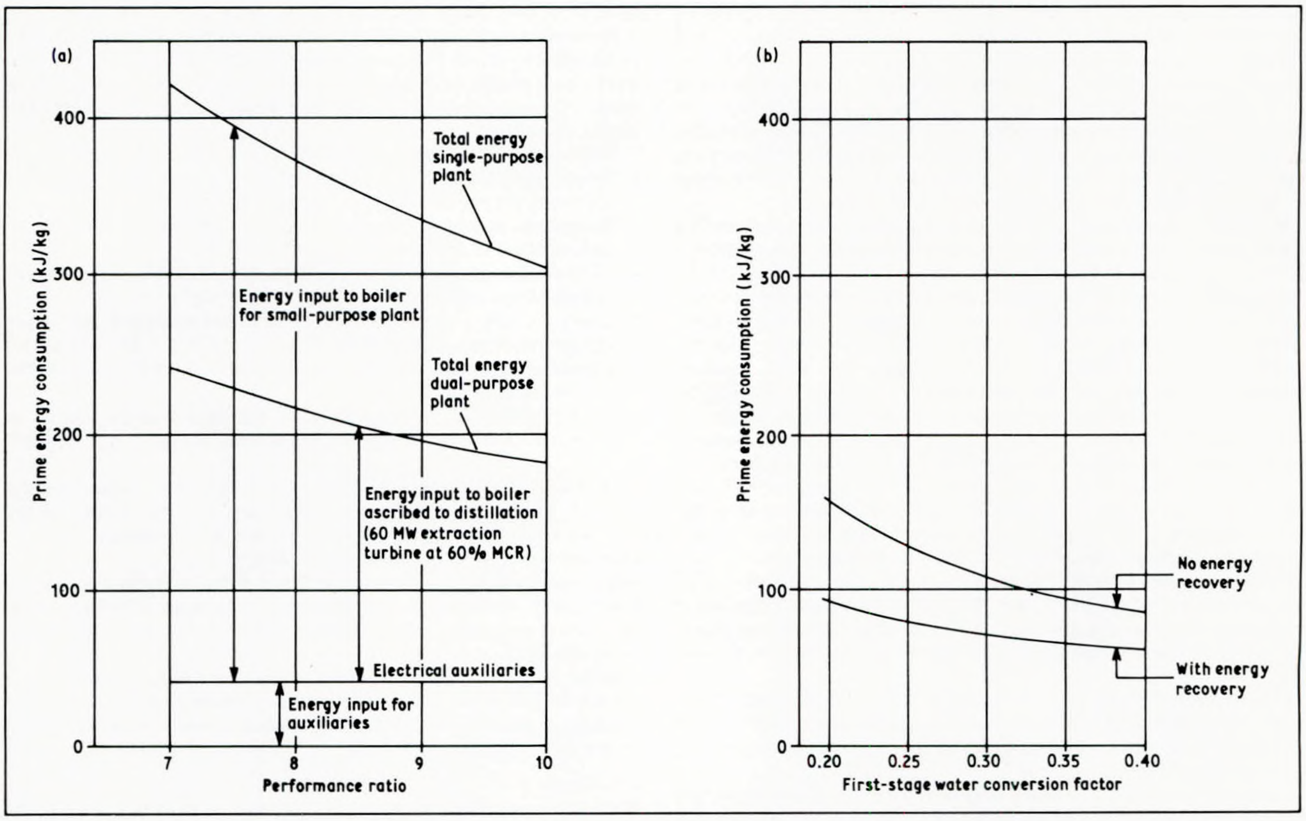

FIG. D1 (a) Prime energy consumption of single and dual purpose MSF distillation plants; (b) prime energy consumption of two-stage sea water RO plant with and without energy recovery

To evaluate the process fully, the costs of other factors have to be taken into account. RO membrane replacement is of key importance and for large plant can be the deciding factor. For small plant sizes, such as used for ships, sea water RO would probably now be lower than distillation in overall cost.

Turning now to chemical considerations, with reference to pretreatment, it would have been helpful if the paper had included a discussion on the mechanism and prevention of calcium carbonate scale formation. Calcium sulphate scale formation is not a problem in sea water RO systems as, due to the low conversion rates, the saturation solubility is not exceeded in the reject brine streams. Calcium carbonate scaling can be prevented by controlled acid dosing using the Stiff-Davis Index to calculate the calcium carbonate saturation solubility in the reject brine.

Adoption of this approach has enabled a major land-based sea water RO plant in the USA to operate at around a 30% conversion ratio without the need to acid dose.

In addition, more than 300 small sea water RO systems are in operation in locations such as oil production platforms. The systems operate at around 15% conversion ratio without acid dosing. It is suggested that, for shipboard application, the use of acid should be avoided on safety grounds and the use of the Stiff-Davis approach enables this to be achieved.

It should, however, be mentioned that this approach cannot be adopted for systems using cellulose acetate membranes. These membranes are subject to hydrolysis at pH values above 7.0 and it is therefore necessary to use acid to control the pH of the reject brine stream.

On the subject of product water post-treatment, the WHO recommend upper limits of 200 ppm chloride and 500 ppm TDS for potable water. Whilst water with a 500 ppm TDS limit can be produced in a single-pass system, the 200 ppm chloride limit will invariably be exceeded.

It is also commented that various national health organizations are recommending that potable water contains a minimum quantity of calcium salts, usually 50 ppm expressed as $CaCO_3$. This is to avoid possible cardiovascular problems.

Assuming that permeate produced by sea water RO contains around 500 ppm TDS, the sodium content would approximate to 400 ppm and the calcium content expressed as $CaCO_3$ would approximate to 6. This high sodium to calcium ratio is undesirable. The calcium concentration can conveniently be increased by the addition of calcium chloride and sodium bicarbonate for pH correction. To enable the resalinated water to have a TDS content below 500 ppm, the TDS of the permeate would need to be below approximately 400 ppm. This again favours a two-stage system.

Table DI: Energy consumption of typical land-based plant

PROCESS	HEAT INPUT (kJ/kg)	POWER INPUT (kWh/m^3)	PRIME ENERGY (kJ/kg)	TYPICAL ENERGY COST (£/m^3)
Single-purpose MSF 9:1 PR	295	3.7	336	0.65
Dual-purpose MSF	155	3.7	196.6	0.39
Sea water RO with energy recovery	—	6.5	72.5	0.17
Sea water RO, no energy recovery		9.8	109.7	0.26

LT CDR J. R. LING RN (Staff of C-in-C Fleet): The authors failed to stress two major attractions of RO for use in a warship environment. First, although comparisons of weight and size have been examined, the flexibility of the RO plant can be used to great advantage when ship stability is a major factor. Filtration arrangements can be reasonably remote or at differing levels to the pumps and membranes. Membranes can also be constructed in varying lengths and configurations. Second, the number of moving parts, i.e. pumps, is drastically reduced when compared with conventional distillation units and their associated steam generators or power supply. This reduces and localizes potential noise sources which, when operating in an anti-submarine role, is highly desirable.

The authors were justly proud of their success in operating plant close inshore using sand filters. Mention was made in the paper of Department of Trade approval for the plants. DOT regulations currently state that these units should not be operated within 20 miles from shore. What actions, if any, are being taken to ensure that these two factors will be compatible and what operating instructions will be given to the users of RO to ensure compliance with DOT regulations?

All membranes currently in use by the MOD are manufactured in either the USA or Japan. What is the present state of research in this country and is it anticipated that membranes will be manufactured in this country in the near future to reduce our dependability on imports?

W. S. WAYNE (Shell International Marine Limited): I have three questions which I would like to address to the authors. First, does their equipment have full DOT approval as outlined in the paper? In other words, could we go out tomorrow and order a reverse osmosis plant from Ames Crosta Babcock for installation on board a UK-registered merchant vessel?

Second, are there any problems associated with, or deterioration of, the element if the plant is shut down for, say, a week or two? Alternatively, are there any special procedures to observe when the plant is shut down?

Third, the authors make brief reference in the paper to chemical cleansing of the element. Could they please indicate what is involved and the approximate time taken for cleaning, say, a 20 tonne/day plant in marine service?

Authors' Reply

We thank Cdr Dean for his comments. On the subject of sand filters, operation of DOT approved desalinators is not allowed within 20 miles of a coastline; therefore the increase in size and cost due to sand filters was not included in Table V. It is our experience that, in coastal waters, sand filters are required and will extend the life of the cartridge filters. For an RO system, sand filters will approximately double the volume of the space envelope and increase the cost by 50%. Other desalination systems will require pretreatment facilities which will also increase their cost and size. We have found that in extremely dirty waters, i.e. Stanley Harbour, sand filters increased the life of the cartridge filters from 1–2 days to 3–4 weeks. This is still a high use of cartridge filters but the waters of Stanley Harbour contain unusually large quantities of colloidal material.

With regard to preheating of the feed water, this will allow a larger output from a plant, subject to a recovery limitation, or the plant size to be reduced for the same output. The economics of the situation are the cost of membranes versus heat exchanger surface. Our experience shows that the cost of extra membranes for operation at low temperatures is less than heat exchanger surface. Using membranes in this way has the added advantage of keeping the plant simple, with only isolating valves required to reduce the number of RO vessels for operation at higher feed temperatures.

To answer Cdr Ranken's comments on water quality, all DOT approved plants must produce water of a minimum quality specified in the World Health Organization Standards for drinking water. This covers both salt and bacterial content. Tests have shown that the rejection in a single-stage RO plant will produce a water of the required standard but, as an additional precaution, post-chlorination is used to safeguard the ship's system.

Cdr Ranken's questions are answered as follows.

1. The most economical pumps for the small flows and high pressures involved on marine RO plants have proved to be triplex plunger pumps. High-speed single-stage centrifugal pumps are currently being developed to suit these flow conditions but are proving to be comparatively inefficient and expensive. The disadvantage of plunger pumps is the pulsating nature of the discharge, which has to be catered for in the design. Plunger pumps have efficiencies of up to 85% and the installed power would be 7.5 kW for an output of 5–20 tonnes/day and up to 33.5 kW for an output of 80 tonnes/day.
2. The maximum pressure allowable on modern elements is 1000 lbf/in^2.
3. In a single-stage plant, efficiently designed, the waste will be 70% of the feed rate. For small plants with only a few elements, this is not always possible and the waste can range from 70–90%. In a two-stage plant the waste will be about 75% of the feed flow, i.e. of the same order as a single-stage plant, owing to the high recovery in the second stage (80–90%).
4. We have discussed the heating of the RO feed water, which adds complications, in answer to Cdr Dean's questions. If heating is easily attained, then the maximum feed temperature is 40°C.
5. For normal operation in clean sea water, i.e. greater than 20 miles from the coast, cleaning will be infrequent. If the plants are operated in coastal waters with sand filtration of the feed, cleaning should be carried out at least once per month. Cleaning of elements is indicated by trends shown in the operating data; i.e. if the applied pressure increases by 10%, then the elements should be cleaned. Well-kept operating data lead to good operation of the plants.

In reply to Mr Burnett, in our opinion, the points that we listed in our presentation are definite advantages over other methods of desalination. For example, lower power consumption, compactness, quick start-up, low maintenance and ease of operation, low capital cost etc. all make RO an attractive desalination package.

Membrane manufacture has now reached the level where consistency can be guaranteed. The element supplier tests each element before shipment and we fully test each plant before despatch.

We have no first-hand experience of plate-type membranes but understand that they are used where heavy fouling occurs and the plates are separated for cleaning. This configuration leads to a low surface area to volume ratio, i.e. the plants are bulky.

The DOT requires all plants with ten or less elements to carry one spare element; fouled elements can operate indefinitely, depending on the nature of the foulant, but at a reduced output. If the foulant is precipitated salts, total blockage can occur but this is rare. Providing the membrane has not been physically punctured, the water quality will be acceptable.

The modern feed additives are of liquid form and make-up is simple and quick. Automation of this is possible but costly.

During a recent test, the noise levels measured 1 m away from one of our Series 20 units was 82 dBA. This was a standard plant without soundproofing.

Typical weights and volumes for RO plants are given in our paper.

In response to Messrs Wade and Heaton, because of the different energy sources it is difficult to compare like with like, but if one goes back to basic principles and calculates the basic power input, the figures given in the paper show the differences.

When doing an overall costing, element replacement costs are important but large plants will have good pretreatment facilities, which will extend the life of the membranes. It is expected that sea water elements will attain the life of brackish elements, i.e. 3–5 years.

The precipitation of calcium carbonate depends on temperature and recovery. Providing these are kept within certain limits, plants can operate without acid addition.

A single-pass RO system with a 99% rejection of salt produces from sea water a chloride level in the permeate within WHO requirements.

To answer Lt Cdr Ling, users should not operate plants within 20 miles of the shore but a Government Committee was formed to study the factors affecting the success of the Falklands plants. This committee, of which Ames Crosta Babcock was a member, formalized guidelines for inshore operation in the Falklands. It is expected that these guidelines will be adopted on a wider basis.

Very little research into the production of membranes has taken place in the UK. It is possible that membranes could be assembled in the UK but manufacture, which requires specialized knowledge and high capital investment, will not be carried out in the UK in the foreseeable future.

In reply to Mr Wayne, Ames Crosta Babcock's Marine Series RO plants are fully DOT-approved for installation on UK-registered ships.

When a plant is shut down for a week or two, the elements can be stored by flushing through with a sodium bisulphite solution and leaving the plant or by flushing the plant with clean sea water each day.

Chemical cleaning involves stopping the plant, making up the cleaning solution, recycling the solution through the elements using the booster pump and flushing with clean water when the flush is complete. This may take 1–2 h.