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ASSESSMENT OF A DESALINATION PLANT FOR THE OBTAINMENT OF DRINKING WATER

UC/TON/87/028

TONGA

Report on : Small/Medium Scale Desalination in Kingdom of Tonga,
August/September 1987*

Prepared for the Government of Tonga
by the United Nations Industrial Development Organization
acting as executing agency for the United Nations Development Programme

Based on the work of Dr. J. P. Gerofi
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EXECUTIVE SUMMARY

The current reticulated water supply in Pangai-Hihifo is very poor, because of excessive dissolved solids. At the time of the mission, the salinity of the supply was eight times the WHO recommended limits.

If water of the quantity and quality that is available in Nuku'alofa and cities of the developed world is to be supplied in Pangai-Hihifo, then desalination appears to be the only source, apart from shipping it from another country.

A new bore was tested and found to have much lower salinity than the wells in use. Its safe yield should be ascertained by means of a drilling and monitoring programme.

If the bore can supply the feedwater demands of a desalination plant of whatever size is selected (200 or 400 m^3/day), then it could be used as the source for a reverse osmosis (RO) or electrodialysis (ED) plant. If the bore cannot porvide sufficient water, then the only practical option is to use an RO plant drawing water from the same source as the present Tonga Water Board wells. This may be the best solution even if adequate water is available from the new source, because of pretreatment problems.

A 400 m^3/day desalination plant required in the erms of reference would provide adequate water for all residents of Lifuka and Foa, at a level of consumption considerably exceeding that currently seen in Nuku'alofa.

While it would be possible to build such a plant in one go, it appears that a plant of half the size - 200 m^3/day - would meet the needs of Paqngai-Hihifo for some time to come. The plant could, if necessary, be built with the possibility of expansion in the future.

Whatever the size of plant constructed, the operating costs will be considerable, and a strategy will be needed to meet these. If the operating costs of a 400 m^3/day plant using water from the current Water Board wells were to be recouped from water charges, the price of water would need to rise to about \$1.57/m^3, a six-fold increase. It is believed that many residents of Pangai-Hihifo will avoid using the reticulated water if the price rises that high.

If a desalination plant is constructed for the reticulation system, its size should be 200 m^3/day or smaller, in the first instance.

If the problem of finding operating expenses cannot be overcome, but donor countries are prepared to supply a more expensive renewable energy plant, the operating costs will be cut considerably.

If a desalination plant were installed to supply the reticulation system, there are a number of parallel activities that would need to take place, including refurbishment of the supply system, repair of customers' installations, staff training and development cost recovery strategy.

If neither the capital nor the operating expenses can be found, then there are lower cost options available, which will improve the availability of water. Of these, it is suggested that additional guttering should be installed to feed existing tanks, and that a small desalination plant should be purchased for drought relief. This plant should, however, be run as often as possible, and used to train a core of operators.

PANGAI DESALINATION STUDY

EXTENDED SUMMARY

1. The current water supply system in Pangai serves a population of about 2 400.

2. The quality of the water is poor, varying in salinity between 1 000 ppm and 8 500 ppm, depending on rainfall.

3. Fewer than half the houses in the Pangai-Hihifo area, which has reticulated water available are connected to the system.

4. Even in those houses that are connected, people avoid using the water wherever possible, and the main use is toilet flushing. In times of water shortage, the water is used more for bathing and clothes washing.

5. About 75% of houses have rainwater tanks that collect water from their roofs. These, and shallow wells, are the main sources of drinking water.

6. The replacement value of the tanks and guttering is of the order of $T 180 000.

7. The tank program has not been entirely successful, in that local communities were organised to build the tanks, and the instructions were not always followed to the letter. As a result, many of the tanks leaked. A subsequent repair program improved the position somewhat, although fewer than half the tanks are entirely leak free.

8. Maintenance of the tanks and guttering is also less than perfect, so the amount of water collected is considerably less than it could be.

9. Examination of test bores drilled on Lifuka and Foa revealed no sources of potable water. On the basis of these, it must be concluded that there is little chance of finding a significant lens with such water.

10. The remaining options for potable water supply are:

    1. Better catchment of rainwater
    2. Desalination
    3. Carting water from a reliable source, probably Samoa.

11. There are three different processes of desalination that could be suitable for Pangai. They are:

    1. Distillation
    2. Reverse Osmosis
    3. Electrodialysis

12. One of the test wells monitored on this mission had water of salinity significantly lower than that of the Tonga Water Board wells. It is still too saline to drink. Its safe yield should be investigated, since its use would cut the cost of desalination. If it cannot be used for desalination, it may be usable for irrigation.

13. Distillation is suitable for all types of water, but its capital cost is high compared with other processes in the size range considered. Electrodialysis is suitable mainly for waters of salinity less than 3 000 ppm. If the test well above can produce enough water, electrodialysis would be a good contender. Otherwise, reverse osmosis seems to be the most likely choice, with the Tonga Water Board wells or the test well being a suitable feed.

14. The demand for water will rise if the quality is improved, and also the desalination plant will need twice as much feedwater as it produces. It will therefore be necessary to extract of the order of four times the quantity being taken from the current wells. It is extremely unlikely that the wells could supply that quantity without becoming much more saline.

15. It would therefore be necessary to provide several more wells or infiltration galleries to maintain the feedwater quality at its present level.

16. The capital cost of a suitable reverse osmosis plant is of the order of $A 400 000, FOB Sydney. Another $ 100 000 would be needed to cover installation, wells, etc.

17. The operating costs of such a plant would be approximately $ 500 per day, amounting to $ 1.25 per m^3 of water, for energy, chemicals and membranes alone. That is over four times the current price of reticulated water. Assuming that the present charges cover pumping and reticulation, it must be concluded that the price to the consumer would need to go up by a factor of six to cover operating costs alone.

    A person using 100 L of water a day would have to pay approximately $ 0.16 for it - making an annual bill of about $ 58.

18. The GDP per capita in the Ha'apai group is around $T 650 per annum. Unemployment is running at about 16%.

    Even if the population were paying only operating costs for their desalinated water, they would be paying out almost 10% of their contribution to the GDP for water. It seems likely that there would be some resistance to such an arrangement.

19. If capital recovery were included, the costs would be higher. Assuming a plant life of 15 years and the ruling Tongan interest rate of 10%, the capital recovery would be about $ 65,000 per annum, or an additional $ 0.44 per m^3 of water, bringing the total cost to at least $ 2 per m^3.

20. Since many people already have tanks, there would be very strong incentives on people to use tank water instead of tapwater. The desalination plant would probably be operating well below capacity for much of the year. If capital recovery and interest charges were levied on the users, they would have to be spread over a smaller number of users, resulting in a higher unit cost than indicated.

21. Because of the poor quality of the present water supply and the low level of maintenance, there are leaks in the supply system. In view of the cost of the improved water, such leaks would be unacceptable, as would faulty water meters. It would therefore be necessary to mount a repair campaign on the Board's and the consumers' equipment, coinciding with the commissioning of the desalination plant.

22. Based on reasonable allowances for water consumption in Tonga, it seems that the projected size of the plant - 400 m^3/day - is about double what would be needed to supply the demand given the present lifestyle. If a smaller plant were installed, it could always be expanded at a later date.

23. While the water supply problem in Ha'apai seems severe, it does not appear to be life-threatening. No evidence has been presented to us that people are suffering from the effects of the poor quality water, largely because they do not drink it.

24. The tank supplies exist, and with some augmentation and more careful rationing, could tide the population through the severest of droughts. When all else fails, they have recourse to unripe coconuts for drinking water.

25. Nonetheless, if it is desired to improve the standard of living in the area, and stop the drift to Nuku'alofa, there is good reason to improve the water supply.

26. If the proposal as stated in the terms of reference is not implemented, the alternatives are:

    1. Build a plant of, say, 200 m^3/day, and rehabilitate the water supply.

    2. Build a very small plant of, say, 10 to 20 m^3/day, suitable for providing only essential drinking and cooking supplies, and use it only during dry periods.

    3. Concentrate on improving the guttering and tank supply. Currently, only about half the available roof area is guttered, and substantial improvement in the dry period would be available without any increase in tank volume.

    4. Develop another method of collecting and storing rainwater - for example by paving the airport runway and constructing tanks to store the runoff.

    5. Ship water from Samoa.

27. A small desalination unit would cost of the order of $30,000, and would only need to be used in times of drought. It presupposes that the existing style of water supply - with drinking water being obtained from tanks and poor quality water being reticulated - will continue. Such a plant could be needed for, say, three months a year, and water could be distributed in plastic containers. At other times it could be run for training purposes, and the water fed into the reticulation system.

28. Doubling the tank capacity and using the full roof catchment would probably cost about $ 200 000. While the amount of water available from such a source is necessarily limited, it is a system with very low running costs.

29. Gutter and tank systems, provided they are properly constructed, should be easy to maintain and not require special skills. They provide a decentralised water supply system, compared with a desalination plant, in which the supply depends on the skills available at the central plant.

30. Compared with other systems, desalination requires skilled staff. Usually, a chemist is on the staff or available at short notice for the larger plants.

31. All water supply systems have their limitations. A desalination plant can only produce its rated output, and a tank system can only provide what is stored in it.

32. A better water supply is part of achieving a healthier, higher standard of living. The level to which the improvement should be pitched depends on the available resources. It is a reasonable long-term aim to have a desalination plant on Lifuka, and a capacity of 200 m^3/day would be adequate for some time to come. If funding constraints do not allow immediate construction of a plant of this size, a combination of some of the suggestions above will provide some degree of relief to the shortage of drinking water.

33. The possibility of solar salt manufacture on Lifuka could be investigated. This is peripheral to the terms of reference, but appeared as an outcome of consideration of a combined water/salt plant.

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CURRENCY

In this report, Tongan and Australian dollars are used interchangeably, since their values were tied at the time of the study. Unless otherwise specified, all costs are in Tongan or Australian dollars.

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1. THE KINGDOM OF TONGA

1.1 Geography

The Kingdom of Tonga consists of 170 islands, of which 37 are inhabited. They are located in the South Pacific Ocean, stretching from about 23.5°S to about 15°S in latitude and are at approximately 175°W in longitude.

The total land area of the Kingdom is about 646 km^2, of which 260 km^2 is the main island of Tongatapu. The total ocean area included is about 700 000 km^2.

From the southernmost island, Eua, to the northernmost, Niuafo'ou, is about 1000 km.

The Ha'apai group is about 150 km north-east of Tongatapu and comprises some 43 islands, of which only 16 are permanently inhabited. Lifuka (population approximately 3 000) is the largest island, and is the site of Pangai, administrative centre for the group.

Soils are so permeable that normal stream drainage does not form. The soils are derived from both volcanic ash and from reef formations. The fertile soils, subtropical climate and gently rolling topography make most islands verdant with a wide variety of plants. The need for fertilisers is minimal, and land is allowed to lie fallow every few seasons.

1.2 Population

The population of the Kingdom at the time of the 1986 census was 94 535.

63 614 people, or two thirds of the population lived on Tongatapu. 8 979 people live in Ha'apai.

Population growth has previously been reported as about 3% overall, but it is far from uniform. The latest census suggests much lower growth. Because education, health services, entertainment, electricity, etc are more readily available on Tongatapu, there is a net migration towards Nuku'alofa.

Population in the Ha'apai group, the driest part of the Kingdom, has not grown for many years.

The average age of the population was reported to us as 15 years.

1.3 Geology

The islands are coral islands, raised atolls, or remains of volcanos.

Those to the west of the Tofua trough are of volcanic origin. Those to the east of it are built from reef deposits at a time when the sea was higher than it is now. These eastern islands are part of a tectonically active coastal plate being subducted into the trench.

On the main island of Tongatapu, the water-bearing limestone is between 160 m and 235 m thick, covered by volcanic ash up to 5 m thick.

Of the islands of volcanic origin, only the Vavau group is significant, and no water shortages have been brought to our attention from among them.

1.4 Climate and Rainfall

The country extends from 15°S to 23.5°S, and enjoys a sub-tropical to tropical climate. Temperatures vary more from day to night than from season to season. Northern Tonga has an average annual temperature of 26°C, while southern Tonga (including Ha'apai and Tongatapu), has an average of 23°. In the hot season (Dec to Apr) all parts of Tonga have about the same temperature, but in the cool season, the southern groups have significantly cooler nights.

Maximum temperatures typically range from from 25° to 29° in the south and from 27° to 30° in the north. Minima fall to 18° in Nuku'alofa and 20° elsewhere.

Detailed weather records have only been kept for Fua'amoto Airport, near Nuku'alofa, and records in other locations are generally restricted to temperature, pressure and relative humidity. The Headmaster of the Marist Brothers High School in Ha'apai has been keeping careful records of the weather at the school, and some information can be gained from satellite records.

Relative humidity rarely falls below 60%, and can rise to 90%.

Rainfall varies among the island groups. In Nuku'alofa, the mean annual rainfall is 1.88 m, while in Ha'apai it is only 1.71 m. The rainfall in the other groups is higher than that in Nuku'alofa. The minimum rainfall ever recorded is .84 m for Nuku'alofa and 0.83 m for Ha'apai. More than 1.2 m is received approximately 9 years in 10. According to study by the New Zealand Meteorological Service, periods of abnormally high or low rainfall lasting more than three months are extremely rare.

Residents report substantial orographic effects in rainfall - islands with substantial elevation receive more rain than flat ones. This means that small islands off the major southern islands may have substantially lower rainfalls than the nearest recording stations.

Evaporation and transpiration accounts for between 80 and 160 mm of water per month, depending on location and season. Ha'apai experiences the strongest evapotranspiration.

The mean annual sunshine hours are estimated as follows:

Niuafo'oou	2193
Vava'u	2150
Ha'apai	2151
Tongatapu	2125

Mean wind speeds vary somewhat over the country. In Ha'apai, the average wind speed recorded is generally 8 to 9 knots (about 4 m/s). The windspeeds are higher at elevated points and on smaller islands.

Tonga is subject to cyclones, and in extreme cases, hurricanes. The last hurricane, Isaac, in 1982, caused considerable damage.

1.5 The Economy

The economy depends very heavily on primary industry, which makes up over 40% of the GDP. Mining and manufacturing together contribute only 5%. The total GDP, as estimated by the World Bank, and its distribution, are shown below for 1984-5:

TABLE 1. ESTIMATED GDP - TONGA, 1984-5

Sector	$T thousands	%
Agriculture, Forestry, Fisheries	28 541	41
Mining and Quarrying	407	1
Manufacturing	6 571	10
Electricity and Water	532	1
Construction	4 902	7
Wholesale and Retail	7 833	11
Transport, Storage, Communication	4 179	6
Finance and Real Estate	3 108	4
Community, Social and Personal Services	12 325	18
Not elsewhere included	740	1
TOTAL (at factor cost)	69 138	100
Taxes less subsidies	10 872	
TOTAL (at market prices)	80 010	

Tongan statistics indicate that imports in 1982-3 cost about $T 99 million, while exports were about $T 18 million, of which two thirds was farm produce. World Bank estimates for 1984-5 give a value for exports of $ 10.9 million.

The balance of payments deficit is offset through foreign capital inflow, aid, tourism and services and remittances from Tongans abroad. When the last three of these are accounted for, the current account deficit for the year remains at $T 3.4 million. However, when aid and capital inflow are included, the nation's monetary reserves improve by $T 1.9 million.

Government recurrent revenue and expenditure in 1982-3 were both around $T 20 million.

In 1982-3, about $T 20 million was received from bi-lateral and multilateral aid agencies.

1.6 Education

Primary education is widespread throughout the Kingdom, and a few new schools are planned. Most primary schools are run by the Government, and there are schools located on many of the small islands.

Secondary education is largely the responsibility of religious organisations, and 87% of secondary students are in non-government schools. Secondary schools are generally confined to the main centres within each island group, and the final year of secondary school, leading to the NZ Higher School Certificate, is available only in Nuku'alofa.

Students thus have to leave their island homes if they want to progress beyond primary education.

Local facilities are available for training primary and secondary teachers.

A Maritime Training School has recently been completed.

The University of the South Pacific has a facility in Nuku'alofa.

There are no facilities for trade training through technical colleges or similar institutions.

1.7 Energy Resources

There are no fossil fuel resources.

Electricity is generated from diesel fuel on the four most populous islands.

Fuelwood is widely available, and a study is currently under way to ascertain the extent of the resource. Non-productive coconut trees can also be used as a construction material, and there are coconut sawmilling projects in operation.

The potential for use of solar energy is moderate to good, by comparison with other countries.

Wind energy potential is fair, and the Tonga Water Board has used windmills to pump water from aquifers.

There is a proposal for using wave energy to generate electricity on Tongatapu. The area in question has a very suitable ocean floor and wave pattern.

1.8 Hydrology

There are no permanent watercourses on any of the islands. In locations with less permeable soils, there are some watercourses which flow only in wet weather. The runoff generally consists of sheet flow to the ocean.

On Tongatapu there are clay strata in the soils but these do not bar the downward percolation of water into the porous limestone that underlies the soil on most islands.

On most islands a lens of fresh water forms in the porous soil and rock, and floats on seawater that infiltrates from around the shore.

On Tongatapu, the groundwater contains some minerals from seawater, largely from salt spray. In shallow wells, calcium carbonate and bicarbonate dominate, and there is a transition towards sodium chloride as the wells get deeper. This pattern is probably typical of all islands with fresh water lenses.

On some islands, full lens development does not occur. In that case, a small amount of fresh water is usually available from shallow wells whose bottoms are above sea level.

1.9 Water Supply

Three levels of water supply facility exist. These are:

1. Reticulated water provided by the Tonga Water Board. This is confined to Nuku'alofa, Neiafu, and Pangai. The source is inevitably groundwater, which is pumped using electrical or wind energy into the reticulation system.

2. Village water schemes, which may or may not be reticulated, run by Village Water Committees. The Tonga Water Board acts in an advisory capacity to the Ministry of Health who are responsible for the implementation of most of these schemes. They use groundwater.

3. Water from rainwater tanks.

Over the last few years, there has been an extensive programme of tank construction on those islands with the most serious water shortages. This has been done largely with foreign aid funds.

The programme has concentrated on ferrocement tanks built by the local villagers, and fed from the roofs of houses and community facilities. There are thus private tanks and community tanks.

The programme has not been entirely successful. A large percentage of the tanks leaked seriously, and many have been repaired. The local people have not been able to maintain them or the guttering that feeds them.

Apart from structural problems with the tanks, there is a risk that they will become breeding grounds for mosquitoes, since the lids supplied for them are often broken or removed.

1.10 Water Supply Improvements

The fourth development plan of the Kingdom of Tonga has the following objectives in respect of water supply:

1. Provide safe and reliable water supply for both the urban and rural populations

2. Contribute to the social and economic productivity of the community by improving the health of the population through the provision of safe water

3. Increase the equity of provision of health services by ensuring a high standard of water quality and availability in all island groups and rural areas

4. Increase community involvement and self-reliance in rural water supply schemes.

Specifically, the plan called for 91% of the population to be served by organised water supplies by the end of 1985. It includes:

1. Rural water supply schemes to supply 59,530 people in 117 villages

2. Installation of new wells, reservoirs and windmill-driven pumps for the Nuku'alofa water supply

3. New wells, tanks and pumps for the Neiafu water supply

4. Extension of the reticulation from the Neiafu water supply

5. New wells, tanks and windmill-driven pumps for the Pangai water supply

6. Extension of the reticulation from the Pangai water supply

Much of the above programme has now been completed.

An extensive programme funded by foreign aid constructed rainwater tanks on islands where there was no satisfactory groundwater supply. The programme required local communities to do the construction of the ferrocement tanks with materials supplied to them. The instructions for making the tanks were not always followed, with the result that between 85% and 95% of the tanks leaked.

A follow-up programme to repair the leaks has been undertaken by the Foundation for the Peoples of the South Pacific. This programme has had only partial success, with only 30% of the tanks worked on being fully waterproof.

2. LIFUKA

2.1 Geography

The Ha'apai group is about 150 km north-east of Tongatapu and comprises some 43 islands, of which only 16 are permanently inhabited.

Lifuka (population approximately 3 000) is the main island in the Ha'apai Group. It has a land area of approximately 11 sq km. There are five villages on it - Koulo, Holopeka, Mavea, Hato'u and Hihifo. The last three effectively make up the township of Pangai, which is the administrative centre for the Ha'apai group. The Tonga Water Board has established a reticulated water supply for Pangai.

Lifuka is joined by a causeway to the neighbouring island of Foa, on which there are four villages, Faleloa, Lotofoa, Fotua and Fangale'ounga. Foa has a land area of about 13 sq km.

Both islands appear to be typical coral atolls, with a maximum elevation above sea level of about 15 m. The eastern sides of the islands drop sharply towards the Tonga trench, while on the western side there are shallow lagoons.

Most of the population lives on the western side of the islands. Pigs, chickens and ducks roam around the villages, and other livestock are tethered.

On the allotments outside the villages, the most common crops are coconuts, bananas, citrus, guava, root crops and vegetables.

2.2 Population

Provisional figures made available from the 1986 census show that the population of Lifuka was 2 840, of which 2 383 live in the Pangai-Hihifo township. The population of Foa was 1 409.

According to an internal paper prepared in the Central Planning Department, Nuku'alofa, the population of Lifuka and the Ha'apai group generally has been dropping steadily for many years as the following table shows:

TABLE 2 - POPULATION, LIFUKA AND FOA

Year	Population	
	Lifuka	Foa
1956	3 220	
1966	3 161	
1976	2 946	1 701
1986	2 840	1 409

This trend is no doubt due to the attractions of Nuku'alofa, including entertainment, services and education, as well as the trend for Tongans to move overseas, particularly to New Zealand. It appears far more pronounced for Foa, with fewer services than Lifuka. Water supply is one of the services that are better in Nuku'alofa.

According to the 1986 census, the number of households on Lifuka was 504, of which 426 were in Pangai itself.

The 1986 census was different from earlier ones in that it assessed the de facto situation rather than the de jure one, but population trends are still consistent with those from previous censuses.

2.3 Living Conditions

Since Hurricane Isaac demolished most of the homes on Lifuka and Foa, the bulk of the current accommodation is made up of wooden houses with sloping corrugated iron roofs.

Facilities vary from house to house. The bulk of houses now have electricity, and in the first month after the introduction of telephones in July, 1987, there were over 100 connections, many of which are Government offices, schools, stores, etc.

The bathing and toilet facilities have been surveyed in the 1986 population census and also in independent studies by the Ministry of Health. The results of the latter are shown in Table 3.

There are some inconsistencies between the two sets of data, probably due to slightly different definitions and terminology, but the general impression given by both is identical.

The Tonga Water Board's supply is drawn from wells and is brackish. The salinity varies with the rainfall and the season, and may be anywhere between 1 000 and 8 000 ppm according to reports given to the writer. The water is not suitable for drinking. Only about half the houses with supply available are actually connected.

Many of the houses and public buildings are equipped with guttering and rainwater tanks, which supply drinking water. Others rely on shallow wells, which provide potable water, in contrast to the well for the reticulated supply.

2.4 The Economy

World Bank estimates put the average annual wage for Tonga at about $T 1030. Average wages by geographic location were not available, but estimates of GDP per capita are, and indicate that the GDP per capita for the Ha'apai group is about 62% of the average for the Kingdom, equal lowest with Eua, at around $T 335 in 1981-2.

Unemployment in Ha'apai is not significantly worse than on Tonagatapu. In Pangai-Hihifo at the time of the 1986 population census, 99 (16%) of the 611-strong labour force was seeking work. On Foa, 53 (over 12%) people out of a labour force of 431 were seeking work. In 1976, for the Ha'apai group as a whole, the unemployment rate was about 15%.

Of the employed males in the Group, over 76% were employed in agriculture, forestry or fishing, as shown in Table 4.

TABLE 3

HOUSEHOLD FACILITIES

	Hihifo	Ha'atou	Navea	TOTAL
Occupied Dwellings	163	87	unknown	
Dwellings	213	133	115	461
Public Buildings	16	12	unknown	
BATHROOMS				
European	146	108	94	348
Tongan	22	19	14	55
None	10	6	7	23
Total	178	133	115	426
TOILETS				
Septic	39	26	37	102
Pour Flush	116	8	20	144
Pit	23	63	62	148
None	10	6	5	21
Total	188	103	124	415
WATER SUPPLY				
Tank	180	121	59	360
Piped	72	33	61	166
Wells	52	18	10	80
None	10	0	2	12
TOTAL	314	172	132	618
PUBLIC TANKS	4	1	0	5

TABLE 4 - EMPLOYMENT BY SECTOR, MALES, HA'APAI GROUP

Agriculture, Fishing, Forestry	1471
Manufacturing	12
Gas, Electricity, Water	10
Construction	51
Restaurants, Hotels, Retail, Wholesale	18
Transport, Storage, Communication	59
Community, Social Personal Services	235
Not Classified	57
TOTAL	1914

The Government has established an administrative centre in Pangai, and employs about 90 people spread over various departments covering the Ha'apai group. The departments include Agriculture, Post Office, Cooperatives Dept, Health, Tonga Electric Power Board, Works, Education, Tonga Water Board, Commodities Board and the Police.

There are also elected district officers and town officers throughout the group.

Industry is extremely limited. In 1984, there were two bakeries and one food processing plant.

It can thus be concluded that in Pangai-Hihifo about one third of the workforce is employed outside the agriculture-forestry-fisheries sector.

2.5 The Climate

The temperature in Ha'apai is remarkably even. The hottest period of the year is December-January, while the coldest is July-August. The following data indicates the range of variation of temperatures:

	January	August
Mean Max	29.3	25.5
Mean	26.4	22.6
Mean Min	23.6	19.7

TABLE 5. RAINFALL - PANGAI

Month	Minimum	9 yrs/10	MEAN	1 yr/10	Max	1987
January	15	60	206	400	649	25.4
February	35	70	199	335	403	106.3
March	53	120	253	480	593	382.3
April	6	55	288	320	436	5.7
May	0	20	95	195	233	69.7
June	5	6	74	135	187	56.5
July	2	20	90	195	238	68.2
August	1	20	112	210	245	
September	7	30	105	240	308	
October	6	30	104	225	316	
November	11	25	133	285	512	
December	14	35	152	345	613	
ANNUAL TOTAL	825	1250	1710	2305	2660	
TOTAL TO JULY			1205			714.1

Average sunshine hours for Ha'apai are 2151 per year. The monthly average varies from about 160 hours in June-July to about 195 hours in December-January.

The trade winds predominate all year round in Tonga, but especially in the period May to October, when 75% of all winds are from the South-east quarter, with some from the North-east. In the hot season (December to April), East and South-east winds still dominate, but there are some winds from the north.

Strong winds are mostly associated with tropical cyclones, although the speed of the trade winds tends to increase in the later part of the dry season. Wind speed is greatest in the early afternoon.

The average wind speed in Ha'apai is 4.1 m/s, with a low of 2.7 m/s in April, and a high of 4.5 m/s in November. As far as energy supply is concerned, this is a low to moderate speed, and the potential for use of wind energy can be described as only mediocre.

Relative humidity is generally between 65% and 90%.

2.6 The Current Water Supply

2.6.1 The Tonga Water Board System

The Tonga Water Board's current water supply system covers Pangai and Hihifo.

The water source is two wells dug in 1971 and located as shown on Fig 6. They are separated by about 200 m and are located around the middle of the widest part of the island. Their depth is about 8 m, of which the first 4 m is in soil, and the rest in coral limestone.

There are no drawings available on the current configuration of the pumps and storage system. Local inquiries indiacted that the supply and storage system was connected as shown in Fig 1a. Most of the piping is underground, and the area around the tanks is heavily overgrown, so it was not feasible to make an independent check of the pipe layout.

The pipes leading to the overhead tanks are badly corroded. The tanks themselves show signs of corrosion, there are some leaks from the tanks and the tank stands are severely corroded.

The pipe layout as it was explained could be improved. A more useful layout would be as shown in Fig. 1b. This arrangement would allow the town to be fed either from the tanks or from the pump, and, when the system was fed from the tanks, ensure that there was no possibility of water leaking back into the wells.

There are three pumps at the wells. No 1 well has a Southern Cross type NFA pump with a reduced size impeller, plus a windmill pump. The latter seems to have a capacity of only a few litres a second under normal wind conditions, and was not in operating condition when we visited the site.

No 2 well has a Southern Cross type NFA pump with impeller of unknown size.

Both pumps are connected to diesel engines. There is currently no flow meter to record the amount of water pumped from the wells into the tanks and supply system. One exists, but has ceased functioning because of scaling from the very saline water.

The engines have been changed over, and there is no indication of the operating speed of the pumps over time. It is thus not possible, without servicing the pumps and measuring the engine speed with a tachometer, to get a reasonable estimate for the quantity of water pumped from the wells, as opposed to that bought by the consumers.

The reticulation system from the wells is constructed from PVC pipe. There are two major mains, running parallel through the town, supplying the area shown in Fig. 2.

The number of customers appears from our examination of the Tonga Water Board records to be 203, although higher numbers were quoted to us. Information from the Census is inconclusive in this matter, because many houses have the piped supply as well as tanks. According to the Health Department survey, 166 dwellings out of a total of 426 take the piped supply. The remaining 37 customers are schools, churches and Government buildings, etc.

The water is sold to customers at $1.25 per thousand gallons ($0.27 per m^3), with a minimum monthly charge of $1.25.

The total monthly consumption for the system (the sum of all meter readings) was calculated for two months, March, 1987 and July, 1987. The first half of 1987 has been particularly dry. July registered 68.2 mm and March had 382.3 mm. The months between March and July were unusually dry, as shown in Table 5.

Consumption records must be treated with some caution, since many meters are out of action, and the records show an average consumption on which the charges are based. Other meters may be quite inaccurate because of scale deposits in the working parts.

It can be seen that March was a month of relatively high rainfall, both by comparison with the same period in other years, and and by comparison with other months of 1987. July was a very dry month, following three other dry months, in which the rainfall was considerably below average. Since most customers also have tank supplies, one would expect some shift towards the piped supply in dry conditions. In fact that did not occur in the months surveyed. The total meter readings for the Tonga Water Board system were:

March	1 733 435 L
July	1 630 445 L

Since the whole population is not served by the water supply, it is difficult to construct a meaningful figure for average per capita consumption. A useful figure can be obtained by calculating the average consumption per customer, and this amounts to:

March	8294 L	267 L/day
July	8031 L	259 L/day

Examination of the Water Board's records reveals that there is a small number of large users, in particular:

TABLE 6. MAJOR WATER USERS, PANGAI

	March	July
The Tonga Electric Power Board	66 658	100 000
Mormon Church, Hihifo	33 028	7 640
Hospital	45 000	45 000
School	88 022	44 979
School (St Joseph's)	77 737	47 740
Seletute's Guest House	65 694	52 914
Copra Board	20 000	20 000
Coconut Mill	25 319	81 111
TOTAL LARGE USERS	421 458	399 384

It can thus be seen that the eight largest users consume about 25% of the total piped water used in Pangai.

Another interesting statistic is the total consumption per household, eliminating the large users. The validity of this number is somewhat restricted, since people who may or may not have the Water Board supply in their homes may work or go to school at a place where the supply is available, and may thus use the supply for toilet flushing or washing.

The consumption per household may be converted approximately to a consumption per person, by dividing by the average household size from the census. On this basis the following results are obtained:

	March	July
Average per household L	7 903	4 877
Average per household/day L	255	157
Average per person/day L	45.5	28.1

It is not clear how much if this water is actually used, and how much is lost in the consumers' installations. It is very likely that there will be considerable loss from dripping taps and leaking cisterns. This is because of the very saline supply, which corrodes metal parts, and also deposits scale on valve seats, etc. The standard of maintenance of these components is not sufficient to prevent loss of water due to these problems.

There may also be loss from the reticulation system, although it is mainly constructed from PVC piping. The pipes and valves near the wells are galvanised steel, and any valves in the distribution system would also be metal.

Because it was not possible to measure the amount of water being delivered from the wells and because the accuracy of the meters cannot be relied upon under the conditions existing in Pangai, it is not possible to estimate the losses between the wells and the customers' meters. However, similar measurements have been made on the Nuku'alofa system by the Tonga Water Board. They compared the demand in the early hours of the morning, when, in theory, the demand should have been very low, with that during the rest of the day. A typical demand curve is shown in Fig. 3. It suggests that roughly half of the water leaving the reservoir reaches the customers' meters.

Determining the loss of water in customers' premises is more difficult. There are instances of severe leaks which are obvious from the meter readings, and result in reasonably prompt remedial action because of the large bill received. However, slow leaks that represent less than about 200 L/day per customer would result in an additional charge of less than $ 1.50 per month and may be missed.

2.6.2 Other Water Sources

The poor quality and relative newness of the piped water supply system has meant that people have had to rely on other water supplies.

The traditional source of water is the well. In Pangai, the wells are typically relatively shallow, and yield water that is generally less saline than that of the Tonga Water Board, although the salinity may exceed the WHO recommendations.

Because many families keep pigs and other animals around the house, open wells can pose a health hazard, and Waterhouse, in his recent report on water supply in Tonga, recommended against their use for drinking.

Since Hurricane Isaac, corrugated iron roofs have become almost universal, and there have been extensive tank building programmes to conserve rainwater collected on these roofs. According to the Health Ministry's survey, there are 360 houses in Pangai-Hihifo with tanks, out of a total of about 461. This information is shown in Table 3.

A number of international aid bodies have financed tank construction in Ha'apai. In general, the programme has not been wholly successful, since local people did not always follow the instructions exactly and about 70% of the tanks leaked. A program of tank rehabilation was undertaken by the Foundation for the Peoples of the South Pacific. They also conducted an evaluation of the tanks in 1986.

The conclusion was that the repair program only sealed 30% of the leaking tanks.

There are other problems with the tanks, also. The designs used until now have a removable lid on the top. The taps often stop functioning, or get bumped by animals and rendered inoperative. The usual repsonse is to remove the lid and to remove water with a bucket.

The WHO commissioned a study of the groundwater on Lifuka. It was completed by Chester Lao in August, 1985, after the construction of the present water supply system. The report concluded that there were most probably two separate aquifers on the island, and that the reticulated supply was drawn from the deeper, more saline, body of water. The report is discussed in more detail in section 3.

The WHO report recommends further monitoring and evaluation of the groundwater resources before any further development, but it was widely believed that a better quality supply could be obtained by using different wells and/or by more careful extraction from the existing well.

The results of the present study show that, even if this conclusion were correct, there does not appear to be a substantial body of groundwater that can be used without treatment available on Lifuka or the adjacent island of Foa. The upper aquifer of which the WHO report speaks appears to be of very limited extent, and is subject to pollution. It is unlikely to be able to provide a significant fraction of the town's needs.

2.7 The Demand for Water

Individuals' use of water varies widely according to their circumstances. Customs, affluence and climate affect community averages, and within any relatively homogeneous community there will be wide variations from person to person.

The amount of water needed for survival is very low compared with usage in most affluent countries. 5 L per person per day is ample to cater for drinking and cooking needs. All other needs can be met using seawater if necessary.

However, seawater or brackish water is unpleasant to use for washing bodies or clothes, and people avoid it as far as possible. Also, brackish water and seawater are extremely corrosive to metal pipes and fittings, and taps, etc tend to require replacement fairly often.

The quantity of water used depends on the facilities available. In the Tongan situation, the type of bathroom and toilet a family has will be a major determiner of water use. A Tongan bathroom uses a bucket which the person tips over him- or her-self. A European bathroom has a shower, or perhaps a bath. The climate in Pangai is relatively warm, and many Tongans like to bathe twice a day.

Of the types of toilet used in Tonga, only two - the mechanical flush and the pour flush - use any water. The mechanical flush system usually uses about 13 L per flush, while the pour flush uses as much as the user wants to put in, say about 4 L. It appears that in many Tongan households, the toilet is not flushed each time it is used, but rather once or twice a day.

In Pangai, there are virtually no washing machines, so clothes washing can be considered to be done entirely by hand.

Accordingly, a reasonable estimate of water usage per person can be based on the following allowances:

Drinking and cooking (per person per day)	5 L
Personal washing - Tongan bathroom (per bath)	10 L
Personal washing - European bathroom (per shower)	30 L
Toilet flushing - Mechanical flush (per flush)	13 L
Toilet flushing - Pour flush (per flush)	4 L
Clothes washing (per person per week)	20 L
House cleaning (per house per week)	20 L

Thus a reasonable daily allowance for water for a person using a Tongan bathroom and a pour flush toilet would be approximately 45 L, while that for a person using a European bathroom and mechanical flush toilet would be approximately 90 L. Naturally, these values vary widely from person to person. In particular, if hot water were freely available, the amount of water used for bathing, particularly in the European-style bathrooms could be expected to rise dramatically.

Lloyd Belz, formerly WHO consultant on sanitation in Tonga, has also made estimates of water consumption in Tonga, with particular reference to Tongatapu. His consumption estimates (per person per day) for the purposes of planning water supplies were as follows

Using outside toilet - mechanical flush	68 L/person/day
Using inside toilet - mechanical flush	82 L/person/day
"Government quarters"	225 L/person/day

"Government quarters" are houses built by the Governemnt to full western standards, and are generally allocated to expatriate experts seconded to the Tongan public service or to senior Tongan public servants.

Belz's estimates were somewhat higher than what he believed the actual consumption to be at the time that he made them, to allow for increased affluence during the life of projects he was planning.

The two sets of estimates give a useful indication of the range of water consumption likely to be encountered.

2.8 The Necessary Size of Desalination Plant

Based on the existing mix of facilities, it is possible to estimate a reasonable daily water consumption for Pangai-Hihifo, and to use that as a basis for sizing a desalination facility.

The procedure uses the estimates of consumption for various purposes developed above, and takes into account the types of bathroom and toilet that people have.

It will be assumed that each person uses 9 L of water per day, for drinking, cooking, washing and cleaning. On top of that, two baths/showers and two toilet flushes per person will be allowed.

On this basis, the total personal consumption for Pangai-Hihifo would be about 170 m^3/day. A plant of capacity 200 m^3/day would probably cater for all demand, plus a small allowance for down-time. A consumption of 200 m^3/day represents a per capita consumption of approximately 84 L/day - safely in excess of the average daily allowances calculated above, and of those allowed by Belz for Nuku'alofa.

However, it should be recognised that an improvement in the quality and convenience of the water supply will stimulate an increase in demand. In particular, if good water were available on a continuous basis, people would probably take more and longer showers, those without European bathrooms would slowly move to instal them, and the more affluent would start installing hot water systems. In the very long term, water usage would tend towards the levels in the Government quarters in Nuku'alofa. When that occurred, the suggested size of desalination plant of 400 m^3/day would be just adequate.

Also, there would be pressure from the villages of Holopeka and Koulo, and then eventually from villages on the adjoining island of Foa, for an improvement in their water supply, possibly by connection to the reticulation system. The two villages on Lifuka would add about 350 people to the network served by the Tonga Water Board, resulting in a demand increase of up to 15%, while those on Foa would add about 1400 people, resulting in a demand increase of up to 50%.

3. PREVIOUS GROUNDWATER STUDIES ON LIFUKA

There are two recent studies that have covered the island of Lifuka. The first is a general study of water supply in Tonga, conducted by a hydrogeologist seconded from New Zealand, Mr B. C. Waterhouse, in 1986 and the second is one by Chester Lao, a groundwater consultant from Hawaii, on behalf of WHO, conducted in 1985.

3.1 The Waterhouse Report

The salient points made by Waterhouse are:

1. There is a need for systematic data collection to establish the nature of the freshwater lenses and the safe yield from them. Earlier studies had also called for such studies but they have yet to be implemented.
2. On Tongatapu, the pumping of groundwater has resulted in an increase in the salinity of the water coming out.
3. There were problems on Tongatapu with misreading of meters and with unserviceable meters.
4. There are potential problems both with salinity increase due to overpumping of wells, and with the infiltration of pollutants of various kinds, due to poor siting of waste disposal facilities, toilets, animal feedlots, etc.
5. Waterhouse believes that the uncontrolled abstraction from the Pangai wells has resulted in the destruction of the freshwater lens.
6. Village water schemes on Foa had water of acceptable quality (salinity of 100 ppm to 300 ppm).
7. Hand-dug wells that penetrate only a short way into the lens can provide potable water provided the drawoff is limited to that required for individual household purposes.
8. There are potential health risks due to the use of these shallow wells due to possible pollution by both human and animal activities.
9. Waterhouse reports that during the Acting Manager of the Tonga Water Board's emergency visit to Ha'apai (undated), the tap water had a salinity of 1 000 ppm, and that well salinity increased as the wells were pumped.
10. The Tongan Government Geologist should be the first point of contact in any future water resource investigations.

3.2 The Lao Report

Lao spent eight days on Lifuka and Foa, examining the surface and sub-surface geology. Water samples from most wells were analysed. The principal conclusions were as follows:

1. When constructed, the Tonga Water Board wells yielded water that met WHO criteria.

2. At the time of the study, the salinity of the wells was 2 500 to 3 000 ppm.

3. Well No 2 was fresher at the top and saltier at the bottom than well No 1.

4. The reason for the high salinity of the Water Board wells could be overpumping, a thin lens, a modestly thick lens with very thick transition zone, or a combination of all these factors. Only by drilling several deep monitor wells can the nature of the problem be resolved.

5. Many of the private home wells had water considerably less salty than the Tonga Water Board supply. The relatively low salinity of some of the home wells and the phase difference between tidal variations in them and the Water Board wells strongly suggests that they are supplied from a separate aquifer from the basal aquifer. If the two aquifer hypothesis is confirmed by test drilling, the main limestone aquifer has only meagre potential for supplying low salinity water for distribution systems.

6. There should be a moratorium on any further development from the basal water lenses until a program of well drilling and monitoring is completed. The wells should be monitored for salinity bimonthly.

7. The salt content of the Water Board wells can be reduced by two methods - reducing the pumping rate and increasing the pumping time, or drilling horizontal infiltration tunnels. The quantitative effect of these measures is not predictable in advance, and it is not certain that the resulting water will meet WHO standards.

As part of this present study, the author held a meeting with Chester Lao, to review his findings in the light of the measurements taken and described below. Lao concluded that:

1. The freshwater lens in the main aquifer is very thin and easily degraded. It may give water suitable for purposes other than drinking and cooking in all but the driest periods.

2. The near-surface aquifer continues to be the main route for rainwater to run out to the sea, and there may be a small freshwater lens on the western shore of the island.

3. The size of this lens is unlikely to be sufficient to provide the quantity of potable water needed for the whole town.

4. The water in the small, shallow lens is quite likely to be polluted, in the light of the number of latrines dug in various parts of it, and the large number of animals in gardens and near open wells.

5. The results confirm his hypothesis than a layer of saturated clay provides the barrier between the surface aquifer and the basal aquifer, from which the Water Board draws its supply. See Fig. 4.

4. RESULTS OF TEST WELL MONITORING

WHO has had seven test wells drilled on Lifuka and Foa, and these were monitored in conjunction with Richard Stoll of WHO during the mission. Their sites are shown on Figs 5 and 6.

The curves of salinity versus depth are shown in Fig 7 (Foa) and Fig 8 (Lifuka). It should be noted that the figures plotted are salinometer readings, calibrated to sodium chloride solutions. The true total dissolved solids value is a little different, because of the mix of salts actually in the water.

Of the four wells on Foa, none showed any significant freshwater content. On those where sufficient depth was available, there was a steady gradation of salinity from top to bottom.

As a result, one must conclude that the likelihood of finding significant deep groundwater on Foa is small.

On Lifuka, the performance of one well, No 5, showed some hope, in that there is a body of water about 7 m deep with relatively constant salinity. However, the total salinity is higher than the WHO limits at approximately 1 700 ppm, and the organic content is high. The water has a very unpleasant smell. A full mineral analysis of this water is shown in Table 7.

Of the other test wells on Lifuka, both showed a similar pattern to the Foa wells. One well, No 7, was almost dry, with less than 50 cm of water. The salinity of that well doubled from 200 ppm at the top water level (about 3.6 m underground) to 400 ppm at the bottom. This well is located about 500 m from the west coast of the island. Its behaviour suggests that there cannot be a large quantity of potable water available from the upper aquifer that Lao discusses. Use of this shallow water would probably not satisfy the needs of the whole town.

Chester Lao advises some caution in the interpretation of the well data, because of the method of drilling used, and because the wells were not purged after drilling.

At the time these wells were monitored, the Foa village supplies in Faleloa and Fotua were checked for salinity and found to have a TDS of approximately 1 700 and 5 900 ppm respectively.

It is significant to note that Waterhouse and Lao both recorded good quality water from village supplies on Lifuka and Foa. Waterhouse reports on the Acting Manager of the Tonga Water Board's emergency visit to Ha'apai (undated) in which the Faleloa well had a salinity of 100 ppm in the morning and 300 ppm after a day's pumping.

Lao tested the Faleloa well and found a conductance of 1.93 mSiemens, indicating a salinity of about 1 300 ppm, significantly lower than the salinity recorded during this mission in the very dry period of 1987.

The Tonga Water Board wells were monitored during pumping. It was found that when pumping commenced at 5.30 am, the salinity was about 7 900 ppm, and after 4 hours' pumping it had risen to 8 500 ppm, as shown in the laboratory analysis in Table 8. According to the salinometer, the salinity of the second sample was 8 000 ppm. These readings contrast with earlier ones, conducted in moister conditions. Lao, in August 1985, recorded conductivity readings of 8.2 to 10.2 mSiemens from the top to the bottom of the well. This corresponds to a salinity of 5 500 to 6 500 ppm.

All indications from the test wells are that the geological structure of Lifuka and Foa is not in accordance with the classical model of a coral atoll, with a lens of fresh water in porous sand or limestone. It seems unlikely that any substantial freshwater lens will be found that is suitable for drinking without further treatment.

It is also clear that the recent rainfall history plays a large role in the salinity of the water from all the wells discussed.

TABLE 7

MINERAL ANALYSIS OF No 5 WELL, LIFUKA

SAMPLE: 969 - WATER SAMPLE D

pH		6.80
Conductivity, µS/cm @ 25°C		2530
Turbidity, N.T.U.		81
Colour, Pt/Co Units	TRUE 23	APPARENT 480
Molybdate Reactive Silica, mg/L as SiO_2		18.4
Total Dissolved Solids, mg/L		1780
Total Alkalinity, mg/L as $CaCO_3$		347
Total Hardness, mg/L as $CaCO_3$		598
Calcium Hardness, mg/L as $CaCO_3$		400
Magnesium Hardness, mg/L as $CaCO_3$		198
Total Iron, mg/L as Fe		130
Total Managanese, mg/L as Mn		< 0.05
Total Organic Carbon, mg/L as C		294

	mg/L	meq/L
CATIONS		
Sodium, Na	270	11.75
Potassium, K	48	1.23
Calcium, Ca	160	7.98
Magnesium, Mg	48	3.95
Strontium, Sr	1.75	0.04
Soluble Iron, Fe	0.80	0.03
		24.98

	mg/L	meq/L
ANIONS		
Chloride, Cl	485	13.68
Sulphate, SO_4	10.2	0.21
Bicarbonate, HCO_3	423	6.93
Carbonate, CO_3	0	0
Nitrate, NO_3	< 0.5	0
Fluoride, F.	0.55	0.03
	1447	20.85

TABLE 8.

MINERAL ANALYSIS OF TONGA WATER BOARD WELL No 1
(after 4 hours' pumping)

SAMPLE: 968 - WATER SAMPLE C

pH	8.55
Conductivity, µS/cm @ 25°C	12500
Turbidity, N.T.U.	0.40
Colour, Pt/Co Units	TRUE < 1 APPARENT 1
Molybdate Reactive Silica, mg/L as SiO_2	27.9
Total Dissolved Solids, mg/L	8560
Total Alkalinity, mg/L as $CaCO_3$	349
Total Hardness, mg/L as $CaCO_3$	1605
Calcium Hardness, mg/L as $CaCO_3$	575
Magnesium Hardness, mg/L as $CaCO_3$	1030
Total Iron, mg/L as Fe	0.05
Total Manganese, mg/L as Mn	< 0.05
Total Organic Carbon, mg/L as C	1.2

	mg/L	meq/L
CATIONS		
Sodium, Na	2400	104.4
Potassium, K	93	2.4
Calcium, Ca	230	11.5
Magnesium, Mg	250	20.6
Strontium, Sr	4.30	0.1
Soluble Iron, Fe	-	-
		139.0

	mg/L	meq/L
ANIONS		
Chloride, Cl	4240	119.6
Sulphate, SO_4	550	11.5
Bicarbonate, HCO_3	426	7.0
Carbonate, CO_3	-	0
Nitrate, NO_3	6.2	0.1
Fluoride, F.	0.49	0
	8200	138.2

5. ACCEPTABLE WATER QUALITY

There are three facets to water quality. These are:

1. Presence of bacteria
2. Presence of organic or inorganic poisons
3. Presence of organic or inorganic matter which may make the water unpalatable.

In most countries of the world, the first two problems are more common than the third.

The WHO has produced a three volume document, "Guidelines for Drinking Water Quality," (WHO, Geneva, 1984 and 1985), discussing acceptable levels for all types of contaminants.

Earlier editions of the same document listed both "recommended" and "maximum acceptable" levels for inorganic contaminants. The newest edition lists only "guideline values". It states that the guidelines give a quality that "is suitable for human consumption and for all usual domestic purposes, including personal hygiene........Although the guideline values describe a water quality that is acceptable for lifelong consumption, the establishment of these guidelines should not be regarded as implying that the quality of drinking water can be degraded to the recommended level."

The Pangai water supply is deficient in the third category listed above - defined by the WHO as aesthetic quality. However, the salinity of the Pangai supply is so high at times that it is undrinkable by most people's definition and very unpleasant to use for bathing and clothes washing.

What is acceptable depends on what one is used to, and what is available. The WHO's guideline values are reproduced in Table 9.

TABLE 9.

WHO GUIDELINE VALUES FOR AESTHETIC QUALITY

Aluminium	0.2	ppm	
Chloride	250	ppm	
Colour	15	true colour	
Copper	1.0	ppm	
Detergents	-		No foaming, taste or odour
Hardness	500	ppm as $CaCO_3$	
Hydrogen Sulphide	-		Not detectable by consumers
Iron	0.3	ppm	
Manganese	0.1	ppm	
pH	6.5 - 8.5		
Sodium	200	ppm	
Sulphates	400	ppm	
Taste and Odour			Inoffensive to most consumers
Turbidity	5	NTU	
Zinc	5.0	ppm	
TOTAL DISSOLVED SOLIDS	1 000	ppm	

The output from a desalination plant is generally designed to be considerably better than the guidelines listed above. Generally, RO and ED plants are designed to produce water of about 300 to 500 ppm total dissolved solids, and that level is recommended for any plant installed on Lifuka.

If a distillation plant were chosen, it would normally produce much purer water - less than 10 ppm total dissolved solids. Such water is not necessarily more palatable or better than less pure water, and it is often appropriate to blend a little of the feedwater back into the product to give it flavour.

6. METHODS OF DESALINATION

The methods of desalination available on the commercial market are described in detail in Appendix A. Points particularly relevant to their application to Pangai are listed below.

6.1 Distillation

Distillation is the oldest method of desalination and involves evaporating part of the feedwater and condensing it later. The process is very energy intensive, but can utilise low grade waste heat. It can be made more efficient by using several stages of evaporator, where condensing steam from one stage is used as the heat source to evaporate more water at a lower pressure in the next.

It will cope with extremely saline feeds, and the design only changes marginally with varying feed salinity. The product is very pure.

Small plants are generally very expensive compared with the membrane processes described below.

6.2 Vapour Compression (VC)

This method is in principle a distillation process, but the energy source is mechanical. Vapour is compressed to increase its temperature, allowing it to heat incoming feed water and evaporate it at a lower pressure.

Its principal advantages are that the plants can be compact and that they can deal with water of low or high salinity.

Prices and energy consumption are not low compared with membrane plants, but their versatility and lack of need for pretreatment give them an important role.

6.3 Reverse Osmosis (RO)

Reverse osmosis is the newest and fastest-growing method of desalination. It involves forcing pressurised water through a selective membrane that passes water molecules, but not salt.

It has numerous advantages. It is compact, modular in construction, and cheap compared with distillation and vapour compression for small units.

It uses high quality energy in the form of electricity. The energy consumption and the amount and type of chemical pretreatment required are critically dependent on the composition of the water to be desalinated.

6.4 Electrodialysis (ED)

This process also uses membranes, but instead of passing the water through the membrane, draws dissolved ions through alternate pairs of cation-selective and anion-selective membranes under the influence of an electric field.

A relatively recent variant on the process - electrodialysis reversal - requires chemical pretreatment only for very "difficult" feedwaters.

Apart from this potential advantage, the process operates at very low pressure compared with RO, and thus can be plumbed in plastic fittings, with little risk of leakage or pipe failure. Simple pumps are adequate to provide the necessary pressure.

For low salinity feeds, the energy consumption of ED plants can be less than that for RO plants, although the newer low pressure RO membranes have eroded a lot of this advantage.

7. POSSIBLE SOURCES OF WATER FOR DESALINATION

If a desalination plant were built, it could draw its feed water from four possible sources. These are:

1. The existing Tonga Water Board Wells

2. The new low salinity bore (No 5)

3. Shallow wells near the coast

4. The sea.

These will be discussed in turn.

7.1 The Existing Tonga Water Board Wells

These wells provide a relatively large volume of water. The quality of the water is clearly variable, and seems to depend on rainfall. The available evidence of test well logs in the vicinity and on Foa, plus salinity measurements conducted at various times in the past, suggests that there is a substantial body of water available from the aquifer being tapped with a salinity of between 1 000 and 8 000 ppm.

Extracting the required quantity of water without destroying the lens will certainly require additional wells, but there can be no absolute certainty that the wells will not increase in salinity over time.

It appears that there is an area of at least one square kilometre under which the aquifer is accessible.

7.2. The Low Salinity Bore

This bore has a salinity which is beyond the WHO guidelines for drinking water, but still is much less saline than the Tonga Water Board wells. The water also has high organic content, and an unacceptable smell.

Although there is a deposit of relatively low salinity water several metres deep, its horizontal extent is at this stage unknown. It does not extend more than 500 m south, because there is another test well, No 6, that has much higher salinity, there. Its easterly and westerly extent is limited by the land mass to be no more than about 600 m.

Until further test drilling is conducted, it is not possible to estimate the safe yield of this aquifer, or to understand its relationship with the other aquifers that have already been identified.

Subject to the organic content being harmless, the water from this well could be used directly for irrigation for salt-tolerant crops.

The salinity measurements from this bore have been taken from an untapped source, while the salinity of the Water Board wells is taken after years of consistent pumping. It may thus turn out that the new bore has a very low safe yield - totally insufficient for water supply purposes.

The high level of organic content and the dissolved organic gases require a more complex desalination plant than the Water Board wells would.

7.3. Shallow Wells Near the Coast

Among the wells in this category, only the Faleloa and Fotua village supplies were tested during this mission. In view of the relatively limited nature of the possible reserves and the increase in salinity observed in the above wells during the recent dry period, it seems very unlikely that such wells would be able to provide the quantity and quality of water required to supply the whole of Pangai-Hihifo.

7.4. The Sea

The sea provides an effectively limitless source of water. The physical properties of the water are very stable. However, its salinity, of around 35 000 ppm TDS, is much higher than any of the other sources available. Distillation and vapour compression can cope with seawater as effectively as brackish water, but the membrane processes incur considerable capital and operating cost penalties if used on seawater.

On the other hand, the process of seawater pretreatment desalination is now standard, and readily transferrable anywhere in Tonga.

8. ENERGY SUPPLY IN PANGAI

The energy resources on the island of Lifuka are:

Liquid Fuels
Electricity
Wood
Solar energy
Wind Energy

8.1 Liquid Fuels and Electricity

Pangai-Hihifo has an electricity distribution system. It is driven by two diesel generators, each of capacity approximately 75 kVA (about 65 kW).

Most of the day, one generator is sufficient to provide the town's needs, but for about 3 hours each evening, both are run. According to the station's meters, the output of the station is typically around 350 kWh per day, although the raw output of each the generator windings is about 630 kWh.

The fuel consumption of the plant is around 250 L/day. This corresponds to an energy content of 2680 kWh. It thus appears that the station is operating at a sent-out thermal efficiency of around 13%. 87% of the energy content of the fuel is being dissipated as station services and as heat in the cooling water and the exhaust. Of the total energy consumed, about 76% is dissipated as heat in the station.

Part of the reason for this inefficiency is the fact that the generators operate most of the time at very low load. A typical daily load curve is shown in Fig. 9. The maximum demand on that day, August 12, was about 50 kVA, within the capacity of one of the generators, even though two were running. The maximum demand only lasts a very short time, with the demand for about 17 hours of the day being less than 15 kVA.

Accordingly, there appears to be about 2000 kWh/day of waste heat available at the power station. If this heat were available as a uniform flow over 24 hours, it would be sufficient to produce about 3 m^3/day of fresh water from a simple single stage waste heat still. If the distillation plant were more complex - say a 6 effect plant, then it would be sufficient to produce about 18 m^3/day.

The power station uses diesel fuel to generate electricity. This fuel is supplied in 200 L drums shipped from Nuku'alofa. It could also be used for providing heat for a distillation plant.

It is noted with some concern that the power station is one of the largest consumers of the reticulated water supply. If the water is used directly for plant cooling, the dissolved solids will most probably cause scaling in the radiators and engine, reduce the efficiency of the cooling system, and the efficiency of the energy conversion, and eventually cause the plant to stop functioning.

8.2 Solid Fuels

The main source of solid fuels is coconut residues and senile coconut trees.

A detailed survey of solid fuel resources has recently been conducted in Tonga by a Graduate Student from the Environmental Studies Centre at the University of Tasmania. Results are not yet available.

Visual impressions suggest that there is no great abundance and it is needed for cooking.

Senile coconut trees can also be used as a source of construction materials, and in many places this represents a more rational use of the resource than combustion.

The energy content of timber depends on its nature and condition, but an estimate that is useful for approximate calculations is 16 GJ/tonne.

8.3 Solar Energy

Solar energy resources are quite high compared with other sites in the world, at about 2150 sunshine hours a year. Actual energy flux has not been measured, but is likely to be about 25 MJ/m^{2}day.

Solar energy can be used to produce both thermal energy and electricity. If thermal energy is produced, the amount of energy available per m^2 depends critically on the temperature at which it is required. The collector output from flat plate collectors with copper oxide selective surface is indicated below:

Temperature Reqd	Output (MJ/day)	Av Output (kW)
55	9.8	0.11
65	8.4	0.10
75	7.0	0.08
85	5.5	0.06

In very dry periods, when desalination is most needed, the output of the collectors will be somewhat higher (of the order of 10 to 20%) than the typical figures given above.

A single effect, inefficient, distillation plant can operate comfortably at 65°, while a very efficient multiple effect plant will need a higher temperature, preferably 85° or more. The very highest efficiencies can only be achieved with temperatures around 100°, but using such high temperatures may cause problems with scaling.

Flat plate collectors are available in various qualities. There are two types of selective surface that would be suitable in this application - copper oxide and black chrome. Copper oxide collectors are available ex Australia for about $A 77/m^2, while black chrome collectors cost about $A 97/m^2. The calculations below are based on copper oxide surfaces, although there could be some economic advantage in using black chrome for the higher temperature plants.

Other types of collector, such as stationary concentrating collectors and evacuated tubular collectors, have not yet been commercially proven. Tracking collectors are capable of producing higher temperatures, which are not really useful for distillation, and the cost per unit energy collected is higher than for simpler collectors.

If electricity is produced, one can expect a conversion efficiency of about 9% from photovoltaic cells. Currently most of the cells on the market commercially are monocrystalline cells and ribbon cells. They cost about $A 7 per peak watt output in large quantities. More advanced production techniques and cell configurations are soon to come onto the market. In particular, amorphous cells show great promise of significant cost reductions, although their conversion efficiency is a little lower than that of the monocrystalline cells.

In order to provide a reasonably even production rate from the plant, energy storage is needed. Currently this is usually in the form of lead-acid batteries.

8.4 Wind Energy

In most locations wind is very variable and wind systems require far more energy storage than equivalent solar energy systems.

A wind generator produces nothing at wind velocities below its cut-in speed, and its rated power at and above rated speed. Between these two limits, its output is proportional to the cube of the wind speed. If the wind speed becomes too high, the turbine cuts out completely. Thus an average speed is of little assistance in calculating the size of windmill needed for any particular application. A histogram showing the frequency of different wind speeds is best for this purpose. So far, wind data made available for most countries under study is limited to average speeds, so very little can be stated with certaintly about the wind resource.

The data suggest that use of wind energy is possible, although speeds are relatively low, and very large turbines would be needed. Suitable wind turbines must be chosen with care, so that the cut-in speed and rated speed are as low as possible. Some products that could do the job are:

NAME & MODEL NO.	RATED POWER kW	RATED SPEED m/s	CUT-IN SPEED m/s
Dakota Lynner	50	8.0	2.7
	15	10.2	2.7
	8	10.2	2.7
	5	10.2	2.7
	3	10.2	2.7
	2	10.2	2.7
Mehrkam Energy Dev. Co	40	11.2	2.2
Windworks Inc	10	9.0	3.5
Astral-Wilcon AW 10B	10	10.0	3.5
Jacobs Wind Energy System	10	12.0	3.2
Wind Power Systems 10-9-1G-1P-60	9	9.0	4.0
10-8-BC-48-PM	8	9.0	3.0
American Energy Savers Reinke	5	11.0	2.5
Aerowatt SA 4100FP7G	4.5	7.0	2.0
M.A.N.	11	8.0	3.5

There are also other products on the market, with higher cut-in speeds. They would need to have their designs modified to be useful on Ha'apai.

Typically, the average output of a wind turbine system is of the order of 10% to 20% of its rated power.

Optimum choice of wind turbine depends on the wind speed distribution, which is currently unknown. Prices have not been sought for the above products, but turbines of rated power 20 kW typically cost in the range $30 000 to $35 000, depending on type and make. Higher powered turbines are now coming onto the market, with prices around $A 1 600 per kW.

9. METHODS OF PROVIDING 400 m^3/day OF DESALINATED WATER

9.1. Distillation Plants

A distillation plant of capacity 400 m^3/day is of relatively small size, and there are a number of possible suppliers. The plant characteristics and energy consumption depend very little on the salinity of the feed.

There are two possible evaporation systems that could be used - multiple effect and multistage flash. Multistage flash is the more widely used system, although it appears that multiple effect is easier to control and can more easily be made to be energy efficient.

Depending on the design, the plant will have an energy consumption of between 2300 MJ/m^3 and 200 MJ/m^3. The more efficient, the higher the capital cost will be, and the more care will be needed in operation. Nonetheless, there are high efficiency plants in trouble-free operation in a number of places around the world, and there is no reason to believe that a plant consuming about 200 MJ/m^3 could not operate successfully in Pangai-Hihifo.

Capital costs for distillation plants in the size range being considered tend to be rather high, compared with other processes. A reasonable estimate for a six to eight effect plant of 400 m^3/day capacity is of the order of $A 1 000 000.

All distillation plants require pumps to extract the product and brines streams, and most also require a vacuum pump to maintain sub-atmospheric pressure and withdraw non-condensible gases. These pumps must be driven by electric motors, or possibly by diesel engines.

The amount of pumping energy depends on the type and size of plant being used. Generally, small plants have less efficient pumps than large plants. A well designed plant can use less than 1 kWh/m^3 of product, but if the design does not make allowance for minimisation of pumping energy, the consumption can be many times this figure.

The type of thermal energy needed is heat at less than 120°C, and appropriate sources of energy are:

9.1.1. Liquid fuels

Any liquid fuel will do the job, but all conventional fuels must be imported. It would be most practical to use the same fuel as the power station uses - ADO - a relatively clean fuel. Heavy fuel oils could also be used, with some cost saving at the point of purchase, but it would then be necessary to have two different types of fuel available at Ha'apai. The added difficulty of using the heavy fuels makes it a doubtful proposition to use them in this particular application.

A 400 m^3/day plant with energy consumption about 200 MJ/m^3 would require about 80 GJ per day of thermal energy. It would also require electrical energy for the pumps. This would be at least 1 kWh/m^3, but unless special design precautions were taken, it could be as high as 4 kWh/m^3. Based on the more efficient figure, the plant would consume 400 kWh/day.

Thus the distillation plant would consume about 1.75 tonnes of ADO per day. According to the Department of Lands, Survey and Natural Resources, the true tax free cost of ADO landed in Ha'apai is about $0.45/L, or $374/tonne.

. The marginal generating cost of electricity (excluding capital items) in Tonga is about $0.19/kWh.

An efficient plant would thus cost about $ 730 per day, or about $ 266,000 per year to run, for energy alone. Labour and chemical costs could bring the running cost up to almost $ 300,000.

9.1.2. Solid fuels

Based on a calorific value of 16 GJ/tonne for coconut residues, a wood-fired distillation plant would consume about 5 tonnes of wood a day, or 1800 tonnes per year. It would also require the same amount of electricity as an equivalent oil-fired plant.

A distillation plant using fuelwood would require a suitable furnace and boiler. Wood-burning furnaces are generally more difficult to control than liquid fuel furnaces, and in general need relatively constant supervision. The major risk is that the furnace produces too much heat, causing scaling in the plant, although good design could reduce the likelihood of this happening.

To the author's knowledge, there is no wood-powered distillation plant in operation, although it is technically possible.

9.1.3. Solar energy

In the prevailing climate in Tonga, conventional flat plate collectors are suitable for driving all but the highest temperature distillation plants.

The approximate output of thermal collectors as a function of temperature has been indicated in section 8.

In practice, the energy efficiency of a distillation plant is somewhat limited by the top plant temperature. If the top temperature were 65°C, it would be expensive and difficult to build a plant of more than about 7 effects, or with an energy consumption less than about 400 MJ/m^3 of product. If the top temperature were raised to 85°C, then it would probably be possible to have about 12 effects, with an energy consumption of about 220 MJ/m^3.

Assuming that all solar energy available was collected by the collectors, and that there are no losses in energy storage, the collector areas needed for the two types of plant are as follows:

		Area
Inefficient Plant	(65°)	19000 m^2
Efficient Plant	(85°)	16000 m^2

The purchase price of the collectors for a solar distillation system can thus be summarised as follows:

Inefficient Plant	$ 1.46 million
Efficient Plant	$ 1.23 million

Transport and installation costs, plus energy storage facilities would add approximately 60% to the above prices.

9.1.4. Waste Heat

For the purposes of this assessment, distillation plants that use solar energy can be considered identical to those using waste heat. Their energy consumptions are the same.

However, normally, waste heat plants are single or dual effect, reflecting the low cost of the waste heat, and the normal balance between water demand and power demand. Provided that the waste heat produced by a diesel generator was adequate in quantity and temperature, there would be no reason not to use a more efficient plant.

Waste heat is usually available in association with industrial activities, power stations and other heat engine applications. The only available source in Pangai is the power station.

Generators such as the ones installed in Pangai are generally run with a cooling water temperature around 65°C. If a 7 effect plant were used in conjunction with it, then up to about 18 m^3/day of water could be produced from the power station.

This falls far short of the total requirement of 400 m^3/day.

9.2. Reverse Osmosis

Reverse Osmosis requires mechanical energy, which is usually supplied from an electric motor, although other sources, such as direct coupling to an internal combustion engine or a wind turbine are possible.

The capital cost and energy consumption of reverse osmosis depends on the salinity of the feedwater, the desired product purity and on the sophistication of the plant concerned.

For the size being considered, one can assume that the motor and pump combination are 60% efficient. It is possible to use more efficient pumps, at the expense of capital cost and need for maintenance.

The plant configuration and cost will depend on which water source is utilised. Seawater will require special seawater membranes, and will operate at a high pressure.

Typically, modern seawater reverse osmosis plants operating with skilled staff have energy consumptions around 9 kWh/m^3 of product. Figures as low as 6 kWh/m^3 have been claimed from plants with energy recovery turbines on the reject stream.

Plants installed on ships are usually designed to be as simple as possible, and are not nearly as energy efficient as those discussed above. Typically, a small plant will consume about 25 kWh/m_3 of product.

The simpler plants usually do not have any form of chemical pretreatment. In order to prevent the membranes from clogging, they purify only a small proportion of the feedwater (10% or less). This means that 90% of the water that is pressurised in the unit runs out to waste, losing its hydraulic energy. In the more sophisticated plants, only about 70% of the feed is so rejected, and in the newer, larger plants energy recovery turbines are used to recoup the hydraulic energy in the waste stream. The more efficient plants all use chemical pretreatment - usually about 5 different steps, including filtration.

As in distillation, there is a clear trade-off between plant complexity and energy consumption. Membrane life is also traded off in the simpler plants. Thus in large land-based plants with full pretreatment, manufacturers will guarantee a membrane life of five years, while in small marine plants it is not uncommon for membranes to be destroyed in a matter of months.

Small plants are often less efficient than larger ones, because it is difficult to obtain efficient pumps and motors in small sizes. This becomes particularly marked with plants of output less than about 2 m^3/day.

On remote islands, particularly, the cost of energy is far more significant than on the mainland of a large industrialised country. It is thus important for energy consumption to be minimised, consistent with the operating skills to be found where the plants are located.

If the salinity of the water is lower, the energy consumption will also be lower. For lower salinity water it is possible to use brackish water membranes, and also to recover a larger proportion of the feedwater. In the case of the Tonga Water Board wells, with salinity reaching approximately 8 000 ppm in dry periods, it would be (just) possible to use brackish water membranes and a lower pressure.

With a pressure of 2.6 MPa one could expect an energy consumption of about 3.5 kWh/m^3, yielding a daily energy consumption of 1 400 kWh and a consumption rate of 58 kW.

If it were possible to use the low salinity aquifer found during this mission, then it may be possible to use a lower pressure and higher recovery rate than for the Tonga Water Board wells. Such a plant could run at a pressure of 1.5 MPa and may consume approximately 1.5 kWh/m^3. It would require a daily electricity supply of 600 kWh, and a consumption rate of 25 kW. The nature of the feedwater requires some pretreatment, whose energy consumption has been allowed for in the estimate.

The range of energy consumption possible for seawater plants has already been indicated. Similar design factors apply to brackish water plants, and the figures given above indicate a reasonable value, given the local conditions. It is possible to get lower energy consumption by using more pretreatment and a higher conversion rate, at the expense of greater risk to the membranes.

In summary, typical energy consumptions are:

Plant type	Power kW	Energy/m^3 kWh	Energy/day kWh
Seawater, low efficiency	416	25	10 000
Seawater, high efficiency	133	8	3 200
TWB well water	58	3.5	1 400
New well	25	1.5	600

Capital costs (FOB Sydney) for the RO units are as follows:

Seawater	$ 500 000
8 000 ppm water	$ 400 000
1 700 ppm water	$ 500 000 (including pretreatment)

The sources of energy available for driving the plants are:

Liquid fuels (generally via electricity)
Solar energy
Wind energy

9.2.1. Electricity and Liquid Fuels

It can be seen from the consumption figures above that only the brackish water options could be operated from the existing electricity grid on a full-time basis. The peak demand on the system is about 50 kW, and the generating capacity is about 130 kW.

The electricity demand is very peaky, as discussed in section 8, with one of the two generators able to supply the demand for all but about three hours of the day. The possibility thus exists of building a plant which is slightly (say 25%) oversized, and operating it only in the off-peak periods for electricity demand. Under such circumstances, the Electric Power Board's marginal cost for electricity of around $0.19/kWh is a reasonable estimate of the true cost to the nation of providing extra power to the desalination plant.

The daily and annual operating costs for all the RO plants discussed above would then be as follows:

	Daily	Annual
Seawater plant - inefficient	insufficient capacity	
Seawater plant - efficient	insufficient capacity	
Brackish water plant - existing wells	$ 270	$ 96 000
Brackish water plant - low salinity well	$ 120	$ 42 000

Another option for operating the plant is to instal a dedicated diesel generator with output equal to the consumption of the desired plant. In that case, the delivered cost of diesel fuel to Pangai is the most relevant basis for determining operating costs.

Provided that the generators are carefully chosen and the plant is run at constant output 24 hours a day, it should be possible to achieve a sent-out thermal efficiency of about 30%. The fuel costs for such a plant, based on a fuel price, landed in Ha'apai of $0.45/L are about $0.15/kWh, in line with the Tonga Electric Power Board's marginal costs.

Maintenance costs for the diesel plant must also be considered. However, if staff were on hand to deal with the desalination plant, the maintenance of the generators would become part of their duties.

In practice, the generator and reverse osmosis plant would both be slightly oversized, and product would be stored to allow for maintenance outages. It could also be useful to divide the plant and generating capacity into two separate units, so partial production can be maintained from one unit while the other is being serviced.

Diesel generators require regular maintenance, and it would probably be wise to provide, say, three generators, of which any two were capable of driving the whole plant.

9.2.2. Solar Energy

In view of the relatively high cost of liquid fuel and generator maintenance in remote locations, renewable energy sources are a tempting possibility. Solar energy is a variable and unpredictable energy source. There are two limiting cases which define possible approaches to operating a reverse osmosis plant using solar energy. These are:

9.2.2.1 Continuous operation

The plant operates day and night, during sunshine and cloudy periods. This is achieved using a solar array much larger than that needed to power the plant on a sunny day, and batteries to store energy surplus to the plant's immediate needs.

As the battery storage system is inherently only about 70% efficient, there are losses involved in using this system.

Simulations have been used to calculate the photovoltaic cell area and battery capacity needed to provide almost continuous operation. Based on providing 90% availability, these are as follows:

	Cell Area m^2	Battery Capacity kWh
Seawater plant - inefficient	39 000	9 700
Seawater plant - efficient	14 800	3 800
Brackish water plant - existing wells	6 500	1 700
Brackish water plant - low salinity well	2 800	700

Current battery costs are about $A 190/kWh of useful storage, while photovoltaic cells cost approximately $A 640/$m^2$, giving the following purchase costs for the major components of the energy supply system of the example reverse osmosis systems:

	Cells	Battery
Seawater plant - inefficient	19 000 000	1 260 000
Seawater plant - efficient	6 200 000	500 000
Brackish water plant - existing wells	2 700 000	219 000
Brackish water plant - low salinity well	1 150 000	95 000

It can be seen that the capital cost of the energy sub-system is quite high - higher than that of the desalination plant itself. The batteries are more than a capital cost, in that they need replacement approximately once every three to five years, and they also need regular inspection and maintenance.

The life and reliability of the batteries can be improved by using nickel-cadmium cells instead of the traditional lead-acid cells, but nickel-cadmium batteries cost about five times the price of lead-acid batteries.

9.2.2.2 Intermittent operation

Another approach is to abandon the idea of running the plant continuously. A number of different operating philosophies are possible, for example:

1. Operate the plant only during daylight hours, and use a larger installed capacity to obtain the same average output
2. Build a plant that can run at differing throughputs depending on how much solar energy is available. This would probably also run only during daylight
3. Build a plant that is not intended to operate except in bright sunshine.

All these designs decrease the amount of battery storage needed, but none can totally eliminate the battery, because the reverse osmosis plant requires a certain minimum pressure to produce water of acceptable quality, and the membranes can only stand a certain maximum pressure. In seawater desalination, the difference between these two pressures is not very great, but in brackish water desalination, it may often be possible to allow the pressure to vary over a reasonable range.

The first two approaches are applicable to plants intended to run all year round, and by reducing the proportion of energy passed through the battery they can be more efficient than a plant which operates continuously.

The third approach is specifically intended for areas where cloudy skies rarely occur during extended dry periods.

Detailed design of such plants is beyond the scope of this report, but one conceptual design would involve an RO plant in two sections - one section with twice the capacity of the other. This would allow the plant to operate at optimum pressure at three capacities - ie

low - smaller section only
medium - larger section only
high - both sections.

A suitable operating strategy would be to have a small battery which would be on charge whenever the available energy was insufficient to run the smaller section, or when there was more energy available than the operating section of the plant needed, but less than enough to run it at the next level of capacity. At the end of each day, any excess battery capacity could be exhausted by running the plant at any appropriate level.

Provided the logic and control components are reliable, this strategy provides an energy efficient plant with a minimum of storage and complexity. The capital cost of the plant will not be much lower than than one for continuous operation, but the operating costs will be lower, because the battery bank is much smaller.

9.2.3 Wind Energy

The design choices for a wind powered RO system are similar to those for a solar powered system, but there is no need to differentiate between night and day. Wind fluctuations are usually less predictable than solar radiation fluctuations, so any system intended to operate only in times of continuous wind would need to be carefully designed. The correlation between dry periods and good wind is not as good as that between dry periods and high solar radiation. On the other hand, the capital cost per unit of peak output of wind turbines is considerably less than that of photovoltaics.

There are several windmills installed in Tonga, mainly for water pumping. Their capacities are relatively low, compared with the energy required for a 400 m^3/day desalination plant. Several of the windmills seem to be out of service, as was the one at the Tonga Water Board wells on Lifuka at the time of this mission.

Detailed wind records are needed to calculate the appropriate size of wind turbine for this application. An approximate calculation of the swept area required for any given power output has been used by Langworthy, in his Wind Powered Electricity Information Package, published by CRRERIS, and his method assumes that it is possible to use an average efficiency with the average wind speed.

The lowest salinity water available would require about 220 000 kWh per annum, or an average of about 25 kW. The average power available from a wind generator is:

$$P = C\ D\ v^3$$

where P is the average power (W) per unit area
C is the turbine efficiency, assumed here to be 0.2
D is the air density, assumed here to be 1.2 kg/m^3
v is the average wind speed, set here to 4 m/s

Thus the energy per unit area is approximately 15 W, and to get 25 kW, the total swept area of the blades would need to be 1 700 m^2. If one chose the largest unit on the list in section 8, the Merkham Energy Development model 4-225, one would need about 4 windmills each with diameter 23 m.

One could also choose larger wind turbines which have been developed for coupling to electricity grids, but such plants are not really in the commercial domain at this stage.

A budget price for a wind turbine of diameter 23 m is approximately $A 80 000. Towers would need to be constructed for them and some form of power conditioning equipment would be required. Thus the energy collection subsystem could cost approximately $A 450 000, considerably less than photovoltaic cells to do the same job. On the other hand, the battery requirement would be higher, probably more expensive than the wind turbines. Design of the storage requires information on calm periods, which is presently not available. It may be more practical to use a diesel-powered backup, or draw energy from the existing power station when necessary.

One example given by Langworthy is for a system with 4 days' storage. If that level of storage is necessary on Lifuka, then a system for desalinating the TWB wells would require a battery bank costing $ 456 000.

9.3 Electrodialysis

Electrodialysis is only applicable to the two brackish water sources.

The energy consumption is dependent on the water quality required and the ambient temperature. For product comfortably within the WHO standards, it is likely to be around 1.3 kWh/m^3 for the low salinity supply and around 8 kWh/m^3 for water of salinity of 8 000 ppm, such as may come from the Tonga Water Board wells.

All the remarks made on energy supply for the RO systems can be modified to apply to ED. The energy consumption of the ED plants is approximately equal to that for the corresponding RO unit for the low salinity water. For the Tonga Water Board wells, the ED energy consumption is over twice that for the corresponding RO unit. Using ED instead of RO for this application would thus involve an annual energy cost penalty of approximately 290 000 kWh, costing approximately $T 55 000 at marginal cost rates.

Capital cost estimates for suitable ED plants are $ 375 000 for the low salinity feed and $ 410 000 for the 8 000 ppm feed.

It appears, then, that ED can only be an interesting proposition for the lowest salinity source.

On the other hand, ED is more easily adaptable to unusual situations. It is possible to vary the pumping rate and the stack current to match the process to varying feed salinity. Reducing the stack current density is a way of reducing energy requirements.

9.4 Selection of Desalination System

Of the four types of desalination system available, ED is suitable for one type of water source. Approximate quotations received suggest that ED would be cheaper than RO for the low salinity feedwater. However, the low salinity feed requires degasification, chlorination, clarification and filtration before it can be used, and the resulting plant would be relatively complex. Without a drilling program, it is not possible to say what the safe yield of this feed is.

Feedwater from wells of the quality of the Tonga Water Board supply, feeding an RO plant, would result in a relatively simple and energy efficient plant using a water source whose adequacy was relatively certain.

Distillation requires a lot of energy, and is best suited to seawater, and/or situations where waste heat is available. The capital cost of distillation cannot be justified in this situation, since there is not enough waste heat available to produce more than a few m^3/day of water.

Distillation can produce very concentrated brine, and could thus be used in a joint salt-making and distillation operation. However, such an operation produces interdependent industries, without any significant advantage over separate salt-making and desalination plants.

Salt production using solar evaporation could be viable in its own right on Lifuka, and could replace an import with a locally produced commodity. It is a relatively low technology industry, requiring only expertise as the imported input.

Vapour Compression is also best suited to seawater, and consumes far more energy than RO, especially if the water is brackish. Its capital cost is also higher than that for RO.

RO is applicable to all waters found in Tonga, although the detailed design and membrane selection would differ depending on the feedwater. There is keen interest in RO within the Tonga Water Board, and three technicians have been to an RO training course in Japan.

The capital and running costs of the various options using conventional energy are estimated in Table 10. Capital costs for RO are based on budget quotes from large suppliers, whose prices may be of the order of 30% higher than smaller firms who do not have the reputation of the large companies. The capacity of the smaller firms to provide service and performance guarantees varies from firm to firm.

TABLE 10

400 m^3/day DESALINATION PLANT - CAPITAL AND OPERATING COSTS

Method Water Source	Distillation any	RO TWB wells	RO New well	ED New well
Capital Cost	1 000 000	400 000	450 000	375 000
Installation	100 000	100 000	120 000	120 000
Capital Recovery (including interest)	144 650	65 750	74 955	65 093
Energy	187 000	97 000	42 000	42 000
Consumables	30 000	66 000	66 000	45 000
Labour	8 000	10 000	10 000	10 000
TOTAL	369 650	238 750	192 955	162 093
Cost/m^3 (at plant)	2.80	1.81	1.46	1.23
Cost/m^3 (excl cap rec)	1.70	1.31	0.89	0.73

Table 10 also shows the quantifiable operating costs. It includes a capital recovery term, based on the concept of borrowing 100% of the capital, and repaying it, with interest, in equal instalments over the life of the plant. The plant life was assumed to be 15 years and the interest rate was taken as 10% (believed to be the ruling rate in Tonga). At the end of the 15 year period, one can repeat the process. Thus replacement costs are fully accounted for.

Cost per m^3 is based on 330 days per year of full operation. Distribution costs are excluded, and it is reasonable to add the present water charge ($0.27 per m^3) to that calculated in the table to get the total cost. If capital costs are excluded from the water cost calculation, the price per m^3 drops, but even under the cheapest possible (not necessarily achievable) scenario, the cost including reticulation costs will be about $1.00 per m^3.

While use of the new well has some advantages as far as energy consumption and water cost are concerned, it requires additional treatment to make the water suitable for desalination and potable. The processes required are degasification, flocculation and clarification and filtration. These processes all require additional equipment. The combination of the extra complexity, the additional pumping energy and the additional capital cost make the use of the water from the new wells less attractive.

The size of the reserves in the lens supplying the new well is as yet unknown. On one side the presence of another bore with higher salinity defines its maximum extent, but in the other directions, additional bores would need to be dug to determine the safe yield. Until that is known, it is not possible to recommend basing the design of any desalination plant on use of that well.

If a plant of capacity several hundreds of cubic metres per day, operating from the main aquifer (1 000 to 8 000 ppm), were to be constructed in Pangai-Hihifo, the preferred choice is RO. RO has the advantage of having a wide range of competitive suppliers, and being applicable to seawater. Thus expertise developed on Lifuka could be transferred elsewhere in the Kingdom, where the only reliable feedwater was seawater.

ED could be reconsidered if adequate yield were available from the new well, but until a drilling program is complete, no recommendation for its use can be made.

Although there is an apparent saving associated with the possible use of the new bore, its potential value should not be overestimated. The additional pretreatment needed for the type of water encountered will necessarily involve a more complex plant than the Water Board wells. As a result, one can expect more problems, which will be more difficult to isolate and rectify. These will cause costs which are essentially unquantifiable at this stage.

In an ED plant, the consumable parts are the electrodes. The membrane stack can be dismantled, cleaned and reassembled. In a situation where there is a skilled and well-motivated operating team, it could be expected that they could keep the membrane stack going for many years. However, dismantling such a stack, cleaning it, finding leaks and reassembling it is a time-consuming and painstaking job, and if it had to be done, could take a long time, during which the plant would be out of action.

On the other hand, the amount of cleaning that can be done to misused RO membranes is limited. But they and the other vulnerable part, the pump, can be exchanged in a very short time, and the plant can be restarted. In a well-designed and maintained plant, RO membranes last about three years, but if they are not treated correctly, they can wear out in a few months.

It has been implicit in the analyses carried out above that the plants considered were as simple as possible, in order to minimise maintenance difficulties. Recently, a new company, the Reliable Water Company, has announced that it intends to market a range of RO plants with "artificial intelligence". The aim of the design is to make a control and monitoring computer sense operating problems and correct them by altering parameters where possible. Where that is not possible, it will diagnose the problem, call for a technician and issue instructions for the repair. The RO plant itself will naturally require a lot of monitoring and control equipment, which would not be installed on a normal plant.

The company proposes to offer the product on the basis of selling water, not the plant itself. It is an interesting development, and if it proves itself, it may have application to situations like Lifuka, despite the fact that it will be a very complex piece of machinery.

9.5 Renewable Energy Plants

There are no solar or wind-powered desalination plants of the size stipulated that can be called "commercially available". Any application of solar or wind energy to the Pangai water supply will thus involve some new combinations of existing technologies.

There have been a number of solar desalination plants constructed in different locations in the world. Generally, there have never been more than two of any one design built. There are also a few wind-powered RO plants, and a recent Australian study has suggested that wind-powered ED was more economical than wind-powered RO for low salinity water. This conclusion is not accepted by all RO plant manufacturers.

The component prices for solar plants have been indicated in the text above. An approximate indication of the total capital cost of solar plants is given below.

TABLE 11

APPROXIMATE CAPITAL COST OF SOLAR DESALINATION PLANTS

Plant Type	Desalination	Collectors	Storage	Installn	TOTAL
Distillation	1 000 000	2 000 000*	160 000*	600 000	3 760 000
RO - TWB Wells	400 000	2 700 000	219 000	500 000+	3 819 000
RO - New Well	450 000	1 150 000	95 000	400 000+	2 095 000
ED - New Well	375 000	1 150 000	80 000	300 000+	1 905 000

* Includes photovoltaics and batteries for pumping.
\+ Includes minor items and power conditioning.

It can be seen that if the solar option is adopted, the relativities in capital cost change, and the distillation option becomes more attractive, although detailed quotes would be needed to choose between the options in the table. Distillation would have the advantage of being able to operate on any feedwater, and of being able to produce concentrated brine for salt manufacture.

Energy costs, as shown in Table 11, would be saved if one went from conventional to solar energy, but there would be additional operating costs associated with the collector array, battery maintenance and battery replacement. In economic terms, the annual saving of less than $100 000 on the TWB RO system would cost over $ 3 million in capital cost. This is clearly not justifiable, economically.

As stated above, there is insufficient information available to be able to give reliable indications for wind-powered plant costs. However, it is in the nature of the water supply problem, that when it is at its worst, the supply of sunshine will be relatively good. This inverse correlation does not necessarily hold good for wind. If the example given above of 4 days' storage were realistic for Lifuka, then solar power would be more attractive than wind power. The possibility of wind power backed up by diesel generators still remains.

9.6 Possible Suppliers

RO has been identified as the most likely of the desalination systems to be employed on Lifuka. There are many possible suppliers. The closest country with significant expertise in desalination is Australia. Three possible suppliers are:

Permutit-Boby, Wattle Road and Short St, Brookvale, NSW, 2100

NEI John Thompson Australia, 39 Waterloo Road, North Ryde, NSW, 2113

Aquapore, 20 Picken St, Silverwater, NSW, 2141.

ED may be an option if the No 5 well can be used cost-effectively. There are not many suppliers of ED equipment. The only two known to us in Australia are:

Austep, 499 St Kilda Road, Melbourne, Vic, 3004

Permutit-Boby, Wattle Road and Short St, Brookvale, NSW, 2100.

Austep are the agents for Ionics Inc, while Permutit-Boby are the Australian arm of the UK company that is licensor to Ionics of part of the process.

9.7 Environmental Effects

A desalination plant (no matter what type) will have the following effects:

1. It will use energy
2. It will create a stream of pure water and a stream of concentrated brine
3. It will cause the consumption of water in the community to increase
4. It will increase the rate of withdrawal of water from the ground
5. It will have a visual impact.

If a conventional plant is selected, the energy conversion process will increase the amount of air pollution. Compared with Nuku'alofa, or with larger cities, the level of air pollution generated around Lifuka very low. While this plant account for a significant proportion of the pollution produced, it will be low in absolute terms.

The stream of concentrated brine will have to be disposed of in some way. The most convenient way is by release into the sea. Precautions will need to be taken in siting the outfall, in order to ensure that it dissipates into the seawater without forming a stagnant pool of concentrated brine, which may harm marine life.

Additives are often used in desalination plants to prevent scaling, and to clean the membranes. The amount of antiscalant used is a few parts per million. The anti-scalants have been approved for discharge into seawater in many places throughout the world, and it is not anticipated that any difficulties will arise on Lifuka. Cleaning compounds are used in greater concentrations, and it may be necessary to control their release so that they are diluted when they reach the sea. Cleaning is an operation that takes place about once a week.

The effect on the environment of greater water use by the population is not predictable. It may result in greater moisture content of the surface soils in some places, but no serious consequences can be foreseen at this stage. On the other hand, one would expect a higher standard of cleanliness and a reduction of infectious diseases.

Increased withdrawal of groundwater has already been discussed above. By spreading the demand over a sufficient number of wells, adverse effects cna be avoided.

The visual impact of the plant will be significant, but not dominant. The plant will be considerably less intrusive, visually, than the telecommunications station, and can, if desired, be surrounded by natural vegetation to lessen its impact.

10. PROJECT IMPLEMENTATION

10.1 Plant Siting

All plants require a feedwater input, a product output and a brine reject output. They also require an energy supply, which could be from the Tonga Electric Power Board's mains, or from a local diesel generator.

The feedwater will come from the wellfield, the product will go into the reticulation system, and the brine can be discharged into the sea.

The plant location is not critical. It would be simplest to locate it where it could hook directly into the reticulation system, and discharge directly into the sea, and use a minimum of piping from the well-field. The plant should be easily accessible from the town and the wharf. These constraints cannot be satisfied simultaneously. The availability of electricity is not critical, since it is unlikely that the existing cables could cope with the additional load, but it would be useful to be able to use existing poles.

There are benefits in locating the plant on the well-field, since it puts all the equipment close together. On the other hand, the island is not very large, and some separation between wells is desirable.

On balance, it can be said that if the wells were dug on the southern end of the island, in the area of the existing Water Board wells, the plant should be somewhere in the area marked on Fig. 10. If a suitable area cannot be secured, then other sites could be used, with the major penalty being extra piping.

10.2 Co-requisites to Successful Implementation

If the desalination plant were supplied and installed on Lifuka, a number of steps would need to be taken concurrently with its commissioning, to ensure that it provided the benefit intended, and that it had funds to continue operating. These are discussed below:

10.2.1 Feedwater Supply

The current source of water is two wells, relatively close together, whose salinity ranges up to 8 500 ppm in dry periods. Installation of a desalination plant of capacity 400 m^3/day would result in a withdrawal from the wells of about 800 m^3/day. Currently, the usage averages about 57 m^3/day, although the amount pumped from the wells could be considerably more because of leakage in the mains. It is reasonable to assume that the amount pumped from the wells is in the range 60 to 100 m^3/day.

Thus if the output from the desalination plant were fully utilised, the amount of groundwater required would be of the order of 10 times that currently pumped. It is already believed by Lao that the pumping rate from the aquifer may be too high.

In order to sustain the required feedwater rate, it will be necessary to provide extra wells. Probably, about 12 wells would be needed to ensure that the salinity gradient such as is does not deteriorate further.

Alternatively, a smaller number of wells with horizontal galleries could be used.

10.2.2 The Existing Reticulation System

It has been indicated is section 2 that it is not easily possible to check on the extent of leakage from the mains, because of a lack of suitable metering. It is reasonable to assume that the leakage problem is not as serious as that on Tongatapu, but that some leakage problems exist.

In view of the production costs of desalinated water, it is highly desirable to eliminate losses in the reticulation system. This would involve checking pipe joints thoughout the system, with special attention being paid to joints to meters, and to those sections that are galvanised steel.

The existing reservoir is in poor condition, and would probably be too small for a system that provided good quality water. It would need to be replaced.

Demand for water will increase, provided people can pay for it. If the 400 m^3/day is to be utilised, there will be more connections and the reticulation system will need to be augmented. Much of this work could be done after the system is commissioned.

10.2.3 Customers' Installations

The high salinity of the supply has resulted in corrosion and scaling in taps and cisterns. While the customer must pay for any losses downstream of the meter, it could be difficult to collect payment if the price of the water reflected full production costs and if there were a leak in someone's plumbing. This is simply the result of the low per capita income of the area.

While a high water cost may provide strong incentives to keep the taps in good condition, the lack of skilled labour and tradition of good maintenance will mean that householders will require assistance and encouragement to keep their taps from dripping.

A program of tap washer replacement and valve seat grinding would need to accompany the introduction of the desalinated water.

If an attempt is made to recover operating costs from the users, it will be necessary to raise the price of water considerably, as discussed below. A higher water price will make it essential to charge equitably for the water, and accurate metering will be important. At present many meters are inoperative. All meters should be checked and descaled when the new system is commissioned.

10.2.4 Operation and Maintenance

The desalination plant will require a team of operating and maintenance staff. They will be required to read meters and gauges, keep records of operation, and recognise trends that may suggest the need for maintenance, clean the equipment and premises, add chemicals, etc.

The size of the plant in question would suggest that at least one person should be in attendance at all times, with a maintenance staff of about two present during the day. Along with administrative staff and a superintendent, this brings the total staff complement to at least eight.

At least two of the staff would need to have a basic understanding of water chemistry.

People with the skills needed to run this plant are at a premium in Tonga. The manager of the Tonga Water Board, Mr Filipe Koloi, has taken a keen interest in reverse osmosis, and has sent three of his technicians to a training course in Japan. Unfortunately, none of the people who went had a background in water chemistry and there is no plant in Tonga that they are able to practise their skills on. It therefore seems that when a large desalination plant is implemented, it will be necessary for these people to undertake a refresher course, and additional people will need to be recruited to run the plant.

It would be highly desirable for the staff to be recruited about 12 months before the plant is commissioned, and for them to be sent for training to an operating plant for about 6 months. They could then watch the installation and commissioning of their own plant, and begin to operate it under supervision of the supplier. It could be part of the contract that the supplier leave an operator on site for about three months after start-up.

10.2.4 Energy Supply

The consumption of the plant will depend on the type chosen and the feedwater quality. However, even the lowest salinity feedwater would result in an electricity consumption close to the capacity of one of the two available generators in the existing power station. Because there is already a period of about 3 hours in which both units must be run, it is evident that extra capacity is needed.

It is possible to provide this at the power station, or in a dedicated facility attached to the desalination plant. In the latter case, it may be desirable to drive the pumps of an RO plant directly from a diesel engine.

10.2.5 Basis for Cost Recovery

A plant operating on the Tonga Water Board's well water could cost approximately $170 000 per annum to run, if it operated at peak capacity. This money is required to pay for electricity, chemicals, membranes and staff. Much of it (fuel, chemicals and membranes) would be a foreign exchange commitment.

It is necessary to make provision for this amount from somewhere. The options are:

1. Direct Government funding of some sort

2. Collection of full operating costs through sale of water

3. Cross-subsidy from Nuku'alofa, where a much larger population has access to water that is relatively cheap

4. Some form of continuing support from an aid donor.

In principle, these measures could be adopted individually, or in any desired combination.

A renewable energy plant would still require funds for membranes, chemicals, spares and labour. This could cost about $50,000 per year.

If the plant produced its full output 90% of the time, it would make about 130 000 m^3/year. If the operating costs of a conventional plant using the Tonga Water Board wells were recouped by selling this water, it would need to cost $1.30 per m^3, at the plant gate. There is already a charge of about $0.27 for water from the existing wells, which would presumably have to remain to cover the pumping and reticulation costs. Thus the water charges would have to rise from $0.27 to $1.57 per m^3, just to cover the full operating costs of the plant.

Covering the capital cost would bring the total water cost to about $2.10/$m^3$.

Covering the operating costs of a solar plant would require a lower water charge, of around $ 0.85 per m^3, irrespective of the water source.

Whether or not the operation were financed largely out of water charges collected in Pangai-Hihifo, considerable attention would need to be devoted to setting suitable water charges.

The constraints are as follows:

1. During many months of the year, residents have access to tank water. If the price is set too high, the desalinated water may not be used. If capital recovery is not an issue, that is not a very serious problem, although it represents a waste of resources.

2. The residents do not have much money.

3. It would be counterproductive to set charges so high that people could not make use of the facility.

4. It would be wasteful of resources if the price of water were so low that there was no incentive to conserve water, and eventually, when the full capacity of the plant was taken up, there could be shortage due to wastage.

10.3 Implementation Schedule

Fig. 11 shows an approximate schedule that could apply to the project. It should be noted that the schedule has several optional (and almost independent) activities on it. These are sub-projects that can be undertaken before the desalination plant itself is installed, and relate to:

1. Interim improvements to the water supply, using more guttering and a small emergency desalination plant.

2. Investigation of well no. 5, to see what its safe yield is, and to ascertain whether it would be better to use it or the TWB source for the large desalination plant. If this phase were omitted, the desalination plant could be installed to use the existing source, suitably augmented with new wells and/or infiltration galleries.

11. MEANS OF FUNDING

Economic details for Tonga and for Lifuka have been given in sections 1 and 2. It is clear that the capital cost of a 400 m^3/day plant is substantial by comparison with the total GDP of the country.

Discussions were held with the Central Planning Department, Nuku'alofa, to ascertain what possibilities existed for purchasing a plant of value approximately $ 500 000. It was concluded that there was no possibility of Government funds being made available. Even considerably smaller amounts of money for such projects were difficult to obtain.

Consideration was given to local funding, within Lifuka. The capital costs represents about half the annual GDP of the island, and it is therefore considered unlikely that the capital cost could be raised in this way. As indicated earlier, even paying for the running costs through water charges will make a significant impact on the budgets of most families.

The Central Planning Department knew of no projects currently being planned for Lifuka that would require good quality potable water.

Private funding carries with it the need to recover the capital and pay interest on the debt. Because of the likely high cost of water and the residents' access to tank water for significant periods of the year, it is likely that the plant's full capacity will not be used, making it necessary to spread the capital cost over a relatively small quantity of water. Normal project evaluation would suggest that this is not a project suitable for private implementation.

However, there are now a number of desalination companies that are considering supplying equipment on the basis of selling water. Among these is the Reliable Water Company, which proposes to manufacture highly automated computer-controlled plants which will instruct the operator on each step of operation and maintenance. They have expressed an interest in finding suitable sites for their plants, and it may be possible to have them install a facility at no cost to Tonga.

The final alternative is to seek aid funds to supply the desalination plant. Full consideration and evaluation of possible donor countries and agencies is beyond the scope of this study, but there are a number of countries that may be receptive to a request for bilateral aid. These include:

1. Germany. There is a longstanding relationship between Tonga and Germany, and there are a number of German projects being executed in Tonga. There are also a number of German companies that make desalination equipment, both conventional and solar/wind. There may be a coincidence of interests on this matter.

2. France. Relations between France and Tonga seem to have become warmer recently. The French Atomic Energy Commission (Commissariat a l'Energie Atomique) has constructed a number of renewable energy desalination plants of different types. In Tahiti, there is a French Government organisation, SPIRE, (South Pacific Institute for Renewable Energy) that has also had involvement with solar and wind powered desalination. The French Government has generally supported the dissemination of French technology.

3. The EEC. The EEC has established an office in Tonga, and may be prepared to fund a desalination project using plants from member countries, including France and Germany, as well as others which manufacture them.

4. Japan. The Japanese International Cooperation Association (JICA) has a significant presence in Tonga. There are many Japanese companies supplying desalination plants. This project may be attractive to them.

5. Australia. The Australian Development Assistance Bureau (ADAB) has an on-going aid program for Tonga. There are a number of Australian companies capable of supplying deslination equipment.

6. New Zealand. New Zealand Aid is also very significant for Tonga, but there is no significant desalination industry in New Zealand.

7. The USA. The USA has a large number of desalination plant suppliers, and USAID may be interested in becoming involved in the project.

Despite the lack of funds in Tonga, there are human resources. A significant local contribution in terms of unskilled and semi-skilled labour could be expected in any of the projects described. This could be for:

site preparation
loading and unloading
repair and extension of the reticulation system
repair of customers' installations.

The renewable energy technologies all have very high capital cost. With present fuel prices, a solar or wind energy plant would not be economically viable compared to a conventional plant. Also, there are no such plants which are being offered on a normal commercial basis, all being developmental in some respect.

Nonetheless, it may be easier to obtain a donation of an expensive plant which requires little or no fuel, than it is to get a cheaper plant and to find funds each year for fuel. Many of the countries mentioned above have built prototype solar and wind powered desalination plants and they may be prepared to make one available to Tonga.

12. POSSIBLE ALTERNATIVE SOLUTIONS

It can be seen from the foregoing that provision of a 400 m^3/day desalination plant at Pangai would be expensive in terms of both capital and operating costs, unless a very expensive renewable energy plant were used.

So far, none of the renewable energy plants constructed has been on a strictly commercial basis, each one being a demonstration of some sort. Nonetheless, it is technically possible to design and construct a highly reliable renewable energy plant, using either solar or wind energy. In Pangai, the most likely candidate is solar energy, and any further consideration of wind energy would require further wind monitoring.

A solar energy plant would cost between five and ten times the cost of a conventional plant, although the fuel bill would be zero. In strict economic terms, this is not a viable option, but it may be easier to get a large capital grant than to try for aid funds to pay for an on-going fuel bill.

Ultimately, the area, including villages on northern Lifuka and Foa, would require 400 m^3/day plant to cater for all the population on the basis of the normal expectations of people in a developed country.

At present, however, consumption of water, particularly in the area served by the Tonga Water Board, is considerably less than 400 m^3/day, and even if the water quality were considerably improved, it is unlikely that the consumption would exceed 200 m^3/day, provided people were still required to pay for the water.

Therefore, four levels of alternative, all cheaper than the proposed plant are available, should funds not be available for the purchase and operation of the 400 m^3/day plant. They are:

1. A 200 m^3/day plant, which could ultimately be expanded in size.

2. A dual reticulation system, with untreated water being used for toilet flushing, especially in large buildings. A smaller desalination plant, say 120 m^3/day, could be used for the potable water.

3. A very small desalination plant, capable of providing drinking water only, for use in droughts.

4. Improvements to rainwater catchment systems.

The last two of the above could be implemented concurrently. All the options will be discussed below. Another approach could be to ship water from another country, such as Samoa, provided sufficient water was available. The viability of such an operation would need to be the subject of a separate study.

12.1 A 200 m^3/day Desalination Plant

Most of the remarks that apply to the 400 m^3/day plant also apply to the smaller one. In summary, the following actions are a prerequisite to successful operation of the system:

1. Installation of several more wells to spread the withdrawal over as wide as possible an area
2. Repair of the reticulation system, including any reservoirs, to eliminate leaks as far as possible
3. Repair of customers' installations, including taps and cisterns, to eliminate leaks
4. Repair of all water meters, to ensure that scaling from the present supply did not affect the accuracy of the readings
5. Provision and training of a team of, say, eight staff, who would be responsible for the operation and maintenance of the plant.
5. Provision of an adequate electricity supply to operate the plant
6. Implementation of a pricing structure that was affordable to the local populace, yet did not encourage waste.
7. If the pricing structure did not fully recover the operating costs of the plant, then additional sources of revenue would need to be allocated to provide for them. Cross-subsidy from water supplies in locations where desalination was not needed could be considered, if that was desired, since the revenue base in Nuku'alofa is so much larger than in Pangai-Hihifo.

The price of a 200 m^3 plant would be about 70% of the price of the full 400 m^3/day one. The operating costs, per unit output, would be slightly higher. It could always be extended to to full size, and provision could easily be made in site selection and intake/outfall construction for this to be done.

12. Dual Supply System

Treated water is not needed for all purposes. In particular, toilet flushing could be separated from other uses. This could be done on three levels:

1. A full dual reticulation system, in which all consumers can be connected to both a treated supply and an untreated supply.
2. A partial dual system, in which large users of water which does not need treatment have a second supply, which could be a private well on their premises
3. A dual system in which all users are encouraged to dig their own shallow wells for uses other than drinking and cooking.

The economics of the first sub-option depend on the ultimate use of flushing toilets, and the willingness of people to use untreated water for other purposes.

Essentially, it would require the laying of about 6 km of water mains, and supply of water meters, and consumers' facilities.

The second option could be achieved by supplying untreated water only to the major users listed in section 2.5. (The Tonga Electric Power Board should be excluded, since it should use treated water.) The seven organisations concerned could probably each sink their own well, and use a small electric pump to supply the untreated water as needed.

In both cases, the reduction of the desalination plant capacity will only be of the order of $50,000, and the major impact of the smaller capacity will be in lower running costs.

12.3 A Small Emergency Desalination Plant

To supply about 5 L/day for each inhabitant of Lifuka and Foa would require a plant of capacity 15 to 20 m^3/day - a small plant by most standards.

There are a number of options available. These include:

1. A waste heat plant based on the power station.
2. An RO plant using the TWB wells
3. A portable RO plant, using seawater, which could be used on other islands.

All the above merit consideration. The capital cost a seawater RO plant would be approximately $A 30 000 to 40 000, and it could be supplied skid-mounted. If constructed in a transportable form, with its own energy source, it could be transported to other less populated islands where reservoirs could be filled on a, say, fortnightly basis.

Provided the plant were maintained in a working condition, and staff were available to operate it, the plant would ensure that there was no risk of a shortage of drinking water.

A number of demonstration solar or wind plants could fill the need for emergency backup, if portability was not a requirement.

The power station may find use for a small desalination plant to supply cooling water.

12.4 Improvements to Rainwater Collection

A full assessment of the roof catchments was not carried out, but an informal survey indicated that only about half of the available roof area was equipped with gutters. On most houses (about 78%) there is already a tank, fed from a gutter collecting from one side of the house. There are, therefore, three levels of improvement available:

1. Full Use of Existing Catchments

   Add guttering to increase the area from which water flows into the tanks. This would have its biggest effect during the dry months. It is a relatively cheap solution, involving only the cost of components and labour to install them. A typical "hurricane house" would require about 4 m of gutter, 3 m of downpipe, a spout and some clips. Installation would take no more than one person day.

The effect of such an improvement depends on the size of the roof and the degree of the dry spell. During a period with rainfall of 60 mm per month, similar to the dry spell recently experienced, the additional water collected from the second side of the roof of a "hurricane house" would average 32 L/day - that alone would be enough to provide for the basic needs of a typical Tongan family. In the dryest of months on record - with a rainfall of only 5 mm - only about 3 L/day would be available from one side of a roof, making a total supply of 6 L/day. This would only be enough for survival.

There are a number of large communal buildings, notably churches, which have the potential for collecting significant amounts of water. This water could be used for a communal "back-up" supply, under control of a town officer, as is done on outlying islands.

2. Extra Tanks

Additional tank capacity is useful to extend the storage of water collected during wet periods for use in dry periods. Additional capacity can only be useful if the populace recognises and acts on the need to conserve water from the wet season for the dry periods.

Typically, houses are equipped with tanks of 10 m^3 capacity. If the catchment area were doubled, it would be reasonable to double the tank capacity also. Various strategies could be adopted for using the tanks. One of the simplest would be to normally use the water from one tank only, and to institute severe consumption limitations whenever it was necessary to start using the second tank.

A 10 m^3 tank could provide 5 L/person/day for a family of six for almost a year. Since the very dry period is extremely unlikely to exceed about 5 months, a consumption limit of 10 L/person/day would probably be feasible.

It should be noted, however, that supplying an additional 10 m^3 tank for each house, plus larger tanks for some of the public buildings, would cost about $200,000 - about half the installed cost of a desalination plant. The tanks would provide considerably less theoretical insurance against water shortage, but do so with very low running and maintenance costs and less risk of total breakdown.

3. Other Catchments

Despite the relatively low population density on Lifuka, the land is fairly fully utilised. This is because of the Tongan land tenure system, whereby each adult male is entitled to apply for a lot of about 8.5 ha. The King and Royal Family also have significant holdings on Lifuka.

Agriculture is the most important economic activity on Lifuka. It would therefore be inappropriate to alienate large tracts of land to make water catchment areas.

However, there is one area that could be used without any adverse effect on land use. That is the airport runway. It currently has a coral surface which allows water to drain away. It could be paved and drained into a holding reservoir, which could then feed an elevated reservoir.

The paved area would be about 30 000 m^2, enough to provide almost half the needs of the presently reticulated area, provided adequate storage were available. A suitable storage reservoir would be 5 m high and 100 m by 100 m squere.

The cost of paving will depend on the nature of the existing coral runway. Without a civil engineering survey, it is not possible to tell whether such a solution would be financially attractive, but it would probably yield benefits to aviation and tourism also. The Australian Development Assistance Bureau is currently upgrading the runway on Tongatapu, and could probably provide an appraisal of the Pangai runway.

12.5 Education

The Tongan way of life is based on a traditional subsistence culture that relies on the benign climate, the relative fertility of the soil and the availability of food from the sea.

The concept of storing goods in order to overcome future shortages is not particularly well-developed, and was largely unnecessary for the traditional lifestyle.

The supply of running water on a small, remote, coral island is considerably more difficult, technically, than it is on the mainlands of the developed countries, which have the rainfall and topography to enable easy collection and storage of water. It is extremely expensive to provide the same quantity of running water per person on Lifuka, as that expected in the USA, Europe or Australia.

The population of Lifuka does not have the financial resources to pay for the quantities used, and abused, in the developed countries. It would therefore be appropriate to encourage the conservation of water. Ideally, any education program would have segments at several stages through the school curriculum, as well as a direct approach to adults and others not attending schools. It may take many years for such a program to have a significant effect.

If there is a reticulated supply of scarce and/or expensive water, the price structure can be manipulated to encourage conservation. For example, each domestic consumer could be given a base block of consumption at a low price, but any consumption in excess of an appropriately determined threshhold could be much more expensive. Such tariff structures invariably cause some discontent, because it is not possible to set a price break threshhold which is fair to all. However, even price structres like the one presently in force, with a minimum price, regardless of consumption, have received criticism from consumers in other countries.

13. CONCLUSIONS AND RECOMMENDATIONS

If water of the quantity and quality that is available in Nuku'alofa and cities of the developed world is to be supplied in Pangai-Hihifo, then desalination appears to be the only source, apart from shipping it from another country.

The safe yield from the relatively low salinity bore should be ascertained by means of a drilling and monitoring program.

If the bore can supply the feedwater demands of a desalination plant of whatever size is selected (200 or 400 m^3/day), then it could be used as the source for an RO or ED plant. The plant could be selected on the basis of competitive bids, with some preference being given to RO, even if there were a price penalty, because the technology is transferable to islands with no brackish water feed. The added complexity of the pretreatment needed to use the new well will add unquantifiable additional costs to the plant operating costs.

A 400 m^3/day desalination plant would provide adequate water for all residents of Lifuka and Foa, at a level of consumption considerably exceeding that currently seen in Nuku'alofa.

While it would be possible to build such a plant in one go, it appears that a plant of half the size - 200 m^3/day - would meet the needs of Paqngai-Hihifo for some time to come. The plant could, if necessary, be built with the possibility of expansion in the future.

Whatever the size of plant constructed, the operating costs will be considerable, and a strategy will be needed to meet these. If the operating costs of a plant using the Water Board wells were to be recouped from water charges, the price of water would need to rise to about \$1.57/m^3, a six-fold increase. It is believed that many residents of Pangai-Hihifo will avoid using the reticulated water if the price rises that high.

In the first instance, it is believed that if a desalination plant is constructed for the reticulation system, it should be restricted to no more than 200 m^3/day.

If the problem of finding operating expenses cannot be overcome, but donor countries are prepared to supply a renewable energy plant, the operating costs can be cut considerably, resulting in a water cost of around \$0.85/m^3, which may be acceptable if the quality is good.

If a renewable energy plant were chosen, the relative merits of wind and solar energy would need to be considered. This requires long-term monitoring of wind patterns. It is likely, however, that the large battery requirement for a wind-driven system will make it less attractive than a solar-powered one, for this location.

If a desalination plant were installed to supply the reticulation system, there are a number of parallel activities that would need to take place, including refurbishment of the supply system, repair of customers' installations, staff training and development of a strategy for cost recovery.

If neither the capital nor the operating expenses can be found, then there are some lower cost options available, which will improve the availability of water. These include:

More extensive guttering
More tanks
Collecting rainwater from the airport runway
A small desalination plant for drinking water during dry periods
Conservation of resources

Of these, it is recommended that in the first instance, additional guttering should be installed, to feed existing tanks, and that a small desalination plant should be purchased for drought relief. This plant should, however, be run as often as possible, and used to train a core of operators. In periods of adequate rainfall, the product could be fed into the reticulation system, and in droughts in could be issued in containers.

It should be noted that the installation of a small plant in the first instance would enable local staff to gain experience with the technology at relatively low financial risk, and enable smooth introduction of larger plants at a later date.

Matters peripheral to the terms of reference:

1. The possibility of establishing a salt-production industry on Lifuka using solar energy could be investigated

2. The cooling water system of the Pangai power station should be checked to ensure that water from the reticulation system is not causing scaling in the plant.

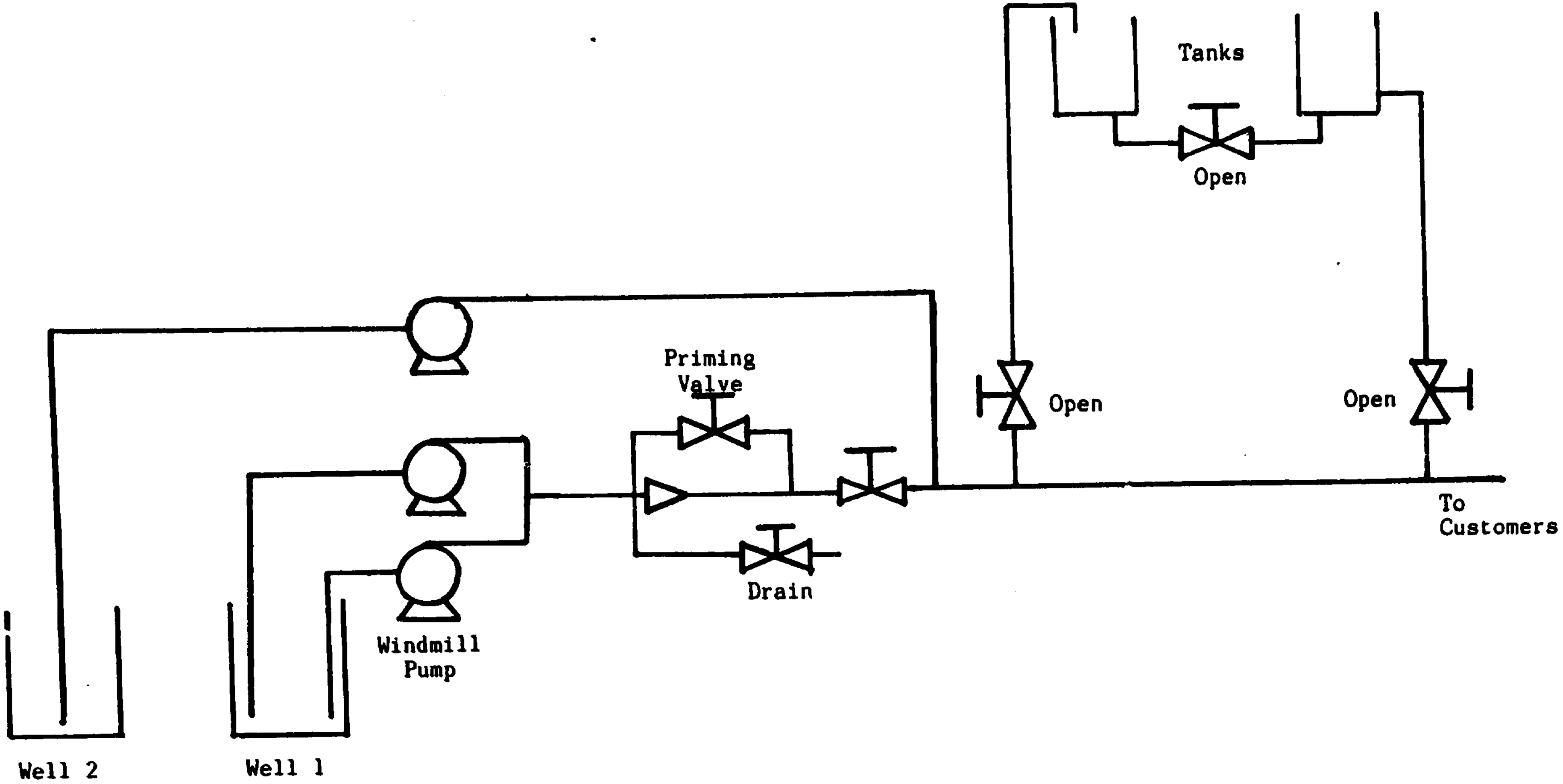


Fig. 1a. Reported configuration of pipes and valves at Pangai Water Supply wellfield. (Pumps have foot-valves incorporated to prevent drain-back.)

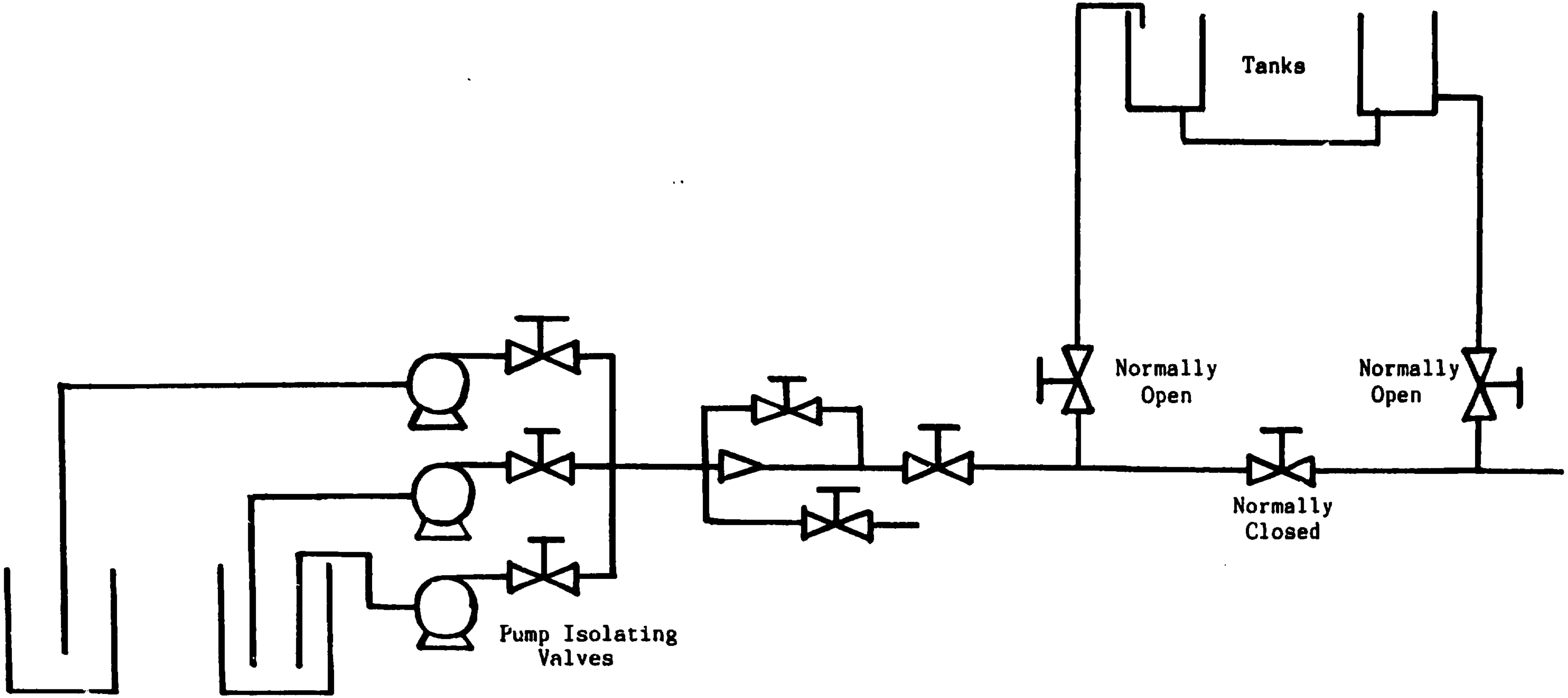


Fig. 1b. Alternative configuration of valves and pipes for Pangai water supply.

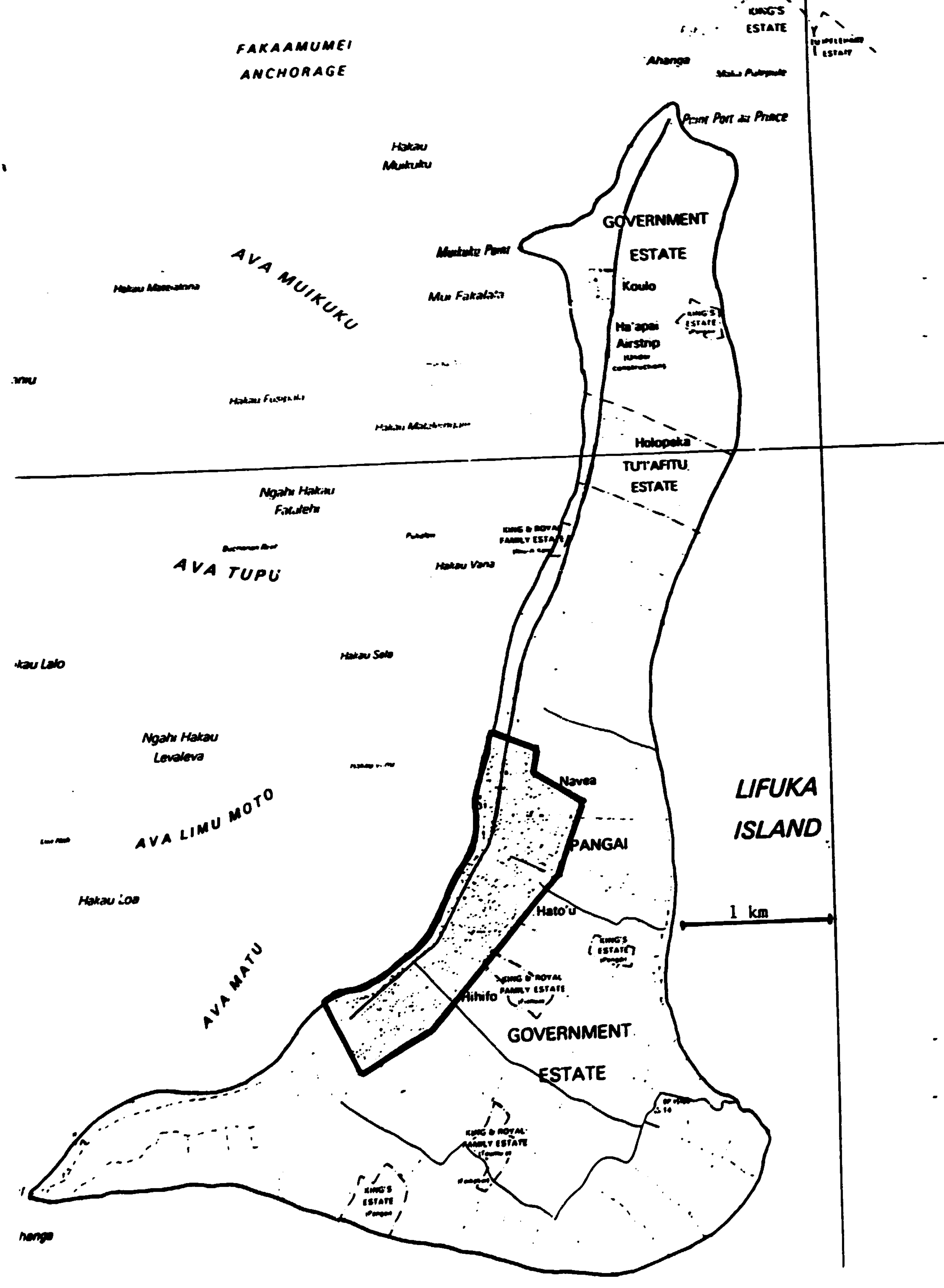


Fig. 2. Area in which reticulated water and electricity are available in Pangai-Hihifo.

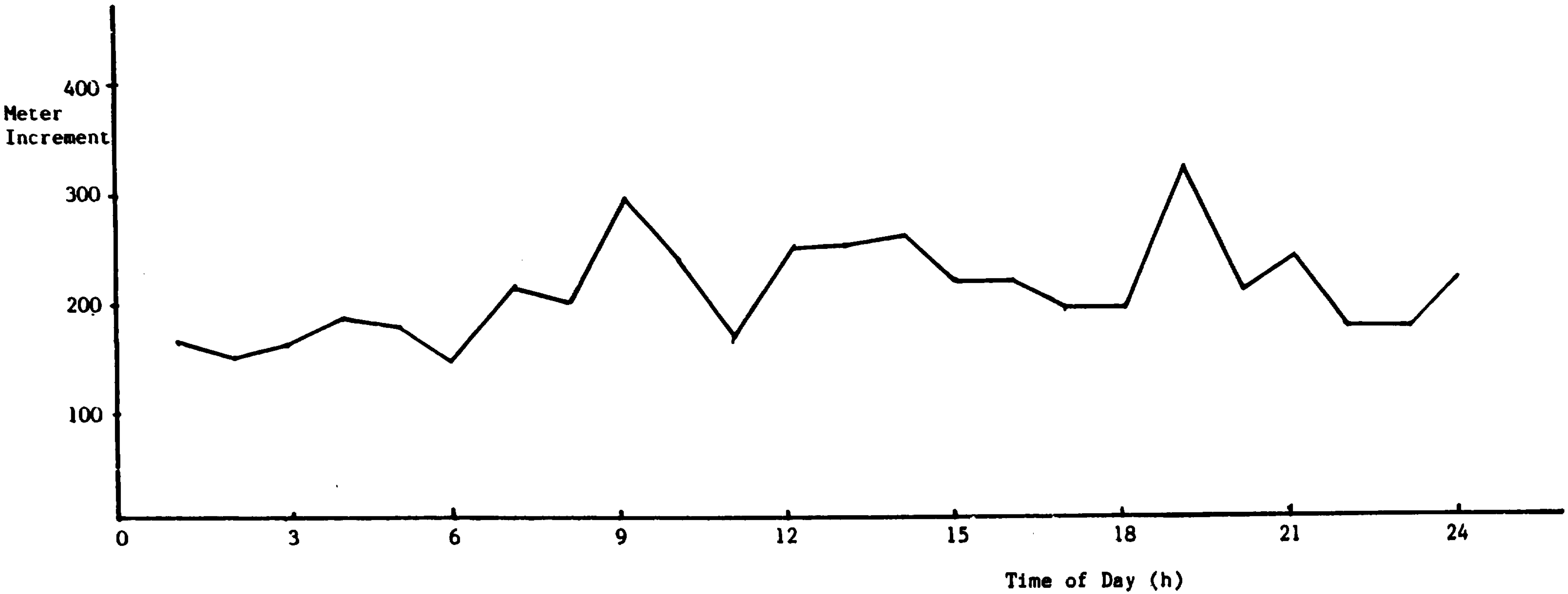


Fig. 3. Hourly meter readings of main meter at Mataki'eua (Tongatapu).

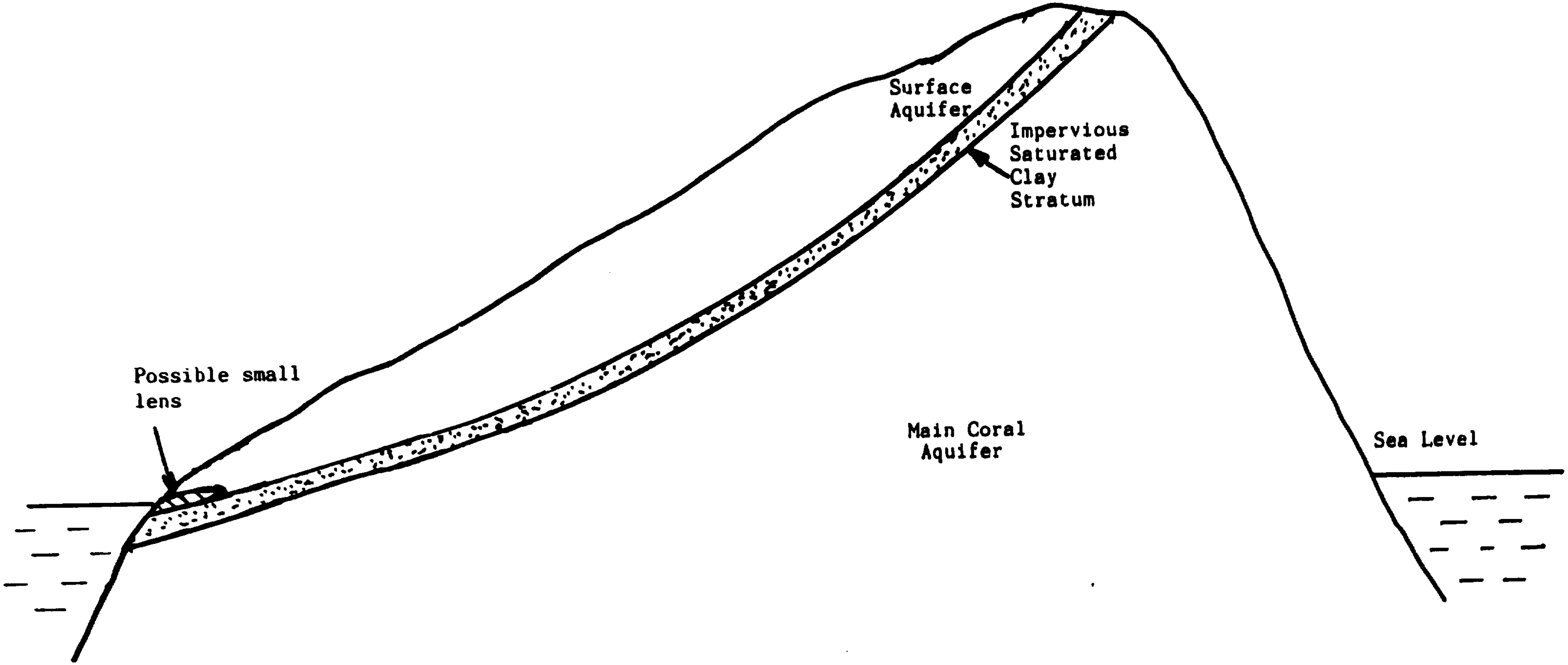


Fig. 4. Section through Lifuka (looking North), illustrating Lao's hypothesis for the absence of a normally developed freshwater lens.

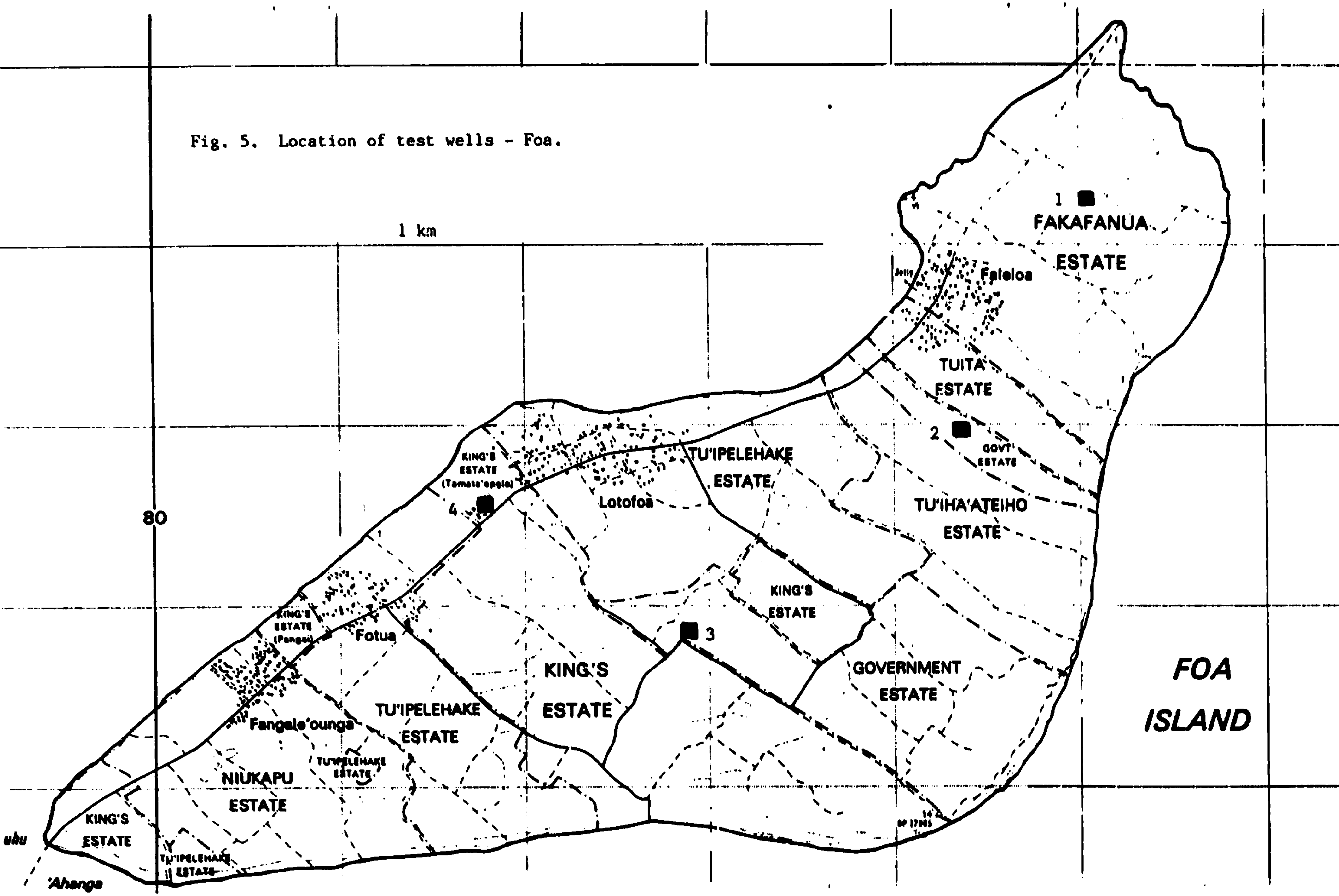


Fig. 5. Location of test wells - Foa.

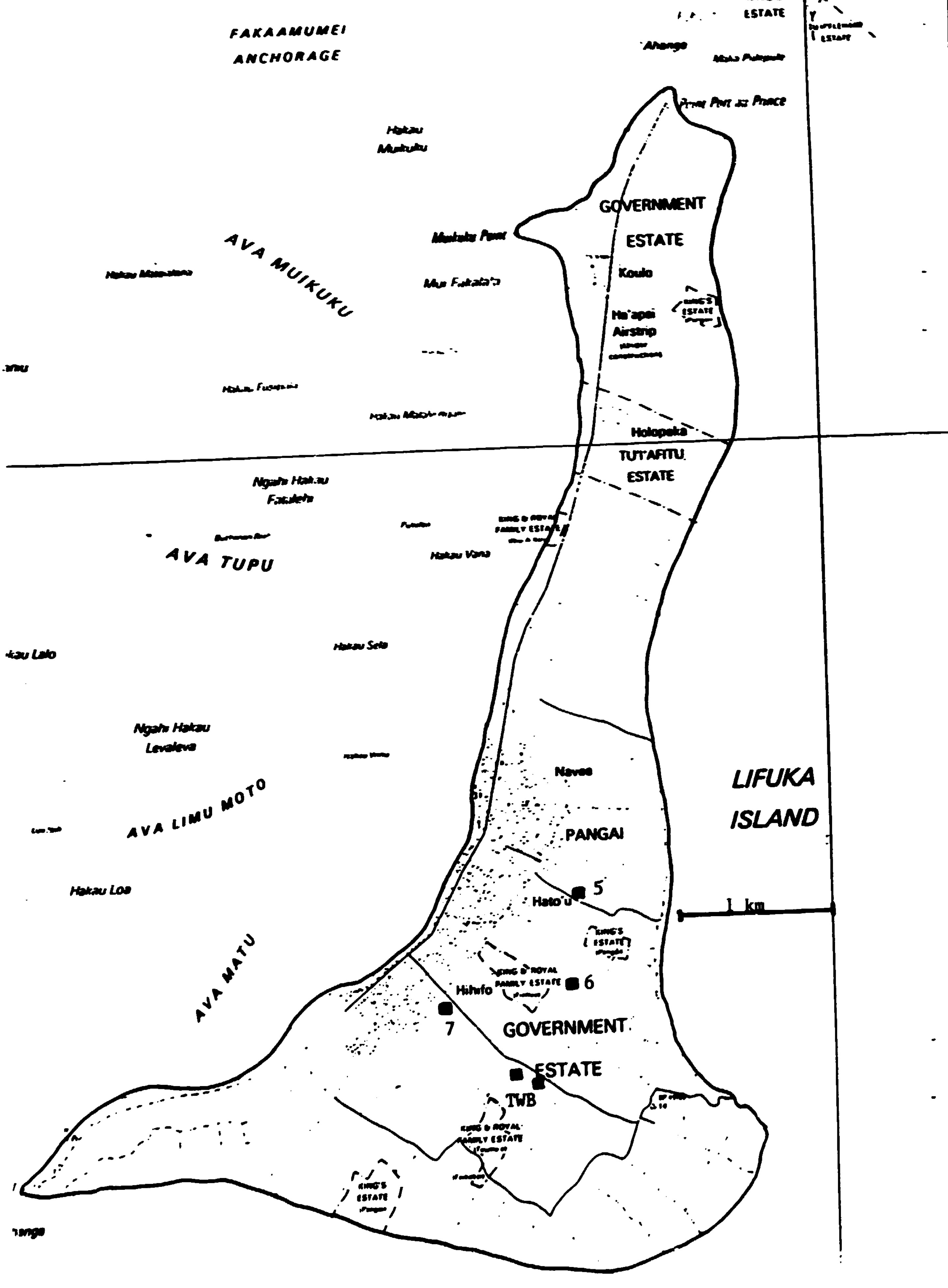


Fig. 6. Location of test wells and Tonga Water Board (TWB) wells) - Lifuka.

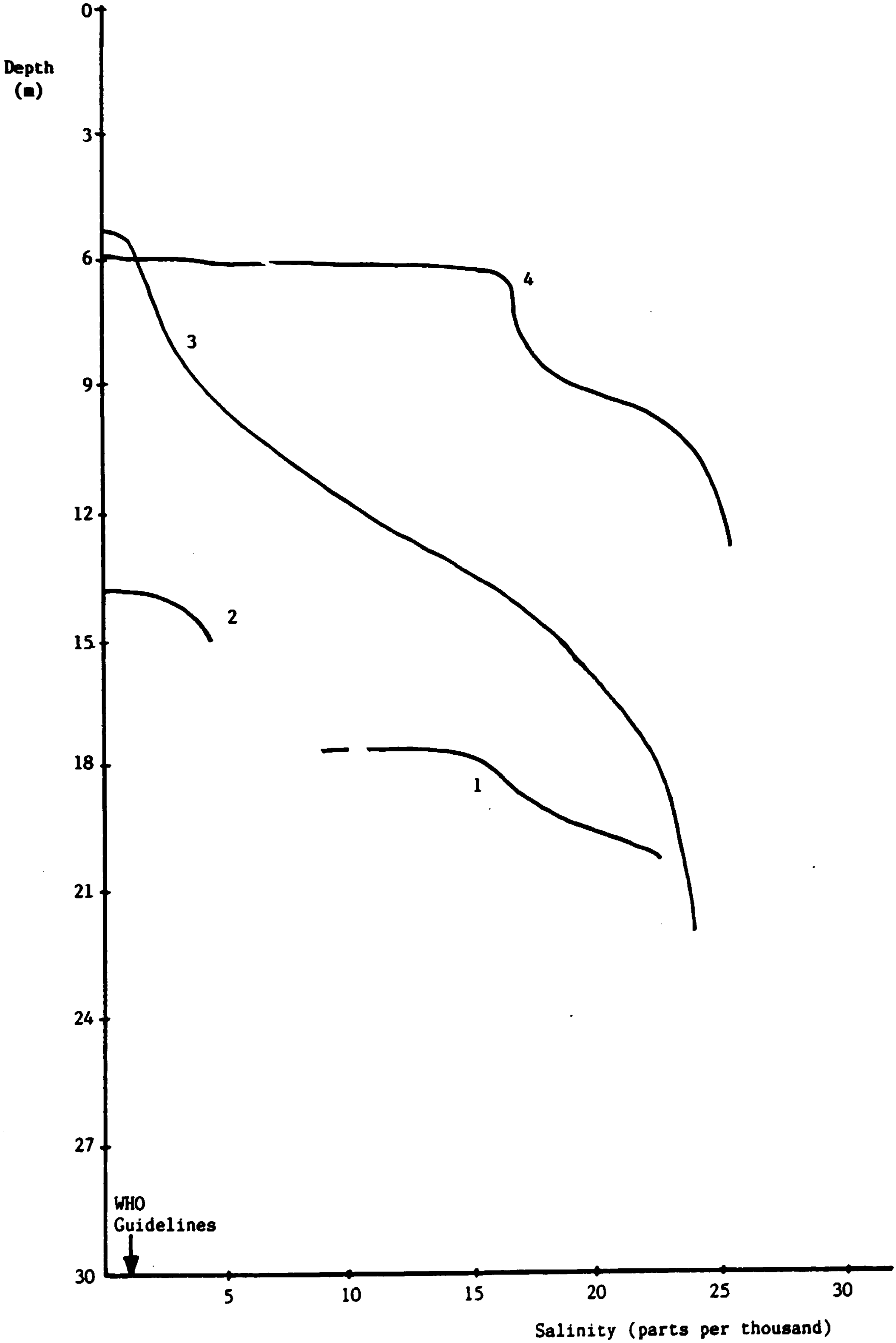


Fig. 7. Salinometer readings for test wells on Foa (values approximate true salinity).

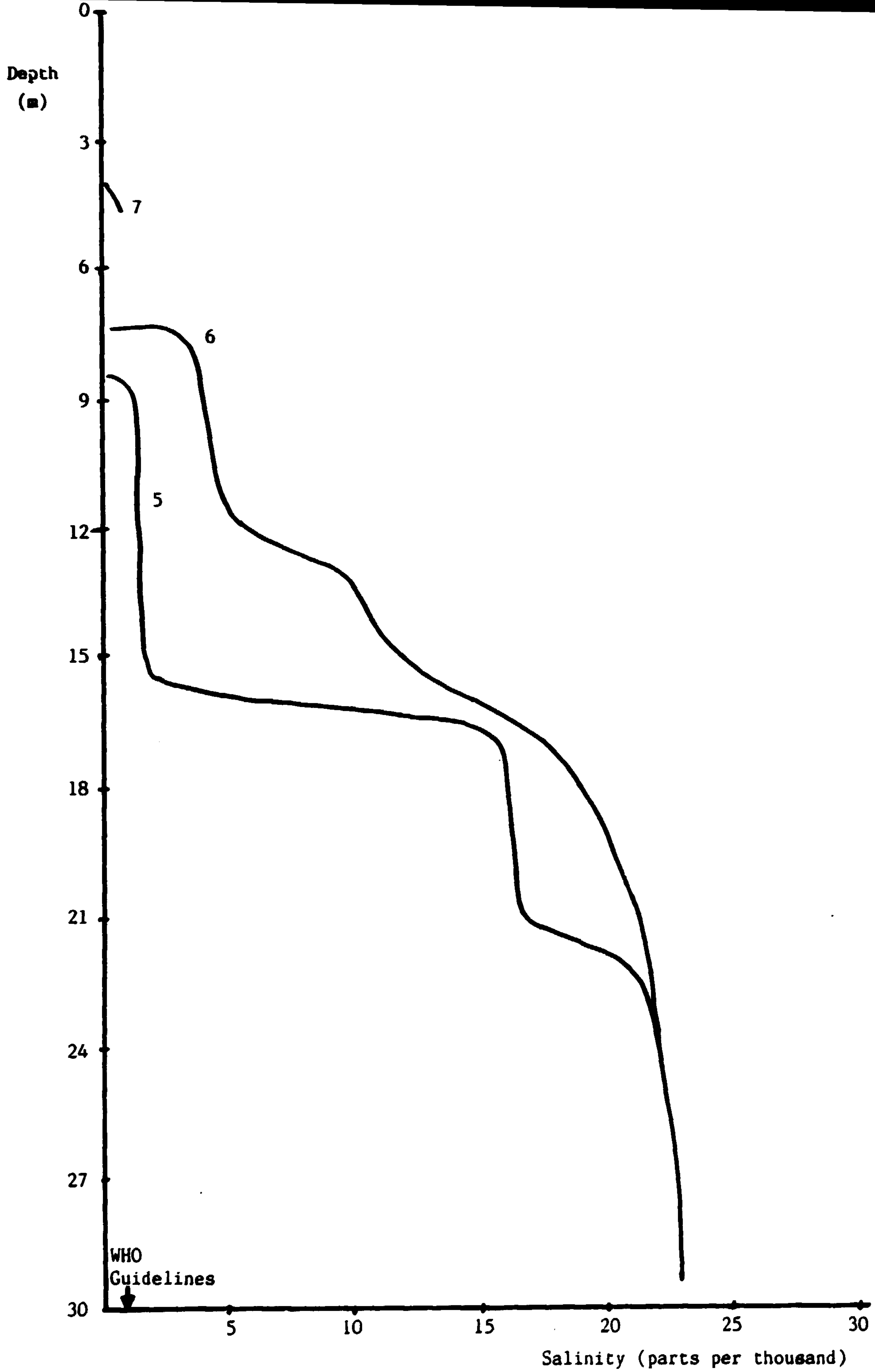


Fig. 8. Salinometer readings for test wells on Lifuka (values approximate true salinity.

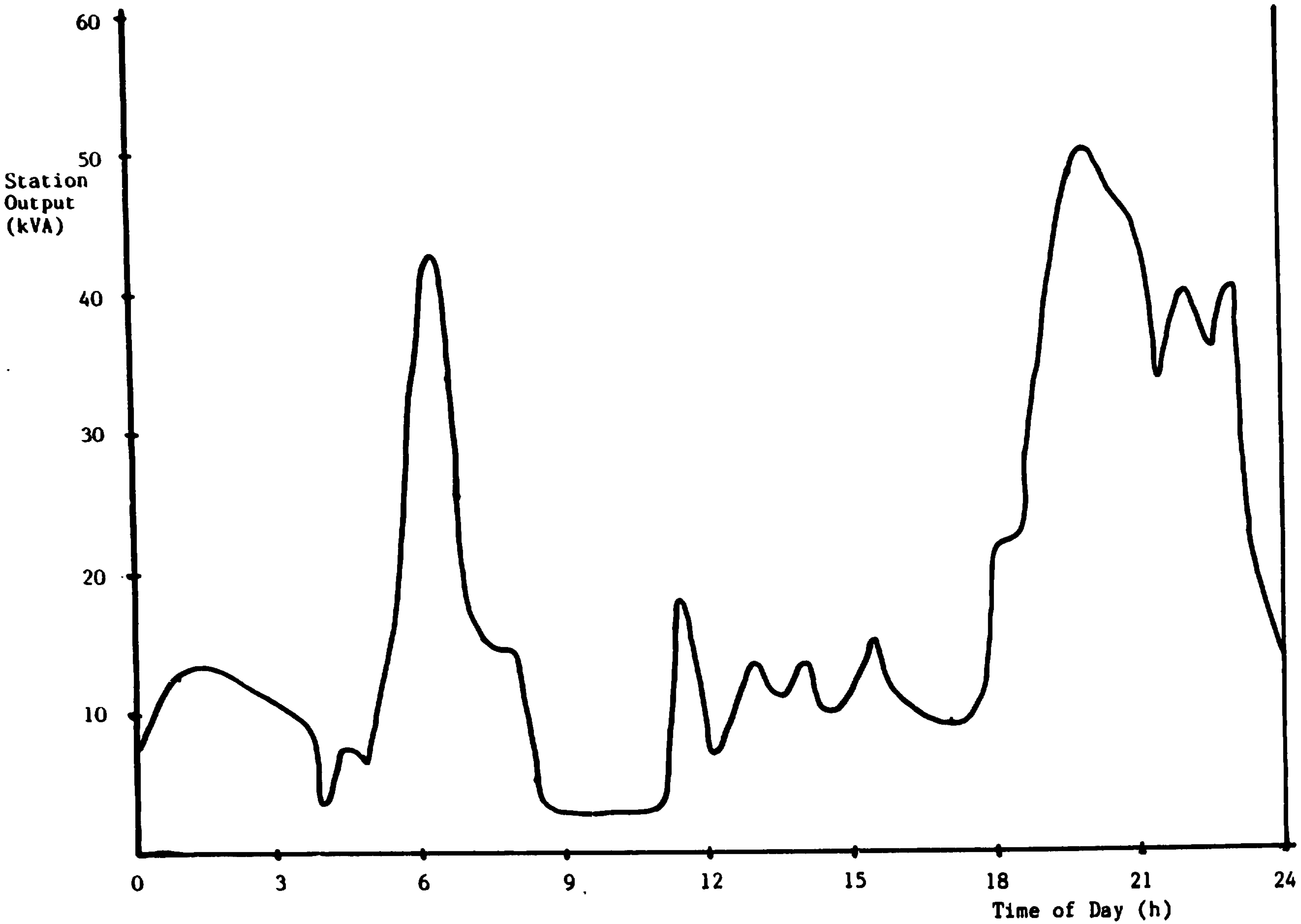


Fig. 9. Typical daily load curve for the Pangai Power Station (August 12, 1987)

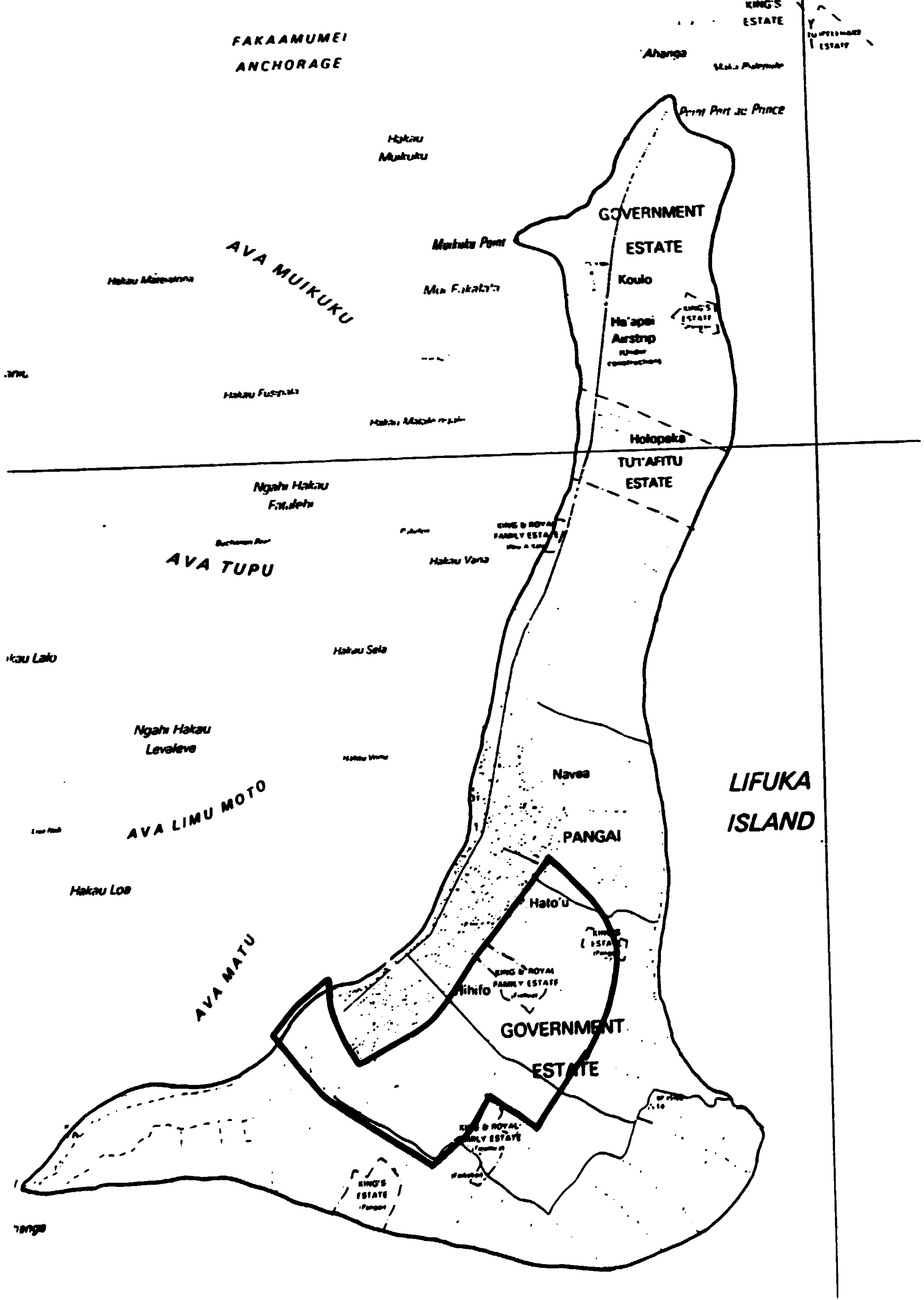
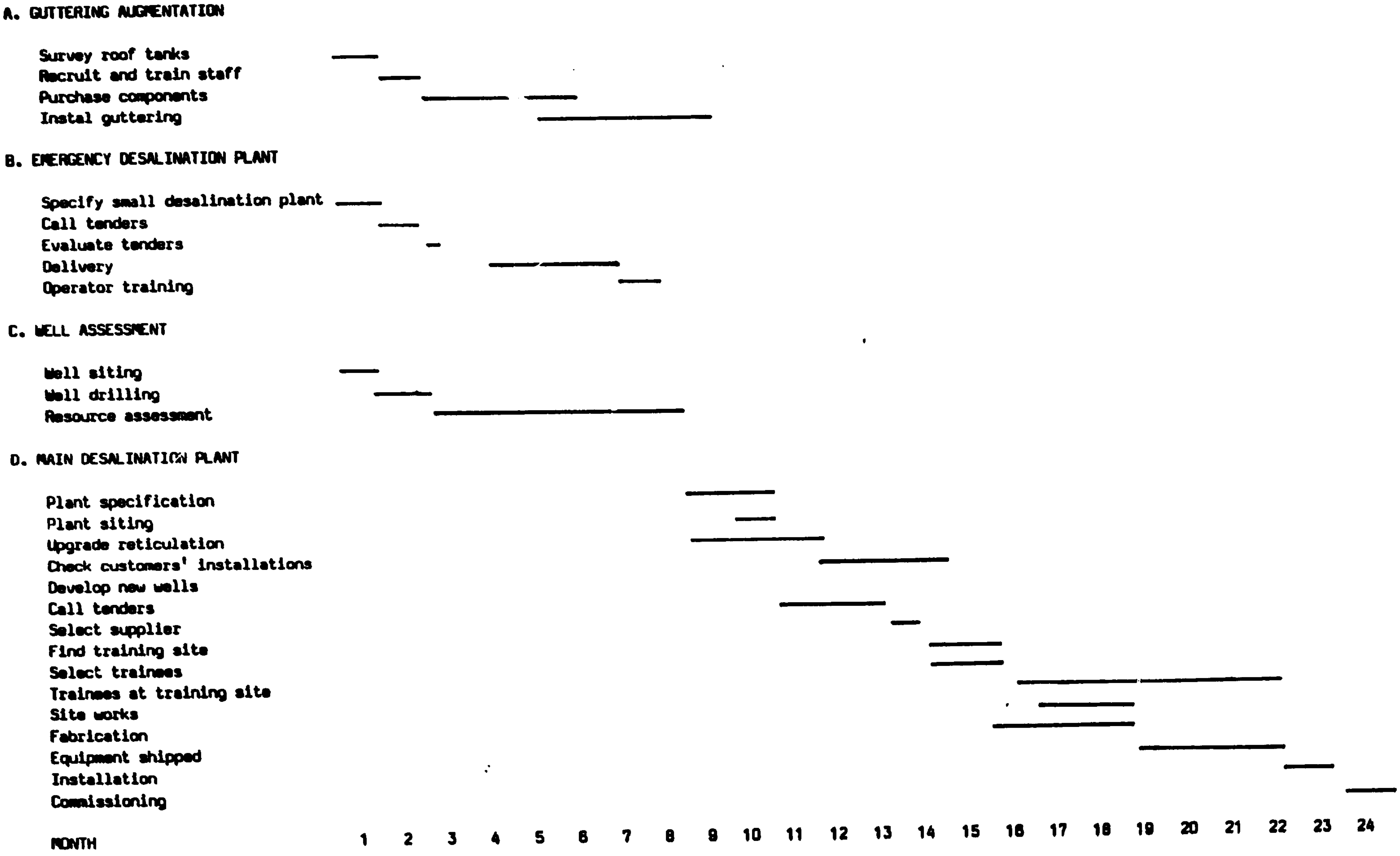


Fig. 10. Area in which a desalination plant could be located.

Fig. 11

Project Implementation Schedule



Note: Sections A, B and C are not necessarily prerequisites to implementation of section D.

APPENDIX A

METHODS OF DESALINATION

This Appendix contains a general description of the conventional techniques of desalination.

A 1. DISTILLATION

In distillation, fresh water is produced by evaporating seawater and collecting the condensate. In all but the most primitive of plants the latent heat given up by the condensing steam is reused to evaporate more seawater. In the multi-stage flash process the latent heat of condensation is used to preheat feed water, while in the multiple effect process it is used primarily to evaporate more feed water (at a lower pressure than the steam). The principal types of distillation plant are described below.

A 1.1 Multiple Effect Evaporators

A conceptual diagram of a multiple effect evaporator is shown in Fig. A 1. In each effect steam is condensed on one side of a tube and the heat of condensation derived from this is utilized to evaporate saline water on the other side of the tube wall. Thus the heat of vaporisation imparted to the water to produce the initial vaporisation is efficiently reused through the subsequent exchange of the heats of condensation and vaporisation in later effects.

The subsequent use and reuse of the heats of vaporisation and condensation to promote boiling is accomplished by reducing the pressure in each of the effects relative to the one preceding it. This allows the brine to boil at lower and lower temperatures as it flows through the plant. Because of this multiple-effect plants have a performance ratio which is proportional to the number of effects . If the plant were perfect in insulation , heat transfer surface, etc., the performance ratio in each effect would be close to 1. In practice one can expect a performance ratio of 0.7 to 0.85 per stage.

(a) Submerged Tube: An early design in which the water was heated using submerged tubes, in which vapour condensed.

Because nucleate boiling is unavoidable, the brine pool cannot be vaporised as efficiently as in other types of plant and scale forms on the hot submerged tubes, reducing the output. Submerged-tube plants utilising waste heat for industrial, marine and other special installations are still being manufactured. These are basically one-stage units which run at temperatures in the range of 48°-60°C to minimise scaling. The thermal efficiencies of the plants are low but, since the energy cost is minimal, this is usually not critical.

(b) Vertical Tube: The vertical-tube evaporator (VTE) configuration was intended to resolve some of the problems of the submerged-tube configuration. The configuration is shown in Fig. A2. Vertical tubes are suspended above the brine pool, and the brine is allowed to flow on the inside of the tubes while the vapour is condensed on the outside.

The plants are designed so that the liquid flows as a thin film on the tube surfaces, exposing a large surface area for heat transfer and evaporation. The principle of the process is to promote evaporation from the liquid's free surface and prevent nucleate boiling, and scaling. In present-day multiple-effect plants (both vertical and horizontal tube) a feed heater section is added to each effect. This reduces the amount of external steam required to heat the feed to its boiling point. All the large vertical tube plants that have been built use the falling brine film configuration. These require intersatage pumps unless the performance ratio is low. On the other hand, there are some small rising film vertical-tube plants operating successfully which do not have any interstage pumps.

(c) Horizontal Tube (HTME): A conceptual diagram of a horizontal-tube multiple effect configuration is shown in Fig. A3. Although the principle of operation is the same as for the vertical tube evaporator, the brine and steam are applied on opposite sides of the tubes in the two systems. The brine is distributed as a film on the outside of the tubes where it is partially evaporated by heat derived from condensation of vapour (to freshwater) on the inside of the tubes.

The effects are amenable to being stacked both vertically and horizontally. The configuration of the vertical arrangement permits greater use of gravity to move liquid between effects. Limited operational experience with horizontal-tube units in Belgium indicates that scale formation and removal is significantly less problematic in the horizontal-tube than in the vertical tube units.

A1.2 Multi-Stage Flash (Fig. A.4)

If the pressure of a liquid is suddenly reduced (adiabatically) some of the liquid will "flash" to steam. If the extent of the pressure reduction is such that it falls below the saturation pressure at the temperature of the fluid in question, violent boiling will occur, resulting in cooling of the fluid until equilibrium is re-established. In a flash plant, the pressure reduction is usually achieved by passing the feedwater through orifices.

The vapour produced by flashing is condensed on the outside of tubes which are conveying the incoming seawater to the hot end of the plant. This serves to recover much of the heat of evaporation.

After passing through the last heat recovery section and before re-entering the first stage for flashing the feedwater is further heated in the brine heater using externally supplied steam. Then it is flashed sequentially in each stage and the vapour is condensed on the outside of the tube carrying the salt feedwater to the brine heater. The product is collected and is passed on from stage to stage in parallel with the brine. In each stage the product is also flashed.

The percentage of brine actually vaporised in each stage is small. Under ideal conditions, only about half of one percent of the water flowing through a stage could be vaporised. Thus, the MSF process is characterised by high flows through the plant relative to the amount of water produced.

Due to the large amount of flashing brine required in an MSF plant, some of the brine from the last stage is often mixed with incoming feedwater, and recirculated through the heat recovery sections to the brine heater and is then flashed again through all the stages. Such plants are called recycle plants.

An average high-temperature recycle MSF plant recovers as fresh water only about 25-50% of the flow through the plant. This contrasts with a well-designed multi-effect plant, which recovers 40-65% of the feed. Once-through plants, which are now regaining favour recover only about 10% of the feed.

The advantages of MSF plants lie in their ability to be constructed in large capacities, the fact that boiling does not take place on a hot tube surface (it flashes instead) and the design and operational experience accumulated over the past 20 years.

Their disadvantages involve the potential for scaling and corrosion (which has been alleviated somewhat by new anti-scale chemicals), the difficulty involved in start-up, the inability to operate the plant below 70-80% of design capacity, the difficulty of building a very efficient plant and the necessity for pumping, treating and heating large quantities of saltwater relative to the product.

A 1.3 Vapour Compression

Vapour compression differs from other distillation processes in that it does not utilise heat as its primary energy source. It relies instead on mechanically compressing water vapour to increase its pressure and condensation temperature. The plant is designed so that the condensation of the compressed vapour takes place on one side of the tube that acts as a heat transfer surface. Evaporating feedwater is on the other side of the tube and the heat of condensation that is released on one side is utilised as the heat of vaporisation on the other side to boil the feed and produce water vapour (which is then compressed and fed to the other side of the heat transfer surface).

The heat of vaporisation is recycled across the evaporator surface, but not all he feed evaporates, so there is a substantial amount of hot brine produced. Also, the condensed product will be at above ambient temperature. Unless the heat in these streams is recovered, the mechanical energy that must be supplied by the compressor is very high. Therefore, heat exchangers are fitted to preheat the feedwater from the brine and product flows.

A proportion of the brine can be recycled into the evaporator to conserve heat.

The compressor may be either a mechanical one, or, if there is a supply of high pressure steam available, then an ejector may be used. In practice, the compressor, apart from raising the condensation temperature of the vapour, sucks on the feed, and reduces the boiling point on the feed side. Thus the plants usually operate at less than 100°C. New designs incorporate a small vacuum pump, to further reduce the operate the operating temperature and pressure. One manufacturer has used the name "Vacuum Vapour Compression" for such modified designs.

If waste heat is available, then it can be used to preheat the feed in the same way as the product and reject streams do. This reduces the mechanical energy requirements. A heat pump can be used to provide preheating, if appropriate.

Starting the plants is a problem, and usually an auxiliary heater must be fitted to raise the feed temperature to a level where some vapour is available before the compressor can take over.

A2. FREEZING

Compared to distillation freezing should have a number of advantages. It requires the transfer of less energy, needs almost no pretreatment, and has minimal corrosion and metallurgical problems. The heat of fusion, or crystallisation, is 335 kJ/kg of ice. This is less than one-seventh of the heat necessary to transform water to vapour.

The binding forces of ice crystals are such that only water molecules fit the crystal structure, and all other molecules, such as sodium chloride, are excluded. Evidence indicates that impurities found in partially frozen seawater are located on a layer adhering to the outside of the crystals and can easily be washed off. However, when the crystals form large agglomerations, the brine layer on the individual crystals is trapped inside the clumps of ice and hence all the impurities will not readily be removed by simple washing.

Although efforts have been made since the 1950's to produce a commercial seawater desalination plant based on the freezing principle, they have not been successful. Only one commercial plant was sold in the western hemisphere. For various reasons, this installation was not a success. Recently, a solar driven freezing plant has been constructed in Saudi Arabia as a joint US-Saudi research project.

In all freezing desalination processes there are four basic components. These are shown in Fig. A6 and comprise a Freezer, a Washer, a Melter and a Heat Removal System.

There are a number of problems associated with freezing. These include:

1. Difficulties with handling solid crystals in the process
2. The need to handle large volumes of water vapour in vacuum processes.
3. In immiscible refrigerant processes the refrigerant and brine can form emulsions, and salt deposits in the compressor can cause erosion.
4. The ice washer is not always reliable.

Solar freezing processes could operate in one of two ways:

1. Generation of electricity followed by a traditional vapour compression refrigeration plant.

2. Collection of heat and use of an absorption cycle.

The solar freezing plant constructed in Saudi Arabia uses the latter system, with high temperature collectors. It is nowhere near to being a commercial product.

A 3. REVERSE OSMOSIS

A 3.1. Introduction

Reverse osmosis is a separation process in which the water from a pressurised saline solution is separated from the solutes by a selectively permeable membrane. As no heating or phase change takes place, the major energy usage in the process is that required to pressurise the feed. For brackish water desalination the operating pressure generally ranges from 2 to 3 MPa and for seawater desalination, it generally averages from 6 to 8 MPa.

In the process, saline water is pumped to pressurise it against a membrane in a container. As pure water from the feed solution passes through the membrane, the remaining solution becomes more concentrated. A valve allows a portion of the feedwater to be discharged without passing through the membrane. Without this discharge (or blowdown) the concentration of dissolved salts in the feed solution would continually increase, requiring the pump to add ever-increasing energy to overcome the increased osmotic pressure, and precipitation of supersaturated constituents in the brine would occur.

A reverse osmosis system consists of four major components/processes, as shown in Fig A7. They are:

1. Pretreatment
2. High-pressure pump
3. Membrane assembly, and
4. Post-treatment.

A 3.2. Membranes

An effective membrane must be able to (1) withstand high pressure (2) permit the through flow of large amounts of water (3) reject or at least restrict the passage of dissolved solids (4) remain physically and chemically stable in a saline aqueous environment and (5) be readily manufactured with reproducible characteristics. The original cellulose diacetate membranes had some drawbacks due to their lack of hydrolytic stability and their tendency to lose flux by compaction. They have largely been displaced by various blends or derivates of other cellulose acetates, polyamides, and other polymers, etc., which have been found suitable for commercial application. Composite membranes, in which the surface layer, which is selective, is very thin, and blends into a stronger porous layer, are becoming popular.

Various configurations of membrane assembly are available. Plate and frame assemblies have not been commercially successful, and tubular membranes are mainly used in wastewater applications since they are easy to clean and keep clean. The two most widely used assemblies for desalination are spiral and hollow fine fibre membranes. Hollow fine fibre membranes, which were market leaders for many years are now being supplanted by newer designs of spiral membrane.

A 3.3. Fundamentals of RO operation

The principles governing the operation of RO plants are:

1. The water flux through any given membrane is proportional to the effective pressure difference across it.

2. Salt also diffuses through the membranes. This diffusion is independent of the pressure difference, and depends only on the difference in concentration between the feed and product waters and the nature of the membrane.

Because of the cost of membranes and the diffusion problem, the RO plants are operated at relatively high pressures (2-8 MPa) to give a good quality product with relatively low capital cost.

Normally, only 70% or less of a brackish feed is converted in a single pass through the membranes. The more saline the feeds, the lower the normal conversion rate. Higher recovery or conversion rates are possible, but are usually not attempted because of the high concentrations of salts that would develop on the membrane surfaces and cause fouling. In general, high conversion rates require more careful supervision, more maintenance, and more chemical treatment than normal rates. If higher conversion rates are required, one of the multi-stage systems described below should be used.

A 3.4. Process Configuration

There are three possible module configurations. These are:

Parallel - Capacity is added to the process by adding membrane assemblies in parallel to increase production. This modification does not change the overall salt rejection, nor the percentage of recovery of the system.

Reject Staging - is used to increase the recovery of a system. The reject (brine) from one stage is used as feedwater to a following stage so as to recover additional water. Due to the high pressure in the reject stream, no additional pumping is necessary between stages. This configuration entails a slight sacrifice in salt rejection although the power per unit of product water is lower.

The quality of the feedwater must be such that the brine delivered as feed to the additional stages does not cause scaling or other problems with the membranes in the latter stages.

Product staging - is two separate process trains run in series. The product from the first stage is used as feed to the second stage, thus allowing the first stage (using seawater membranes and high pressure) to reduce the TDS of the water to a moderate level. The second stage then can use brackish water membranes to produce a lower TDS. The reject from the second stage can be blended with the raw feedwater for reprocessing. The early seawater plants were usually product staged, but with newer membranes, single stage plants are mostly used for normal seawater.

With a two-stage system, brackish feedwaters of up to 7000 ppm can be desalted with recovery rates of 75% to 90%. Seawater plants (single or two stage) can usually only achieve 25% to 30% recovery.

A 3.5. Major Operating Problems

Most failures in reverse osmosis plants occur because materials are deposited on the membrane surfaces or in the membrane elements, preventing the elements from functioning efficiently. Other problems occur due to mechanical failures, and poor operation.

Fouling - Fouling is the deposition of materials within the plant resulting in reduced performance of the system. These deposits are from four major sources:

Precipitates
Colloids
Particulates
Micro-organisms

The membrane surface is especially sensitive to fouling, which can reduce the water flux to a major degree. It is mostly the result of faulty or inappropriate pretreatment.

Mechanical Failures - Due to the high pressures needed for the transport of water across the membranes, the piping, supports, machinery, etc., can be subjected to water mechanical stresses such as high pressures and vibration.

Corrosion - The feed, brine and product streams can all be corrosive. Many of the chemicals used in the treatment process can also be sources of corrosion.

Membrane failure - Although operating problems may focus on the failure of a membrane to function properly, they often have other causes, usually a problem in the pretreatment system.

A 3.6. Pretreatment

The proper pretreatment of the water before it reaches the membrane is the key to successful operation of a reverse osmosis plant. Membranes are designed to last at least three years, yet in extreme cases of bad pretreatment they can fail within a few weeks. As membranes constitute a major operating cost, such pretreatment errors can increase the cost of water greatly. Membranes can be sensitive to pH, temperature, chemicals, etc., and (like the feedwater passages) are highly sensitive to fouling and clogging. Proper design of the system and pretreatment of the water can minimise these problems and hence protect the membranes.

Pretreatment and post-treatment processes simply involve the application of standard water treatment and chemistry techniques. In the simplest cases with ground water, pretreatment may be unnecessary or at least relatively simple, involving only in-line chemical addition, filtration, etc. Other cases can be so complex as to require attendance by a qualified chemist. Each feedwater must be assessed individually and pretreatment tailored to suit it.

Precipitation can be minimised by reducing the concentration of the constituents subject to precipitation such as calcium, iron, etc., that are exposed to the membrane.

There are a number of ways of doing this including:

1. prior removal by ion exchange, softening or aeration/filtration
2. reducing the recovery rate
3. reducing the pH to increase solubility of precipitable substances.

In any case a threshold inhibitor (such as sodium hexametaphosphate) is usually added to the water to reduce the chance of precipitation of calcium, barium or strontium salts.

Colloids pass through standard filters and cannot be readily removed by ordinary sedimentation processes. They are most often present in surface waters and wells improperly developed in clay strata and are usually removed by coagulating followed by filtration.

Particulates can be removed by sedimetation and filtration methods.

Where microorganisms cause problems in fouling membranes, elements, and permeators, disinfection is used to remove or reduce the microorganisms present. Chlorine has been the most frequently used disinfectant.

A 3.7. Post-Treatment

The product water emerging from the membrane assembly generally needs some type of post-treatment before being distributed as potable water. Such post-treatment includes pH adjustment, usually by the addition of a base, removal of dissolved gases such as CO2 by air stripping, and/or disinfection.

A 3.8. Flux Decline

When membranes are operated at design pressure, the water passage or flux of the membrane can be expected to decrease with time, due to fouling and/or the compaction of the membranes which occurs at elevated pressures. The decline is greatest in the first year of operation. Its value depends on the water temperature, and at 25°C is about 20% in the first year. Allowance must be made in the design for this.

A 3.9 Energy Sources

The major energy requirement is for high pressure pumping to the membranes. Electricity is commonly used as the primary energy source, but other sources, such as diesel or steam engines with direct mechanical drives, have also been used.

In addition to the high pressure pumps, other machinery, such as intake pumps, chemical feeders, and instrumentation also require power. Electric power is the most convenient source for these applications. In general, overall power requirements for conventional plants are about 2 to 4 kWh/m^3 for brackish water reverse osmosis plants and about 8 to 12 kWh/m^3 for seawater plants.

A 3.10 Energy Recovery

The high pressures involved in seawater reverse osmosis have prompted the use of energy recovery systems to utilise a major portion of the energy in the brine reject stream. This stream is usually discharged at approximately 120 kPa less than the feedwater stream to the membranes.

The potential for energy recovery is highest when the fraction of feedwater converted is low. A variety of energy recovery devices such as impulse (Pelton) turbines, and reverse running pumps have been used for other applications. These can produce rotating energy which can be used to augment shaft work in the plant or to provide electric power.

A 4. ELECTRODIALYSIS

A 4.1. Introduction

Electrodialysis is also a membrane process, but it relies on the passage of ions rather than water, through semi-permeable membranes. Two different types of membrane - anion selective and cation selective - are required and the ions are made to migrate through the membranes by an electric field applied at right angles to the plane of the membranes (see Fig. A.9).

The process is thus capable of removing only ionic impurities and has no effect on suspended matter, colloids or bacteria.

The membranes are arranged alternately, an anion- followed by a cation-selective membrane. As the electrodes are charged, the anions are diverted from the main product stream and pass through the anion-selective membrane into the concentrate (or brine) cell. The anions are prevented from moving through the adjacent cell wall, as it is a cation-selective membrane and prevents their passage. Similarly cations move from the dilute stream on the other side of the cation-selective membrane into the concentrate cell. Here they are prevented from moving further toward the negative electrode by the anion- selective membrane. By this arrangement, concentrated and dilute solutions are formed in the spaces between alternating membranes . (Spaces bounded by two membranes are called cells). A cell pair consists of two cells, one from which the ions migrated (diluting cells for the product water) and the other in which the ions concentrate (concentrate cell for the brine stream). A typical plant has several hundred cell pairs.

Membranes are flat sheets and come in a variety of sizes, again depending on the manufacturer and the application. They consist of a plastic material to which ion transfer sites have been added, and a backing material for strength. A typical size is about 50 by 100 cm. They are usually an unbroken sheet except for holes cut out to form flow channels and holes or slots to guide the assembly of the membranes into a stack.

Spacers separate the membranes and provide a pathway for water flow in the cell. The thickness of the membrane depends on the application, and its selection is a trade-off between membrane properties. Thicker membranes usually have greater strength, increased erosion resistance, and longer life, whereas thinner membranes have lower electrical resistance and hence reduced energy requirements. Typically, membranes are about 0.5 mm thick.

Spacers can be formed to provide different types of flow paths. The sheet flow and tortuous path flow are two of the most commonly used designs.

Feedwater passes simultaneously in parallel paths through all of the cells to provide a continuous flow of product water and brine stream, thus washing out the concentrated ions.

By the use of special spacers, more than one hydraulic stage can be placed between a set of electrodes. The number of stacks, stages and electrodes is determined at the time of design, based on site-specific information.

A 4.2. Elements of an Electrodialysis Unit

An electrodialysis unit is made up of:

a DC power supply (rectifier)
a Membrane Stack
a Circulation Pump and sometimes Pretreatment

The membrane stack includes the electrodes, membranes (both anion and cation permeable), spacers, plumbing necessary to transport water to and from the stack, and the hardware necessary to hold the stack together.

A reaction occurs at each of the electrodes (which may be niobium, titanium, carbon, platinum or stainless steel). Hydrogen ions and oxygen and/or chlorine gas are formed at the anode (positive electrode) and hydrogen gas and hydroxyl ions are formed at the cathode. Because a separate stream is generally used in the space adjacent to the electrodes in each stack, the by-products of the reactions are confined to these streams. The anode stream is normally acidic due to the hydrogen ions, and the cathode stream is basic. The pH difference is partially neutralized by combining the streams. In most units, the electrode streams are kept apart and then usually discharged to waste, although in some instances this water is treated and recycled. Some degradation of the electrodes also occurs, but this can be reduced by using the electrodialysis reversal process.

A 4.3 Pretreatment

Pretreatment depends on the feedwater, but it usually includes the removal of suspended or dissolved solids which could adversely affect the membrane surfaces or block the narrow flow paths. Many of the techniques are similar to those used in RO. Where suspended solids are present, sand filters are often used in front of the membranes. Cartridge filters are also provided as a back-up protection.

The use of the ED Reverse process has in most cases eliminated the need for acidification and scale inhibitors, but certain feedwater constituents still require removal. These include:

Free Chlorine
Iron
Manganese
Hydrogen Sulphide
Turbidity

It is also necessary to prevent the growth of organic slime inside the stack. Organisms can grow there if there is material that they can metabolise in the feedwater. A chlorination-dechlorination step is used if the problem is severe, otherwise slimes are removed during cleaning.

Each prospective feedwater should be examined individually to determine the appropriate pretreatment.

A 4.4 Circulation Pump and Hardware

In the electrodialysis process the water pump is used only for circulation of the water through the stack. The pressure required for this circulation varies with the construction of the stacks, number of stages, stacks, etc., but generally a pumping pressure of only 400-500 kPa is needed. This is considerably lower than the 2 MPa required in the brackish water reverse osmosis process. The low preessures allow the use of standard plastic pipe and fittings, yielding lower cost, high resistance to corrosion in a saline environment and ease of construction.

A 4.5. Energy Requirements

The major energy requirements fall into two categories:

1. Pumping energy - usually between 0.5 and 1.0 kWh/m^3
2. Stack current.

The amount of energy consumed by the stack is dependent on the desired purity, the water temperature, the membrane resistance and other design factors. To produce a potable product (500ppm), conventional systems require about 0.7 kWh/m^3 for each 1000 ppm of dissolved solids removed. This figure decreases by about 2% for every 10°C of temperature rise.

New low resistance membranes exhibit much lower energy needs. For example Tokuyama soda membranes require only about 0.26 kWh/m^3 per 1000 ppm removed at 20°C. The low resistance energy saving system has not yet been widely used so it is difficult to compare other aspects of the design with conventional plants.

Maximisation of dissolved solids removal per unit of power by increased current application is limited by polarisation effects. Polarisation occurs during electrodialysis in the dilute (or product) cells when a high enough rate of ion transport takes place to create a depletion of ions in the water adjacent to the membrane. This reduces the conductance of the water resulting in higher energy usage in the stack.

In the absence of ions in the boundary layer, the continued high current density causes a dissociation of water molecules adjacent to the membranes and the diffusion of the hydrogen and hydroxyl ions through the membranes. As these ions enter the concentrating cell, they alter the pH and in the case of the anion transfer membrane this can result in a higher pH that will encourage the scaling of precipitates such as calcium carbonate and the formation of a high resistance gas layer on the membrane surface. In an effort to increase the current density at which polarisation becomes a serious problem, some manufacturers have incorporated turbulence promoters into the spacers.

A 4.6 Electrodialysis Reversal (EDR)

In the reversal process the polarity of the electrodes is reversed 3 to 4 times per hour, and the flows are simultaneously switched by automatic valves in the stacks so that the product cell becomes the brine cell and the brine cell becomes the product cell. The salts are thus transferred in opposite directions across the membranes.

Following the reversal of polarity and flow, the product water is discharged until the cell and lines are flushed out and the desired water quality is restored. This takes approximately 1 to 2 minutes, and aids in breaking up and flushing out scale, slimes and other deposits in the cells.

This automatic cleaning action eliminates the need to continually add acid and/or polyphosphate, the scale formation in the electrode compartments is minimised due to the continuous alternation of the environment from basic to acidic. This greatly extends the intervals between the stack disassemblies. The overall result is reduced maintenance time.

A 4.7. Operating Problems

A variety of operational problems can be experienced with electrodialysis facilities. The major ones are scaling and leaks.

Scaling - scale fouls the membrane surfaces and blocks passages in the stack. The slowly moving water then becomes highly desalted due to the longer period of exposure to the electromotive force. The highly desalted water has a low conductivity and offers a high resistance to current flow. Some scale can be removed by introducing chemicals into the stacks in an attempt to dissolve or loosen the scales so that they can be washed out. In more severe cases the stack is disassembled.

Leaks - operating and/or maintenance problems can result from leaks in two parts of the electrodialysis stacks: (1) between the stacked membranes and spacers; and (2) through the membranes.

Since stacks using membranes and tortuous path spacers are assembled much like a deck of cards, without a sealant or special gaskets, the ability of the stack to remain watertight is dependent on the material fitting tightly together, which, in turn, depends on the spacers and membranes being uniform in thickness and the stack being uniformly pressed together. This can be a problem, since some stacks contain a total of 1,200 to 1,800 membranes and spacers (300 - 450 cell pairs).

Other leaks can develop through cracks or tears in the membrane or spacers as a result of manufacturing defects, improper handling, excessive tightening of the stacks, aging and other causes. The result is usually an intermixing of water between the dilute and concentrate cells, and reduced product water quality. Normally stacks are operated with a slightly higher pressure on the product water side to prevent this intermixing.

ACKNOWLEDGEMENT

Most of the diagrams used in this section have been taken from the U.S.A.I.D. Desalination Manual.

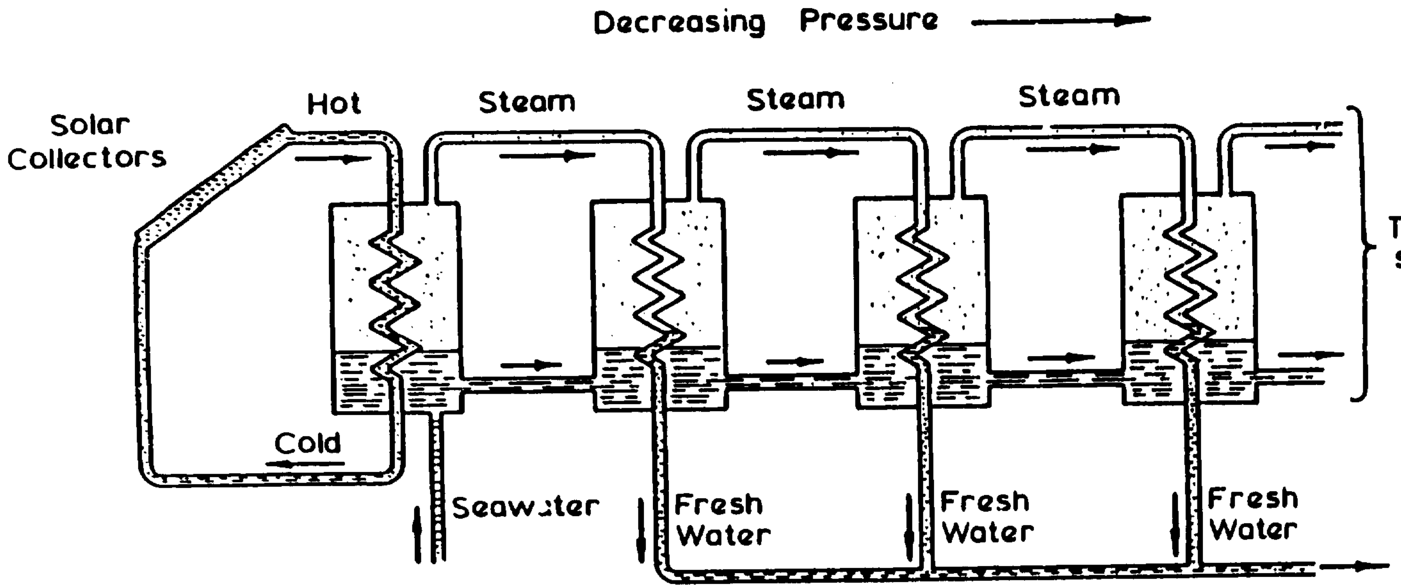


Figure A.1 Conceptual Diagram of a Multiple Effect Evaporator

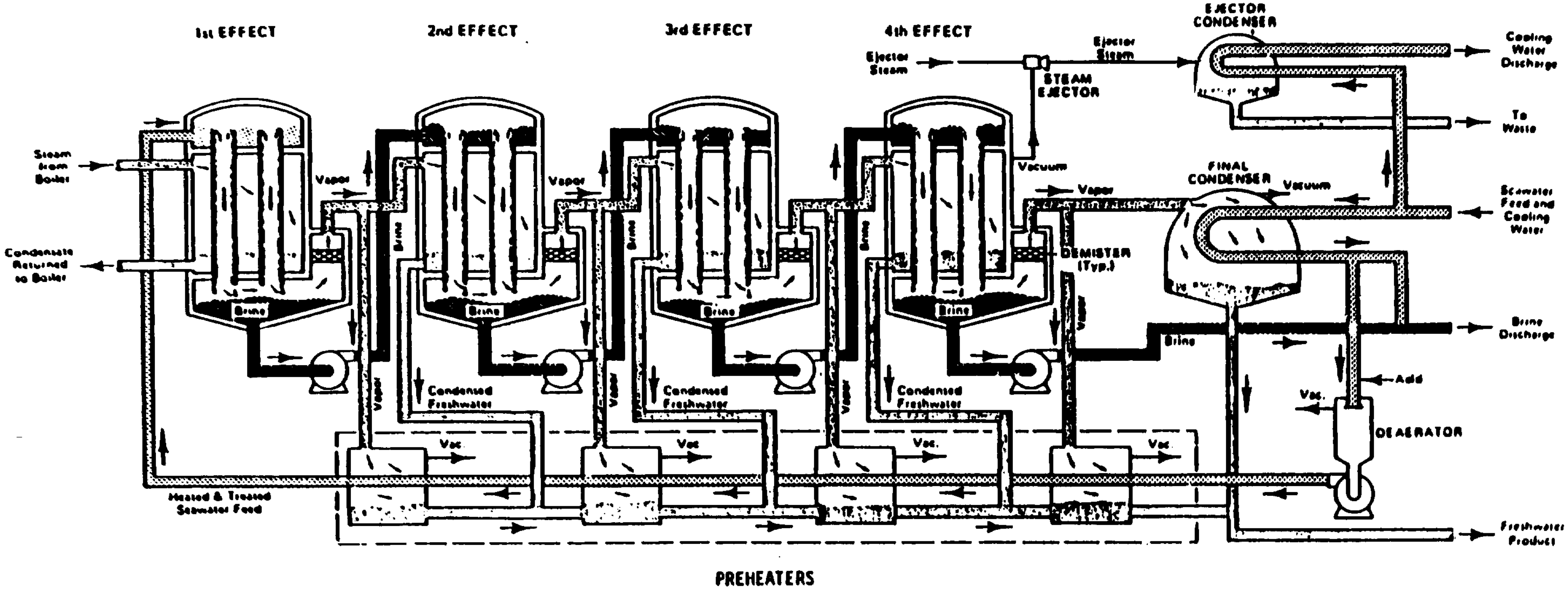


Fig.A.2. Simplified Diagram of a VTE Plant

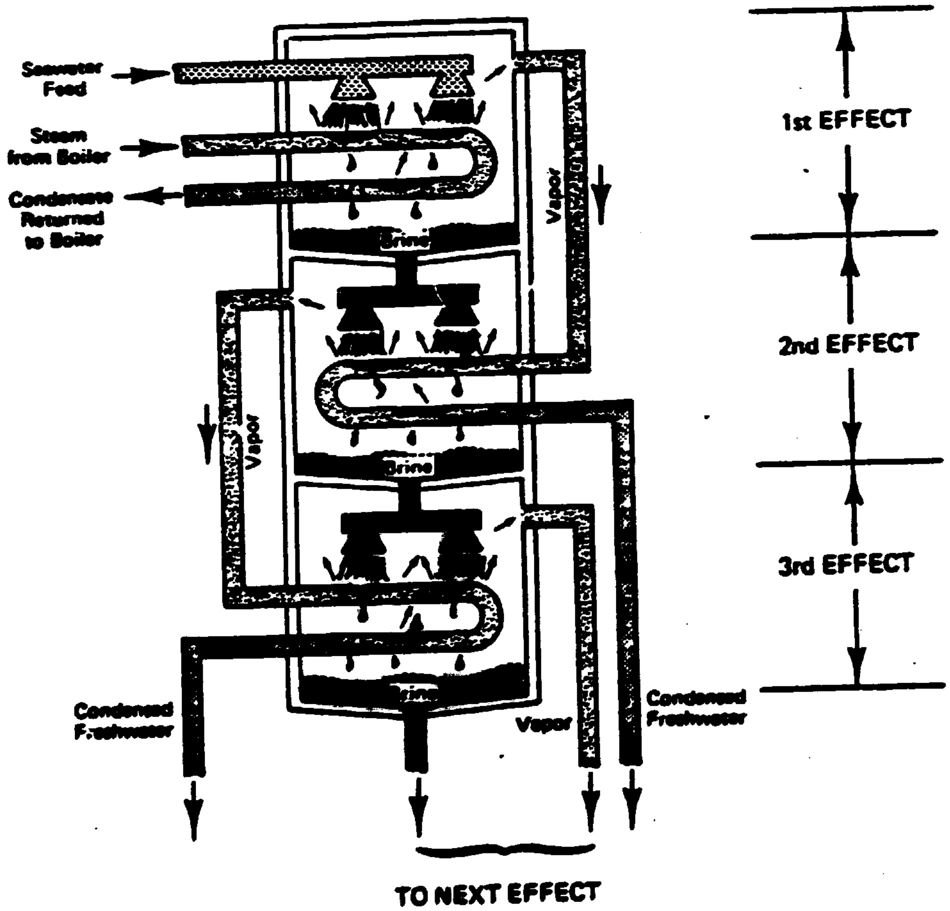
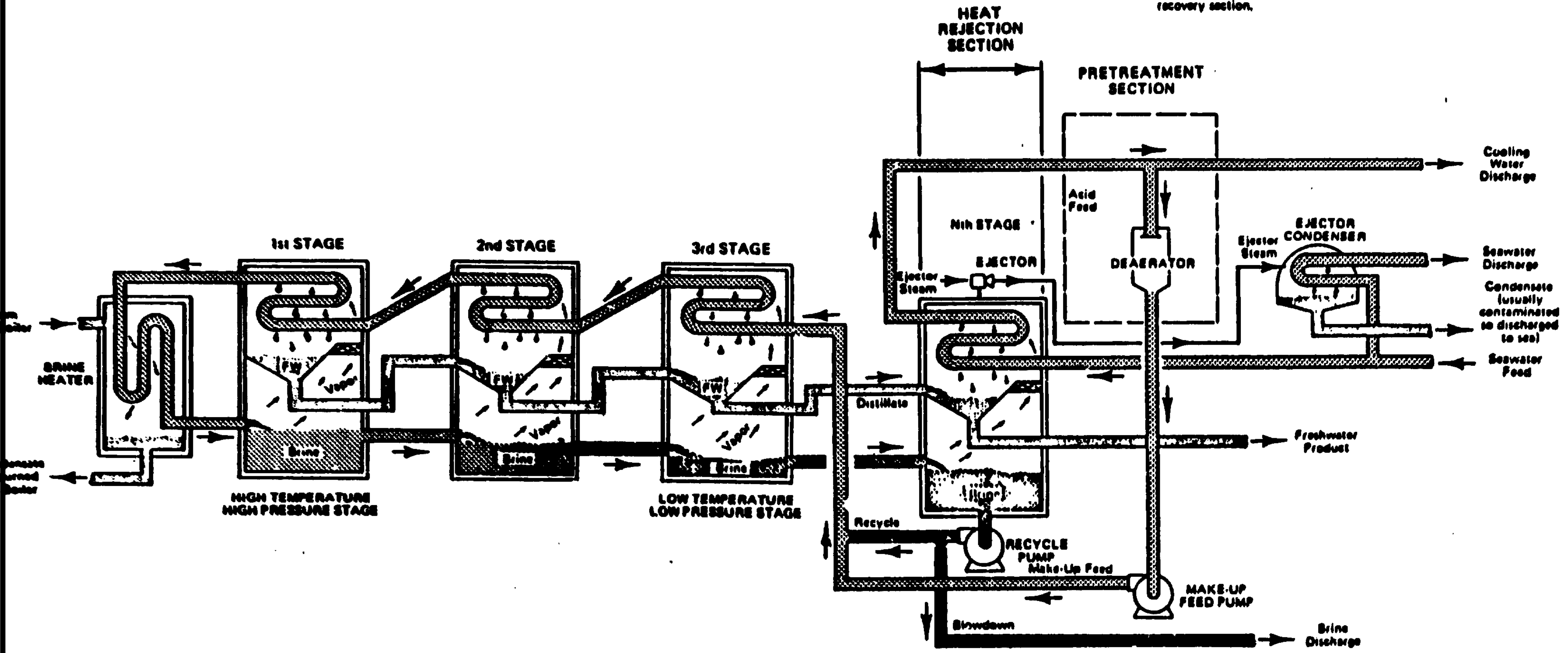


Fig. A.3. Simplified diagram of a vertically stacked horizontal tube plant.



Note: Generally, there are several (often 4) stages in the heat recovery section.

Fig. A.4. Simplified Diagram of an MSF Plant with Recycle.

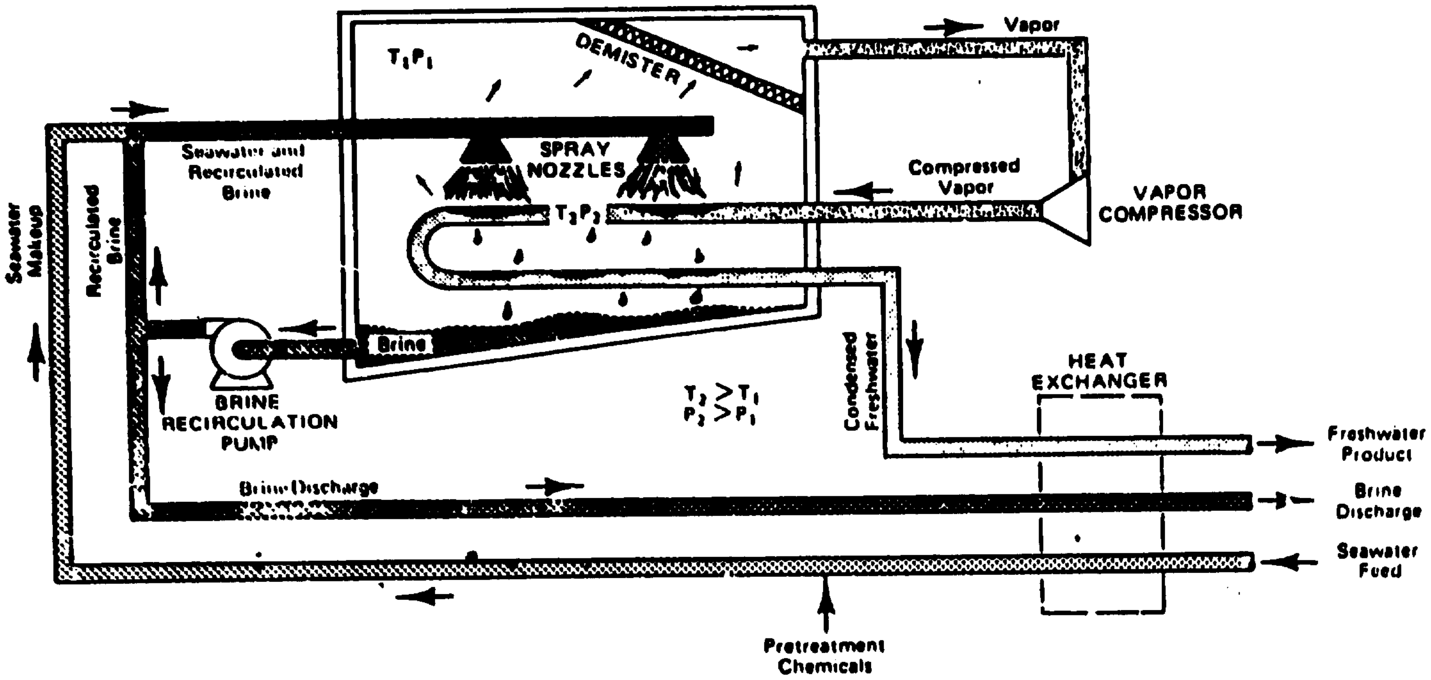
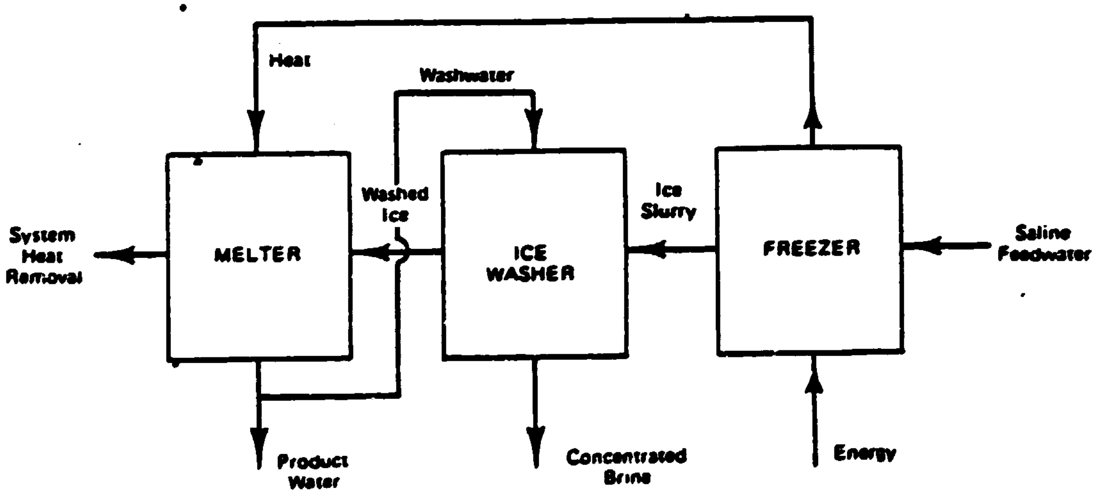


Fig. A.5. Simplified Diagram of a Vapour Compression Plant.

Fig. A.6. Block Diagram Showing Elements Needed in a Freezing Plant.



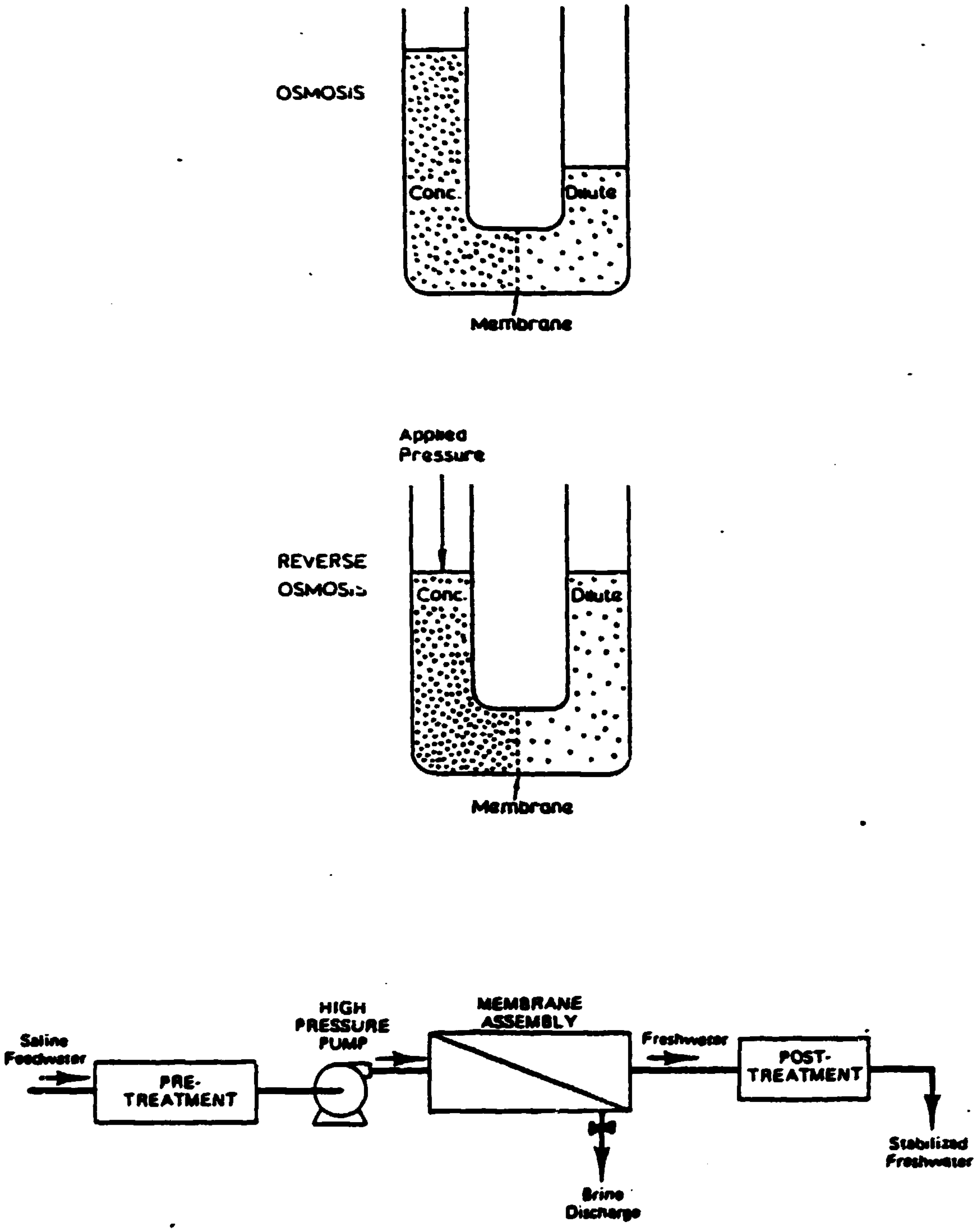
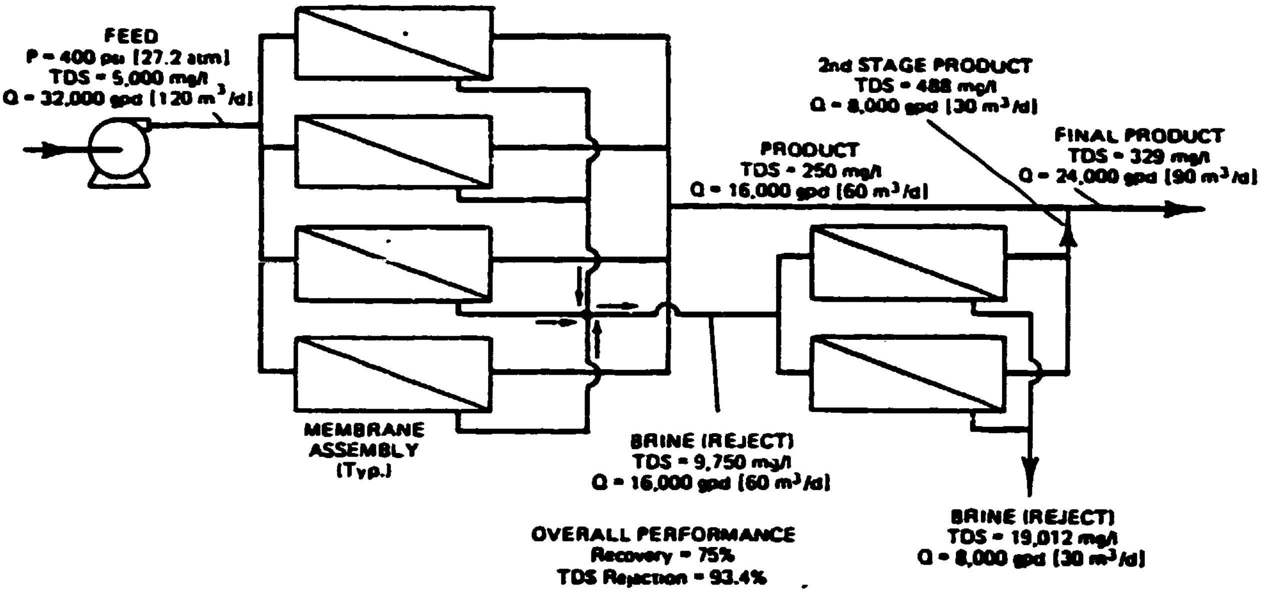
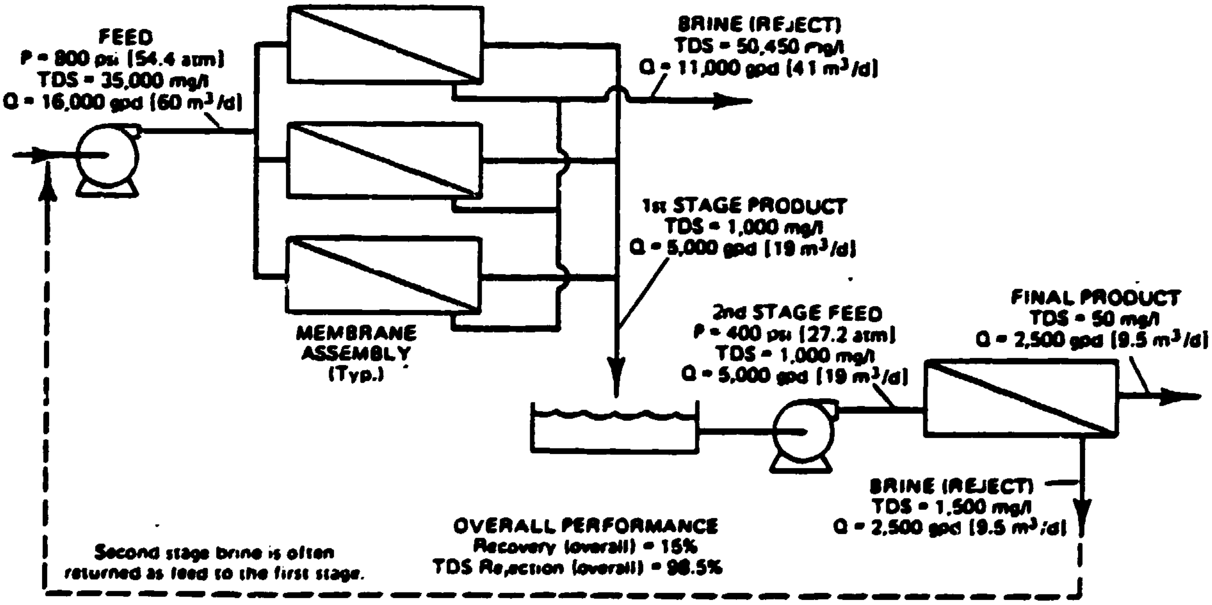


Fig. A.7. Principles of Operation of Reverse Osmosis (above) and Block Diagram of the Process (below).



MULTISTAGE WITH REJECT STAGING



MULTISTAGE WITH PRODUCT STAGING

Fig. A.8. Multistage RO Configurations.

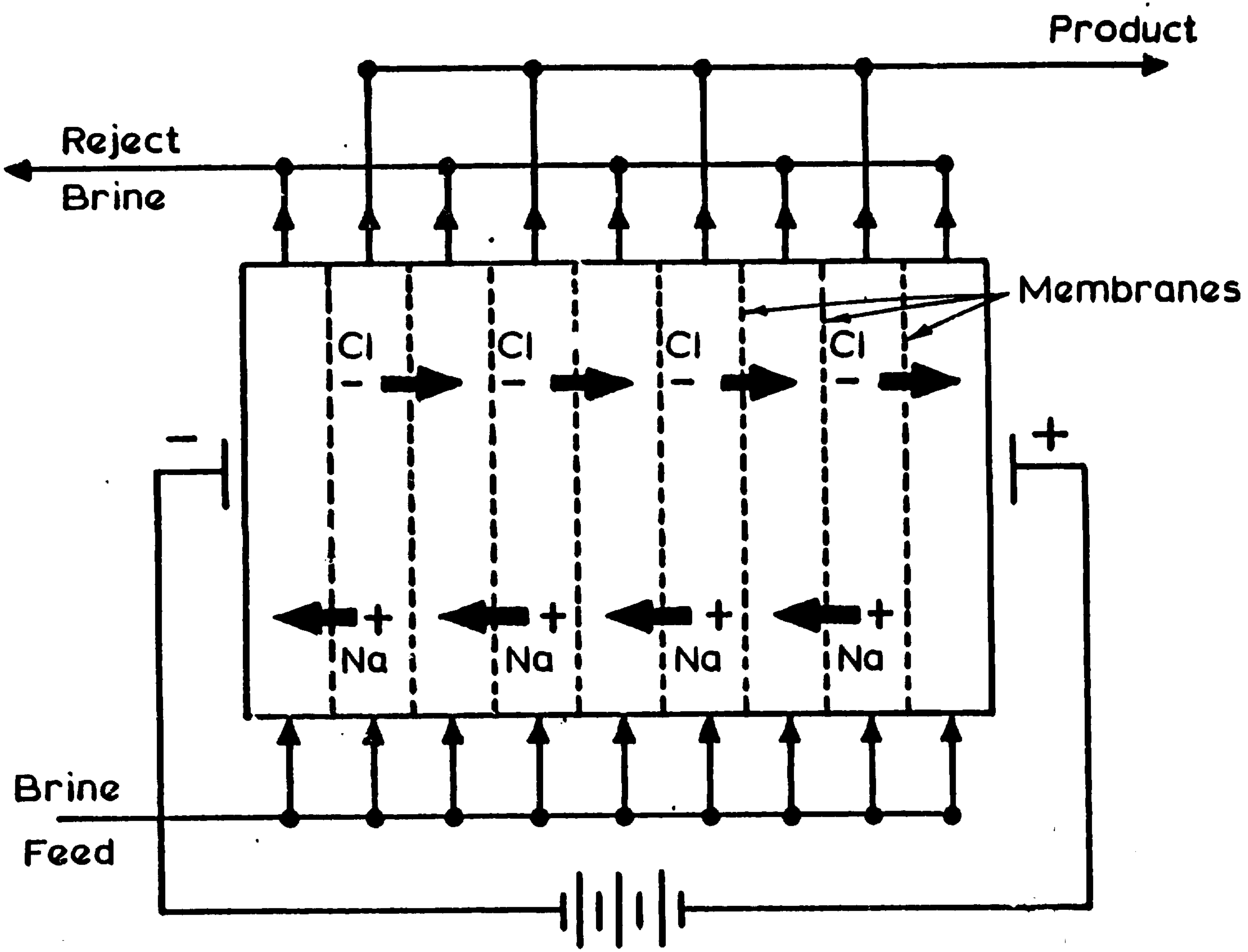


Fig. A.9. Principles of Operation of Electrodialysis.