Technical Section

ENGINEERING ASPECTS OF DESALINATION OF WATER

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Abstract

The importance of desalination in the utilization of water resources has been stressed. The various techniques employed together with the fundamental aspects have been briefly outlined. The technology of the process has been discussed with special reference to materials of construction and design, nuclear desalination, application and economics. The recent developments since 1969 have been touched upon, and 255 references included.

A. INTRODUCTION

The water resources in the world today are quite inadequate with the expanding population and industry and consequent increased requirements. The population is estimated by the UN to double itself to a figure of 7,000 million in 30 years. The amount of water available is over 3.5×10^{15} million gallons (mg) in the oceans, ice fields, lakes and rivers; 2.2×10^{12} mg stored underground, but much of it saline; 3.4×10^{9} mg in the atmosphere; the hydrologic cycle contributes to a negligible portion of the total. Fresh water from natural resources is expected to last only till 2000, the current need being 1.9 million gallons/day (mgd). In the U. S. A. the consumption increases every minute by 25,000 gallons; the present figure is 0.4 mgd, three times that 30 years ago. A deficit of 40 and 290 billion gallons/day is predicted by 1980 and 2000 respectively. The per capita consumption in Moscow will increase in the near future from 92 to 132 gallons/day (gd), as against 5 gd in a primitive society. The quotation from Coleridge is too true at the present time. "Water, water everywhere; nor any drop to drink".

The search for new sources of fresh water surpasses in its urgency both the gold and oil fever and the uranium boom. The Baikal lake in the U.S.S.R. is stated to contain 10 per-cent of the world supply of pure, delicious, fresh, oxygen-rich water, and it is believed that this could be the main source of drinking water to the world population after 2000. There is, of source, the need for even distribution, and projects like the Ganges-Cauvery river link in India will be of considerable help. It is estimated that a bare 2-3 per cent of the world's water resources is drinkable, and not much more is unable for industry. Human beings cannot tolerate continuously in their drinking water more than 2,000 ppm dissolved salts as against a content of 35,000 ppm. (96.5 per cent purity) in sea water, and 500 ppm allowed by the U.S. Bureau of Public Health. According to a recent report only 3 per cent of the Indian population is served at present with piped water supply. It is clear that society is approaching the the dangerous level with respect to water supply and needs.

One has, therefore, to look for alternative methods for processing water for drinking and where necessary for other purposes. Here desalination comes into the picture, and is in reality at the present time amongst the important methods of water treatment. It is recognized that this process becomes attractive when the natural sources are limited or cannot

be exploited economically. At the same time, there are many countries where desalination could be the most economical. A recent UN survey reports 31 developing countries for using this method.

Desalination is known for a long time, as far back as 200 A.D., and distillation is the oldest technique practised on ships. But it is only durirg the last 30 years that it has established itself on a commercial scale for the solution of water supply problems. The largest capacity plants are located in the arid zones of the world.

The demand for desalting plants is growing rapidly in the world. The total installed capacity is now 250 mgd, and is expected to be 600 mgd by 1979. Nine-million-million gallons of saline water will have to be processed in 1975, if the world is to get 10 per cent of its additional water from the oceans. In 1969 there were 852 piants; U.S.A. 286, Kuwait 52, Saudi Arabia 20, Israel 11, Egypt 9, India 6, Turkey 2 and Pakistan 2. The next decade will witness an anticipated increase at 25 per cent per year in their number. Desalination has to be accepted as a standard means of water supply, in spite of the cost. [1-14].

In recent years the problems on desalination are being discussed at an international level, and mention may be made of the following Conferences since 1969 held and planned : (1) Effluent and Water Treatmnnt Exhibition and Convention, London, 1959 ; (2) Twentysecond International Congress CEBEDEAU, Liege, 1969, (3) Symposium on Cheaper Nuclear Power, LAEA, Monoca March 1970; (4) Third International Symposium on Fresh Water from the Sea, Dubrovnik, Yugoslavia, September 1970; (5) Regional Conference on Water Resources Development, ECAFE, Bangkok, September, October 1970 ; (6) International Waste Water Congress, Stockholm, November 1970 ; (7) Seventh Effluent and Water Treatment Exhibition and Convention, London, March-April 1971; (8) International Conference on Earth Resources, May 1971, (9) Fourth International Conference on the Peacefull Uses of Atomic Energy, UN, Geneva, September 1971; (10) UN conference on Problems of the Human Environment, Stockholm, 1972.

There has been an enormous increase in the output of literature in this field, and a large number of publications [15-94] have appeared in recent years-a majority of them from the U.S. Office of Saline Water. The reviews relate to desalination in general [95-97], as well as to specific processes like reverse osmosis [98-105] and others [106-110], and to materials of construction [111-118] An earlier review 119 from this laboratory has discussed in detail the principles and practice of desalination, with special reference to 1968 literature. This paper highlights the developments from 1969 covering the engineering aspects.

B. TECHNIQUES

B. 1 General

Although a number of processes have been developed for desalination in recent years, few of them have been successful for commercial exploitation. In a paper on the thermodynamics of desalination, they have been classified into; (a) those which use thermal energy as major input-distillation ; (b) those which use work energy as input-vapour compression distillation, freezing and reverse osmosis. The energy requirements have been discussed n detail for each. The free energy difference between sea water and its separate constituents in standard states is 2.8 kJ/kg. of water, and this is the energy requirement in an ideal reversible process of separation [11]. Another categorization is into those which (a) Aeparate water from salt-evaporation or distillation, freezing, inverse osmosis and solvent extraction ; (b) separate salt from water-electrolysis, adsorption, ion exchange and controlled diffusion [120]. The basic processes are described, together with the recent developments and fundamental aspects.

B. 2. Distillation

B.2.1. The Multi-Stage Flash (MSF) Distillation process is based on the evaporation of saline water and condensation to yield pure water. Heated brine is introduced in open channel flow into a chamber under reduced pressure. Some of the water evaporates immediately (flashes), and is condensed on tubes cooled by the feed sea

water flowing towards the steam-heated heat input section. A series of such chambers (or stages) at progressively reduced pressure forms the plant. The feed sea water increases in temperature as it passes through the condenser tubes, in the opposite direction to the flashing flow, towards the heat input section. The condensed steam is collected on trays below the condensers and is pumped out of the plant as the product water. The only heat input to a conventional MSF process is at the high temperature end[17].

This is the most successful and widely used method, particularly for large-scale desalting of sea water. One of the important problems here is scaling; in tubes carrying brine this reduces the heat transfer coefficient and consequently the plant capacity. Some additives are employed to minimize the scaling; the temperature limit in the distillation plants is about 121°C[12]. Surface potential is shown to be a pertinent variable in scale formation, and is of significance in controlling the same[86]. The present state of scale control in sea water evaporators has been reviewed[121] An improved MSF process has been described for the production of over 6 mgd of product water, without additional heat cost or plant cost/unit of product[122]. The results of research on heat transfer and fluid dynamics during desalination by multiflash distillation have been reported[123]. The augmenting of a water supply system by the use of distilled water from sea water evaporators has ben discussed with reference to the experience in Kuwait with MSF and electrodialysis[124].

B. 2. 2. In the **Multiple Effect-Long Tube Vertical (LTV)** method, steam is used to evaporate some of the sea water in the first effect. This vapour then condenses in the second, lower temperature effect, and evaporates additional water. The process is repeated for each effect. In the LTV system, evaporation occurs as hot sea water flows downwards inside vertical tube bundles surrounded by steam. The sea water boils on the inside surface of each tube, and the steam generated passes to the next stage, lower pressure effect, to heat the incoming feed and to condense on the outside of the tube bundles forming the product. Scale forms very rapidly in the first stages if the temperature rises much above 120°C. Although the capital cost per unit output is greater than in MSF, this system, which may have up to 17 effects, is probably the most successful evaporator of this type[17].

In a recent patent, waste heat from a turbine generator has been used to heat a series of cells containing sea water in a multiple evaporator effect manner. An external pump provided for the reduction of pressure in the cells. The vapour was condensed to fresh water and a portion was returned to the turbine[125]. The "module" approach is adopted in developing a mathematical model and computer programme system; multistage evaporator process simulation, engineering design simulation, capital and operating cost calculation, and optimum searching processes. It is demonstrated that for a specified production capacity, an optimum design of a vertical tube evaporation desalting plant can be directly and automatically generated[126].

B.2.3 In Vapour Compression Distillation, steam generated from boiling brine is mechanically compressed to increase the vapour pressure and temperature. It is then fed to the stem side of the evaporator tube bundle, where it condenses to form product water and in doing so evaporates more brine. Capital costs have to cover compressors which can handle very large volume of steam together with heat exchangers to raise the feed water, which is not pre-heated by the system, from its normal intake temperature to about 95°C. It operates successfully in small sizes upto 0.12 mgd as in ships[17]. Distillation utilizing a vapour compression and an immiscible liquid-solid medium has been described. Metallic transfer surfaces, high-temperature differentials and scale problems are avoided. Energy requirement is 1/7 to 1/12 that used in conventional distillation[127].

A conventional vapour compression system is analyzed thermodynamically and economically by the concepts of energy and internal economy. Optimum results, for usual electrical energy costs, favour a high thermodynamic efficiency for the compressor, evaprator, condenser and main exchanger. The optimum design depends on economic factors: cost estimates have been made[128].

B.2.4. The **Solar Evaporation** Process generally involves direct-

ing the brine into large shallow pans or troughs which are covered with transparent glass or plastic sheeting tilted to horizontal. The vapours formed by the action of the sun condense against the covering and run down into collecting channels. It is not effective for large scale production, and is more suitable for hot areas with adequate sunshine and access to saline water[12]. A report from Greece states that this is a cheap process, and its efficiency can be improved substantially if rain water can be collected from the roof of the plant [129]. The solar-heated column still is stated to be particularly suitable for the recovery of usable, fresh water from sea or brackish water, simple to construct and operate, and relatively inexpensive [130]. The humidification– dehumidification technique has been developed for water desalination in the arid zones of India. This is the solar - powered method, and is suitable for fresh water needs in millions of gallons [131].

B. 2.5. Miscellaneous Optimization procedures with electronic computers have been described for desalting by distillation[132]. Feedforward control application to a heat exchanger has been described, together with the economic advantages and use in distillation desalting [133]. A modified heat exchanger whose partition composes one membrane permeable and one impermeable to water vapour, and intermediate vapour space is stated to be suitable for desalination by thermal hyperfiltration; the thermal efficiency is high[134]. The sonic distillation process can be used in desalination [135].

B. 3. Freezing

B. 3. 1. General The presence of salts in water depresses its freezing point. Average sea water freezing temperature is about -2°C, which is further reduced by increasing salt concentration. This temperature difference is utilized for production of fresh water from brine. On freezing the brine to the pure water freezing temperature, the pure water freezes out leaving the salt in the solution.

B. 3. 2. In Vacuum Freezing, cooled saline water is sprayed into a vacuum chamber held at an absolute pressure of about 3 mm. of mercury. Part of the water flashes into vapour, removing heat from the remainder to do so. Since this is already close to the freezing point, ice crystals form. The resulting slurry of ice and brine is taken to a washer-melter where, washed of their brine coating, the ice particles yield fresh water. The water vapour from the vacuum chamber passes through a compressor to the washer-melter to provide the heat for the melting process. The method is suitable for small capacity plants - less than 1. 2 mgd, particularly for conversion of scale - forming brackish waters.

B. 3. 3. The Secondary Refrigerant Process uses a liquid hpdrocarbon refrigerant such as butane-which will not mix with water, and is vapourized in direct contact with saline water by heat transfer from the water to the butane. The cooling of the pre-cooled feed water causes ice crystals to form, thus producing ice-brine slurry. Care must be taken to strip the product water of all traces of butane so that taste problems and explosion hazards are eliminated. Desalting by liquid hydrocarbons and a mixture of propane and butane has been reported [136]. A mathematical treatment has been presented for the relation between crystallization temperature and equivalent concentration of solution during freezing with butane [137]. A combined refrigeration unit and sea water desalination still have been described [138].

The freezing process has the advantage that its theoretical energy requirement is lowcompared to distillation, and there is no scaling problem. But it requires a more expensive form of energy for the production of refrigeration, and the water purity is not as high. Washing of ice crystals to remove impurities is a problem, and this reduces fresh water recovery[12].

B. 4. Electrodialysis is the chief process extensively used for commercial, land—based application, apart from MSF distillation. It utilizes the selective property of some membranes in allowing the passage of either positive or negative ions only. They are used in alternate layers, with a gap in between, in large chambers. The brine solution passes through the channels between the membranes while direct, low voltage current is passed across the membranes perpendicular to the current used. The most efficient design cells for reduction of concentration polarization at the high current densities used, resulting in a decrease of current efficiency and a possible deposit on scale.

Current reversal or other techniques are used in this connection, but even then the current densities cannot reach the economic optimum. In addition, there is the problem of membrane fouling.

This method is not economical for sea water, but has been applied to brackish water with a salinity level of up to 5,000 ppm. The fresh water produced contains about 300 ppm salts, which is all right for domestic use. Due to the low conductivity, which increases the energy requirements, electrodialysis is seldom used for the production of water of high purity.[17]

A bench-scale high-temperature unit has been operated sucessfully on sea water upto 70° [139]. Multiple — cell electrodialysis using positive and negative ions recombined has been reported [140]. For the acidification of the feed streams to desalination plants, an electrochemical system was developed, combining fuel cell and electrodialysis technology. The power requirements for the cell are quite modest, about 0.5 kwh/1,000 gallons (thou.gal.) for the acidification of sea water to a level of 100 ppm, and the device is readily adopted to automatic operation[141]. A hydrodynamic theory of demineralization by electrodialysis was developed for a multichannel system with steady laminar flow between plane, parallel membranes. An equation has been derived, and comparison made between the experimental and calculated values of the total current[142]. An analog of this process has been made by considering it as an electrical network composed of resistive elements representative of various electrochemical subprocesses. The importance of ohmic scale polarization is emphasized and predicted by an empirical equation. The average calculated values for the six stages of these plants agree to within 94 per cent of the average measured [143]. The critical parameters of electrodialyzers during water desalination have been estimated[144].

B. 5. Reverse Osmosis is theoretically most attractive, and depends on the properties of certain semipermeable membranes which, when used to separate water from a salt solution, allow fresh water to pass into the brine compartment under the influence of osmotic pressure. If a pressure in excess of this value is applied to the salt solution, fresh water will pass from the brine into the water compartment. Energy requirements should approach the ideal minimum, and the latter is the energy required to pump the feed water to the osmotic pressure. In practice higher pressures are used, from 42 to 105 kg/cm² for water with 5,000-35,000 ppm dissolved salts; the flow rate of product water will be, inversely, from 264 to 132 gd/m² of the cellulose acetate membrane[17].

The main problem is to develop membranes which are mechanically strong, transmit adequate volumes of water while repelling salt and are not too expensive. Difficulties in developing plants of any size have chiefly been with membrane supports and high pressure pumps, as well as membrane clogging [145]. Infrasonic activation of the membrane increases the flow of pure water and miminming the tendency for clogging. Here an external and nonattached source of directional low-frequency vibrational energy in the range 1—16 and up to 500 Hz is applied to the salt water side of the membrane at the interface with sufficient intensity to cause turbulence and friction within the interface[147].

The membranes are highly selective and give a yield of 150 gallons/m² of water per day when operated on a 5 weight per cent sea water brine. In actual operation salt rejection with cellulose acetate is 96—98 per cent, as against the predicted value of 99.7 per cent. Two more papers refer to this membrane[147], [148]. Other membrane materials include Teflon and methyl methacrylate [145], polyhydroxy ethyl methacrylate[149], polyacrylic[150] and grafted[151]. Membrane constants for water transport could be increased or decreased as a result of grafting-styrene to cellulose acetate[151]. The structure[15] and efficency[152] of membranes has been discussed. There are references to the structure and properties of membranes cast from binary solutions[146], and semipermeable membranes from polyamides[153].

Concentration polarization in reverse osmosis under natural convection has been investigated for a case in which the desalination membrane is a vertical flat plate. An equation has been derived to predict the polarization effect at any point along the membrane[154]. It is shown that the polarization can be controlled with small expenditure of energy in laminar flow and thin channels for membrane permeation fluxes

up to 63 gal/ft²-day and a fractional feed water recovery greater than 50 per cent[157]. Concentration polarization moduli have been examined in laminar and turbulent systems, and compared with theoretical developments[56].

In the operation of a reverse osmosis unit using a plate and frame single pass system, a representative set of the data was subjected to statistical analysis by fitting regression models to predict product-quantity and product-quality responses. The modes adequately summarized the data and provided a means of evaluating the significance of changes in the process variables[158]. The non-linear diffusion problem relevant to this process has been studied, and the theoretically predicted membranes fluxes are shown to be in reasonable agreement with the experiment[159]. Transport phenomena in reverse osmosis has been studied[160].

B.6. Ion Exchange is a promising method of treating brackish waters with up to 3,000 ppm dissolved solids. The water is passed through a bed composed of a special resin mixture which removes the salt. After a time the bed becomes spent and has to be regenerated by chemical treatment, and the cost of regeneration limits the process to low salinity waters. The technique of 1-bed deionization, in which cation and anion exchangers are mixed, has several advantages over the conventional 2-bed systems; it is used for water with a maximum salt content of 2,000 ppm[161].

There has been a recent trend in the U.S.A. for revival in consideration of this technique due to the development of high-capacity ion exchangers and ingenious methods for efficient use, recovery and reuse of resin regenerants; introduction of exotic, non-resin, ion exchange techniques. The Desal, Sul-bi-sul, Sirotherm and Continuous Ion Exchange processes have been cited[162], as also the Desal in Japan[163]. The second process has been employed for the construction of a 0.5 mgd plant in the U.S.A. for the desalination of brackish water to supply water for municipal and industrial use. The continuous counter current ion exchange method will produce water with 150 ppm from mine waste water with 1,500 ppm dissolved solids[164]. Technical studies have been made for the automatic control of ion exchangers in complete desalting units through conductivity difference measurement[165].

B.7. Others Amongst other methods, mention may be made of the Hydrate process, wherein separation is not easy. A potential method of desalination involves extraction at low temperature using triethylamine[166]. Equilibrium and kinetic tests, with the thermosorb process, indicated that activated carbon beds are comparable to ion exchange resins regarding effective capacity/weight of sorbent, and are superior with respect to initial cost and durability[67]. Sea water containing 3.5 per cent sodium chloride has been converted to potable water with 0.2 per cent chloride by column crystallization with a pulsating spiral[167]. The magnetic method depends on concentrating ions in certain regions by use of a magnetic field, followed by removal of relatively purer water in the remaining region: removal of 15-92 per cent of ions from 3.5 per cent sodium chloride, with a flow rate of 33 g/min[168]. A paper from the U.S.S.R. outlines the standard plans for the chemical purification of water for a 2,400—3,600 MW electric power plant[169].

New processes for desalting brackish water have been mentioned, including applications and costs: (a) use of a high-capacity weakly basic ion exchange resin, IRA-68; and a second unit containing IRA-84, a weak acidic cation resin; (b) the sul-bi-sul process, using a special anion resin; (c) freezing compression, (d) direct contact freezing and (e) hydrate formation[170].

Electrolysis, reverse osmosis, ion exchange, vacuum freezing and vapour compression distillation are applicable at total dissolved solid levels of 4000, 4000, 4000, 5000 and greater than 8000 ppm respectively. MSF and multi-effect falling-film evaporation are most attractive for sea coast locations, since large amounts of cooling water are required[171].

C. MATERIALS OF CONSTRUCTION

C. 1 General The selection of suitable materials has an important bearing on the economics

and usefulness of equipment used in desalination. Tubing requirements alone are stated in terms of thousands of miles, and with the cupro-nickel alloy commonly used the heat exchange devices account for 40 per cent plant investment. The material should be resistant to corrosion, or a cheaper one might serve the purpose with process modification. It should lend itself readily to modifications in tube mill production, new designs-particularly for better heat transfer, and new assembly and construction techniques. Further, the plant should not be out of service for overhaul and repair to meet the continuous water supply needs, and operate for long periods-30 to 50 years, before replacement. It is obvious that desalination plants can supplement fresh Water supplies, only with the availability of proper materials at competitive costs. One should, therefore, look for improved metals and alloys, fabrication techniques, inspection procedures. reliability and adequate corrosion data. The situation with respect to copper-nickel alloys, aluminium, steels, titanium and others up to 1969 has been discussed in detail in a previous paper [19,119].

C. 2. Copper-Nickel Alloys Monel alloy 400 has been used for a compact desalinator for small communities with no other source [172]. In Holland, a flash distillation plant with an output of 6 mgd has been put up [173]. A third paper relates to the improvement in the plant efficiency and reduction in capital costs by the use of demisterspads of Monel 400 mesh which separate the distilled water vapour from entrained droplets of sea water. The output is 1 mgd in Kuwait [174]. Water boxes made of mild steel are protected from corrosion in desalination plant by a thin lining of 90/10 coper-nickel Spot-welded in position [175, 176]. The large flash evaporation units of the desalination-power generation complex on the Scheldt estuary in Holland are described with special reference to the extensive use of nickel 10 and 30 alloys to meet the corrosive, erosive and pollution conditions [177]. The majority of the plants in the world are based on these two compositions, with some additions like iron and manganese to improve the corrosion and erosion resistance [116, 120]. Recent experience with copper alloys in desalting environments has been described [178].

C. 3. Aluminium. has met strong competition from copper-nickel and titanium, and for structural purposes from carbon-steel. An all-aluminium American plant operates on the Brown process, at temperatures well below the conventional MSF figure of 250°F. Pilot trials were successful over a four year period, producing up to 10,000 gd of fresh water. The aluminium pipes, valves and tubing were free of scaling, corrosion or erosion damage. The metal is relatively cheap and plentiful, and the new process could be a breakthrough [76, 179]. It has been used in the wiped-film evaporator, for all parts in contact with the fluid [81]. If aluminium plants turn out to be feasible, the result will be cheaper water and a stimulus for the building of flash distillation units in relation to competition from other water sources. India should think of aluminium while put up desalination plants.

C. 4. Others Four-year tests have been made in the U.S.A. with **titanium** tubing, to obtain alloys suitable for desalination service at 250-350°F. An alloy with 2 per cent nickel appears most promising. The cost of the tubing is declining at the rate of 10 per cent/year, and it will, therefore, continue to replace copper tubing in those areas whose high corrosion failures have been reported. It is estimated that 3.2 million feet of titanium tubing is presently in service under hot-brine conditions [180].

The corrosion performance of **Stainless Steels** in distillation-type desalination plants is excellent under certain conditions; the water/brine should be oxygen-free. Potential measurements are found to be useful for evaluation, and types 304 and 316 are promising [114]. Another material is aluminium brass, containing aluminium 1 and zinc [120] 21 per cent and balance copper.

C. 5. Testing. The behaviour of materials has been tested for corrosion in desalination ; copper base alloys, stainless steel, nickel chromium-iron alloys, and other nickel-alloys [175]. Similar studies have been made in brines and saline atmosphere, with zinc, mild and stainless steel, copper, brass, bronze, Monel and aluminium. Atmospheric salinity

and wind direction should be considered in locating the plants[181].

The corrosion resistance of 14 copper and its alloys has been studied over a two-year period, under conditions simulating the brine heater section of multi-effect, multi-stage flash desalination plants. Data have been collected for velocities of 4, 18 and 16 fps at 121°C [182]. The performance of aluminium 2 and zinc 20 has been compared with cupro-nickel 10 in sea water. For aluminium brass tubes through which passes aerated sea water at less than 50° or degassed brine at less than 120°, it would be expected than the plant life would be 20 years with a water velocity of about 1.5 m/sec.[183]

The corrosion of carbon-steel in distillation-type installations has been studied in Caspian sea water, with respect to effect of temperature or agitation, deoxygenation and water composition, and contact with copper alloys or stainless steel [184]. Phosphate-chromate mixtures are reported to be effective for the inhibition of mild steel corrosion under desalination conditions[185]. The performance of stainless steel has been evaluated in a test programme for a 3,000 gd plant [186,187]. Tests have been designed to determine the effects of process variables on aluminium alloys for desalination service [188]. The means and prospects of developing a structural concrete to replace the alloys generally used for the construction of sea water distillation plant are reviewed. The hydraulic binding agent and aggregates can be selected on the basis of half-static corrosion tests in brines at up to 150° [189].

The relative resistance of alloys, from binary iron-chromium to multi-component based on molybdenum addition, to pitting corrosion in deaerated synthetic sea water, at temperature up to 250°F, has been evaluated on the basis of critical pitting potentials obtained from anodic polarization measurements. The best is a quaternary iron-chromium-molybdenum, with small amounts of manganese, cobalt, nickel and/or copper; this designed for use as condenser tubes in MSF evaporator desalination plant[85].

D. DESIGN

D. 1 Distillation Various types of plants have been set up in different parts of the world, and details of their description with illustrations are available. They range from very small units, from about 50 gd to 12 mgd: beyond this figure it would not be economical. A multiplicity of units, in large plants, adds to the flexibility; it allows one or more units to be shut down for maintenance or where full output capacity is not required. It is also the maximum size which will allow performance and costs to be reliably predicted.

Distillation plants have their own boiler and ancillary equipment-pumps, evaporators and control, in the absence of a cheap source of heat at the site. This is the case with one-piece "packaged" assemblies for marine use. They can be shipped in, coupled with hoses if necessary to a sea water supply, to produce fresh water within a few hours of arrival. These MSF units are in the range of capacity from 4 to 14 thou. gal./day. Limited to a few stages, they possess a much lower gained output ratio (GOR) than do the larger permanently sited installations. Here the designs may be more reliable and trouble-free than those with higher GOR. Higher reliability, reduced down-time and lessened operator and maintenance involvement can offer a better practical system at an overall lower true water cost. The research and development work to improve the design and overall economics has been described earlier [119].

The Babcock desalination has been designed primarily for use in conjunction with a diesel engine, using the waste heat from the engine cooling water; or low grade or exhaust steam; or with an electrically heated boiler [172]. The MSF process is noted as the first successful scale free design, but recent development in the multiple effect, falling film design has demonstrated that this hardware can also be operated scale free. What is needed is proper equipment design and process control[23]. The design and operation of large desalting plants has been described, based on the experience of Westinghouse Electric International Co. The first plant was built in 1957 in Kuwait; this was followed by a 1 mgd flash distillation unit in 1961 at Point Loma, near San Diego, California. Flash evaporation proved to be the most economical for large units. Two new features were incorporated in the Guantanamo Bay plant for

U. S. Navy needs in 1964 : thin-wall tubing was used for the first time, with less capital cost, and the dual-purpose nature resulted in optimized fuel efficiency. Titanium tubing was used for a 1.5 mgd plant during the next year at St. Croix in the Virgin Islands ; there was no corrosion in three years operation. In 1967 a 1.4 mgd unit was put up for U.S. Steel Co.[100].

The design and economic study of a single-purpose, gas - turbine powered vapour compression plant for evaporation (VTE) of sea water in the U.S.A. has been discussed in detail. The tube bundle here utilizes 90/10 copper-nickel ¾ inch O.D. double-fluted tubes[101]. In a vapour decompression apparatus for water desalination in Australia, the boiler is constructed of copper—silicon—manganese bronze. A 12-gallon capacity system with a 6 inch stroke x 6 inch bore compressor driven by a one H. P. motor distils 50 gd of sea water per day. It is compact, uses heat input efficiently and requires little maintenance[102]. A power plant is described having the dual-purpose of supplying power, in the form of mechanical or electrical energy, and producing fresh water from salt water. It includes a gas - turbine engine which drives a generator, a spray chamber through with the turbine exhaust gas is passed and into which salt water is sprayed, and a condenser cooled by the salt water to condense fresh water from turbine exhaust. The operation is not complicated, and no high temperatures or pressures are involved. Such a plant may be highly useful for supporting settlements in arid sea cost regions[103]. The design and operation of plants with stainless steel has been outlined [114].

D. 2. Reverse Osmosis. The design and construction of a 2—stage 2,500 gd unit has been described. The first and second stages are operated at 1,000-1,200 psig and 650 pig to produce a product containing 3,000—5,000 and less than 500 ppm dissolved solids. The most effective membranes were fabricated from solutions consisting of cellulose acetate formamide, pyridine and acetone. A 3—module test bed was set up and operated for one month, during which the flux remained relatively constant at about 10 gal/ft²/day with an average salt rejection of 90 per cent[54]. A reverse osmosis module for low—pressure, laminarflow has been developed. The first of its kind, it uses two concentric cylinders, with Eastman membrane on the outer surface of the inner and on the inner surface of the outer cylinder. The laminar brine flow channel between membranes is only 0.05 inch - without spacers, minimizing concentration polarization and prolonging module life. It is designed for use as a home drinking water purifier, up to 3 gd, for areas with high-salt water supply and will retail for $ 130 in Southern California stores.[104]

Equations have been developed for stage-wise reverse osmosis process design, based on the Kimura-Sourirajan analogue of the data water and solute transport through the Loeb-Sourirajan -type porous cellulose acetate membranes. The cascade theory is applied to the multi-stage process [105].

D. 3. Others An improved design for **electrosorption** stacks and methods of making electrosorption membrances has been suggested. The estimates indicate that the cost for demineralizing water with low total dissolved solids and high hardness by this method compares with electrodialysis ; it is less for water with high total dissolved solids and low hardness. The design and operation for corrosion control of a desalination plant in Peru has been described [106].

E. NUCLEAR DESALINATION

Nuclear energy has been recently used as the heat source for the economic production of fresh water by distillation, together with electrical power ; this is the duel-purpose system. In the U. K. a plant with a capacity of 30 mgd is under design by the Atomic Energy Authority - adequate to meet the needs of a city like Sheffield. The Advanced Gas-cooled Reactor (AGR) is coupled to a conventinal MSF plant in three integrated units, each yielding 10 mgd. A scheme has been worked out for a reactor producing 200 MW of power and 83 mgd of fresh water from 8 flash distillation units. The prototype System Generating Heavy Water Reactor (SGHW) began operating at Winfreth Health, West England from 1967, and is now working to its full power of 100 MW. Specially developed for versatility in size, it boils water in pressure tubes from the heat of fission ; heavy water is used as a moderator. It

produces steam at a lower pressure than the AGR - also being considered on dual-purpose plant, and more water for a given power output [14], [119].

A dual-purpose plant was designed in the U. S. A. for the production by 1971 of 150 mgd of desalted water and 1,800 MW of power, on the basis of a feasibility study covering the important engineering and economic aspects. The total investment was estimated to be $ 357 million. In view of the exorbitant costs, this project at Bolsa Island, Southern Califorcia has since been given up. [197], [198]. The economic potential of this process by the coproduction of industrial chemicals and fertilizers has also been studied.

The ORNL of the U.S. Atomic Energy Commission proposes a closed-cycle process for removing the scaleforming elements from sea water prior to its entry into the evaporation section of the plant; this appears to be practical on technical and economic grounds. In the 1,000 mgd plant, sea water is descaled 0.01/thou. gal. of fresh water, competitive with plants employing sulphuric acid treatment. Such a plant could be a joint undertaking, the utility company producing power and fresh water, and another marketing the byproduct chlorine and hydrogen. It could be particularly attractive in the U.S.A., in view of the expansion rate of 10 per cent per year for the chlorine market. With some modifications, products like magnesium, ammonium nitrate, sodium chloride, bromine and iodine can be obtained [199].

A fast neutron nuclear installation in the U.S.S.R. has been described for the production of 5×10^5 kw electricity and desalted water. The methods for prevention of scale formation are given, together with the operating parameters [200]. The design and performance of a nuclear industrial desalination plant with fast neutron reactor at Shevchenko has been discussed [201]. A review has been made of cost studies on nuclear reactor systems that both generate power and desalinate sea water. Vapour compression combined with MSF distillation promises great flexibility and potential economy, but considerable development of large-scale compressors is required. Limitations of the water/power ratio for gas-and water-cooled reactors are considered, together with the extension of the ratio by combined work/heat dual-process methods [202].

A recent design study refers to a 3962-MM (t) heavy-water organic-cooled reactor coupled to a 750 mgd desalination plant; the feed water is heated with MSF evaporation. It is designed with a gain ratio of 20.4 lbs of product/1000 Btu, and a maximum brine temperature of 250°F. The primary advantage is high thermal performance, without high brine temperatures or very low temperature differences. The back pressure steam turbine, in combination with the vapour compression cycle, is an effective method of utilizing prime steam in a high water/power ratio plant. [191]

Another paper from U.S.A.E.C. refers to the "nuplex" concept (dual-purpose) : use of nuclear reactors to provide heat to desalt water in evaporators and to drive steam turbines. Generation of low-cost electrical power would contribute to the nuplex's economic viability through production of fertilizers, basic chemicals and metals [203]. The effect of low-cost nuclear energy on the chlorine-caustic industry has also been discussed. It is pointed that in large industrial complexes, such plants can be used to produce hydrochloric acid to treat the feed to desalination plants producing fresh water [204].

Sea water desalination plants associated with a natural uranium gas-graphite type nuclear reactor and operating with different distillation processes have been reported from France [205]. Nuclear desalination has been dealt with in four other papers from Austria [206], U.K., [207] and U.S.A. (with breeder reactors) [208], [209].

Nuclear energy at low cost is the answer to the increasing power requirements of India. The total power generation capacity in 1970 is estimated to be 15.5 million kw, as aginst 2.5 million kw in 1951; the estimate for the decade beinning 1975 is 60,000 MW. The uuclear power station at Tarapur started functioning in 1969 with a capacity of MW; 105 stations in 15 countries produced 20,000 MW. Rana Pratap Sagar and Kalpakkam projects are expected to produce 400 MW each by 1971 and 1973 respectively. One new station of 500 MW is expected to be installed every year all over the world beyond 1972-1973

and research work is being carried out on fast breeder reactors (as in Kalpakkam using plutonium) in the U. K., U. S. A., U.S.S.R., W. Germany and France. In the long-term analysis, however, India's interests are linked with thorium [210], [211].

It is obvious that nuclear desalination should be taken into consideration in this country while putting up large-sized desalting plants, particularly near the seacoast regions with plans for agro-industrial complexes. A detailed article outlines India's economic and technological plans to utilize nuclear energy to provide water, power and fertilizer. The different types of plants-single and dual-posepur and their operation have been discussed, with special reference to the U.S.A. A case has been made out, with all details, for a dual-purpose plant at Bombay with an output of 100mgd [212]. Such projects should, of course, be thought of with a good deal of caution, in view of the American experiment.

F. APPLICATIONS

F. 1. General The large-size plants are located in the arid areas, and a list of 25 units is available with respect to location, capacity, type and manufacturer [12]. As of the beginning of 1967, there were 656 plants in operation[210]. distillation 635, electrodialysis 20 and freezing 1. Flash evaporation is used by the majority of the distillation units.

F. 2. Distillation The aluminium pilot plant set up in North Carolina, U.S.A. with a capacity of 50,000 gd has good heat transfer qualities at half the cost of competitive materials, in addition to savings on weight. The mobile unit used by the US Armed Forces have 32 units costing $ 0.5 million, each with a capacity of 150 gal./hour[179]. An installation under construction in Holland is a combined desalination and electrical power plant. The multiple effect flash evaporation has a capacity of 8mgd at maximum temperature and the power plant 25 MW. There are 2 units, 35 heat recovery and 3 heat removal stages; 8 compartments assembly with a maximum brine temperature of 120°; heat consumption 50 kcal/kg water; water/steam ratio 10.5 The brine is partially recirculated, and a good part of the distillate will be used immediately as high-quality industrial water. The total cost of the project is 35 million florins [214].

The effect of water production, water/current ratio, electrical energy requirement of pumps, and steam operating temperature on the cost of desalination plants operated in conjuction with conventional power plants with oil-firing and steam turbines, nuclear power plants with compressed water reactor and saturated steam turbine, and nuclear power plant with high-temperature reactor was studied; the basis was a model plant producing 128 mgd of water and 250 MW. The optimum steam operating temperature was 130—40° for conventional power plants, reactors with gas turbines and reactors with saturated steam turbines having a capacity equal to or greater than 39 mgd of water, but 83° for reactors with steam turbines and 13 mgd. Reactors with saturated steam turbines had the lowest energy requirement and water capacity; the former increased considerably above 140° for gas processes. Both variables were highest for gas turbines [216].

In Key West, Florida water was being pumped for the City from the US mainland through a 130 mile pipeline, with a capacity of 6 mgd; this was insufficient to meet its needs and that of the navy. The cost of constructing another 130 mile pipeline was found to be greater than that of a modern desalting plant. The 2.6 mgd flash distillation plant (single purpose) - on a 3.3 acre site costing $ 4 million, produced its billionth gallon of desalted water in February 1969. Large plants provide reliable service for 35 years or more [190].

A typical nuplex has two nuclear power plants with a capacity of 2,000 MW (e), combination of flash and vertical tube evaporators, farm land of 0.3 million acres; aluminium refinery, ammonia synthesis plant, phosphorus furnaces, chlorine-caustic and magnesium plants; intensive fish culture: In addition to power which costs 5-6 mills/kwh, it produces 1 billion gd of fresh water perennially for irrigation. Rice cultivation at a desalted water cost of $ 0.30/thou. gal. would be competitive with the world price of rice delivered in Asia. Wheat production may also be feasible if the cost is reduced to $ 0.20/ thou. gal. Waste sea water used as a coolant for evaporators might be used as

a source of warm water for aqua culture[208].

A recent patent describes sea water evaporation in fluidized bed heating medium can be low-value steam at 40 psi, steam at 250 psi or sodium potassium coolant from a breeder reactor. A 1. 1 mgd plant with 4 beds, 20 ft diam x 20 ft high with 17,600 ft² or 3520 tubes each in diam x 20 ft long, are used. The heat transfer tubes occupy 7 per cent of the vessel volume, and the steam vapour velocity is 2.5. ft/sec. The four respective steam temperatures from the beds are 230, 193, 156 and 120°F. This produced 0.31, 0.29, 0·26 and 0.24 mgd from the four beds.[216].

A water desalting scheme that conserves energy by combining reverse osmosis and distillation (flash evaporation) units in parallel promises low costs for high capacity plants. This is the Duo-Cycle process developed in the U.S.A. The sole energy source here is high pressure steam. First it expands through turbines to drive high pressure pumps that feed water to the reverse osmosis plant; then the turbine exhaust steam provides heat for the distillation unit. The two outputs are blended to produce potable water at 131 mgd. A conventional MSF plant operating on about this much steam would be able to produce only about 50 mgd. Another recent paper refers to this system, as well as to some of the large plants: Soviet project on the Caspian Sea, French plant under construction in Kuwait and the third in Tijuana, Mexico with a capacity of 30, 25 and 7.5. mgd. respectively [218]. Solar stills have been proposed to Provide drinking water at Puerto penasco, on the arid Mexican shore. The system gives promise for providing power, water and food for people living on desert sea coasts. Wasted heat from a diesel engine is used to pump sea water into the system; this is converted to energy to evaporate sea water[219].

F. 3. Other Processes The cost of **reverse osmosis** plants is less than that of flash distillation units, and this technique may bring a new era of dramatic cost reductions (not for large plants): it is promising for brackish water [190]. These systems are extensively used in the US electronics industry for the production of ultra - pure water[220]. A demineralizer with a capacity of 7 mgd was used for 15 years with one change of resin; this sparks interest in the **mixed-bed** process[221]. Potable - water - 120 ppm salts and 12 ppm hydrocarbons, and saturated brines are produced from saline waters by single-stage **extraction with liquid hydrocarbon** at 650° F and 2,600 psia; the vessels are constructed of high—strength steel lined with titanium. The proposed plant has heat exchange towers up to 18 ft diam x 24 ft height[222]. Surplus water in the water system of a 300 MW powerstation in the U.S.S.R. has been demineralized on units with a capacity of 1 mgd.[223]

F. 4. Other Applications The secondary applications for desalination are for treatment of **brackish waters; specialized industrial uses; pollution control,** where reverse osmosis is most promising, and MSF and electrodialysis can also be used — but concentrated waste disposal is a problem[179]. To ease the water pollution problem, 2 mgd of waste water, from Solvay-process soda ash plants and containing 800 tons of calcium and sodium chlorides, has been proposed for desalination to water for municipal or industrial use. The waste recovery in the dairy industry could generate a $ 250 million market in desalting equipment. There are 2,000 metal — plating plants in the U. S. A. that could each use $ 25,000 desalting units [224]. The water supply and sewage systems for a 2 million city have been analyzed: conventional advanced waste treatment, and with complete waste-water recycle. Low - cost energy has a significant impact only on the last, which includes a unique desalting process combining **electrodialysis and distillation.** The cost of the total water system is from $0.33 to 0.45/thou. gal. for the conventional to the recycle[225].

On board **space** vehicles, urine and waste waters are distilled and condensed under 0 to 1 g conditions using waste heat from the vehicle propulsion and capillarity and surface tention for control of liquid [226]. Astronaut's drinking water during long flights to Mars or elsewhere may be supplied by a radioisotope - powered water reclamation system, designed by the Air Force's Aerospace Medical Research Laboratory at Wright - Patterson, Ohio, U. S. A. The vacuum distillation vapour filtered catalytic oxidation water recovery system recloims drinking water from the crewmens respiration,

perspiration and urine. For a 90-day test, it has 2 evaporators and 3 residue storage units ; each of the former contains four 75W units using Plutonium-238 as the distilled water passes on its way to drinking water storage, also has a 50W Plutonium-unit ; this removes organic carbon and odorants from the water. The system operates at 270° F, instead of the usual 1200°F. The distillation units function at 100°F and 50 mm mercury pressure, and the operation takes less than 5 minutes. Each residue storage unit is used for 30 calendar or 120 man-days. The radioisotope heating elements are the most foolproof part of the assembly[227]. US Apollo - 14 astronauts are to seek water on the moon during February 1971, locked in rocks deep below the surface. This would be a boon to lunar exploration, so that local sources could be tapped instead of carrying water from the earth [228].

A waste water reclamation project is being built in Israel in the Dan region, to increase the nation's water supply by 12 per cent, and most of it is to be used for irrigation. To take care of the salinity that may build up gradually, a nuclear desalting plant will be installed [229]. The scientific, economic and irrigation problems of the Negev desert in Israel have been discussed with reference to sea water desalting [230]. Desalination of salty and brackish water has been considered to supply water on the Spanish Mediterranean coast. Flash distillation was to be the best of the distillation processes, and electrodialysis effective for brackish water.

A solar distillation plant is in operation at Las Marinas, supplying 535 gd to a 50-family agricultural community [231]. Experimental desalination of Terek Delta soil with a deep drainage network by a rice crop has been reported with 7.5 mg water/ha. During a year, the average salt content in the upper 1-m horizon decreased from 1.23 to 0.78 per cent' and during the second year to 0.6 per cent. A similar decrease was observed in the salt content of underground water of the upper water-carrying horizon. The rice yield was 4.05 tons/ha. [232]. A pilot project has been put out for the conversion of sea to potable water on the North sea coast in West Germany.

Desalination is expected to come to the rescue to meet the acute water shortage in many parts of India, at least in the forseable future. The work done so far needs to be strengthened, so that the plants can be installed straight-away without further R and D studies. Solar stills appear to be promising ; electrodia'ysis, reverse osmosis and flash distillation units have been designed and tried. The nuclear complex is, no doubt, fascinating, and the case for Bombay has been cited earlier. Some of these plants might at least meet defence requirements in emergency. It is felt that the current know - how is adequate for handling systems from a few hundred gallons to 5 mgd[6].

The available data on the operation of desalination plant using different processes in many countries are summarised and presented in Table 1. They refer to sea as well as brackish water, some noval techniques, and plants of various sizes. Together with Table 2 below on costs, this should provide adequate background information while planning fresh projects under different conditions in other parts of the world.

This technique may prove economically capable of supplying the needs in areas where there is a sea coast, or where surface or ground water is brackish and the development of such water is not practicable. It is clear that, in certain cases, the urgent need for a reliable water supply will eclipse the cost ; illustrations in this behalf are already there. In the Channel Islands, a 1.5 mgd plant is under construction in Jersey to augment conventional supply. The 0.5 mgd unit in Guernsey, U. K. is meant for public supply, to ensure that there will be adequate water for the tomato crop in case of shortage or drought[179]. The continued irrigation of the citrus crop in Israel, its main export, is threatened by the increasing salinity of the ground water currently used for the purpose ; this is approaching the tolerance limit of 170 ppm. A solution to such a problem could be a mixture of saline ground and desalinated waters. Leaving apart such specific needs, the conventional supply methods will no doubt prevail in the field of irrigation for many years to come. It has been pointed out that large — scale desalination may not reach the U. K. for another 30 — 40 years; perhaps

Table 1

Operating Data for Desalination Plants

Sl. No. and Country	Process	Operating Data	Remarks	Reference
1. U. K.	MSF Distln.	0.24 mgd; 3.25 gd/person, at 0.01 < (less than) $ (dollar)	To supply 12 communities 100 miles apart; 5,000 persons	95
2. U.S.A.	"	2.6 mgd; 50 stages, operation effcy: only 68 Btu/th distillate	Largest and most efficient built so far; Key West, Florida	190
3. U.K.	Distln.	1,070-9, 320 gd, to only 3-4 ppm	For small communities, work sites, hotels, military instln. ships	172
4. Holland	"	6 mgd	At Terneuzen	173
5. U.S.S.R.	" — Solar	Local ground waters; 10,3000 gd/hactare disaln area	Cheapest water supplied at distance 40 km from the nearest fresh water source	234
6. India	"	25 gd; average effcy of energy utilization 30%	Operpting data for pilot plant	235
7. Italy	Electrodialysis	Brakish well water; 0.24 mgd; 2,200 to 300 ppm; current 3.6 kwh/m^3 fresh water 91 lira/m^3	To supply Vieste, population 40,000	236,237
8. Libya	"	" ; 4.2 mgd; 2,000 to 650 ppm	Drinking, for Benghazi; largest in the world	238
9. U.S.A.	"	1.50/thou.gal.($ 7 in 1960 transported by rail tank cats)	Drinking/cooking, for Coalinga, California	4
10. India	"	Brackish water; 3,960 gd; 100 V	Pilot plant; Tulsion 14 and WB membranes	239
11. "	"	" ; 45 compartment cell, 20 gd, flow rate 3 l/hr, 600 mA; desalting 82 and 80. 5%; power consumption 18 and 45 W	For permaplex A-20 and C-20 membranes resp.	240
12. U.S.A.	"	Brackish well water; 1.2 mgd; 1,300 to 500 ppm	For Sarasota, Florida, 8.000 persons; largest and lowest cost	241
13. U.S.A. Libya	Reverse Osmosis	Largest in Dallas; feed water 165 ppm 5,000 gd; 11,500 to 380 ppm	Highly satisfactory for brackish water Potable water for American Oil Co.	242
14. U.S.A.	"	Brackish water; 1,000 gd; 3,5000 to 300 ppm; recovery 50-80%	Potable water	43
15. "	"	" ; 20 g/ft^2/day	Rejection NaCl 80 and Na_2SO_4 97%	52
16. U.K.	"	Brackish borchole water; 5,000 gd; to < (less than) 100 ppm	Suitable for polluted water	243
17. U.S.A.	Freezing	15,000 gd; to 500 ppm and 0.2 ppm hydrocarbon	Secondary refrigeration; n-butane better than its mixture with iso-butane or l-butene alone	42
18. U.K.	"	10,000 gd	Butane; no ext. heat source; only plant	244
19. U.S.S.R.	Ion Exchange	Saline water 35 g/l Na Cl or salts from sea water; 400 and 800 amp/dm^2; salt removed 78-87, 81-94%; yield 75, 60%	Cation MK-40 and anion MA-40 ex. membranes	245
20. "	Wind-powered	to 1 g/l; cost 1/4 of any other method		246
21. Kuwait		23 mgd; $ 0-93-1.37/thou. gal. (1/200 that of imported water)	Water to develop oil resources	17
22. U.S.S.R.		4.8 mgd drinking water	No preliminary chemical treatment	247

10—20 years earlier by cost reductions[179].

G. ECONOMICS

It is not easy to present a precise picture of the costs in desalination practice. Quite a number of factors have to be considered: plant capacity, the process and design, materials of construction, thermal efficiency, cost of power, water source etc. The economics of the problem has been touched upon at several instances before. Detailed information is available on cost in relation to capacity [12], plant investment and favourable application areas for each process [82], desalting versus traditional methods - capital and water cost improvement : single and dual purpose [190], and general survey[248].

Variations in capital and operating costs, and in the quality of inland waters, indicate that each of the 6 processes will have areas of application in which it is superior. The estimates are based in one report on cost of energy-system/electrical power, land and indirect-capital: interest during construction/ engineering design and construction supervision/start up expenses/working capital; no provision for taxes, cost of feedwater intake, brine disposal, storing or pumping. The annual maintenance-materials and supply costs are 0.5 per cent of fixed plant cost for reverse osmosis and distillation, and 1.5 per cent for freezing and electrodialysis processes [82]. The breakup figures in another case are: capital cost 33, operation and maintenance 21 and power 46 per cent [179]. Capital and annual production costs have been worked out for a vapour compression distillation unit [191]. In the flash evaporation cum reverse osmosis system, there is a potential cut of 20 per cent in plant investment and 25 per cent in operation, compared with the former process alone. The U. S. Office of Saline Water proposes to increase the total desalting funds from the current figure of $ 25 million to $ 29.4 million during 1971 [218].

In the paper on the thermodynamics, the energy requirements and costs are discussed at some length with equations; the capital cost here is half that of the total. The cost of water supply by natural desalination even in the very non-arid U. K. is 40 times that of the energy cost for the ideal process; that of conventional water supply - natural catchment process, is $0. 24-0.36/thou.gal. The actual cost by artificial desalination appears to be rather high, $0.60—1.00/thou. gal. It is, however, stated that the latter may be ultimately cheaper than the conventional[11]. With natural brackish waters, the greatest potential for cost reduction lies in the development of near-neutral membranes with slight anion selectivity[69]. Electrosorption technique are found to be applicable to brackish water desalting in the same cost range as electrodialysis[249]. An engineering evaluation of an ion-adsorption process for such waters shows that it is not economically competitive with electrodialysis[66]. The cost factors in the reverse osmosis process have been outlined in detail[250].

In the field of agriculture, a very practical figure is $0.01/thou. gal. for the product water to be utilized for irrigation in extensive arid zones. The attainment of such low costs is perhaps not in the near future. One has also to bear in mind that, with the kind of open channel irrigations practised in such areas, only about half the water supplied actually reaches the crops. It has been pointed out before that desalted water could be a useful supplement to existing water for cash crops[17]. More recently the economic feasibility of using desalted water from sea and brackish water for agriculture, in spite of the cost, has been shown The cost of water is 21—34 Dpf/m^3, with power at 30—50 kwh/m^3. Vegetables selling at 10 DM/kg are air lifted from Lebanon to an oasis on the Arabian Gulf[251].

Table 2 gives the latest data on the cost of water desalinated from plants of various capacities and employing different processes. Most of the figures come from the U. S. A. It is seen that the cost is spread over a wide range, the lowest being $0. 10/thou. gal. from nuclear desalination to the highest of $ 1.89/thou.gal. from ion exchange. The plant costs are, of course, fantastic for developing countries. Efforts are being made everywhere to reduce the cost of the product by: dula-purpose operation, scale control choice of suitable materials of construction and adequate design and better heat transfer.

It is obvious that, at the

TABLE 2

Cost of Desalinated Water

Serial No. and Country	Process	Capacity, mgd	Cost/thou. gal	Remarks	Reference
1. U.K.	MSF Distin.	3,30 single purpose	0.97, 0.77	Capital cost $ 3.84 million	75,179
	"	" dual "	0.64-0.86.	" 2.16-3.12 million	
			0.51-0.68		
	Electrodialysis	0.5	0.34	" 0.:25 million	
		conventional not >	(more than) 0.36	During the next 30 years	
2. U.S.A.	Distln-multiple effect, vap. comprn.	1,0.5	0.42 L, 0.54		81
3. "	" flash	2.6	0.86		190
4. "	" -vap. comprn Nuclear	8, 750	0.39, 0.22	Capital cost 7.5 million	191
5. "	" -Brown	0.25, 1-5 convetional	0.25-0.50, 0.85		75, 179
6. U.S.S.R.	" -Solar		1.5-2.0 rubles/m³		234
7. U.S.A.	" and Rev. Osmosis	131	0.47-0.56	Cost L $ 120 million combination cheaper 217	
8. "	Electrodialysis	50	0.07-0.20		232
9. "	"	1	1.05	Brackish water-3,620 ppm	53
10. "	"	1.2	0.18		241
11. "	Freezing	1-10	1.00-0.45		42
12.	Ion Exchange	1	1.89-0.41		253
13. Austria	Nuclear	10	0.10		206
14. U.S.A.	Hydrocarbon extn., single stage	10	0.99	Capatial cost $ 18 million	222
15. "		Desalted, conventional	0.85-1.15, 0.32		254

present time, desalinated water cannot compete with water from natural sources. There are, of course certain parts of the world where conventional water is quite expensive - due to shortage or to high transformation costs from the source to the point of consumption. One significant feature is that conventional water costs are cantinually rising, and in some place are already above those for economic desalting. On the other hand, improvements in desalination techniques are expected to bring down the cost of fresh water to reasonable/economic levels in the near future.

H. FUTURE TRENDS

It is seen from this outline that desalination is a very promising technique to meet the water shortage. This is the answer where there is no other alternative in emergency for the civilian population, or for military needs; or where conventional water supply is more costly. Problems of pollution and waste disposal can also be handled by desalination technology. There are prospects of application to food and agriculture, in a certain context, and make the deserts bloom.

The economics of the processes will no doubt hold the key to future developments. This means that large capacity plants will have to be put up wherever practicable. But the demand, in the forseeable future, appears to be more for small capacity units- from a few hundred thousand to a few mgd, rather than the desirable 50-150 mgd installations[10]. The likely contenders for large-scale plants are multi-flash or vertical tube units either nuclear or fossil-fuel fired, and combined electricity generation/ desalination[66]. The coupling of humidification evaporators with multi-flash or multiple-effect evaporators is foreseen as economically attractive[205]. R and D work is being pursued in several countries, with a view to evolve improved/ modified processes and reduce the costs as far as possible.

The integration of atomic power plants with large desalination systems is expected to be amongst the major developments of the morrow. There is the primary advantage of utilising energy during low electricity demand periods and also using low grade heat that may be available. However, such units will be suitable only for regions where the power and water demand are within the limits of output in these systems, excluding thereby many developing countries whose demand for water is far greater than that for power[12].

The dual-purpose concept is particularly promising for desalting plants that serve industrial complexes and municipalities. It certainly has a place in the long range planning of underdeveloped areas seeking to attract industry. Nuclear energy is particularly suited for large, dual-purpose plants. In the 1910's, when the fast breeder reactors become commercially available, they will further enhance the advantages of nuclear power, and have a favourable effect on the economics of larger flash distillation plants. The system will become increasingly important to water desalting, but not when the needs are less than 50 mgd[109]. Advanced desalting technology using the nuplex and intensive farming methods may overcome a major obstacle to making the desert habitable[208, 209].

It is concluded that, although desalination of water is somewhat in its infancy, it could be a major source of water supply in the future with its vast potential of bringing life into dead, arid zones. The development of desalination can break man's dependence on the cycle of solar evaporation and precipitation, using mainly the rejection energy of power production.

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