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DESALINATION TECHNOLOGY FOR THE RECOVERY OF
FRESH WATER AT REFINERIES AND OTHER COASTAL INDUSTRIES

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INDIA

Technical Report: Desalination of Water For Bharat Petroleum Bombay Refinery*

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

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EXECUTIVE SUMMARY

A study was undertaken of the possible ways of providing about 4,000 m³/day of desalinated seawater for the Bharat Petroleum refinery in Bombay.

It was concluded that:

1. Whatever method was employed, the existing seawater intake would need to have some form of clarifier installed to reduce the level of suspended solids
2. Of the available options, waste heat distillation gave the lowest water costs, by a wide margin, and its use had other benefits also
3. Waste heat distillation was more difficult to install than other methods, since it required a connection to the refinery's process cooling in the Crude Distillation Unit
4. Reverse Osmosis would be difficult and risky to implement in this application, and a pilot plant would be required
5. Water costs from the waste heat unit are about Rs 25/m³.

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1. INTRODUCTION

The Bharat Petroleum Refinery currently uses approximately 4,000 m³ of water per day in its process. This is supplied from the Bombay Municipal Supply. The refinery also uses about 15,000 m³/hour of seawater for process cooling.

The refinery wishes to conserve water, and to become independent of the Municipal Supply, which currently charges about Rs 12/m³ up to a certain threshold, and about Rs 18/m³ for all excess consumption above the threshold.

The refinery has tried sinking wells on its site, but the yield of these wells is insufficient to provide even a reasonable proportion of the projected needs.

The municipal water is currently passed through a demineralisation plant, and the inlet water qualities for that plant are as follows:

	Normal	Max
Total Suspended Solids mg/l	18	25
TDS	80	125
Silica as SiO ₂	20	32
Iron as Fe	0.1	0.5
Calcium as CaO	13	15
Magnesium as MgO	0.4	9.4
Sulphate as SO ₄	10	24
Chloride as Cl ⁻	6	12
P-alkalinity as CaCO ₃	0	10
M-alkalinity as CaCO ₃	50	65
Total Hardness as CaCO ₃	47	50
Organic Matter (KMnO ₄ consumed)	1	1
Free Chlorine as Cl ₂	1	1
Turbidity	5	5
pH	7 to 8.3	

The demineralisation plant produces water of pH from 7.5 to 9.5 with a conductivity at 20C of less than 10 micromhos. Operating costs for the plant are about Rs 5 per m³.

Analyses for the seawater vary from a TDS of 21,000 ppm to about 40,000 ppm. The intake is on a relatively shallow shoreline on the upper reaches of Bombay harbour. There is fresh water inflow from Thana Creek. The site is in a tropical area, and the sea appears very calm at that point. It is therefore likely that in the dry season, the salinity will be around the upper value quoted above (compared with "standard" seawater of 35,000 ppm).

The seawater pumped into the refinery is passed through a settling tank before being used. A sample of the water taken downstream of the settling tank took about two hours to show significant improvement in clarity. The

amount of sediment at the bottom of the bottle confirms figures given in seawater analyses of about 700 to 1000 ppm of suspended solids. The settling time suggests a particle size of the order of 10 microns. A second sample, taken a few days later, showed slightly lower suspended solids, and longer settling time (ie smaller particle size).

The water is chlorinated as it is pumped from the shore, and it also contains an undetermined amount of oil.

The sea is the only obvious source of feed water, other than the municipal supply, and it is intended to desalinate seawater for process requirements.

2. REQUIREMENT

The company states that it will need about 4,000 m³/day of raw water, mainly to feed into its demineralisation plant. The plant has a design feed salinity of 80 ppm, and any desalination plant installed would need to exceed this quality on an average basis. A salinity of 50 ppm and a plant capacity of 5,000 m³/day will be used for design purposes.

The refinery would like to become independent of the Bombay Municipal Supply.

The space available for a plant is limited. An area of about 4,000 m² has been earmarked for the purpose, and additional land would be hard to find. The site proposed is adjacent to the cooling water pumphouse, as shown in Fig. 1.

3. OPTIONS FOR DESALINATION

3.1. Reverse Osmosis

Reverse Osmosis (RO) was first commercialised for desalinating brackish waters of up to about 8,000 ppm total dissolved solids. Over the last 10 years, RO has established itself as a viable competitor with the older distillation processes for medium sized seawater desalination plants. The normal application of seawater RO is to produce potable water (about 500 ppm TDS) from seawater of up to 40,000 ppm TDS.

The key elements of an RO plant are:

1. Water intake
2. Pretreatment
3. High pressure pumps
4. Membranes
5. Post-treatment.

All elements of the plant are interrelated.

3.1.1. The Intake

Normally, the aim in designing the water intake is to minimise total dissolved solids, suspended matter and gases. Lowering the salinity of the source will reduce the capital and operating costs of the membrane stack and pump, while lowering the suspended matter and gases will reduce pretreatment costs.

The present water source at the Bharat Refinery is very high in both salinity and suspended matter, and the water would need extensive pretreatment before being fed into the RO plant.

It may be possible to find a clearer source of highly brackish water by digging a number of wells near the shore. It would be necessary to ensure that the yield was adequate without dewatering the ground. It would also be important to ensure that other contaminants, such as oil or hydrogen sulphide were not picked up. A reduction in the TDS of any groundwater used, compared with seawater, would be an added bonus.

If the present intake system is retained, it will be necessary to reduce the suspended solids before desalination.

The company has plans to convert their once-through seawater cooling system to a recirculating system, with a blowdown rate of about 10%. This implies a circulating water salinity of about 52,000 ppm. The company is also considering the installation of an inclined plane separator to reduce the suspended solids in the circulating seawater. The design aim of the separator is 50 ppm output. Cooling towers will be located above the existing settling ponds. The intake for the RO plant would need to be before the water was fed into the recirculating system, since the salinity of the recirculated water would be too high for a normal RO installation.

However, the existing demand for cooling water will fall from about 15,000 m³/hour to about 2,000 m³/hour, plus the demand of the desalination plant, which is likely to be about 1,000 m³/hour. Thus the total flow from the intake at the jetty will fall by a factor of 5.

3.1.2. Pretreatment

The remarks that follow are based on the assumption that the refinery will draw its desalination plant feedwater from the existing source, and that some form of clarification, common with the seawater cooling system makeup, will be provided.

The seawater is subject to considerable pollution from industries and ships, as well as sewage. Ships also create turbidity.

Because of the wide variations in rainfall from season to season, and changes in the amount of pollution released into the harbour, no single analysis of the water can be relied upon to be definitive.

Two analyses available for the seawater are as follows:

	Low	High
Total Suspended Solids mg/l	670	700
TDS	21064	41397
Silica as SiO ₂	45	82
Iron as Fe	2	9
Calcium as CaCO ₃	800	1020
Magnesium as MgCO ₃	720	5680
Sulphate as SO ₄	1518	2687
Chloride as Cl ⁻	11218	22010
P-alkalinity as CaCO ₃	0	5
M-alkalinity as CaCO ₃	15	125
Total Hardness as CaCO ₃	3750	6700
Free Chlorine as Cl ₂	1	1
pH	7.6	7.8

The reason for the difference between the two analyses is not known, but apart from differences in industrial pollution, it could be due to one being taken during the dry season and the other during the monsoon. Tide level probably also plays a part, especially with suspended solids.

Suspended Solids

A number of options are available for removal of solids from the feedwater. They include:

1. Sedimentation ponds
2. Inclined Plane Separators
3. Media Filters (eg sand filters)
4. Dissolved Air Flotation
5. Cyclones.

A number of combinations of the above have the potential to provide adequate solids separation, provided it is properly designed.

The ponds are the simplest device, and if space were available, they would be desirable on the basis of their simplicity alone. To give a 10 hour residence time, the pond would need to be 70 m by 70 m by 2 m for the RO plant alone. This area is difficult to find on the refinery site, but it appears that at least 10 hours will be needed. A flocculant would assist in the settling process, reducing the area required by a factor of up to 10, but would increase the volume of sludge produced. It may be possible to combine the removal of colloidal iron compounds with the settling stage.

An inclined plate separator requires considerably less space than a settling pond to perform the same duty, at the expense of complexity. There is some risk of clogging between the plates.

Media filters would only be practical in this case if an initial cyclone or other stage reduced the suspended solids to below 40 ppm.

It is improbable that the inclined plane separator mentioned above will produce water with have sufficiently low suspended solids for use by the RO plant without further treatment.

The Dissolved Air Flotation plant has the advantage that the aeration and coagulation will remove some of iron as well as suspended solids.

The flow for the RO plant alone would produce about 20 tonnes of sludge a day, which would need to be disposed of in an acceptable way.

Silica

One of the analyses of the seawater suggests a dissolved silica level of 45 ppm, while the other says 82 ppm. Inside the RO modules, there will be increased concentration of silica, which may exceed the solubility limit.

Silica becomes a more serious problem in combination with metal oxides, of which iron oxides are a likely candidate. Silica can often be kept in solution by increasing the pH, but that tends to encourage calcium carbonate scaling.

Ways to remove silica include:

Adsorption onto iron salts in a coagulation stage. Ferric sulphate added in relatively high doses will cause precipitation of iron hydroxide.

Lime softening. In this case, the precipitating magnesium hydroxide will collect the silica. It is more efficient at elevated temperatures, but the RO membranes cannot cope with temperatures above about 40C.

Anion exchange is the most direct way of removing silica.

Iron

Iron compounds can precipitate in the membrane elements, and it is necessary to precipitate it before the membranes, or keep it in the divalent state as the water passes through the membrane. The state in which the iron is present is not clear from the analyses.

Normally, membrane manufacturers limit iron levels to 0.1 ppm, about 1% of the level in the feed.

The iron can be oxidised by aeration, and then precipitated out using a flocculant.

Chlorine

The free chlorine level in the feed is approximately 10 times that allowed by membrane manufacturers for composite thin film membranes, and therefore dechlorination is required. This may be accomplished by sodium metabisulphite addition or use of an activated carbon filter. The latter would also deal with other likely contaminants in the water.

Oil

RO membranes are not tolerant of oil contamination. The Bharat Petroleum laboratory indicates a normal oil content of the water of 4 ppm. The analysis was done for the purpose of sizing cooling towers for the proposed closed circuit cooling system, and oil content of 10 ppm was indicated under process upset conditions.

The water drawn directly from the sea will probably have less oil content, but a sample taken from the outlet of the settlement pond near the plant pumphouse had a visible oil slick on it. While a small amount of dissolved oil may pass through the membranes, manufacturers specify that the feedwater should contain no oil at all, and oil contamination will foul the membranes. This could be a major problem in the use of RO in this situation.

Cross-flow micro-filtration will remove oil and other organic contaminants.

There are also a number of other filters, such as the Varvoid filter, and certain gravel filters that can be used to reduce the oil content.

An activated carbon filter may be adequate to remove small amounts of oil, but would clog very quickly if the level approached 10 ppm.

Other pretreatment processes needed for the RO plant are:

1. Media Filtration

Sand filters or multimedia filters are usually part of the pretreatment. The filtration is only provided if needed. In this case, the need will depend the extent to which the initial solids removal stage clarifies the water. It is likely that some form of media filtration will be needed.

2. Cartridge Filtration.

This is a backup to the other methods of solids removal, and involves a 5 to 20 micron filter. It is intended that these filters last at least a few months.

3. Inhibitor addition.

A scale inhibitor, such as Flocon or Sodium Hexametaphosphate is added through a metering pump to the feed line, usually before the high pressure pump. Sulphuric or hydrochloric acid is sometimes used in addition to the inhibitor, to reduce the pH, and keep calcium salts in solution.

3.1.3. Pretreatment Proposed for This Plant

There are several ways of removing most of the unwanted components of the feedwater. Membrane and plant manufacturers were asked about the best way to deal with the seawater available at the refinery site, and the following pretreatment scheme emerged, based on experience with similar waters in another project:

Coagulation

Dissolved Air Flotation

Lime softening

Acidification (stage 1)

Gravity or pressure filtration

Acidification and inhibitor addition

Bisulphite addition.

An alternative approach suggested by another supplier involves cross-flow microfiltration, followed by activated carbon filtration. However, it is not clear that that approach would adequately remove the iron and silica without additional treatment, and the cost of the cross-flow microfiltration alone approximates the total cost of the first alternative. The demand for activated carbon could be high, and if this option were adopted, it may be necessary to consider on-site regeneration.

In view of the variable quality of the seawater and the complexity of the pretreatment process needed, any supplier would probably require the construction of a pilot pretreatment plant before committing himself to a design (and price). If no such plant were built, one may find modifications needed in the plant after construction.

3.1.4. High Pressure Pumps (and Energy Recovery Turbine)

RO membranes are not capable of reducing the TDS from 40,000 ppm to 50 ppm in one stage. Therefore, the plant will need to have two stages. The first stage will reduce the salinity to about 500 ppm. The second stage will reduce the salinity to the required 50 ppm.

For a 5,000 m³/day plant, the first stage will have a flowrate of approximately 18,000 m³/day at a pressure of approximately 5.4 MPa, while the second stage will have a pressure of about 1.5 MPa and a flowrate of about 6,000 m³/day.

In both cases, the most suitable pumps will be multistage centrifugal pumps for the size of plant being considered here. There are several manufacturers who have produced pumps specially for RO applications, taking into account the materials problems caused by the high salinity of the initial feed. Ferrous materials (other than specialised stainless steels) cannot come into contact with the water, otherwise membrane damage will occur.

There will be a reject stream of about 13,000 m³/day from the first stage. This will be at a pressure of about 5 MPa, and the hydraulic energy can be recovered using a suitable turbine. Pelton wheels or centrifugal turbines can be used. An efficiency of about 70% can be expected, leading to a recovery of about half the mechanical energy in the first stage. The total hydraulic energy used in the second stage will be less than 10% of that used in the first stage.

3.1.5. The RO Elements

There are three methods for constructing an RO membrane. These are:

- Hollow fine fibre
- Plate and Frame
- Spiral wound.

The hollow fibre membrane design involves very narrow passages through which the feedwater must pass, and it is extremely vulnerable to clogging. Cleaning is unlikely to be successful. Such membranes are available from only one manufacturer.

Plate and frame units are only available from two manufacturers. They occupy a lot of space, and are primarily suitable for wastewater purification. The nature of the feedwater in this case suggests that such membranes could be applicable, but there are cost and space penalties involved with their use.

Spiral wound membranes are the most commonly used and widely manufactured. These are the most likely to be made in India and the most easily substituted.

Two membrane materials are currently in common use. They are cellulose acetate and composite thin film. The former are tolerant to chlorine but require careful pH control, while the latter do not tolerate chlorine, but can operate over a wide range of pH. Generally, the composite membranes give better salt rejection, and seawater membranes are almost invariably of this material.

A preliminary design for the plant indicates that the first stage could consist of 408 Filmtec SW8040 membranes operating at about 6.2 MPa, and the second stage could consist of 120 Filmtec BW8040 membranes operating at about 2.7 MPa. This is based on an overall plant conversion rate of about 29%. Higher conversion rates (up to 40%) may be possible, but will make the plant more vulnerable to any excursion from the normal operating conditions.

Other brands of membrane could also be used. In particular, Hydranautics are soon to start manufacturing cellulose acetate brackish water membranes in India. If these are used, it will be necessary to control the pH of the output from the first stage of the plant, by addition of acids or bases.

Composite thin film membranes are usually used for seawater plants, rather than cellulose acetate. Cellulose acetate is more prone to attack by bacteria, and requires close control of pH.

3.1.6. Post-treatment

The product may require some pH adjustment (probably CO₂ stripping) and disinfection, although if it is being fed directly into a demineralisation plant, both steps could be unnecessary.

3.1.7. Land Requirements

The space requirements for an RO plant are, to an extent, under the designer's control, in that the membranes can be stacked vertically if necessary. Typically, a plant of 5,000 m³/day could require an area of around 600 m² for the membranes, pumps, chemical dosing and control area. About 1,000 m² could be required for the pretreatment stages mentioned.

If a simple sedimentation pond without flocculants is used, its area alone will cover the about 5,000 m². It is thus highly desirable to use a more compact method of solids removal.

3.1.8. Energy Requirements

Again, the designer has some scope. With the conversion rates mentioned above, the principal areas in which variation can occur are:

1. Pump efficiencies
2. Electromechanical drive efficiencies
3. Presence, absence and efficiency of energy recovery turbine.

The conversion rate in the first stage of the plant is also a major determiner of energy consumption. Conversion rates of up to 45% have been used successfully with seawater, but that requires very careful control over feedwater quality. The energy savings from increasing the recovery rate are reduced if an energy recovery turbine is installed.

A seawater RO plant of the size under consideration could have an energy recovery from a minimum of about 5 kWh/m³ to 15 kWh/m³. A realistic design, including feed pumps, etc and energy recovery would probably have an energy consumption of around 8 kWh/m³.

Thus the total energy demand of the plant is likely to be around 1.7 MW (electric). Without energy recovery, the energy demand would be close to 2.5 MW.

3.2. Distillation

Simple distillation is a very energy-intensive process, requiring 2300 MJ/m^3 of product. Designs which re-use the latent heat of vaporisation to evaporate more water have therefore been developed, and units with thermal energy consumptions of 230 MJ/m^3 or less are now readily available.

Distillation plants also require electrical energy for pumping. With careful design, this can be kept to 1 kWh/m^3 , or less, in the size range under consideration here.

Making allowance for the conversion efficiency involved in generating electricity, it could be said that the RO plant discussed above, with an efficiency of 8 kWh/m^3 was really consuming about 25 kWh/m^3 or about 90 MJ/m^3 of primary energy. That is less than half the consumption of a relatively efficient distillation plant.

Since energy costs are a major component of the total cost of desalinated water, distillation is normally not a viable option compared with RO. There are three possible circumstances under which distillation may be more appropriate than RO. They are:

1. The thermal requirements can be provided from a source of waste heat
2. The system is a dual-purpose plant in which power generation and distillation are both performed
3. The feedwater is such that RO requires very complex or extensive pretreatment, or the recovery rate is severely limited.

In the present case, both the first and third points may apply. There is waste heat at 120C or more available from a number of points in the plant. The plant uses over $4 \text{ m}^3/\text{sec}$ of cooling water, and its temperature is typically raised by 10C in the process. In approximate terms, it appears that the seawater cooling system is carrying away approximately 150 MW of waste heat. Of course, some of this waste heat is at such a low temperature that it is not usable for water distillation.

By comparison, one make of modern $5,000 \text{ m}^3/\text{day}$ multiple effect plant of a reliable design with proven operating record consumes about 15.5 MW . Other less efficient and consequently cheaper designs are also available. The least efficient waste heat plants of the appropriate size would consume about 140 MW .

There are two principles of operation used in distillation plants - multistage flash (MSF) and multiple effect evaporation (ME). Successful designs are available in both types.

Because of scaling problems, modern, successful designs of distillation plant tend to operate at low top temperatures (under vacuum), less than 90C and usually less than 70C . Thus the temperatures required could be generated from waste heat in the refinery.

In addition to the heat transferred to the cooling water and the atmosphere, there is also a small amount of flared gas, averaging about 10 tonnes per day. The minimum rate of flaring is reported as being about 5 tonnes per day. It is estimated that this energy source could only guarantee an output of about 15% of the needs of an efficient 5,000 m³/day distillation plant, unless the gas were compressed and stored.

It can thus be seen that there is abundant waste heat available to provide the required water output.

However, there are complications associated with the use of waste heat distillation plants. These include:

1. The plant may not be located adjacent to the waste heat sources, and therefore, a few hundred metres of insulated piping may need to be provided
2. There are several sources of waste heat. There are three major plants producing it - the crude distillation plant, the catalytic cracker and the FCC plant. Within each one, there are several heat exchangers. Depending on the design parameters for the distillation plant and the heat transfer system, the available heat may need to be collected from more than one heat exchanger
3. The processes require that the product be cooled to a certain temperature. On the other hand, normal water distillation plants preheat their feedwater so the primary heat source only heats the feed from, say, 60C to 75C. The design adopted would need to ensure that the refinery's cooling needs were compatible with the desalination plants heating needs
4. The heat fed into the desalination plant must ultimately be rejected at a lower temperature. As it would otherwise have been fed into the BPCL cooling system, there is no reason why the general refinery cooling system could not also cool the desalination plant. However, the temperature differences will be lower than without the desalination plant, and so the cooling water quantity required will be higher. The desalination plant will require of the order of 1500 m³/hour, but that is less than 20% of the current cooling water use in the refinery.

If all the above problems can be overcome, then a waste heat distillation system would operate with an electricity demand of around 300 kW, saving about 1.4 MW compared with the RO system.

The quality of product from a single distillation plant is very good. Most manufacturers have no trouble meeting a specification of 10 ppm for the product. Thus use of distilled water in the demineralised water plant will reduce the demand for regeneration of the resins.

3.2.1. Possible Sources of Waste Heat

It has been indicated above that although there is abundant waste heat available in the refinery to run a distillation plant, the locations at which it is rejected by the processes are dispersed, and there are many heat exchangers involved. Also, the product streams need to be cooled to around 50C in most cases.

Thus although there is enough waste heat, it is not easy to capture.

A preliminary examination of the refinery revealed the following possible heat sources that could be coupled to the desalination plant:

1. The airfin cooler in the Crude Distillation Unit. This unit cools and partially condenses a stream of about 7,000 tonnes per day. The stream enters the cooler at 134C and exits at 84C.

BPCL staff estimate that about 25 MW (of which 10 MW is sensible heat) is rejected through this cooler.

Sensible heat or low pressure steam at up to 130C could be generated from this heat flow, and the quantity of heat is adequate to provide 5,000 m³/day of water from a distillation plant with a performance ratio of about 5.

The product is further cooled in a conventional heat exchanger to 41C.

2. The heavy naphta stream of 2,634 tonnes per day from column D1 is cooled from 139C to 81C, and partially condenses, in 10 heat exchangers arranged in series-parallel. About 17 MW is removed by the heat exchangers.
3. The outlet from column D3, of about 1,915 tonnes per day, is cooled from 139C to 81C. and releases about 8.8 MW.
4. The gasoil 1 stream releases about 7 MW of heat when it is water cooled from 171C to about 50C.
5. The flared gas described above can produce a constant energy supply of about 5 MW if there is no compression and storage, and about twice that if there is. BPCL advises that they have examined the possibility of storage and found it uneconomic.

The first three sources are from the crude distillation unit, while the fourth is from the FCC unit.

The first of the above sources alone would yield sufficient waste heat for a distillation plant of performance ratio around 6. The second source produces enough heat to run a distillation plant of performance ratio 10.

Energy from the other sources could supplement the first source to raise the steam temperature and pressure and/or to allow the use of a cheaper, less efficient plant. It would also be possible to produce more water than the amount specified, and supply the excess to nearby industries as distilled water.

An added bonus of replacing the airfin coolers (ie using the output from CO 1) is a reduction in electricity consumption. The fans on the coolers consume approximately 200 kW.

3.2.2. Practical Considerations

The physical remoteness of the FCC from the Crude Distillation Unit makes it impractical to collect the relatively small amount of heat available at the FCC.

A proportion of the flared gas can be piped around the site relatively easily if needed. For the sake of simplicity and cost saving, it is highly desirable to collect the necessary heat from the minimum possible number of sources.

The most appropriate single source of waste heat appears to be the airfin coolers. These are mounted on the top of a structure beside the distillation column as shown in Fig. 2.

The product stream comes out of the column, descends about 10 m, and enters the airfin coolers, which are arranged in five parallel banks, each with two coolers in series. At this point, the product is at about 134C. The coolers are normally all in circuit, with control being exercised by the switching on or off of individual fans on the units.

From the airfin coolers, the product descends to a series-parallel arrangement of final coolers, which operate on seawater. The final coolers cool the product from 84C to about 45C.

Conceptually, the simplest way of utilising the waste heat for desalination is to remove the airfin coolers and replace them with liquid heat exchangers using a closed demineralised water loop which feeds the desalination plant. It appears that liquid heat exchangers could be installed on the floor that gives access to the airfin cooler motors. Preparatory work could take place while the airfin coolers were still running

Installation involves shutting down the plant for sufficient time to do the job. It appears that the replacement of the coolers would take many weeks. A more elaborate connection arrangement of the new heat exchangers may enable reduction of the plant down-time.

Additionally, it is essential that some form of backup cooling be available to ensure that a shut-down of the desalination plant did not cause a refinery shut-down. This could be done using additional heat exchangers near the distillation column. Provided the heat transfer loop to the desalination plant was very reliable, the additional coolers could be at the desalination plant, and also serve the function of trim cooling.

Because of the dense utilisation of the land around the crude distillation unit, lifting off the airfin units and replacing them with the new heat exchangers could be difficult, but is possible. The 10 airfin coolers could probably be replaced by 3 to 4 large heat exchangers, so it may be possible to leave one or two banks of airfin coolers in place.

Use of the heat from the D1 column is easier in terms of the physical rearrangements required. The cooling and condensation takes place in normal shell and tube heat exchangers located close to the ground. However, the thermal requirements are more difficult to adjust.

The heavy naphta is cooled to 38C by the cooling water, which itself rises to 50C and is subsequently used in an open box cooler to cool two product streams that may congeal if allowed to cool too far. The box cooler takes the cooling water output stream from a number of other exchangers also, including E12A, E12B, E4, E15A, E24, E9A, E10A, E10B, E8 and E18.

The box cooler could continue to function in one of three ways:

1. with a stream of water mixed from other heat exchanger outlets and cooling water to give a suitable quantity of cooling water at about 50C.
2. with a stream of cooling water at less than 50C, using a control system (eg a thyristor speed control on a pump) to adjust the flow to ensure the products did not congeal
3. with the return flow in the desalination plant heat transfer loop.

Of the choices involving the DI stream, the first appears to be the most attractive. The last would require the box cooler to be sealed, to prevent evaporation of and contamination of the heat transfer fluid, and, unless a pressure-tight seal were made, the heat transfer loop could not be pressurised throughout, complicating the design.

Overall, provided the replacement of the airfin coolers is physically possible, they provide the source of waste heat that requires least interference with the rest of the plant, and also more scope to produce more water than 4,000 m³/day. The removal of the fans provides an electricity saving approximately equal to the consumption of the distillation plant.

As the distillation column can operate at part load, it seems desirable to provide a desalination plant that can produce the required amount of water even if the refinery output is reduced. The easiest way of doing this is to replace the airfin coolers, and to use a desalination plant that can produce the required 5,000 m³/day with less than the total available heat.

3.2.3. Land Requirements

Conventional, horizontally arranged, distillation plants of the size under consideration require a little more land than equivalent RO plants. In this case, the RO plant must have two stages, and requires extensive pretreatment, and therefore the space requirement for the RO plant will be higher than usual.

There are a number of vertically stacked distillation plants available, and these could be used if necessary. Their space requirements are less than for horizontal plants.

The space requirement also depends on the energy efficiency of the distillation unit - the more energy-efficient it is the more heat exchange area is required, and, hence, the more land is required.

The largest plant being considered in this application actually covers less than 600 m², and a site of 800 m³ would accommodate it.

The site earmarked for the desalination plant was chosen with RO in mind. It is located approximately 600 m from the airfin cooler that has been identified as the major source of waste heat. If the site is not changed, then a very long heat transfer loop will be needed.

An alternative site for a distillation plant is shown in Fig. 3. It is currently only partially occupied, containing the Field Engineering Office and some workshops. Even with the largest of the candidate plants, the space required could be found by moving one very small building - the shed in the riggers' yard - and the yard itself. If this were possible, the distillation plant could be located within 50 m of the heat source, resulting in considerable savings in reticulation and simplification of the heat transfer problem.

3.2.4. Transferring Energy to the Distillation Plant

The details of how the heat transfer system would be arranged would need to be decided in consultation with the refinery management and the distillation plant supplier.

In principle, the heat transfer could be accomplished using either latent heat (ie steam) or sensible heat (pressurised water). In practice, the low temperature and pressure available from the airfin coolers alone make the use of steam difficult, because of the low density and large pipe diameter required. Also, the use of steam would probably limit the heat transfer loop temperature to 84C, to preserve the cooling parameters of the process stream. Using sensible heat in the heat transfer fluid allows the process side of the loop to be designed with the same philosophy as the present arrangement.

However, heat transfer and plant control for the distillation plant are best done using condensing heat transfer.

If no additional heat source is used, it appears most appropriate to use a pressurised water heat transfer loop with a flash chamber at the distillation plant end. Preliminary calculations indicate that if the site close to the crude distillation unit could be used, a pipe diameter of approximately 100 mm would give relatively low pressure drop, and an insulation thickness of about 25 mm would be adequate.

If the more remote site were used, then it would be appropriate to consider a pipe diameter of 150 to 200 mm, with insulation between 25 mm and 50 mm. Depending on the details of the design, the return line from the desalination plant may or may not be insulated.

The liquid flow required would be between 5 and 10 kg/s, while if a steam loop were used, the flow the flow would be about 10 times that.

The most effective way of transferring heat to the desalination plant from the heat transfer loop is by having a flash chamber before the desalination plant. That will increase the heat transfer coefficient and control the desalination plant temperature.

The heat exchangers at each end of the heat transfer loop will also involve some phase change on the process stream side, but such heat exchangers are standard pieces of chemical plant.

A backup set of heat exchangers, with suitable failsafe valving, could be located beside the desalination plant, to take over should the desalination plant be shut down, or should the heat rejected exceed the needs of the plant.

3.2.5. Pretreatment

Normal seawater in a low temperature distillation plant generally requires only the addition of a scale inhibitor, such as Belgard EVN. Some plants, such as the Sasakura plant require the use of acid, rather than the less corrosive scale inhibitors. Chlorination is used if there is a risk of biological contamination, but the BPCL water has already been chlorinated. Some plants may require some cheap means of reducing iron or copper in the water.

No special precautions need to be taken against silica, iron or small amounts of oil. However, it is likely that the some of the oil will carry over into the product.

In this case, the seawater contains so much suspended matter that it would be unwise to feed it into any expensive plant, but the amount of clarification needed is considerably less than that for RO, and if there is a temporary increase in suspended solids due to a malfunction, the consequences will not be serious.

3.2.6. Specific Plant Designs

There are several design choices to be made in selecting a distillation plant. These include:

1. Multiple effect or MSF
2. Top brine temperature
3. Energy efficiency.

MSF is the traditional method of distillation in large plants. Typically, top brine temperatures are 90C to 110C. Energy efficiency, in terms of performance ratio is usually around 6.5 for 90C, and around 8 for 110C. (A performance ratio of 6.5 corresponds to about 350 kJ/kg of product.)

High top brine temperatures increase the risk of scaling and of corrosion, and the more successful recent designs have tended to use lower temperatures.

Achieving high efficiency at lower temperatures is generally easier using multiple effect plants.

Multiple effect plants are also easier to operate at part load, allowing the plant to operate effectively even if the distillation column is running at reduced output.

In the refinery application, there is no shortage of waste heat, but it is most practical to use one, or at most two, heat sources. The heat from any one source is limited, and so it is most practical to consider multiple effect plants.

A number of companies make plants that could function using waste heat from the crude distillation unit. Those with products most suited to the current application include:

1. IDE

IDE make a series of multiple effect plants of high energy efficiency. The basic design has 12 effects, a top brine temperature of only 70C, and a performance ratio of 8.6 (ie a heat consumption of about 270 MJ/m³). The electricity consumption is about 250 kW.

A nominal 5,000 m³/day unit (MED 5000) would be 90 m long, 6.5 m wide and 11.5 m high.

A variant on the design uses a small amount of high pressure steam to recompress the vapour, allowing one to either make more water, or reduce the energy demand for a specific water demand, provided high pressure steam is available.

However, in this situation, there is more than enough waste heat available, and it is possible to use a less efficient plant, with only 8 effects. This plant would require a space of about 60 m in length and 15 m in width. A narrower site could be used if necessary.

The company's reputation is excellent, and reports on existing plants indicate excellent reliability. They are prepared to consider local manufacture for substantial portions of the plant.

IDE multiple effect plants of capacity 9,000 m³/day have been installed in an oil refinery on Curacao Island, Netherlands Antilles.

2. Sasakura Engineering Co

This Japanese company makes a series of multiple effect stacked plants, with various standard sizes. There is a design of 5,000 m³/day, with 12 effects. It requires steam at about 100 kPa for heating, plus a small amount of steam at 500 kPa, for an ejector pump.

The design can be modified to use hot water for the heat source, and a vacuum pump instead of the ejector.

The 5,000 m³/day unit occupies a space of about 15 m by 18 m, and is 15 m tall.

Sasakura multiple effect stacked plants have been installed in Shell refineries in Singapore and Oman.

3. Hamon-Sobelco

This Belgian company specialises in thermal energy, including distillation. They have a design of horizontal tube multiple effect plants. Any size can be made to order, but there is a standard 2,500 m³/day design, with 8 effects. Such a plant occupies a site area of 10.5 m by 7 m.

COMPARISON OF DISTILLATION PLANTS

	IDE	Sasakura	Hamon-Sobelco
No of Effects	8	13	8
Heating Steam kg/hr	35	21	2x16.5
Heating Steam press (AtA)	0.35	3	3
Top Brine Temp C	70	96	116
Elec Power kW	250	208	2x120
Site Area m x m	60x15	18x15	21x7
Ejector Steam kg/hr	0	0.75	2x0.35
Ejector Steam press (AtA)	0	9	6
Acid consumption (kg/hr)	0	43	2x14
Polyphosphate consumption	5	0	0
Budget Price \$US millions	4.5	6.2	7
Possible local content	some	little	most

It is believed that using an 8 effect Sasakura plant would cut the price to about \$US 5 million.

Despite its larger land area requirements, the IDE plant is superior for this application, because of the low temperatures used, the lack of need for high pressure steam, the lack of use of strong acids, and the lower price.

MSF Plants

There are many suppliers of MSF plants world-wide. The designs have a lot in common, and often the plants are made by general fabricators to designers' specifications. Manufacturers of "standard" MSF plants include, inter alia:

- Weir-Westgarth (UK)
- Sasakura Engineering (Japan)
- Mitsubishi Heavy Industries (Japan)
- Mitsui Engineering and Shipbuilding (Japan)
- Aqua-Chem (USA)
- Buckau-Wolf (W. Germany)

In general, the relatively high top brine temperatures used in MSF plants make them more difficult, but by no means impossible, to apply to a waste heat source in the Bharat Petroleum refinery. In any given MSF design, lower top temperature simply means lower energy efficiency.

Some more innovative designs that may be of interest in this application include:

1. Aquanova BV

The Aquanova plant is a vertically stacked one using plastic flash chambers, and aluminium. It is made in standard modules of 500 m³/day, and a top brine temperature of 105C. The plant is only 3.6 m high.

16 plants are in operation on the Pacific island of Aruba.

2. Esmil BV

This plant uses a fluidised bed evaporator, and a 500 m³/day plant is in operation on the Dutch island of Texel. Pumping energy is low, because of the fluidised bed.

3. Atlantis Energie

This Swiss company has produced designs of MSF plant that can operate at any fraction of rated output, have high energy efficiency, and use very little pumping energy. As far as we can ascertain, the largest plant produced so far has a capacity of 200m³/day.

4. Spinflash

This US design uses rotating vanes in the flash chambers, and injects air in a countercurrent direction in the tubes for scale control. It is available in a range of standard sizes up to 190 m³/day.

Scale-up of the design is no doubt possible. The 190 m³ unit sells for \$US 315,000.

The choice of suitable distillation plants for this application should take into account the following factors:

Space requirements

Energy efficiency (both thermal and electrical energy)

Local availability of raw materials

Willingness of design owner to have the equipment fabricated locally.

Reliability

3.3. Vapour Compression

Vapour compression plants also use evaporation as their principle of operation, but the energy is added in the form of mechanical energy, compressing vapour, and allowing the vapour to transfer heat to the incoming feed as it condenses.

There are two ways of achieving the compression - using a mechanical compressor or using an ejector. The latter method, while considerably simpler than the former, is much less energy efficient, and such VC plants have efficiencies similar to normal distillation plants.

Mechanical compression plants use specialised compressors which could give maintenance problems.

Vapour compression plants have the advantage of being relatively compact. They are also relatively expensive, and are generally not available in capacities greater than about 2,000 m³/day. In the present application, the need for 3 separate units largely negates the compactness of each unit.

Vapour compression plants do not require heat addition (although performance can be improved if it is utilised), but do require cooling. Other operating advantages and disadvantages of vapour compression plants are very similar to those of distillation plants.

The most efficient vapour compression plants generally consume approximately 16 kWh/m³. Variants in which waste heat is also used can consume around 8 kWh/m³.

It is unlikely that vapour compression has any major advantages over waste heat distillation in this case. However, there may be significant advantages over RO, since the units require only the pretreatment for distillation plants, and they can be obtained as skid-mounted units.

Nonetheless, vapour compression units have very sophisticated compressor units, which could be difficult to service in the long term.

A vapour compression plant with sufficient capacity for the refinery's stated needs would cost about \$US 5 million FOB.

3.4 Electrodialysis

Electrodialysis is a process that uses an electric field to move ions through anion- and cation-selective membranes, purifying the water between them.

The process is suitable for brackish water, but the energy consumption for seawater is excessive.

4. STAFFING REQUIREMENTS

Staffing requirements depend on the quality of staff available, on the reliability of the equipment installed and on local practice. Typically, a stand-alone desalination plant of capacity 4,000 m³/day will have a staff complement as follows:

Supervisory

Superintendent	1
Plant engineer	1
Secretary	1

Maintenance

Mechanics and fitters	3
Chemist	1
Labourer	1

Operating Staff

Supervisor	2
Operators	8

TOTAL	18
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In the case of the refinery, many of the maintenance and supervisory functions will not require a person's full-time attention. The chemist's role could certainly be fulfilled by the company laboratory, especially if a distillation plant is used. The maintenance could largely be integrated with the maintenance of the rest of the plant, leaving, say, one fitter permanently attached to the plant. Secretarial work would be minimal, and existing secretarial facilities could be used if necessary. An existing manager could fulfil the role of superintendent.

Effectively, only 12 people would be dedicated to the plant, although for budgetting purposes, an allowance of about 15 would be reasonable.

5. OPERATING AND MAINTENANCE COSTS

5.1 Operating Costs

The principal operating costs are:

1. Energy
2. Chemicals
3. Labour
4. (for RO plants) Membranes.

5.2 Maintenance costs

These are very difficult to predict, apart from the labour costs which are included under operating costs. Membrane replacement for RO plants is also counted as an operating cost.

It will be assumed that for an RO plant the additional maintenance per annum is 1% of the plant capital cost, while for a distillation plant it is 2%.

6. COMPARISON OF RO AND DISTILLATION ON THE BASIS OF ENERGY USE

The energy costs given by BPCL are as follows:

1. Electricity: Rs 1.0/kWh
2. Fuel oil: Rs 1200/tonne.

It was subsequently indicated that the cost of electricity generated within the plant was only Rs 0.6/kWh.

RO Plant - Energy Consumption: Electricity, approximately 1.7 MW.

On an annual basis, 14900 MWh are consumed by the plant. At Rs 1.0/kWh, the total cost would be about Rs 14,900,000 (Rs 1.49 crore).

Distillation Plant - Energy Consumption: Waste Heat, approximately 16 to 160 MW

Electricity, 350 kW max

As the waste heat is free, the only actual energy cost is for the electricity, and will be about Rs 2,700,000 (Rs 27 lakh) for 2700 MWh.

Thus the annual saving in electricity made by using waste heat is about Rs 12,000,000 (Rs 1.2 crore). With careful design of the waste heat plant, the electricity use could be half that stated above, resulting in an annual saving of about Rs 14,000,000 (Rs 1.4 crore).

If the lower cost for electricity were used, the savings would be between Rs 7,000,000 (Rs 0.7 crore) and Rs 9,000,000 (Rs 0.9 Crore).

Assuming that all other costs were equal (ie the distillation plant required maintenance costing the same as the allowance for membrane replacement), the energy saving would justify a capital cost penalty of about Rs 82,000,000 (Rs 8.2 crore) for the waste heat plant, assuming a discount rate of 12% and a plant life of 15 years.

In fact, an annual allowance of approximately Rs 4,000,000 (Rs 40 lakh) (exclusive of import duties, taxes, etc) would need to be made for membrane replacement in an RO plant.

It therefore appears that there is a strong case for using waste heat distillation if possible.

7. PRELIMINARY CALCULATION OF WATER COST

The true capital costs of various options can only be determined by calling for quotes on the basis of detailed specifications. For the purpose of this report, budget prices have been sought from a number of suppliers. It is on the basis of those that the estimates below are given.

It has been assumed that the plants will both use the existing seawater inlet and outfall systems, and that the feedwater will be clarified by a plant to be installed by Bharat Petroleum.

Capital Costs	\$US Millions	Rs
RO Plant		
Membrane plant	3.4	51.0
Pretreatment	1.8	27.0
Civil work		15.0
Installation - labour (50 man months)		0.3
Installation - supervision	0.04	0.6
Freight	0.1	1.5
Subtotal		95.4
Import Duty (say 100%)		78.0
Excise (at 15%)		26.0
<u>TOTAL</u>		<u>199.4</u>
Distillation Plant		
Plant	4.5	67.5
Heat transfer loop and exchangers		20.0
Civil work	0.5	7.5
Installation - labour (24,000 hrs)		1.0
Installation - supervision	0.25	3.8
Freight	0.2	3.0
Subtotal		102.8
Import Duty (say 100%)		67.5
Excise (at 15%)		25.5
TOTAL		<u>195.8</u>

The investment allowance of 25% is excluded. No local content has been assumed for the plants themselves in these costings.

Annual costs including import duty and excise would be as follows:

	RO Plant	Distillation Plant
Capital Cost	Rs 199,400,000	195,800,000
Capital Charges (int & recovery)	31,900,000	31,300,000
Energy (Rs 1.0/kWh)	14,900,000	2,700,000
Labour (15 staff at Rs 70,000)	1,050,000	1,050,000
Chemicals	27,000,000	2,000,000
Membrane replacement	10,000,000	0
Other maintenance	2,000,000	4,000,000
TOTAL ANNUAL COSTS	Rs 86,850,000	41,250,000
TOTAL WATER PRODUCED (say 90% rated)	1,642,500 cu m	1,642,500 cu m
Effective water cost	Rs 52.9/m ³	Rs 25.1/m ³

(The investment allowance is excluded).

If import duties and excise are excluded, then the cost of water would be about Rs 41 for the RO plant and Rs 16 for the distillation plant.

The capital cost of the distillation unit is based on the lowest budget quote obtained from the manufacturers approached.

If electricity were costed at only Rs 0.6/kWh, the water cost comparison would still favour waste heat distillation (Rs 25 compared with Rs 49, including duties and excise).

8. LOCAL CONTENT IMPLICATIONS

There are high duties on all imported components. The total import duty varies between 105% and 145%.

There is an "excise" of 15% payable on all equipment.

On the other hand, the Government gives a 25% investment allowance on all capital equipment. This is payable in the first year of operation of the plant.

The import duty is a strong incentive to manufacture as much as possible within the country. In any case, Government approval is required for any purchase using foreign exchange.

There is some flexibility in the local content proportion of any plant selected. However, there are some items for which there is no production in India, and for which local sourcing would be impractical.

In some countries, desalination plants have been imported virtually complete on barges, and installed by foreign experts, with virtually no local content. That would clearly be a possibility in this case, although it would be undesirable from many points of view.

The key components of both types of candidate plant will be discussed below in terms of whether they can be purchased within India or not.-

Reverse Osmosis

The membranes themselves are the heart of the process. Membrane manufacture is a very specialised skill, and seawater membranes are especially difficult to produce, since they require very high salt rejection as well as ability to withstand high pressures. It is understood that there is no existing production of seawater membranes in India. These will have to be imported. Their normal life is considered to be three years, and the capital cost of the first set is of the order of \$US 1,500,000.

High pressure multistage centrifugal pumps are manufactured in India, and it is understood that some manufacturers are capable of producing them using materials that are suitable for use in RO plants. This will need to be checked.

Energy recovery turbines are not manufactured locally, and it is most prudent to purchase one from a manufacturer who has demonstrated successes with the technology. Some manufacturers make a single unit that combines the recovery turbine with the high pressure pump, and it may be appropriate to use such a combination.

The plant would need to be a two-stage one, and it is understood that a local manufacturer (Hydranautics) will soon start to produce brackish water RO membranes. These could be used in the plant if desired, but they are cellulose acetate membranes, and the water will require pH control after discharge from the polyamide membranes which are almost essential for the first stage.

Hollow fine fibre membranes should be avoided if possible, because they are not as tolerant of feedwater problems as the newer spiral wound membranes.

Membrane manufacturers supply tubes into which the membranes can be mounted. Appropriate seals and inlet and outlet facilities are incorporated. The tubes may be FRP or stainless steel. It would be possible to have these fabricated in India, but it is not clear that that would be a cost-effective procedure, especially if there is any risk that the membranes would not fit and seal as intended.

Feedwater pretreatment will be needed. Items such as clarifiers and pressure filters will be needed. These items, which, in the main, are not available locally, could be made under licence to an overseas manufacturer if desired, but it would probably be more practical to import them unless there was a demonstrated ongoing demand for the component(s). The plant will require cartridge filters of pore size between 5 and 20 microns. The elements may need to be imported.

Other components include pipes, metering pumps, flow gauges, valves, low pressure pumps, tanks, electrical control equipment, etc. All such equipment can be purchased locally if desired. There is a design choice to be made regarding the sophistication and automation of the control systems and instrumentation. If very sophisticated equipment is chosen, then that will probably need to be imported.

Plant erection could take place using local labour, with the supervision of a small number of overseas experts from a company specialising in seawater reverse osmosis.

Distillation Plants

Distillation plants are available in a number of designs. They are generally fabricated to order, in accordance with designs held by the company concerned.

It would be unwise to use any design other than one from a designer with a proven track record, and if possible, one should choose a plant of which there are working examples with good reliability records.

As the plants are almost always fabricated specially for each order, there is no reason why parts of the plant could not be fabricated in India, if a suitable manufacturer were available. The units generally do not contain very sophisticated parts that cannot be made by metal fabricators with reasonable skills.

The materials of construction vary from plant to plant. Copper-nickel alloys are common, and some plants use aluminium bronze. Others use stainless steel. It is understood that these are not made in India. One very successful type of plant is made of aluminium, which is mined and refined in India.

Local fabrication of the plant would naturally involve the concurrence of the owner of the design, who would need to give technical assistance and supervision throughout the process. IDE and Hamon-Sobelco have indicated that they would be prepared to undertake a substantial part of the plant construction in India.

The ancillary components of distillation plants include pumps, valves, flow metering and control equipment, etc. Because pressures are generally not high, plastic plumbing is a good way of avoiding corrosion. Most ancillary components should be procurable in India. The sourcing of control equipment and instrumentation would, as in the case of RO, depend on the degree of sophistication desired.

Extreme care needs to be taken in choosing metallic components to ensure galvanic corrosion is minimised.

Fundamentally, a distillation plant involves vessels and heat exchange surfaces, and uses concepts similar to those found in other plant in the refinery.

The assembly and installation of a distillation plant involves considerably more local labour than that of an RO plant.

Vapour Compression Plants

These are usually designed to be installed rapidly, and are often skid-mounted. It is unlikely that local manufacture of any part of the plant would be practical.

9. ALTERNATIVE WATER SOURCES

A number of other treatable water sources were identified at the refinery. These include:

1. Freshwater cooling tower blowdown
2. Wells.
3. The outflow from the effluent treatment plant (under construction).

9.1. The Cooling Tower Blowdown

According to BPCL staff, the quantity of cooling water blowdown is about 600 m³/day, about 1% of the total circulating cooling water.

An analysis of the water as carried in the BPCL laboratory is as follows:

Total suspended solids	ppm	90
Total dissolved solids		650
Total hardness as CaCO ₃		235
Calcium as CaCO ₃		117
Magnesium as CaCO ₃		118
Total alkalinity as CaCO ₃		50
Sulphate as SO ₄		50
Chloride as Cl		30
Silica as SiO ₂		100
Phosphate as PO ₄		20 to 25
Zinc sulphate as Zn		3 to 5
pH		6.2 to 6.6

As the cooling water is from the Bombay supply, and the blowdown (1%) and evaporation (1.7%) rates are known, a theoretical calculation can be done to estimate the TDS and individual ion concentrations in the blowdown. The result of that calculation suggests lower values than indicated above - for example on the basis of the raw water analysis and the blowdown quantity, one would expect a blowdown salinity of 216 ppm, not 650.

There are plans to convert the freshwater cooling system to use demineralised water, eliminating the blowdown, and effectively eliminating this possible source of feedwater for a desalination plant.

9.2. The Wells

There are three wells on the refinery site. The yield from the wells is as follows:

Bore 1 (LPG Borewell)	100 m ³ /day
Bore 2 (LPG Borewell)	100 m ³ /day
Bore 3 (Municipal Pumping Stn Borewell)	unknown
Bore 4 (Transport Borewell)	50 m ³ /day
Bore 5 (Transport Borewell)	50 m ³ /day

The flow from these has been analysed, and the water composition is as follows:

	Bore 1	Bore 3	Bore 4
Total dissolved solids	468	430	3048
Total suspended solids			121
Iron (as Fe)	0.1	10	0.15
Chloride (as Cl)	174	126	1728
M Alkalinity (as CaCO ₃)	110	124	52
Total hardness (as CaCO ₃)	196	224	1616
Ammoniacal nitrogen	0.05	0.05	0.05
Albuminoid nitrogen	0.11	0.09	0.12
Nitrate (as NO ₃)	0.07	0.06	0.06
Nitrite (as NO ₂)	0.02	0.02	0.01
pH	7.8	8.0	7.7

All wells were clear, with slight organic contamination.

The combined output of the wells, plus the blowdown of the cooling towers represents approximately 15% of the total water demand of the plant. A number of options for use of these waters exist, eg:

1. Combine some or all the streams and feed them to a brackish water RO unit
2. Combine some of the streams and feed them to the second stage of the seawater RO plant used for the main water supply
3. Use only the blowdown as a supplement for the second stage of the seawater RO unit
4. Combine some of the streams and feed them into the demineralised water plant as part of the raw water supply.

Of all the wells, the transport area ones are of least interest. Their yield is poor, and their salinity relatively high. The LPG borewells yield about 200 m³/day of low salinity water, and that could easily be combined with the cooling water blowdown, and fed into an RO plant. A free-standing plant to treat this water could be made using locally produced membranes, and would consume about 1 kWh/m³. About 80 to 90% of the feedwater could be converted, provided pretreatment were implemented to remove silica and iron. Otherwise, the plant could operate with very little pretreatment if the conversion rate were kept low (say 50%).

If the water were fed back into the demineralisation plant blended with municipal water, the effective salinity would rise to about 200 ppm, more than doubling the rate of resin use.

If a seawater RO plant were being used, then the blend of well water and blowdown water could easily be used in the second stage of the process, reducing the need for seawater membranes by about 25%, and similarly reducing the energy consumption (probably by about 20%). However, the feed would need to be treated, especially to remove silica and iron.

If seawater were being desalinated using a waste heat distillation plant, then there would be little reason to treat the sources being discussed here, since the incremental cost of having a 6,000 m³/day plant over a 4,500 m³/day plant is relatively small. Under normal circumstances, it would be possible to simply blend the distillation plant product with the blowdown and well output, giving a salinity of about 150 ppm, adequate for many purposes. However, in this case, most of the water is being fed into the demineralised water plant, and removal of the dissolved matter will consume resins in proportion to the amount removed.

The refinery has plans to use demineralised water in its cooling towers, essentially reducing the blowdown to close to nothing. If this is implemented, there will clearly be no opportunity to desalinate blowdown water.

9.3. Refinery Wastewater Treatment Plant

The refinery is currently installing a wastewater treatment plant to handle about 240 m³/hour of water. The water concerned is primarily raw water or demineralised water that has passed through the plant and been contaminated, mainly with oil. It also has significant BOD, and may be contaminated with seawater.

Many of streams that will be collected and passed through the treatment plant are contaminated with seawater, and the salinity of the output of the plant is unknown at this stage. It will probably vary, depending on conditions in the refinery. On the basis of a mass balance, the salinity of this water, if it were entirely a mixture of raw water and seawater would be up to 12,600 ppm. If it were a mixture of demineralised water and seawater, the salinity would be very little less.

Water of that salinity can be processed through a two stage RO plant using brackish water membranes to produce a product that can be fed directly into the demineralisation plant.

The major obstacle to the use of RO on this water is its temperature - 45C. RO membranes have a maximum operating temperature of 45C, and the increased temperature results in decreased product purity.

Also, the water will contain other materials. The specification supplied was:

Suspended solids	20	ppm
Sulphides	0.5	ppm
Chlorides	2815	ppm
Silica	45	ppm
Total Dissolved Solids	12425	ppm
Phenols	1	ppm
Oil	10	ppm
B.O.D.	15	ppm.
pH	6 to 10	

In general, the purity of this water is higher than many effluent streams being discharged into the environment. In order to achieve the specified purity on a continuous basis, the treatment process will need very careful monitoring and control.

it is possible that the oil removal could be even more complete than that listed in the specification, provided the acidification and polyelectrolyte addition were just right. A figure of 5 ppm is achievable.

Nonetheless, this water cannot be fed directly into RO membranes. It will need sand filtration to reduce the suspended solids, plus treatment to remove the oil and other organics.

The pretreatment suggested for the seawater plant would be directly applicable to the wastewater also. Although there is a dissolved air flotation unit on the wastewater plant, a second one appears to be required to reduce impurities to a level that an RO plant can tolerate.

In the event that the treatment plant exceeds its specifications on a continuing basis, the pretreatment could be simplified. Alternatively, more settling and skimming of the wastewater before it enters the effluent plant may improve the product quality. Finally, the more polluted stream, only 11% of the total flow, could be pretreated in a small plant before being put into the main plant. These options could also reduce the pretreatment required for the effluent water.

However, these things cannot be known until the plant is operating. Also, it appears inevitable that the quality of the input will vary from time to time, possibly requiring some control of the RO pretreatment plant. It should be borne in mind that removing 99% of 1000 ppm of oil is much easier than removing 99% of a 10 ppm level.

One manufacturer of membranes and RO plants has warned that effluent water from oil refineries may contain trace elements such as barium and strontium, which must be removed before the water can be fed to an RO plant. In this case, a complete mineral analysis of the effluent water is not available

The RO plant itself, if it is feasible to use the effluent water, would be cheaper to construct and operate than one using seawater. It may be possible to use locally produced cellulose acetate membranes, although these are very susceptible to bacterial attack (and bacteria may carry over from the aeration tank in the effluent plant). In any case, production of the Indian membranes has not yet begun, and thus it would be premature to plan on using them.

Normal practice would be to avoid using treated effluent where possible.

At this stage, the application of RO to the effluent water cannot be recommended, in view of the multiple problems associated with it. Once the effluent plant has been commissioned, the question could be reconsidered, but the high temperature of the water plus the pretreatment requirements makes it unlikely to be a viable proposition.

In any case, it would not produce sufficient product water for the refinery's requirements. A possible solution, assuming that the effluent plant operated reliably to specifications, would be to blend the effluent with seawater to produce the feed to the RO plant. That would reduce the feedwater temperature to a tolerable level.

The water could be used in a distillation plant, but the advantages in using it over seawater are few.

10. CONCLUSION

Bharat Petroleum has a number of alternatives to reduce its water demand. These include:

1. Water conservation (including re-use of steam trap condensate and similar sources)
2. Seawater desalination using RO
3. Seawater desalination using waste heat distillation
4. Desalination of the wastewater outlet, using RO
5. Use of vapour compression on either the seawater or the wastewater outlet
6. Desalination of cooling tower blowdown and low salinity well waters.

Of the above, the first and last options alone will not yield the anywhere near the stated requirement of 4,000 m³/day. They are outside the terms of reference of this study, but it has been established that the last option would yield about 700 m³/day of good quality water suitable for use in the demineralised water plant. The capital cost of an RO plant to do this would be considerably less than that of a seawater plant producing 4,000 m³/day. However, it appears that the refinery intends to use demineralised water in its freshwater cooling towers, so this potential source will be lost.

For seawater desalination, RO has a number of advantages. These include:

1. Easy to implement in stages
2. Easy to expand
3. Does not require steam and cooling water connections.

However, in the application at the Bharat Petroleum refinery, there are a number of difficulties in implementing it. These include:

1. The feedwater is very saline and the product required very pure. Therefore a two stage plant will be required.
2. The feedwater needs pretreatment because of:

Very high suspended solids content

Residual chlorine content

Oil content

Possible high silica content (especially in the presence of iron).

High iron content

The variable impurity content makes the pretreatment design uncertain, and suppliers will probably insist on a pilot plant stage.

3. The seawater membranes would need to be imported, as would the energy recovery turbine (if fitted). It is necessary to assume that the membranes would need to be replaced approximately once every three years.
4. About 1.7 MW of electricity would be required to run the plant.

Distillation has the following advantages:

1. It will produce a very pure product, reducing the demand on the demineralisation plant.
2. It can utilise waste heat available in the refinery, and requires only about one quarter of the electricity needed by the RO plant.
3. It is relatively insensitive to the impurities in the feedwater, although the level of suspended solids in the present cooling water system is too high even for a distillation plant.
4. Provided the owner of the plant design agrees, most of the plant could be fabricated in India, possibly using local materials.
5. The type of technology used is similar to other equipment around the refinery, and the skills needed to maintain it and repair it are probably available in-house.
6. If it can replace the air-fin coolers in the Crude Distillation Unit, it will result in considerable savings in electrical energy for the fans.

The disadvantages of distillation are:

1. Connections to a heat source and the cooling water system are needed. The site proposed for a desalination plant is some distance from the principal sources of waste heat.
2. The connection to the heat source involves modifications to the operating parts of the refinery. It is inevitable that there will be some shutdown of the crude distillation unit necessary. With careful planning, this could be minimised, but it is unlikely to be less than three weeks, no matter how cleverly it is done. The refinery itself would need to make an estimate of the time needed to change over the heat exchangers.
3. The feedwater is heated, and there is more opportunity for corrosion.
4. It is not as easy as RO to implement in stages, and it is difficult to add small increments of capacity.

On balance, the implementation of RO on the seawater currently available is an expensive and risky undertaking. The operation of the pretreatment will depend to an extent on the feedwater, and will require close monitoring. An error in the pretreatment could result in irreversible membrane damage. On the basis of the water analyses available, the pretreatment for the RO plant will be among the most complex in use.

If a less difficult seawater were available, then RO would involve fewer risks. Such water may be available from wells drilled along the shoreline. The cost of such wells (even if 10 to 20 were required) would

be less than the savings on pretreatment that could occur if the water was suitable. Clearer seawater would also be of considerable benefit for a distillation plant.

Distillation is much less sensitive than RO to the feedwater quality, and it is relatively certain that a distillation plant will cope effortlessly with any water quality likely to be encountered - provided the level of suspended solids was reduced to about 50 ppm. A waste heat plant uses considerably less high grade energy than an RO plant.

On the basis of the preliminary costings done, it appears that the total water cost from waste heat distillation will be roughly half that for RO.

The difficulties involved in maintaining production during the installation of the distillation unit make it more difficult to implement than RO, despite its other attractions. It is possible that the refinery could schedule the replacement of the airfin coolers to occur during a normal plant shutdown.

Many of the conclusions in this report have been based on the water analyses available. However, there are a number of differences between different analyses of samples taken from the same source, and the cooling water blowdown salinity is higher than would be expected on a theoretical basis.

Therefore, it is recommended that Bharat Petroleum undertake a monitoring program, with monthly analyses of the seawater, the raw water, the well water and the cooling water blowdown, to see if some pattern, correlated with the season, can be established. It would be useful to measure the water temperature. Once the effluent treatment plant is working its output should also be analysed on a regular basis.

Occasional validation of the laboratory procedures by having identical samples analysed in the company and by an independent laboratory would also be useful.

11. RECOMMENDATIONS

1. Bharat Petroleum should attempt to obtain approval to sink bores along the shoreline, and then sink pilot bores to see whether purer seawater or brackish water can be obtained.
2. If these wells do yield better water, then sufficient should be sunk to obtain the water required for cooling and desalination.
3. The seawater, the effluent water, water produced in the refinery and any wellwater from seashore wells should be analysed for mineral and organic content on a regular basis over a period covering both wet and dry seasons.
4. If no clearer water source is available from wells, then the feedwater and cooling water should be clarified to about 50 ppm.
5. Distillation, using waste heat from the refinery, offers the advantages of:

very high likelihood of success
 low energy costs
 low pretreatment costs
 insensitivity to feedwater composition and pretreatment
 very pure product and lower demineralisation costs
 reduced electricity demand for the air-fin coolers

On the basis of the seawater analysed, it is recommended as the best course of action.

6. RO could be a competitor for distillation if the feedwater required less pretreatment.
7. The effluent water, while lower in total dissolved solids, may fluctuate in quality, has a temperature that is too high for the membranes and may contain barium and strontium, which virtually rule out the use of RO.

It would not produce enough water to satisfy the requirements of the refinery.

Generally, it is more practical to use naturally occurring waters for desalination than to use those from effluent treatment plants.

It may be possible to use the effluent water mixed with seawater as the feed to a desalination plant, but the viability of such an arrangement should be assessed only after the effluent plant has been operated for some months.

8. If the refinery is unable to use waste heat, then a pilot pretreatment and RO plant should be constructed, with a capacity of, say, 50 m³/day. The results of operating that plant should determine the design of the final, full scale plant.
9. Consideration could also be given to the use of vapour compression as an alternative to RO, in view of the pretreatment needed in this case.

Overall, waste heat distillation is recommended as the safest and most cost-effective option in this case.

APPENDIX ALARGE DESALINATION PLANTS IN INDIA

LOCATION	CAPACITY cub m/day	PROCESS	FEEDWATER	USE	OPENED	MANUFACTURER
?	718	RO	Brackish	Ind	1976	Ajax
Andaman Is	302	ME	Seawater	Mun	1947	Weir-Westgarth
Bangalore	720	RO	Brackish	Ind	1981	Hydraunitics
Baroda	3750	RO	Brackish	Power	1987	Degremont
Bazibad	114	RO	Brackish	Ind	1985	Ion Exchange
Bhusaval	333	ME	River	Power	1964	Krupp
Burgaon	2880	RO	Brackish	Ind	1984	Ion Exchange
Cahatral	204	RO	Brackish	Ind	1988	Ion Exchange
Calcutta	64	RO	Brackish	Tour	1985	Ion Exchange
Chandigarh	552	RO	Brackish	Ind	1985	Ion Exchange
Cossipore	700	ME	Brackish	Ind	1949	Weir-Westgarth
Durgapur	358	ME	River	Power	1957	Krupp
Gurgaon	2880	RO	Brackish	Ind	1984	Hydranautics
Jamnagar	684	RO	Brackish	Ind	1988	Ion Exchange
Nadiad	432	RO	Brackish	Ind	1984	Ion Exchange
Nasik	144	RO	Brackish	Ind	1980	Ion Exchange
Porbundar	1104	RO	Brackish	Ind	1988	Ion Exchange
Rajkot	100	RO	Brackish	Ind	1988	Ion Exchange
Rewari	180	RO	Brackish	Ind	1986	Ion Exchange
Sahibabad	3120	RO	Brackish	Ind	1988	Ion Exchange
Veraval	1104	RO	Brackish	Ind	1988	Ion Exchange

The list covers only plants of capacity greater than 100 m³/day.

Abbreviations:

Ind - Industrial
 Power - Power station
 Mun - Municipal supply
 Tour - Tourist complex water supply

Source: International Desalination Association

APPENDIX BASSUMED CHEMICAL DOSING IN RO PLANT

Chemical	Concentration ppm	Price Rs/kg
Aluminium Sulphate	80	5
Polyelectrolyte	0.3	50
Sequestrant	110	26
Hydrochloric Acid	200	1
Sodium Bisulphite	10	5
Lime	300	4

It has been assumed that these chemicals are required in the proportions shown, and are added to the RO feed stream of about 16,000 m³/day.

Actual dosing requirements cannot be established without on-site tests using a pilot plant, or the full plant.

Additional chemicals will be required for cleaning.

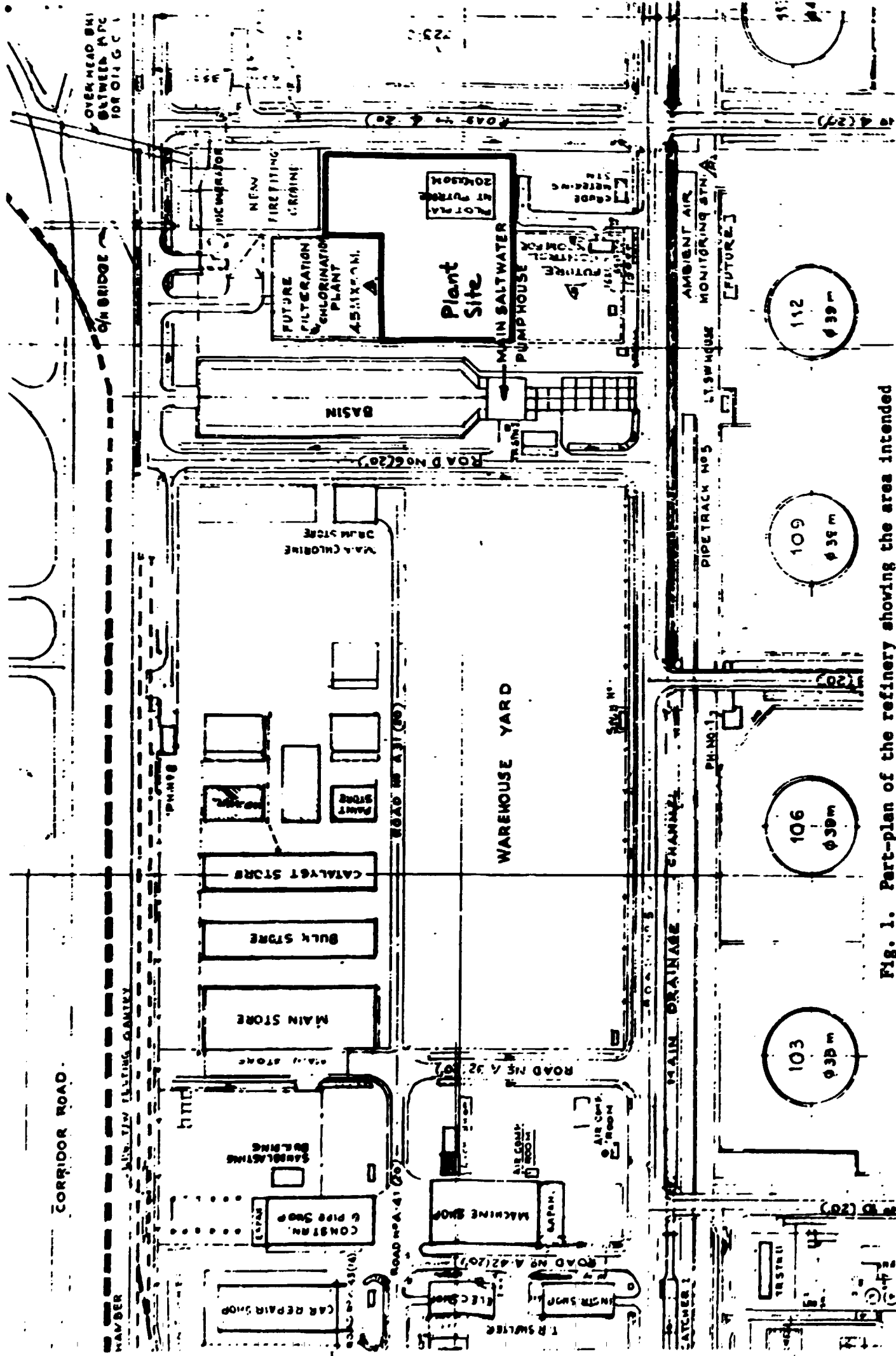


Fig. 1. Part-plan of the refinery showing the area intended

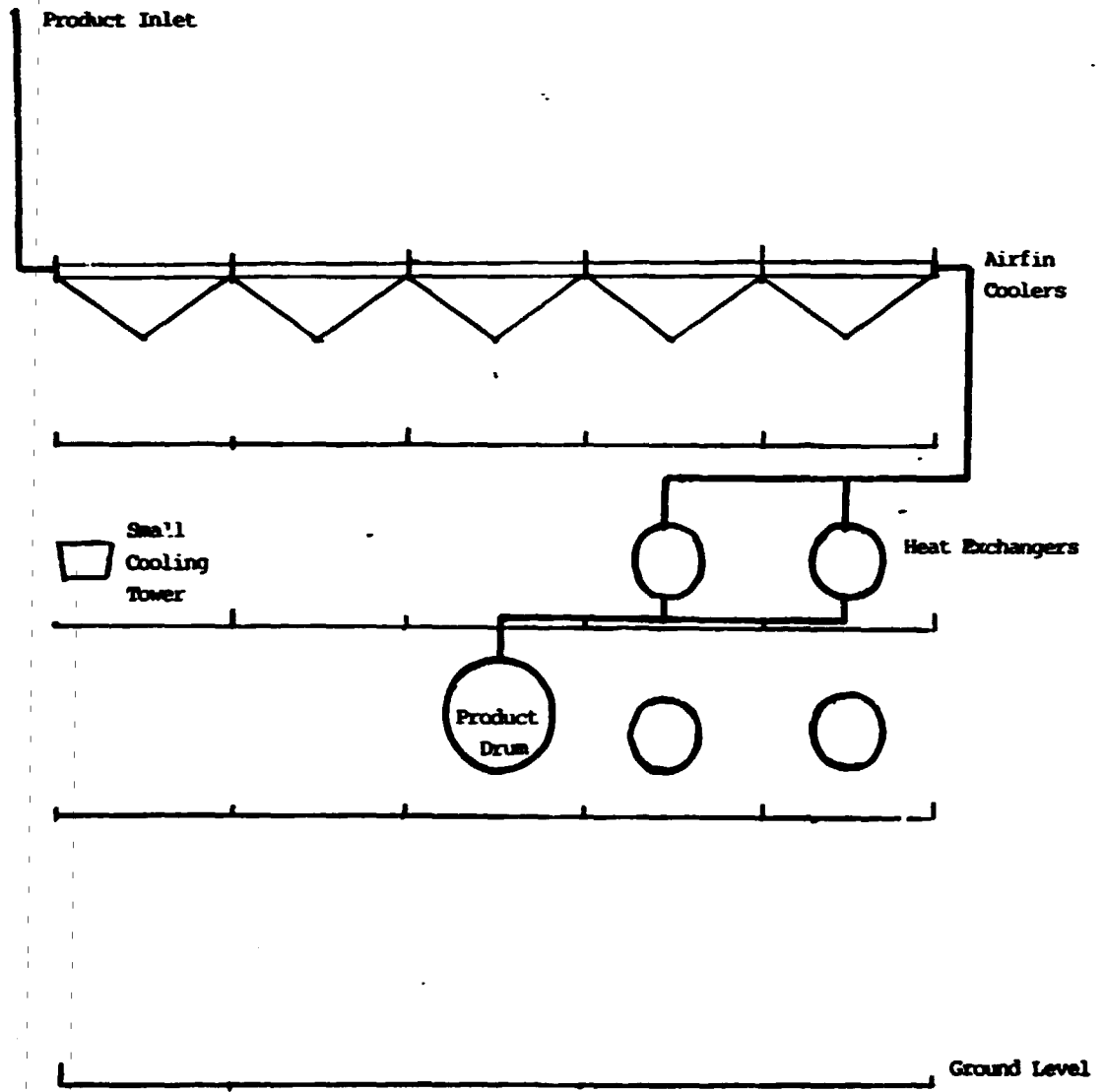


Fig. 2. Arrangement of equipment and product flow on the structure supporting the airfin coolers.

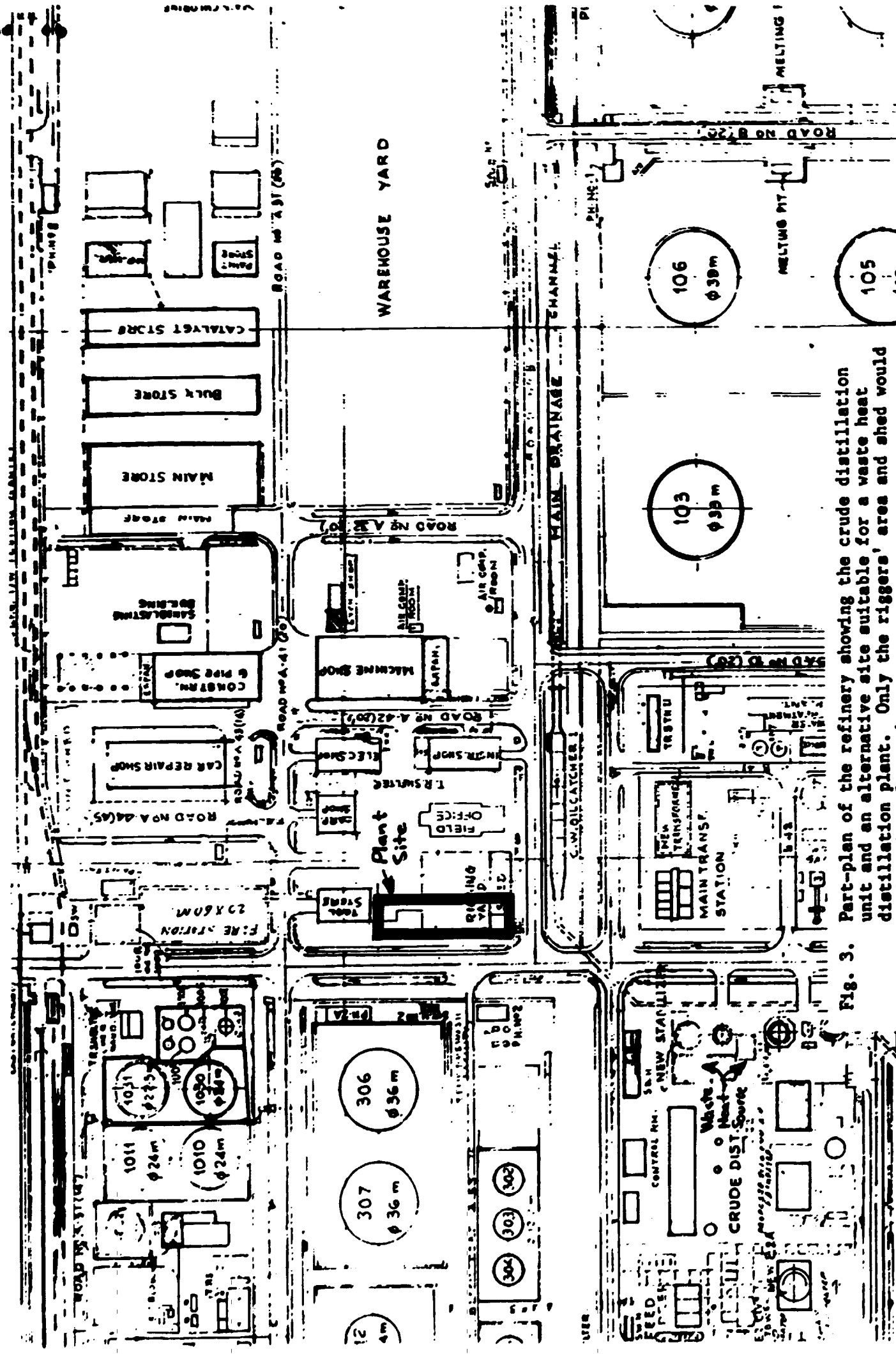


Fig. 3. Part-plan of the refinery showing the crude distillation unit and an alternative site suitable for a waste heat distillation plant. Only the riggers' area and shed would