



Fouling in cooling water systems

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FOULING IN COOLING WATER SYSTEMS

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FOULING IN COOLING WATER SYSTEMS

1. NOTATION AND UNITS

C	circulation rate	m^3/s
B	blowdown	m^3/s
E	evaporation rate	m^3/s
L	leakage rate	m^3/s
M	make-up water	m^3/s
W	windage loss	m^3/s
n	concentration factor	—
x	dissolved solids concentration in make-up water	mg/l
y	dissolved solids concentration in circulating water	mg/l

2. INTRODUCTION

Virtually any water available in sufficient quantity is potentially useful for cooling applications (see Table 2.1), but the wide range of water quality that this implies can lead to a variety of fouling problems. Because very large quantities of water are used for cooling purposes it is quantity rather than quality which is usually the prime consideration. The method of operation of the cooling system, once-through or recirculating, closed or open for example, will also result in an emphasis on different aspects of the general fouling problem.

TABLE 2.1 Sources of Water for Cooling Operations

Water	Source	Type of System
Fresh	Fresh water lakes Rivers and streams Canals	Often once through but may be recirculating*.
	Town's water Borehole Boiler condensate	Usually recirculating*.
	Treated sewage Process water	Recirculating or once through*.
Salt	Sea Esturine Brackish	Usually once through.

* Make-up water to account for losses such as blowdown, evaporation or windage from cooling towers and spray ponds is often, although not necessarily, from the same source as the original water.

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3. SCOPE OF THIS ITEM

This Data Item summarises the state of the art in all aspects of fouling in cooling water systems. It provides a general background to the subject and the associated technology. It explains how quantitative data may be obtained.

Advice and data are given on the features that are of importance at the design stage, not only of the system as a whole, but also of individual items of equipment such as heat exchangers. To this end, heat transfer fouling resistances for different conditions are listed.

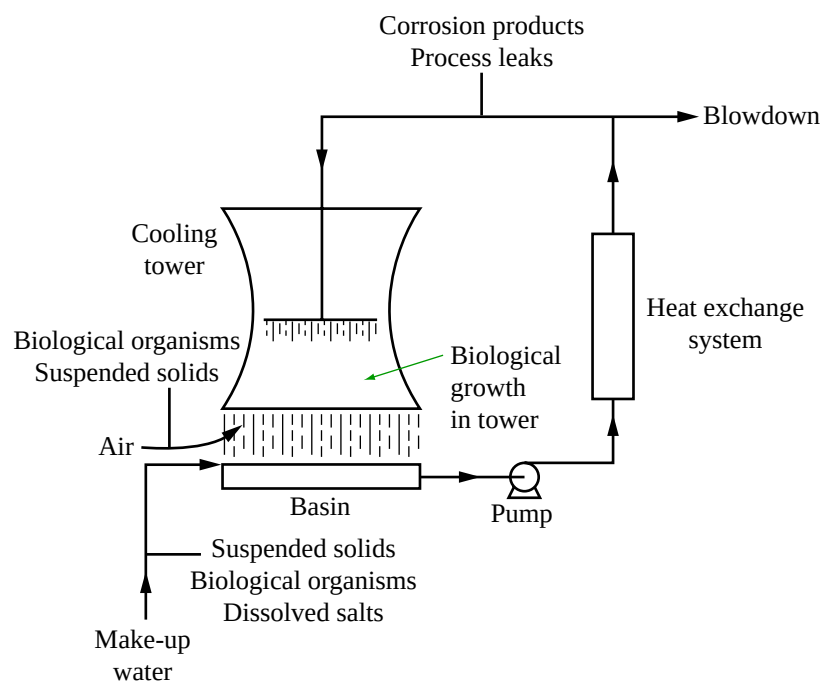
Poor system management, even with good engineering design, can lead to severe problems of fouling. Recommendations on sound management practice for reliable operation are presented. The use of chemical additives is discussed and the merits of different biocides, inhibitors and preventive chemicals generally are considered in order to assist operators with specific systems. The opportunities for on-line mechanical cleaning are also presented but off-line cleaning techniques are not considered to be relevant.

A Glossary (Section 10) defines the terms.

4. FOULING IN COOLING WATER SYSTEMS

The fouling of heat exchangers and other equipment through which the cooling water passes may result from one or more causes as set out in Sketch 4.1 and Table 4.1.

The fouling potentials of different cooling waters demand an understanding of the operative mechanisms before adequate treatment may be applied.



Sketch 4.1 Origin of cooling water contamination

TABLE 4.1 Potential Causes of Fouling in Cooling Water Systems (see Data Item 86038 for more information)

Fouling Source or Mechanism	Possible Effects
Macro organisms, micro organisms.	Deposition and growth.
Particles, silt material and products of corrosion.	Sedimentation and deposition, agglomeration followed by deposition.
Large size debris.	Deposition.
Precipitation of dissolved salts.	Scaling and possibly chemical reaction.
Chemical reaction.	Surface contamination and corrosion.
Process contamination.	Any of the above mechanisms depending on the nature of the contamination.

Before a proper assessment of a potential fouling problem and its control can be made, it is essential to have accurate data on the quality of the make-up and proposed circulating water, *i.e.*

alkalinity or acidity expressed as mg/l,
pH,
hardness expressed as mg/l of CaCO_3 ,
dissolved solids mg/l,
suspended solids mg/l,
dissolved gases mg/l,
microbial activity,
biochemical oxygen demand (BOD),
organic concentration.

In an open recirculating system the quality of the water may be affected by contamination from the air passing through the cooling tower, if one is installed, or from the environment surrounding a spray pond. Process leakage into the cooling system may also produce contamination.

Fouling and corrosion in cooling systems may be overcome by the use of a closed system. Here high quality water is circulated through the system and cooling is effected by indirect methods, for example using a dry cooling tower where the water is cooled by air flow across extended surface heat exchangers. The closed system may still be subject to process leaks which could present a severe problem arising from possible precipitation of contaminant on the inside surface of the tubes of the air cooled heat exchangers. Furthermore, due to sensible heat removal rather than evaporation, operational problems may be experienced in summer. Capacity is limited for the same reason. Closed systems are common in the process and chemical industries.

It is anticipated that, in any particular system, most of, or all, the fouling mechanisms listed in Table 4.1 will be active. The interaction between these mechanisms is complex. If some aspect is overlooked,

severe problems of fouling or corrosion may occur that might otherwise have been avoided.

5. ASSESSMENT OF FOULING POTENTIAL

5.1 Experience

The simplest method of assessing the likely fouling potential of a cooling water is to base the estimate on experience of that particular water. Such a method, however, leaves much to be desired because the conditions under which the cooling water is employed, for example its temperature and velocity, will have a profound effect on the resultant fouling. Unless the proposed operations can be directly related to those from which the experience was derived, there is the potential for serious error. Often the experience cannot be reliably correlated with quantitative operating data of the system. Some form of direct measurement is to be preferred.

5.2 Direct Measurement of Fouling

There are many designs of specific fouling monitoring devices but, in general, all devices use some sort of exposure surface upon which the fouling occurs. Some employ flat removable surfaces, others use standard tubes, others contain an annulus through which the test water is passed. Some surfaces are treated, others are not. The object of the equipment is to attempt to simulate, as far as possible, the conditions of flow and temperature anticipated in the system. The design must be such as to minimise the creation of unrepresentative hydrodynamic effects such as turbulence due to the entry (particularly) or exit. The use of an annulus to simulate flow in a tube may also be open to question due to the difficulty in reconciling Reynolds numbers and hence the degree of turbulence in the two geometries. Typical measurements might include one or more of the following:

- temperature changes,
- heat transfer rates,
- pressure drop,
- deposit thickness.

Variations in interpretation may occur, depending on the actual measurements made.

Some devices are built into the system under test. Others are portable, such as the one developed at the National Engineering Laboratory, East Kilbride: the so-called Portable Fouling Assessment Unit (PFAU), and are capable of being transported from site to site along with the associated mobile laboratory.

5.2.1 Unheated test surfaces

Unheated test sections are by far the simplest in construction, operation and measurement, usually consisting of tubes or plates over which the water is made to flow. After a period of time the surfaces are inspected and assessed for signs or degree of fouling. In other unheated devices the increase in pressure drop is used to estimate the likely fouling. Unheated test sections, although useful, suffer from the drawback that the effects of temperature and heat flow are not assessed. Since heat exchangers are concerned with temperature differences, temperature is an important variable (see Data Item 86038). Small temperature changes may affect biological growth, small changes of temperature in saturated solutions of sparingly soluble salts can encourage deposition on surfaces.

5.2.2 Heated test surfaces

The additional requirement of heating makes these devices more elaborate than an unheated test section. In general the heat is supplied electrically but in some test equipment steam is used. Thermocouples are often used to measure temperature changes brought about by the incidence of fouling. In some designs pressure drop changes are also recorded. More elaborate devices may employ a heat flux meter so that the change in heat transfer may be directly measured.

Attention to the detail of the heating method employed is necessary to ensure the conditions at the real heat transfer surface are properly simulated. Designs which produce overheating at the surface, for instance, are not satisfactory.

5.2.3 The value of fouling assessment devices

The following criteria are considered to be of importance in evaluating devices for the assessment of fouling¹:

- availability,
- accuracy,
- reliability,
- early warning capability,
- ease of data acquisition,
- sensitivity,
- complexity,
- adaptability,
- interferences,
- representativeness,
- similarity to operating heat exchangers,
- ease of installation,
- availability of replacement items,
- cost.

Two types of macrofouling monitors and seventeen microfouling monitors, some of which are available commercially, have been evaluated¹ on the basis of the above criteria. The US National Association of Corrosion Engineers has a task group working on a Code of Practice for on-line monitoring of cooling waters. (Publication of the code is scheduled for 1988). It will provide a basis for the collection and standardisation of data which will be of value in improving design and operation of cooling water systems.

6. DESIGN OF COOLING WATER SYSTEMS WITH SPECIAL REFERENCE TO FOULING

The basic requirement for the design of a cooling water system and associated equipment is a knowledge of the quality of the make-up and recirculating water to be used (see Section 4).

Information concerning the quality, which may change over a period of time, will have a direct bearing on the detailed design insofar as fouling is concerned. Such information may not be readily available for a completely new installation and, under such conditions, assessment will have to be made in the light of experience or preliminary testing. Some adjustment of conditions is always required in any installation to optimise operation so that, as long as the assessment of the potential fouling has been reasonable, most errors can usually be accommodated.

The design of cooling water systems as a whole may be divided into two parts, both needing

consideration.

- (i) The process heat exchangers which the cooling water system services.
- (ii) The circulating system.

6.1 Heat Exchanger Design

There are many different designs of heat exchanger but the two most commonly in use for cooling process fluids are the shell-and-tube and plate types.

In shell-and-tube exchangers it is preferable to arrange for the fluid that is likely to cause fouling to flow through the tubes so that cleaning can be facilitated. Discussion of heat exchanger selection for fouling duties may be found in Data Item 86038.

6.2 Fouling Resistances or Allowances

As described in Data Item 86038, one of the most difficult aspects of heat exchanger design is assigning a value to the heat transfer resistance due to deposits on the surface. Errors can give rise to over- or underdesign, and even enhanced fouling rates.

Limited fouling resistance data are available in the open literature. Tables 6.1 to 6.4 present some data from the literature together with some from private sources. Information about the system concerned is included where possible. It is stressed that these data should be used with caution because of the individual characteristics of particular cooling water systems, and their variability. However the data do represent a useful guide.

The following data report the results of a literature survey together with some recommended values.

TABLE 6.1 Some Recommended Fouling Resistance for Cooling Water²

	SI units	British units
Tubeside velocity: Non-ferrous alloys	1.25 m/s	4 ft/s
Carbon steel and other ferrous alloys	2.0 m/s	6 ft/s
Maximum metal surface temperature	344 K	160°F

Water type	Water temperature		Fouling resistances	
	K	°F	m ² K/W × 10 ⁴	ft ² h °F/Btu × 10 ³
Sea water	Maximum outlet	316 110	1.76 - 3.52	1 - 2
Brackish water	Maximum outlet	316 110	3.52 - 5.28	2 - 3
Treated cooling water	Maximum outlet	322 120	1.76 - 3.52	1 - 2
Spray pond water	Maximum outlet	322 120	1.76 - 3.52	1 - 2
Closed recirculation water	-		1.76	1
River water	-		3.52 - 5.28	2 - 3
Engine jacket water	-		1.76	1
Distilled or closed cycle condensate	-		0.88 - 1.76	0.5 - 1
Treated boiler feed water	-		0.88	0.5
Boiler blow-down water	-		3.52 - 5.28	2 - 3

The survey on which Table 6.1 is based, carried out by the joint HTRI/TEMA Committee to review TEMA fouling standards, revealed that there was a wide range of values of fouling resistance quoted, from 0.88×10^{-4} to 12.3×10^{-4} m² K/W (0.5×10^{-3} to 7.0×10^{-3} ft²h °F/Btu). A value of fouling resistance of 3.52×10^{-4} m² K/W (2×10^{-3} ft²h °F/Btu) was specified in the majority of cases.

These values should be treated with caution since they are not qualified in any way and may, in many instances, be little more than a guess although probably based on experience.

TABLE 6.2 Fouling Resistances for Specified Conditions

Fouling Resistance		Velocity		Temperature				Material of Construction	Water Treatment	Conditions and Comments	Ref.
				K		°F					
m ² K/W × 10 ⁴	ft ² h °F/Btu × 10 ³	m/s	ft/s	Surface	Bulk	Surface	Bulk				
2.0	1.1	1.6	5.25	318	307.4	113	94	Stainless steel	Feed water treated with alum and small amount of lime. Biocide bleach added at the rate of 200 ppm per day.	Water flow in annulus. Water: Total hardness = 220 ppm CaCO ₃ . Total dissolved solids = 700 ppm. pH = 9.0. Deposit: Almost pure magnesium silicate. Duration of tests: 3–8 weeks.	3 4 5
3.1	1.8	1.6	5.25	323	307.4	122	94	Copper			
6.0	3.4	1.6	5.25	328	307.4	131	94	Copper			
12.5	7.1	1.6	5.25	333	307.4	140	94	Copper			
21.0	11.9	1.6	5.25	338	307.4	149	94	Copper			
38.0	21.6	1.6	5.25	343	307.4	158	94	Copper			
900	511.4	0.45	1.48	Initial 333	305	Initial 140	90	Stainless steel	Inhibitors: Chromate–zinc 20–25 ppm chromate. Dispersant: Organo phosphate 2 ppm. Anodic passivator: Inorganic phosphate 5–6 ppm total in–organic phosphate. Chlorine approx. 0.2 ppm continuous. Biocide addition 15 ppm once per week. Sulphuric acid to control pH at 6–6.5.	Plate heat exchanger. Circulating water: Total hardness = 520 ppm CaCO ₃ . Suspended solids = 100 ppm. pH = 6. Deposit appeared to be about 80% inorganic.	6
3.3	1.9	1.34	4.40	Initial 333	305	Initial 140	90	Stainless steel	As above.	As above but deposit appeared to be about 76% inorganic.	6

TABLE 6.3 Some Reported Fouling Resistances for Fresh Water Cooling Systems

Fouling Resistance		Velocity		Temperature		Conditions and Comments	Ref.
$\text{m}^2 \text{ K/W} \times 10^4$	$\text{ft}^2 \text{ h } ^\circ\text{F/Btu} \times 10^3$	m/s	ft/s	K	$^\circ\text{F}$		
10.0	5.7	0.61	2.0	–	–	River water (chlorinated). Fouling resistances after 3 months.	7
8.0	4.5	1.22	4.0	–	–	River water (chlorinated). Fouling resistances after 3 months.	
5.8	3.3	1.83	6.0	–	–	River water (chlorinated). Fouling resistances after 3 months.	
60.0	34.0	0.5	1.6	308	95	Water (chromate treatment). Fouling resistance after 2 months. Deposit: inorganic.	8
9.0	5.1	–	–	–	–	Biofouling from power station condenser cooling water (treated), after 4.25 months.	9
33.0	18.8	> 1	> 3	–	–	Mild steel.	10
35.0	19.9					Copper plated steel.	
350.0	199.0	0.15 –2.7	0.5 –9.0			Recirculating water.	11
350.0	199.0	1–2.13	3–7	–	–	–	12
530.0	300.0	~1	~3	–	–	Stainless steel shell-and-tube exchanger. Open recirculating system. Total hardness 900 ppm. pH 6.5. Shock chlorine treatment once per shift. Fouling resistance maintained at level stated for 3 years.	13
500.0	284	–	–	–	–	Wide range of water qualities.	

TABLE 6.4 Some Reported Fouling Resistances for Fresh Water Cooling Systems

Fouling Resistance		Velocity		Surface Temperature		Conditions and Comments	Ref.
$\text{m}^2 \text{ K/W} \times 10^4$	$\text{ft}^2 \text{ h } ^\circ\text{F/Btu} \times 10^3$	m/s	ft/s	K	$^\circ\text{F}$		
3.5	2.0	–	–	–	–	Caribbean Sea.	14
12.5	7.1	~2	~6.5	305	90	Many ships condensers after 5 months.	15
1.25	0.7	~2	~6.5	305	90	After 120 months.	
2.2	1.25	–	–	–	–	Cupro nickel ships cooler (sea water to high purity water) after 12 months.	15
2.6–5.6	1.5–3.2	–	–	–	–	8 ships condensers tested.	16

6.3 Basic Design Considerations

Simple designs are preferred in order to facilitate cleaning and to eliminate dead spots where deposits may accumulate. The location of heat exchangers needs attention so that cleaning to remove deposits is not impeded. Facilities for off-line chemical cleaning should be provided. Back flushing facilities should be included, particularly if the cooling water flows on the shell side of shell-and-tube heat exchangers. Other features over which the designer has some influence are:

- (i) material of construction,
- (ii) cooling water velocity; particularly important when flow is inside tubes and also affecting Reynolds number and hence flow regime,
- (iii) cooling water temperature,
- (iv) interface temperature,
- (v) turndown requirements of the system that may affect cooling water velocity, cooling water temperature and interface temperature.

Where a complete installation is being designed, as simply opposed to a cooling water facility, there may be scope for improved design to minimise fouling (see Data Item 86038).

6.3.1 Materials of construction

The corrosion resistance of the material of construction will affect the extent of the fouling from corrosion. It may also affect the retention of other deposits, for instance titanium tubes have been known to foul faster than stainless steel under similar conditions.

The use of different metals in different parts of the plant can lead to galvanic corrosion, particularly where they are in contact with cooling water containing dissolved salts. The possibility of galvanic action should be considered at the design stage.

6.3.2 Surface modification

A technique which has been used to limit fouling in cooling water systems is to coat surfaces with a non-stick material. The coating is, in general, a polymer ranging from a monomolecular layer to a thickness of up to 1 mm, although glass linings have been used to a very limited extent. Disadvantages include the added heat transfer resistance associated with the coating, the relatively high cost and the difficulty of maintaining the surface integrity during service.

High surface polish has also been employed to minimise fouling but the disadvantages of relatively high cost and maintenance restrictions are likely.

6.3.3 Cooling water velocity

In order to facilitate cleaning, cooling water is often passed through the tubes of shell-and-tube heat exchangers operating at relatively low pressure. Where the process stream to be cooled is under high pressure, it is passed through the tubes and the cooling water through the shell, to avoid the need for an excessively thick shell.

A velocity in excess of 1 m/s in the usual tube sizes is used to reduce the problem of fouling on the inside

tube walls. At lower velocities the incidence of fouling is likely to be higher. Velocities in excess of 2 m/s may initiate erosion and cause excessive pumping costs.

A velocity of 1 m/s based on the maximum flow area available may be used if cooling water is used on the shell-side. If low velocities are present in the shell, heavy deposits may occur and it becomes virtually impossible to remove the deposit chemically. Off-line mechanical cleaning will be required.

The unique design of the plate heat exchanger facilitates cleaning and the relatively high velocities usually employed help to reduce fouling.

6.3.4 Cooling water temperature

The temperature of the wall in contact with cooling water is an important factor in fouling, since biofouling, scale formation, corrosion and, to some extent, particle deposition are all functions of temperature. In the temperature range encountered in most cooling water systems increased temperature is likely to result in increased fouling. The extent of the effect will depend strongly upon the quality of the water. As a general guide, the cooling water outlet from a heat exchanger should not exceed 45°C with a skin temperature not exceeding 70°C for the metal in contact with the cooling water.

6.4 Cooling Water Circuits

6.4.1 Distribution lines

The distribution lines of any cooling water circuit are a significant part of the system and therefore require careful consideration. A ring main system is to be preferred to a radial main. The former can maintain clean conditions whereas the latter could give rise to settlement if parts of the circuit are not in use. Flow velocity must be maintained in minor circuits and dead legs avoided.

Flushing point connections should be included, as far as possible at strategic points throughout the system, in order that local blockages and restrictions can be removed.

Facilities for isolating individual heat exchangers or banks of heat exchangers without shutting down the entire system should be included, for example by the use of bypass circuits or jump-overs, to aid off-line chemical cleaning. Any pipe work involved should be kept to a minimum to avoid possible sedimentation.

6.4.2 Pumps

Screening is necessary before pump inlets to protect the pumps, with adequate provision for easy cleaning. This facility is particularly necessary where no sidestream filtering of recirculating cooling water is contemplated.

6.4.3 Filtration

There are many different types of filter available that can be used in cooling water systems and nearly all require a back flush system of mains water, or previously filtered water, for cleaning. There are four main types:

- (i) stationary basket, single or duplex,
- (ii) cartridge,
- (iii) rotary basket,

- (iv) sand bed (usually employed in sidestream mode - see below).

All require attention to maintain efficiency and particularly throughput.

Prefiltration may be necessary if abstraction is from a river or canal, in order to reduce the load on the main filters.

Filtration of the total cooling water flow is uneconomic, but sidestream filtration of up to 10% of the recirculating flow is likely to maintain acceptable particle concentrations.

6.5 Cooling Towers

The function of the cooling tower is to provide intimate mixing between air and water so as to effect the cooling of the water through evaporation (removal of heat as latent heat). It is usual for the water to flow countercurrent to upward flowing air in the tower, although in some designs the air enters across the downflowing water. The air flow may be by natural circulation (as in large power stations) or mechanically driven by a suitable fan (as in many chemical plant installations). If the fan is located at the bottom of the tower the arrangement is said to be forced draught or, if at the top, induced draught.

Tower design includes static components such as the concrete or wooden shell containing wood or plastic contact surfaces and a concrete basin that acts as a collection and storage facility for the water. Vacuum-formed plastic fill for cooling towers is generally replacing wood which is subject to chemical, bacterial and fungal attack. The principal advantage of plastic tower packing is low weight, and hence lower construction costs. Large accumulations of biological and particulate matter can occur on these surfaces unless good water quality control is exercised. The combined weight of the deposits together with the water hold-up can be considerable and may lead to distortion or even collapse of the plastic structure.

Design for both natural and forced draught towers should incorporate:

- (i) adequate basin volume to cope with surges,
- (ii) sumps in the basin to trap foulant, together with sludge handling facilities,
- (iii) uniform water distribution at the inlet to the tower,
- (iv) adequate space around the basin to allow vehicle access for cleaning and maintenance operations,
- (v) tower location relative to the prevailing wind direction to minimise contamination of the water with airborne leaves, dust, and other solid material and gaseous contaminants.

It may be necessary to consider problems of icing in winter if the tower is to be intermittently used, or even at normal throughput under severe conditions.

6.6 Dosing Equipment

Dosing facilities have to be included in the design in order to treat cooling water chemically. Dosing equipment may, for large installations, require multiple injection nozzles. In many installations additives are injected on the suction side of the main pump so that the turbulence within the pump provides the desired dispersion. The addition of chemicals to the system, for example chlorine, requires the following criteria to be satisfied.

- (i) The injection system must be designed to give uniform distribution of the additive, so avoiding stratification.
- (ii) Injection rates must be adjustable so that adequate residuals can be maintained. This is specially important as far as oxidising biocides are concerned.
- (iii) The quantity of material injected must be monitored.
- (iv) The injection nozzles should be placed in such a location in the cooling water main from the tower basin that adequate mixing is accomplished before side streams are taken off.
- (v) Adequate safety features associated with the dosing equipment and its operation must be incorporated in the design.

Where dosing facilities are required it will be necessary to provide adequate tankage and possibly mixing facilities for the chemical additives. It is preferable to use solutions rather than slurries wherever possible.

6.7 Standby Equipment

At the design stage consideration should be given to the installation of standby equipment, but with due regard to the additional capital cost involved. Duplication of the main pumps, filters, dosing equipment and other major items may avoid expensive shut-downs of the whole system in the event of component failure. The extent of the duplication will depend upon the water quality, equipment reliability and experience.

6.8 Additional Facilities for Once-through Systems

Once-through systems may be used to avoid the recirculation of hot water and its associated cooling. Special attention to the intake and discharge is required. The intakes should be placed so as to reduce the possibility of drawing mud, silt and other debris into the system. Adequate screens and filters will also be necessary. Normally, proprietary units would be purchased wherever possible.

The debris filter system should be designed to operate continuously and automatically, with little or no operator attention. The components of the system, therefore, would be expected to withstand repetitive flushing, particularly during periods of severe debris accumulation. Complete flushing time should not exceed about three minutes.

Some further requirements are as follows.

- (i) The mesh size of the filter element should be no larger than one third of the tube inside diameter for shell-and-tube heat exchangers, or the space between plates of a plate type or the flow spaces of other equipment under protection.
- (ii) The debris filter should be designed for a head loss of up to 1 m of water at a velocity of around 1.5 m/s in the pipe line.
- (iii) Robust design is essential with failsafe features to prevent blockage due to overloading, loss of power, or component failure.
- (iv) Contact of the mechanical parts with the cooling water should be kept to a minimum in order to reduce maintenance.

The discharge should be downstream in rivers, and sited so as not to contaminate intake streams when