



Fouling in cooling systems using seawater

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FOULING IN COOLING SYSTEMS USING SEAWATER

1. NOTATION AND UNITS

		<i>SI Unit*</i>
A_i	total surface area of inside of tubes	m^2
A_o	total surface area of outside of tubes	m^2
A_w	tube mean wall area	m^2
$a_0 - a_6$	coefficients in Equation (6.7)	-
Cl	chlorinity	g/kg
C	concentration of hypochlorous acid in water, see Equations (12.1) and (12.2)	-
c_p	specific heat capacity at constant pressure	J/kg K
D_{shell}	inside shell diameter	m
d	inside tube diameter	m
d_o	outside tube diameter	m
E_c, E_h	cold and hot side enhancement ratio respectively, see Section 11.1.1	-
f	tube inside wall Fanning friction factor, $f = \frac{\tau_w}{\frac{1}{2}\rho v_a^2} = \frac{\Delta p d}{2\rho v_a^2 L}$	-
I	molar ionic strength, see Equation (6.5)	-
K	rate constant in Equations (12.1) and (12.2)	1/s
L	tube length	m
LSI	Langelier Saturation Index, see Section 6.2.1	-
MSI	modified Langelier Saturation Index, see Section 6.2.1	-
n_t	number of tubes in shell	-
Pr	Prandtl number, $= (c_p \eta / \lambda)$	-
p	pressure	N/m ² (Pa)
Δp	frictional pressure drop	N/m ² (Pa)
$\dot{Q}$	rate of heat transfer between streams or heat load	W
$\dot{q}$	heat flux	W/m ²

See footnote at the end of table.

		<i>SI Unit*</i>
r_w	wall thermal resistance, see Equation (4.1)	K/W
R_f	fouling factor	m ² K/W
R_f^r	irreducible fouling factor, see Equation (12.2)	m ² K/W
R_{fi}	inside tube fouling factor	m ² K/W
R_{fo}	outside tube fouling factor	m ² K/W
Re	Reynolds number (inside tubes = $\rho v_a d / \eta$)	–
S	salinity	g/kg
T	temperature	K or °C
T_c, T_h	cold and hot temperatures respectively	K or °C
T_c	critical temperature	K or °C
ΔT_m	mean temperature difference	K or °C
T_w	tube inside wall temperature	K or °C
$\bar{T}_w$	dimensionless temperature ratio, see Section 11.1.1	–
t	Celsius temperature	°C
t	time	s
U_o	overall heat transfer coefficient based on tube outside surface area, A_o	W/m ² K
$\tilde{U}$	dimensionless overall heat transfer coefficient ratio, see Appendix C1	–
$\dot{V}_t$	tubeside volumetric flow rate	m ³ /s
v_a	superficial axial flow velocity in the tubes (volume flowrate divided by bare tube inside flow area)	m/s
v_f	axial flow velocity in fouled tube	m/s
v_s, v_t	tubeside and shellside flow velocity, respectively	m/s
$\tilde{v}_s, \tilde{v}_t$	dimensionless ratio for tubeside and shellside velocity respectively, see Section 11.1.1	–
x_w	wall thickness	m
α_c, α_h	film heat transfer coefficient related to cold side and hot side respectively	W/m ² K

See footnote at the end of table.

		SI Unit*
α_i, α_o	film heat transfer coefficient related to inside and outside of tube respectively	W/m ² K
α	film heat transfer coefficient ratio, see Appendix C1	–
η	dynamic viscosity	N s/m ²
λ	thermal conductivity	W/m K
λ_c	thermal conductivity of distilled water, see Equation (B2.1)	W/m K
ρ	density	kg/m ³
τ_w	wall shear stress	N/m ²

Subscripts

f	refers to foulant layer or variable under fouled conditions	
o	outlet	
mix	mixture	
r	refers to reference value (esp. in Section 11.1.1 and Appendix C1 where r refers to case with no enhancement)	–

* This Data Item is presented in terms of SI units only (except for the non-consistent unit of g/kg). For users wishing to work in British/US customary units, conversion factors for some of the quantities are given below. Additional conversion factors for physical properties are given in Reference 7.

Some conversion factors

Quantity	Given in → Gives ←	multiplied by → divided by ←	Gives Given in
Length	m	3.280 84	ft
Pressure	m N/m ² (Pa) N/m ² (Pa)	39.370 0.000 145 038 0.020 885 4	in lbf/in ² (psi) lbf/ft ²
Power	W	3.412 14	Btu/h
Area	m ²	10.763 9	ft ²
Mass	kg	2.204 62	lb
Volume	m ³ m ³	35.314 7 6.289 846	ft ³ US barrel
Energy	J J	0.238 846 9.478 2 × 10 ⁻⁴	cal Btu

Temperature conversions

$$^{\circ}\text{C} = \frac{5}{9}(^{\circ}\text{F} - 32), \quad ^{\circ}\text{F} = \frac{9}{5}(^{\circ}\text{C}) + 32, \quad \text{K} = ^{\circ}\text{C} + 273.15, \quad ^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$$

2. INTRODUCTION

2.1 Purpose and Scope

In the use of seawater in heat transfer systems, a major problem is that of fouling. This arises from the rather complex nature of the seawater medium and in particular its propensity to sustain a whole range of aquatic life forms that give rise to biofouling of heat exchanger surfaces.

This Data Item is one of a group of 'User Guides' developed under the guidance of the Oil Industry Fouling Working Party. It presents a condensed summary of the vast amount of information that is available on seawater fouling and related topics. Its objective is to provide the designer and the operator with a ready 'User Guide' on the occurrence, the mechanisms and the mitigation of fouling in these systems. A previous ESDU Data Item on cooling water fouling was issued in 1988¹ and this present Data Item is the first of two Data Items that are aimed at updating this earlier work on seawater and fresh water fouling respectively. A further 'User Guide' to crude oil fouling in pre-heat train heat exchangers is also available².

In what follows, Section 2.2 gives information on water as a coolant in general and seawater in particular. Section 2.3 discusses the composition of seawater and its physical properties.

Section 3 considers the selection of seawater cooling system types, discusses the advantages and disadvantages of direct and indirect systems and describes a common application of each type.

Section 4 gives a brief introduction to the generic subject of fouling and Section 5 introduces the various types of fouling which occur in seawater systems and the parameters that affect them.

Sections 6 - 9 then present more detailed information on the principal forms of fouling, namely crystallisation fouling (Section 6), corrosion fouling (Section 7), biological fouling (Section 8) and suspended solids fouling (Section 9).

The all-important matter of materials selection is discussed in Section 10.

The design of systems to handle and minimise fouling in seawater systems is obviously an important factor and such system design considerations are reviewed in Section 11; particular attention is given to the effects of enhancement of heat transfer coefficient on one side of a heat exchanger on the parameters which control fouling (that is, velocity and temperature) on the other side of the exchanger. A whole range of measures has been suggested for the mitigation, control and on-line removal of fouling and these are reviewed in Section 12. Section 13 presents information on cleaning of fouled heat exchangers. Section 14 provides a brief review of some novel applications, including air-conditioning and Ocean Thermal Energy Conversion (OTEC).

The extensive list of selected references is provided in Section 15. Seawater properties are discussed in Appendix A, and Appendix B provides tabulated values of the physical properties required for many heat exchange calculations.

2.2 Water As a Coolant

Water is the main coolant in industry though environmental pressures (as discussed below) are increasingly militating in favour of the use of air rather than water. Oil refineries, chemical plants, steel mills, power plants, all use water to remove heat from their processes. Generally the water is not consumed, but simply passes through heat exchangers and returns to the source.

Seawater consumption is huge in the power generation industry (see Section 3.3.1). The United States power industry uses around 6700 m³/s (106 million gpm)³; that is, 80% of all industrial cooling water or a third of water usage for all purposes in the USA.

Although seawater consumption is less in the process industries in general, its effective use in offshore processing is crucial.

In electricity utilities and process plants located in coastal zones, seawater is frequently used directly in heat exchangers and condensers (see Section 3.1).

Once-through systems using fresh water are used in locations close to rivers or lakes. However, fresh water supplies are usually not sufficiently abundant and their consumption is increasingly restricted by legislation limiting the thermal load on natural waters and the use of chemical additives for cooling water conditioning. It has, therefore, become common practice to use closed cooling water systems and to reject the heat to the atmosphere via cooling towers or to fresh water or seawater through heat exchangers (see Section 3.2).

On a world scale, fresh water represents only a small fraction of available water. The world's water resources³ are 1.36×10^{18} m³ of which only a small proportion is fresh water. Keens³ gives the following table of distribution of available water:

Oceans	97.2%
Icecaps & Glaciers	2.15%
Atmosphere	0.001%
Ground water	0.626%
Rivers	0.0001%
Fresh water lakes	0.009%
Saline lakes	0.008%

Fresh water conservation in process plant is often economically very important⁴. Thus, cooling with seawater, when it is readily available in the locality, makes use of the largest resource of water. It is estimated³ that 42% of the water used by US power plants is seawater; however, this utilisation is likely to decrease in future because of the severe environmental constraints as will be discussed in Section 3.3.1. Usually, cooling with seawater is done on a once-through basis (though it is occasionally used in cooling towers as discussed in Section 3). It has the following further advantages over cooling by re-circulated fresh water from cooling towers:

- (1) With cooling towers, there is a limit on the return temperature to within around 5°C of the wet bulb temperature and, often, once-through seawater systems give lower available temperatures and, hence, smaller heat exchangers.
- (2) There is continuous loss of (relatively expensive) fresh water from cooling towers. Typically, 0.2% is lost as spray and about 1% as water vapour for each 5°C of cooling in the cooling tower.

There are two possible routes to utilisation of seawater as a heat sink, namely the use of direct and indirect cooling systems. These choices are described in Section 3 and illustrated by industrial examples.

2.3 Seawater Composition And Properties

Seawater is a quite complex liquid; it can vary in cleanliness and salinity from place to place and is also an excellent nutrient medium supporting many forms of animal and plant life⁵. 'Normal' seawater is a mildly alkaline (pH 8.0) aqueous solution containing roughly 35 000 ppm by mass of dissolved solids. However,

the composition of seawater can vary considerably from place to place. Notably, the Baltic Sea has dissolved solid contents which are often less than 25% that for normal seawater⁶. Transient variation of composition can also be significant. For instance, after a rain storm the upper part of the sea may have a low concentration of salts. It should also be stressed that there is considerable seasonal variation in seawater biological activity and suspended solids content. Table 2.1 shows the ionic contents of normal seawater. Though it is often assumed that the main content is common salt (sodium chloride) it will be seen from this table that there are significant amounts of a wide variety of other species. It should be noted that the iron content of seawater shows wide variations; a too-low iron content may be a problem with aluminium, brass and copper nickel tubes, where a certain iron concentration is required to prevent corrosion.

TABLE 2.1 Composition of Normal Seawater⁷

Ion	Concentration in g/kg of seawater (salinity 35 g/kg)
chloride	19.344
sodium	10.773
sulphate	2.712
magnesium	1.294
calcium	0.412
potassium	0.399
bicarbonate	0.142
bromide	0.067
strontium	0.008
boron	0.004
fluoride	0.0013
Total	35.156

Table 2.2 shows that the physical properties of seawater, as they affect heat exchanger equipment, are close to those of fresh water. Specific heat is slightly lower and viscosity is higher, implying slightly greater flows for a given duty and greater pumping energy requirement. Oxygen solubility is lower. Electrical conductivity, on the other hand, is considerably higher: this means that galvanic corrosion will be more likely to occur, but that cathodic protection methods, if used, will be more effective. Further information on seawater properties is given in Appendix A and Appendix B (which is taken from ESDU⁷).

TABLE 2.2 Properties of Seawater (Figures In Brackets Relate To Fresh Water)

Property, SI unit	Temperature		
	0°C	20°C	40°C
Specific heat capacity, kJ/kg K	3.992 (4.209)	3.993 (4.189)	4.000 (4.180)
Vapour pressure, Pa	—	2309 (2344)	7167 (7375)
Oxygen solubility, ppm	11.2 (14.6)	7.2 (9.2)	5.2 (6.5)
Dynamic viscosity, cP (or mN s/m ²)	1.877 (1.775)	1.072 (1.002)	0.704 (0.653)
Thermal conductivity, mW/m K	566 (572)	600 (604)	628(630)
Electrical conductivity, 1/W m	29 (1)*	48 (2)*	71 (3)*

* Typical for borehole near coast; electrical conductivity varies widely according to source and is lower for surface or distilled water.

3. SELECTION OF SEAWATER COOLING SYSTEM TYPE

There are three possible routes to utilisation of seawater as a heat sink:

- (1) **Direct use of seawater;** here, the seawater is pumped directly to the heat exchanger and there is direct transfer of heat (across the heat exchanger surface) from the hot medium being cooled to the seawater cooling medium.
- (2) **Indirect use of seawater;** here, heat is exchanged between the seawater and a secondary fresh water stream which could be fresh water or a mixture of fresh water and, say, glycol, this secondary stream being then used as the cooling medium. In general, for offshore use, water with typically 30% of tri-ethylene glycol (TEG) or mono-ethylene glycol (MEG) is used as the secondary cooling medium. For onshore use, fresh water is often used if climate conditions permit.
- (3) **Use of seawater in cooling towers.** In some areas, it may be economic to utilise seawater in cooling towers; here, the heat rejection is not only to the sea but also to the atmosphere due to partial evaporation of the seawater. This obviously can make available an alternative source of cooling tower water where fresh water is expensive. It can also lead to a considerable reduction of pumping power and thermal pollution. Usually, in such systems, the seawater is cycled through the cooling tower for no more than two cycles, to minimise corrosion and fouling.

Typically, for direct cooling process applications, plate heat exchangers are used for low-pressure duties and shell-and-tube exchangers for high-pressure duties. Plate exchangers would be a common choice for cooling of the cooling medium in indirect systems.

The selection between the two most common (direct and indirect) systems is a prime design decision and needs to be considered carefully. The advantages and disadvantages of the respective systems are summarised as follows.

3.1 Direct systems

Advantages:

- (i) Low water temperature allowing process fluid to be cooled further.
- (ii) Larger temperature differences leading to smaller process heat exchangers if fouling not significant.
- (iii) Simpler system avoiding the need for secondary heat exchangers and the associated instrumentation.

Disadvantages:

- (i) Fouling and corrosion problems associated with seawater are present in the process heat exchanger and may cause severe problems that can be avoided in secondary heat exchangers.
- (ii) Restrictions on materials may pose severe problems.
- (iii) Large pumping requirements if exchangers are in an elevated position as they might be on an offshore platform. A possible assumption is that, if the water is returned below sea level, then the siphon effect would recover the elevation pressure difference. However, reliance on such a siphon effect may not be justified in many circumstances. The problem of large pumping requirements imposed by heat exchangers located in an elevated position has led to replacement of indirect

systems in UK power stations after it was realised that, in applications where the elevation approached 10.3 m (that is, a head equivalent to one atmosphere pressure), cavitation and loss of pump duty (usually followed by restart of a stand-by unit) could lead to water hammer problems. These can cause fracture of heat exchanger end covers. Such problems have been largely overcome by the use of elevated air cooled condensers.

- (iv) Restrictions in the types of heat exchanger that can be employed for the process duty.
- (v) Low wall temperatures on the cooling side that can lead to low wall temperatures on the process side with consequent solids deposition and even blockage.

3.2 Indirect systems

Advantages:

- (i) Allows temperatures on cooling side to be controlled and thus avoiding solids formation on the process side.
- (ii) Removes the seawater fouling/corrosion problem to the secondary heat exchangers where more optimal conditions and optimal choice of heat exchanger can be achieved.
- (iii) Allows optimum selection of heat exchanger type and material of construction for the process heat exchangers.

Disadvantages:

- (i) Higher coolant temperatures in the process exchangers leading to restrictions on the minimum temperature achievable and also larger exchanger surface areas. This increase in area would, of course, be partially offset by the reduction in fouling in these exchangers.
- (ii) More complex system involving two coolant circuits and thus higher capital costs.

The nature of the choices required is perhaps best illustrated by taking examples, as follows.

3.3 Selection Examples

3.3.1 Power generation systems

Huge quantities of seawater are used in cooling in electricity generating stations. For example, a 2000 MW installation would use around 60 m³/s and, in the UK in 1976/77, some 40 million m³/day were used for cooling power station condensers⁸. In power condenser duties, there is a great benefit in minimising the coolant temperature (and hence minimising the condenser pressure) and **direct** seawater cooled condensers were nearly always installed in the past and still represent a significant part of the installed capacity. These installed systems are often of the "surface condenser" type with the cooling seawater inside the tubes and condensation occurring on the outside with special precautions being taken to minimise pressure drop on the shell side.

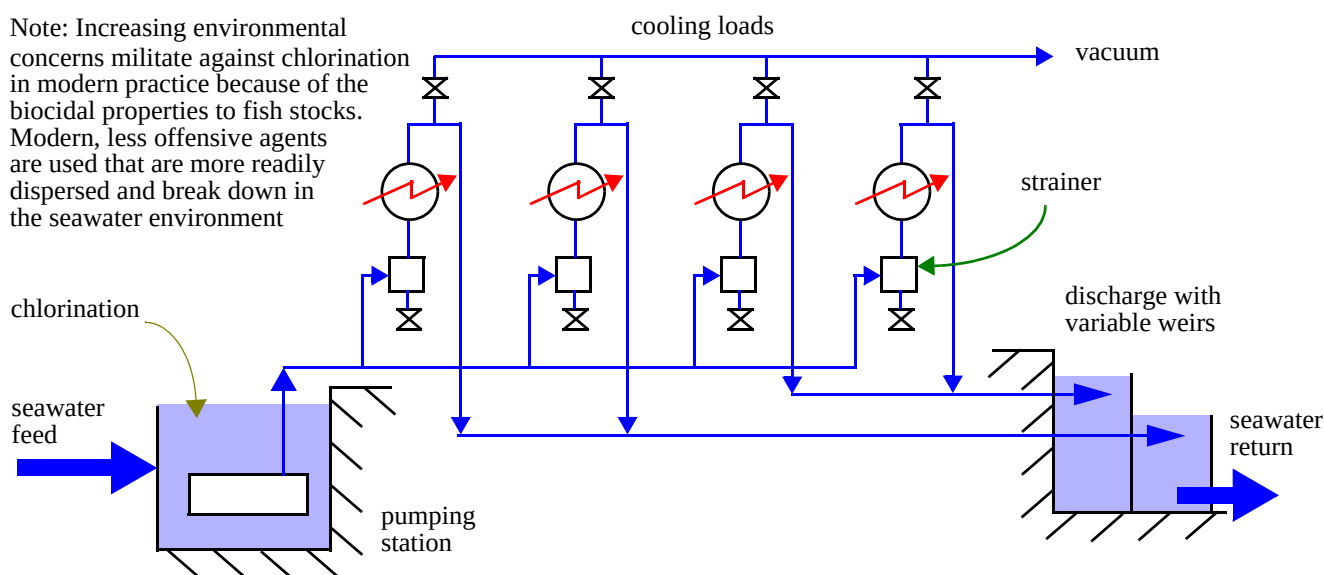
Cooling water fouling has great economic significance. Curlett and Impagliazzo⁹ estimate lifetime costs associated with cooling water fouling of between 6 million and 12 million dollars (US) for a single 600 MW power plant.

However, though there are many areas of the world where seawater cooling may still be specified in large power station condensers, there are now significant environmental restrictions on the use of seawater cooling for such plants. These restrictions have been in place since around 1990 in the UK and North America and have been extended to Mexico and South America in recent times. As a result, no significant seawater cooled large power plant (e.g. 2000 MW) condensers have been constructed in the UK or North America since about 1990, though smaller units are still being installed. In the UK, the oil fired stations at Fawley and Pembroke have now been shut down for economic reasons.

This important change in practice has arisen due to stringent new legislation on thermal pollution. The 1989 US/EPA Clean Water Act Regulations, and the revised 2002 Regulations, require that no new power project is allowed to have a thermal discharge greater than 10°F (5.6 K) across the condenser. Furthermore, there are maximum outlet temperature limits for once-through or cooling water applications that stipulate that discharge should not exceed 109°F (42.8°C). In addition, the bulk sea temperature rise within 5 metres of the point of discharge is restricted to 5°C. Even with multijet ejectors, this is very difficult to achieve economically for large units. Furthermore, it is very difficult to demonstrate the accuracy of predicted “slack water” mixing patterns in tidal seawater heat sinks. Recent large installations have therefore often used air rather than seawater cooling. In other words, *neither* direct *nor* indirect seawater cooling systems were used in these circumstances. However the energy wastage, arising from the increased heat rejection temperature for air cooling systems and from the power utilisation by the fans used to circulate the air, raises serious issues about any net environmental benefit of such legislation.

A typical seawater cooling system for power station condensation is shown in Sketch 3.1. The water is fed from the sea into a pond where modest chlorination is implemented (to reduce fouling – see Section 12) and from there it is pumped through the condensers before being discharged back into the sea. Strainers are commonly used ahead of the heat exchangers using seawater because of the potential for contamination with marine macro-organisms (see Section 8). These are usually in the form of a perforated plate which can be back-flushed without shut-down. For process applications, the circuit may be rather different. Most commonly, in this case, the seawater is pumped directly via trash screens to the heat exchangers and the pond is not employed.

Seawater has been used, of course, for many decades as a cooling medium. Probably the first applications were in powered ships and it is from these applications that much of what is known about this system is derived.



Sketch 3.1 Once-through seawater cooling system (Keens³)

3.3.2 Wet gas systems

In wet natural gas systems, hydrates are formed at temperatures below around 20-25°C and control of the surface temperature is essential. This very much favours **indirect** systems. Furthermore, these applications are often on offshore platforms where exchanger size and weight are important considerations. Printed circuit heat exchangers (PCHE's) are often used in these cases since they are only a small fraction of the volume and weight of an equivalent shell-and-tube heat exchanger. They allow closer temperature approaches and this may reduce the cooling water flow requirements. PCHE's are not generally recommended for direct use with seawater since scaling at temperatures greater than around 40°C may restrict the (narrow) flow passages. In using such indirect systems on offshore platforms, the cooling medium coolers can be placed near the sea surface and this minimises the pumping requirements for the seawater. The net cooling medium pressure loss around the circuit is due only to friction. If direct cooling is used, then the pumping requirement may be greater since, in a circuit with an open exit, the static head component may not be recovered. By using indirect systems, the choice of materials and heat exchanger type is much less restricted. Thus, the low pressure secondary exchangers can be made of seawater-resistant materials (e.g. titanium) and the process exchangers may be constructed, for instance, from carbon steel or from stainless steel (e.g. SS316), neither of which can be used for seawater duty. SS316 is recommended for glycol-water mixtures. Process systems of this type have not generally been subject to the pressures of environmental legislation now arising in the power station case.

4. INTRODUCTION TO HEAT EXCHANGER FOULING

Epstein¹⁰ classifies fouling mechanisms for heat exchangers into particulate fouling, crystallisation fouling, corrosion fouling, chemical reaction fouling and biofouling. Biofouling (both aerobic and non-aerobic) and corrosion fouling are the most important mechanisms for seawater cooling systems but crystallisation fouling and particulate fouling may also be significant in some circumstances. Epstein¹⁰ suggests a general sequence of fouling events which may play a role in all types of fouling; the sequence is

- (1) initiation,
- (2) transport of foulant,
- (3) attachment to the surface,
- (4) release of the deposit, and
- (5) ageing of the deposit on the surface.

Bohnet¹¹ presents an assessment of the state of knowledge in the various elements of Epstein's classification and concludes that the least known areas are the removal and ageing processes; though this assessment was published in 1987, this conclusion is still valid. More detailed information on fouling problems and fouling mechanisms is provided in Bott¹². Recent fouling mitigation strategies and cleaning methods are described in Müller-Steinhagen¹³.

As shown above, the processes of heat exchanger fouling are actually quite complex and there is an increasing need to consider these complexities in designing and operating systems. Fouling is currently accommodated in heat exchanger design as follows.

4.1 Tubular Heat Exchangers

In order to quantify the fouling propensity of the heat exchanger, it is normal to define, for tubular heat exchangers, a *fouling factor* R_f . This is derived from the normal definition of overall heat transfer coefficient, the equation for which has the form:

$$\frac{1}{U_o A_o} = \frac{1}{\alpha_o A_o} + \frac{R_{fo}}{A_o} + r_w + \frac{R_{fi}}{A_i} + \frac{1}{\alpha_i A_i} \quad (4.1)$$

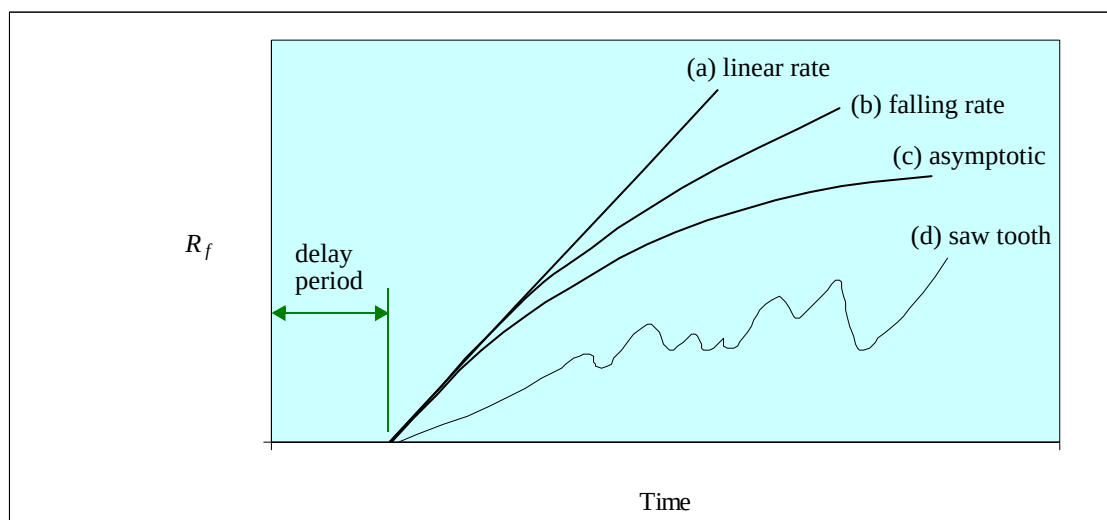
where U_o is the overall heat transfer coefficient based on the outside surface area of the tubes, A_o ; α_i and α_o are the heat transfer coefficients for the inside and outside of the tubes (based on the inside and outside area A_i and A_o), R_{fi} and R_{fo} are the fouling factors for the inside and outside of the tubes respectively and r_w is the tube wall thermal resistance. The wall resistance is given as $r_w = x_w / (\lambda_w A)$ for a flat plate geometry ($A = A_o = A_i$) where x_w is the wall thickness and λ_w is the thermal conductivity of the wall material. For a tubular system, $A_o/A_i = d_o/d$ where d_o is the outside tube diameter and d the inside tube diameter. In this case, $r_w = d_o / (2\lambda_w A_o) \ln(d_o/d)$.

It is common practice in industry to use *fixed* values of fouling factors for tubular exchangers, most usually those listed by the Tubular Exchangers Manufacturers Association (TEMA)¹⁴. The values suggested by TEMA (after conversion to SI units and rounding) are as follows:

Temperature of heating medium	< 120°C		120 – 200°C	
Water temperature	< 50°C		> 50°C	
Flow velocity	≤ 1 m/s	> 1 m/s	≤ 1 m/s	> 1 m/s
Fouling factors (m ² K/W):				
Seawater	0.000 09	0.000 09	0.000 18	0.000 18
Brackish water	0.000 35	0.000 18	0.000 53	0.000 35

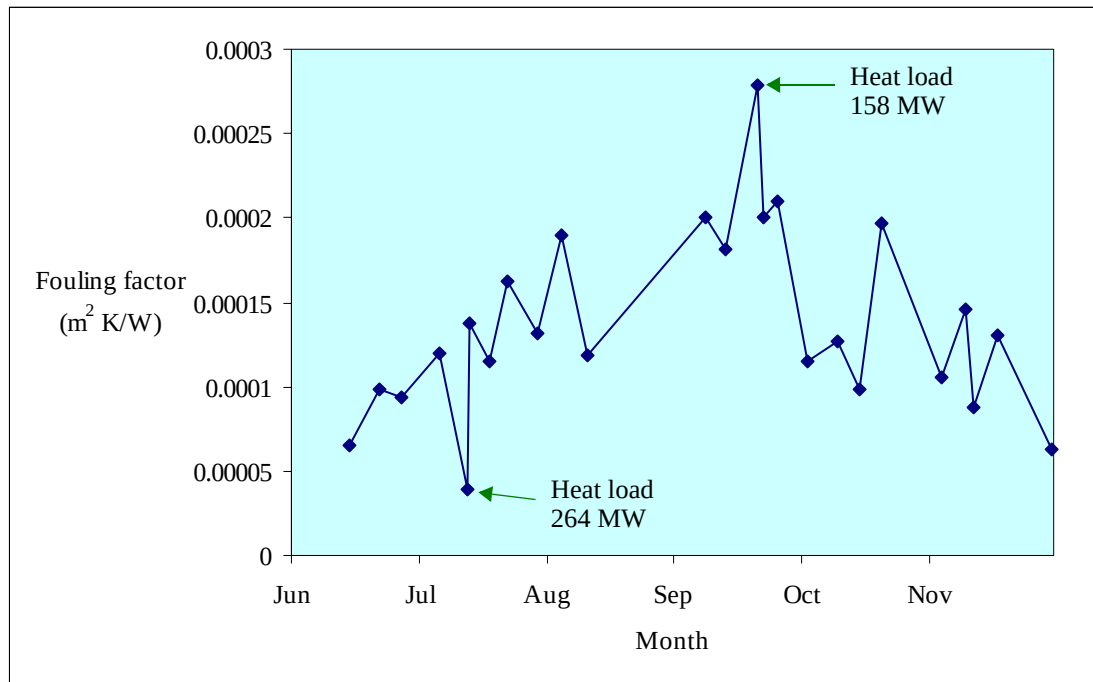
Work carried out under the aegis of TEMA and published in 1998 (Chenoweth¹⁵) suggests, on the basis of examination of available data, a range of fouling factors for seawater of 0.000 275 to 0.000 35 m² K/W. These values are much higher than those recommended in the TEMA standards.

In practice, however, a much wider range of variation in fouling factor is observed. For instance, Dallender and Ostle⁶ report values in the range 0.000 1 to 0.001 2 m²K/W for condensers cooled by seawater. Thus, the value of the fouling factor that applies will depend critically on the circumstances. Also, it should be stressed that fouling is a time-dependent phenomenon. Sketch 4.1 illustrates the various forms of variation of R_f with time that may occur. The assumption of constant values of R_f would be consistent (in the longer term) only with the asymptotic behaviour, (c). In many cases, the fouling factor would continue to increase over the period of operation of a system between cleaning either linearly (a) or with a falling rate (b). In some circumstances, the fouling layer is periodically removed and a “saw tooth” behaviour (d) is observed. A typical example is shown in Sketch 4.2.



Sketch 4.1 Fouling curves showing the various possible fouling rates (Müller-Steinhagen¹⁶)

The presence of a fouling layer restricts the flow channels and this gives rise to an increase in pressure drop; depending on the circuit, this can reduce flows and further reduce the performance of the exchanger. The effects on pressure drop should be borne in mind in specifying the heat exchanger within the context of the available pressure drop.



Sketch 4.2 Fouling history for power plant surface condenser²¹

4.2 Compact Heat Exchangers

For compact heat exchangers, it is common practice to define a duty margin which is the amount that the surface area has to be increased to account for fouling; this might typically be around 10-20%. Care needs to be taken about the way in which the additional area is introduced. Increasing area by increasing the number of channels would decrease velocity and may lead to an infringement of minimum velocity constraints. Alternatively, area might be increased by increasing tube length without affecting velocity but this may infringe pressure drop restraints.

For plate-and-frame heat exchangers, the following fouling factors have been suggested¹⁷:

Coastal seawater: 0.000 043 m² K/W.

Ocean seawater: 0.000 026 m² K/W.

However, for plate heat exchangers, the maximum excess surface area should be also limited to 20-25% of the clean surface requirements.

4.3 Power Station Condensers

For power station condensers, it is common practice to account for fouling using a cleanliness factor which is the fraction of the clean surface heat transfer which occurs after accounting for fouling. This methodology is recommended by the Heat Exchange Institute Inc. (HEI) whose standards¹⁸ tabulate reference values of overall heat transfer coefficients which are functions of velocity and tube diameter.

In contrast to TEMA, HEI does not make quantitative recommendations on how to allow for the effect of fouling; HEI standards state the following: "A design cleanliness factor should be selected by the Purchaser that suitably reflects the probable operating conditions the tubes will experience in service. Non-copper bearing tube materials are more susceptible to biofouling than tubes with a high copper content".

The HEI reference values of overall heat transfer coefficients are based on clean 18 SWG Admiralty metal tubes with 21.1°C (70°F) inlet temperature. These coefficients are then multiplied by factors F_W , F_M and F_C which correct the reference values for the effects of water inlet temperature (F_W), tube material and gauge (F_M) and cleanliness (F_C) respectively. Factors F_W and F_M are essentially calculated from standard correlations for heat transfer and from material and water properties.

It is interesting to calculate cleanliness factors, F_C , based on the TEMA fouling factor, R_f values and the HEI clean surface coefficients. As will be seen from the TEMA values tabulated in Section 4.1, the suggested values of fouling factor, R_f increases from 0.000 09 to 0.000 18 m² K/W as water temperature increases to 50°C. Considering temperatures on either side of this value (namely 40°C and 55°C) and assuming 25.4 mm (1 inch) 20 SWG titanium tubes with a water velocity of 1.22 m/s (4 ft/s) the following values are estimated:

TABLE 4.1 Equivalent HEI Cleanliness Factor, F_C , Calculated From TEMA Fouling Factor, R_f

Wall temperature (°C)	Uncorrected clean U^* (W/m ² K)	F_M^*	F_W^*	Corrected clean U (W/m ² K)	TEMA fouling factor, R_f (m ² K/W)	F_C value calculated from TEMA factor
40	2986	0.88	1.110	2917	0.000 09	0.79
55	2986	0.88	1.165	3061	0.000 18	0.64

*Estimated from the tables in the HEI standards¹⁸.

Note that seawater temperatures in cooling systems are normally lower than 50°C and, thus, the higher value of F_C would be the most appropriate in these systems, assuming that the TEMA values were realistic. However, it seems probable that the F_C values in Table 4.1 estimated from the TEMA fouling factors are far too low. For the case calculated, values in the range 0.9 to 0.95 are more likely (Loraine¹⁹). Care should be taken to ensure that the adding of this extra area does not result in an unacceptable decrease in seawater velocity. To maintain these high cleanliness factors, attention needs to be given to maintaining high velocities and to proper design of inlet conditions, etc, as discussed below.

5. TYPES OF SEAWATER FOULING

The most important forms of fouling occurring in seawater systems are as follows:

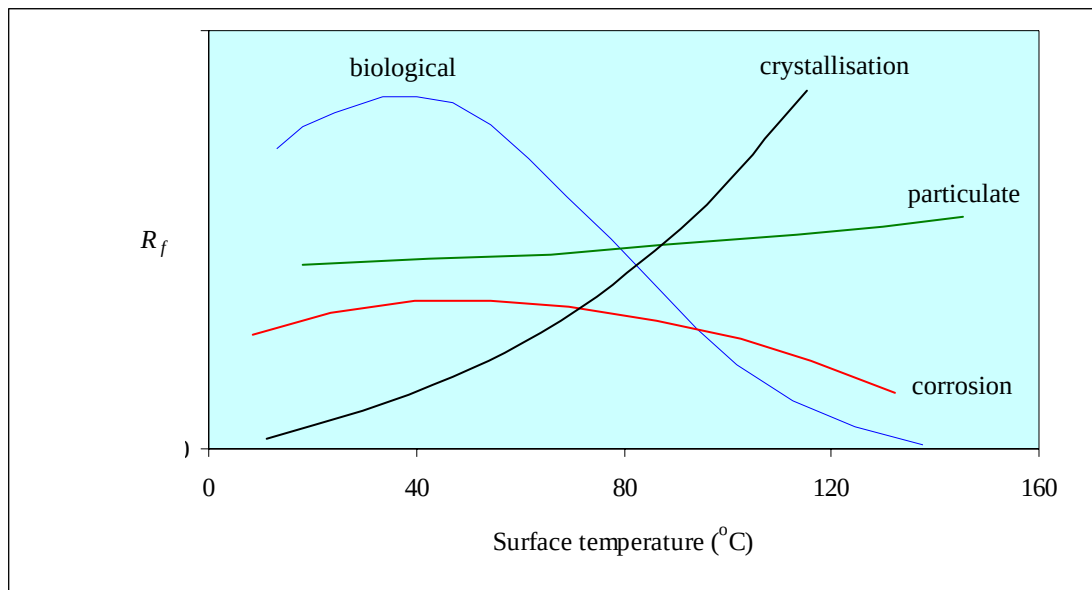
- (1) **Crystalline fouling (Section 6).** This includes the deposition of calcium carbonate, calcium sulphate and other salts that have a solubility that diminishes with increasing temperature, leading to crystallisation of deposits of the salts on the heat exchanger tubes.
- (2) **Corrosion fouling (Section 7).** Some metals are oxidised to produce insulating layers of oxides on the tubes.
- (3) **Biological fouling (Section 8).** A whole range of types of biological growths form on heat exchanger tubes in seawater. The organisms deposited range from bacteria and algae to mussels, barnacles etc.
- (4) **Particulate fouling (Section 9).** Seawater may contain many types of silt, mud, sand or other finely divided particles that may settle on the heat exchanger surfaces and insulate them, providing a fouling resistance.

Of the above mechanisms, the ones presenting the most problems for seawater systems are corrosion fouling and biological fouling.

Of course, in any heat exchanger, there are two sides. Thus, in a condenser operating with seawater cooling, condensing steam must occur on the hot side. Any leakage from the seawater side to the condensing side is likely to give severe problems. However, for the purposes of this present Data Item, only the seawater side is considered.

There are six factors that have a predominant role in governing fouling in seawater systems:

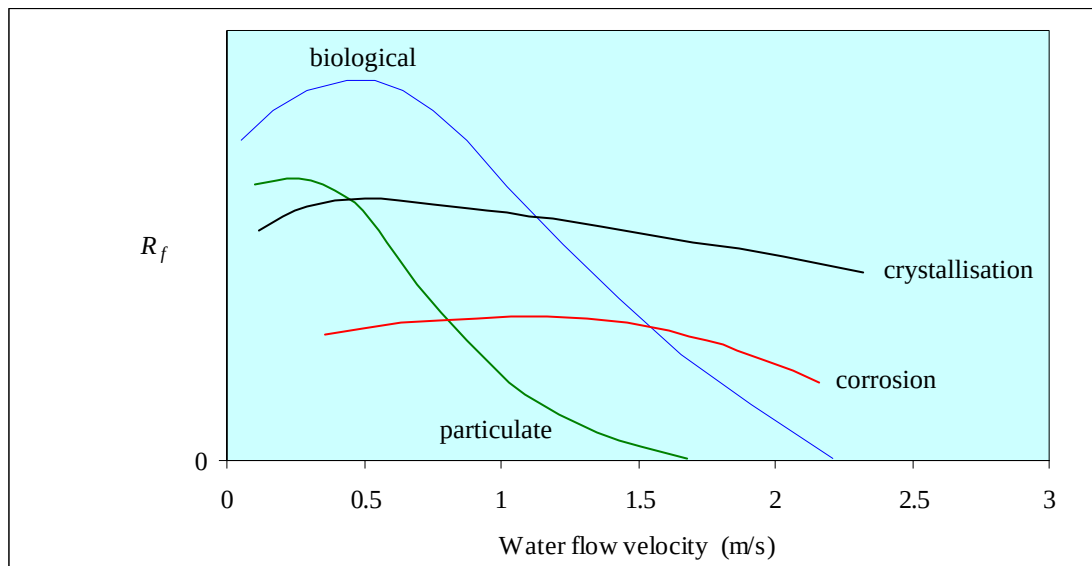
- (1) **Surface temperature.** The temperature at the interface between the seawater and the solid surface (that is, initially the metal but later the foulant layer) is of crucial importance. Sketch 5.1 sketches the effect of temperature on the various types of fouling. Thus, for **crystalline fouling**, the deposition is small at temperatures below 60°C but can become serious at elevated temperatures²¹. Fouling factors for **corrosion fouling** show a peak value as temperature increases; at low temperature, the corrosion rate increases with temperature but the corrosion requires the presence of dissolved oxygen and this dissolved oxygen content is reduced at higher temperatures due to the decreasing solubility of oxygen in water. For **biological fouling**, the rate initially increases with temperature¹² up to about 30-40°C. Foulant organisms are killed at high temperature and, thus, the rate of biological fouling decreases with increasing temperature. There is less effect of temperature on deposition of silt but it should be noted that silt or mud deposits could be dehydrated at higher temperatures, which decreases their conductivity and increases the fouling factor.



Sketch 5.1 Effect of temperature on various fouling mechanisms at constant velocity

- (2) **Bulk temperature.** The value of the bulk temperature is also important. Biological growth becomes faster as bulk temperature increases from ambient values. At high bulk temperatures the organisms may be killed; however, long residence times may be required at elevated bulk temperatures, to kill the organisms present. At the UK CEBG Abberthaw “A” power station, water temperature was increased to 85°C by reversing and throttling the flow. A time of 120 minutes was required at this temperature to kill off mussel growth. The use of higher temperatures would increase the rate at which the mussel growth could be killed but was not possible in this case due to problems of differential thermal expansion (Loraine¹⁹).
- (3) **Water velocity.** The relative effects of water velocity on the various fouling mechanisms are sketched in Sketch 5.2. Water velocity generally has only a small effect on **crystalline fouling** at lower velocities but may tend to shear off the crystalline deposits at higher velocities. **Corrosion fouling** is not strongly affected by water velocity but there is a strong velocity effect in both **biological fouling** and **suspended solids fouling**. With biological fouling, the fouling rate may increase with velocity at low velocities, reflecting the need to supply nutrients to the surface which needs at least a low flow rate to sustain mass transfer. Typical flow velocities for cooling water in condenser tubes are listed in Table 5.1.

For the same turbulence level (and hence shear rate), flow velocities in compact heat exchanger types, such as plate-and-frame heat exchangers are lower than in tubular geometries.



Sketch 5.2 Effect of water velocity on various fouling mechanisms at constant temperature

TABLE 5.1 Cooling Water Flow Velocities in Condensers²⁰

Pipe material	Recommended velocity	Minimum velocity
arsenical copper	< 1.5 m/s	1.0 m/s
admiralty	1.4 - 2.0 m/s	1.0 m/s
aluminium brass	1.8 - 2.2 m/s	1.0 m/s
90-10 cupro-nickel	1.8 - 2.5 m/s	1.5 m/s
90-30 cupro/nickel	2.4 - 3.5 m/s	1.8 m/s
Cu	1.5 - 2.0 m/s	1.0 m/s
Steel	2.0 - 4.0 m/s	1.0 m/s

- (4) **Oxygen concentration.** As was mentioned above, **corrosion fouling** is strongly affected by the amount of oxygen dissolved in the water. This tends to reduce at higher temperatures. Oxygen is also necessary for the maintenance of **biological fouling**, though anaerobic slimes can sometimes occur at low oxygen concentrations.
- (5) **Tube or plate material.** The material of the tube or plate in the heat exchanger plays an important role in fouling. Alloys with more than about 60-70% copper will not support marine growth. Ferrous materials are easily oxidised. Most stainless steels are susceptible to stress corrosion cracking. Duplex high chrome nickel alloy tubing is generally not suitable for seawater duty but some suppliers claim that Superduplex nickel alloy tubing may be used for metal temperatures up to around 50°C. Titanium has excellent resistance to corrosion and usually has no temperature limitations for use in seawater cooling systems (it can be used up to 300°C though it, too, may have stress corrosion cracking problems above 100°C). However, it is more susceptible to biological fouling, particularly if the velocities are too low. Titanium tubes are, though, able to withstand higher velocities and this allows the avoidance of biofouling by suitable increases in velocity. Cathodic protection can increase allowable operating temperatures in seawater considerably.
- (6) **Upstream pipework materials.** Corrosion products from upstream pipework may be transferred to the heat exchanger and create a fouling layer. Care should therefore be taken in the selection of materials for such pipework.

- (7) **Solids.** Superficially, high solids concentrations might be expected to reduce fouling rate. However, there is a significant risk that erosion followed by corrosion will severely damage tubes (particularly with Cu-based alloys). In seawater, sand is the most prevalent solid and erosion may be expected for sand particles with sizes greater than around 50 microns at concentrations more than a few hundred ppm. Titanium and Superduplex alloys are much less prone to erosion-corrosion than copper-based alloys.

It is important to stress that several fouling mechanisms frequently operate simultaneously. Thus, interaction effects may be important in many circumstances. An example here is the complex effect of flow velocity; high velocities *at a given surface temperature* will reduce the potential of biological fouling and silt deposition. However, in most practical applications the higher flow rates would also lead to lower surface temperatures and this may offset the decrease in biological fouling resulting from the increase in velocity (see Sketch 5.1). This underlines the need to treat the fouling problems in terms of overall system design and not just as a series of numbers (*e.g.* TEMA fouling factors), which can be introduced in an arbitrary way. It is possible to also have temporarily varying fouling mechanisms. A power station on the Thames Estuary at West Thurrock, UK (fitted originally with 70-30 copper nickel tubes) suffered from non-aerobic corrosion from polluted Thames water when the flow was downstream but was affected by aerobic corrosion augmented by entrained sharp sand once the flow reversed as the tide came in (Loraine¹⁹).

6. CRYSTALLINE FOULING

Crystalline fouling (often referred to as “scale formation”) refers to deposits which are formed by crystallisation or precipitation of salts from solutions. The precipitation can be of two forms:

- (1) **Sludge.** This is usually the result of precipitation in the bulk giving rise to small crystals that may loosely adhere to the surfaces.
- (2) **Scale.** This usually results from crystallisation on the actual surface, often as a result of temperature changes at the surface.

Crystalline fouling is often the governing mechanism for high-temperature heat exchanger applications typified by offshore gas coolers. Crystalline fouling is strongly influenced by surface temperature and flow velocity. Even brief excursions in temperature (where temperatures exceeded their normal values) could give rise to significant fouling. With noble alloy materials or titanium, much higher velocities can be accommodated, beneficially reducing wall temperature and increasing shear.

6.1 Types Of Scale Formation

Two types of scales can form in heat exchangers with seawater: alkaline scales (calcium carbonate and magnesium hydroxide) and calcium sulphate. In the temperature range 60-85°C (140-185°F) deposition of calcium carbonate predominates and the form normally found is aragonite. Above 85°C (185°F) increasing proportions of magnesium hydroxide are deposited. For calcium sulphate, little deposit occurs if the operating temperature is below 93-120°C (200-250°F) depending on brine concentration. There are some installations (e.g. downholes) where barium sulphate and/or strontium sulphate scales are a major problem, because their hardness is higher than that of the more common sulphate and carbonate scales.

6.2 Scaling Indices

Crystallisation can not occur unless the solubility of the salt in question is exceeded. Scaling indices use the chemistry of an aqueous solution to indicate whether the solution has the potential for scaling or corrosion. Although more sophisticated methods for the prediction of scaling rates are available, water treatment is usually determined using one of the scaling indices.

6.2.1 Calcium carbonate (CaCO₃) scaling

The most common Scaling Index for CaCO₃ is the **Langelier Saturation Index** (LSI^{22, 23}):

$$LSI = pH - pH_s \quad (6.1)$$

Here, pH is defined as $-\log_{10}[H^+]$ where $[H^+]$ is the concentration of hydrogen ions expressed as moles per litre. The pH at saturation, pH_s can be calculated from the formula:

$$\begin{aligned} pH_s &= 9.3 + A + B - C - D, \text{ where} \\ A &= (\log_{10}(\text{TDS}) - 1) / 10, \\ B &= -13.12 \log_{10}(T_c + 273) + 34.55, \\ C &= \log_{10}(\text{CH} - 0.4), \\ D &= \log_{10}(\text{TA}). \end{aligned} \quad (6.2)$$

Here, TDS is the total dissolved solids in the water expressed as mg/litre, T_c is the temperature in °C, CH the calcium hardness due to the presence of Ca^{+2} ions, expressed as mg/litre of CaCO_3 , and TA is the Total Alkalinity. Alkalinity is measured by titration with acid, and is related to the amount of acid required to reduce the pH to 4.5. It is essentially a measure of the “buffering” potential of the water (that is, the reduction of propensity of the water to change pH when small amounts of acid enter it). Alkalinity is conventionally expressed in equivalent mg/litre of CaCO_3 . Measurements of TDS, CH and TA are a normal part of routine water analysis. It is a straightforward matter to determine *LSI* from these measurements using the above equations. Numerous tabular, nomograph and spreadsheet methods are available to carry out this calculation, provided for instance by the water treatment companies. An example of the convenient methods available on the web is at the following address (for example):

<http://www.poolandspachemicals.co.uk/waterbalance.htm>.

The conventional use of the *LSI* is to determine the propensity for scaling and corrosion; thus, scaling may occur if the Langelier Saturation Index is greater than zero and corrosion if *LSI* is negative. It should be emphasised that the *LSI* simply indicates a *driving force* for scale formation. It provides no indication of how much scale or calcium carbonate will actually precipitate, nor how long such deposition will take. It should be noted also that the presence of certain other ionic species may invalidate the use of the Langelier Index as an indicator of scaling propensity. A study of the use of scaling indices is reported by Müller-Steinhagen and Branch²⁴.

Modified Langelier Saturation Index for High Salt Concentrations

If the concentration of salt in water such as seawater is high (>4000 ppm) a Modified Langelier Saturation Index must be used. The Modified Saturation Index is defined as²⁵:

$$MSI = \text{pH} - \text{pCa}^{2+} - \text{p(TA)} - k, \text{ where} \quad (6.3)$$

MSI = Modified Langelier Saturation Index,

pH = measured pH of water,

$\text{pCa}^{2+} = -\log_{10} [\text{Ca}^{2+}]$ where $[\text{Ca}^{2+}]$ is the concentration of Ca^{2+} ions, moles/litre,

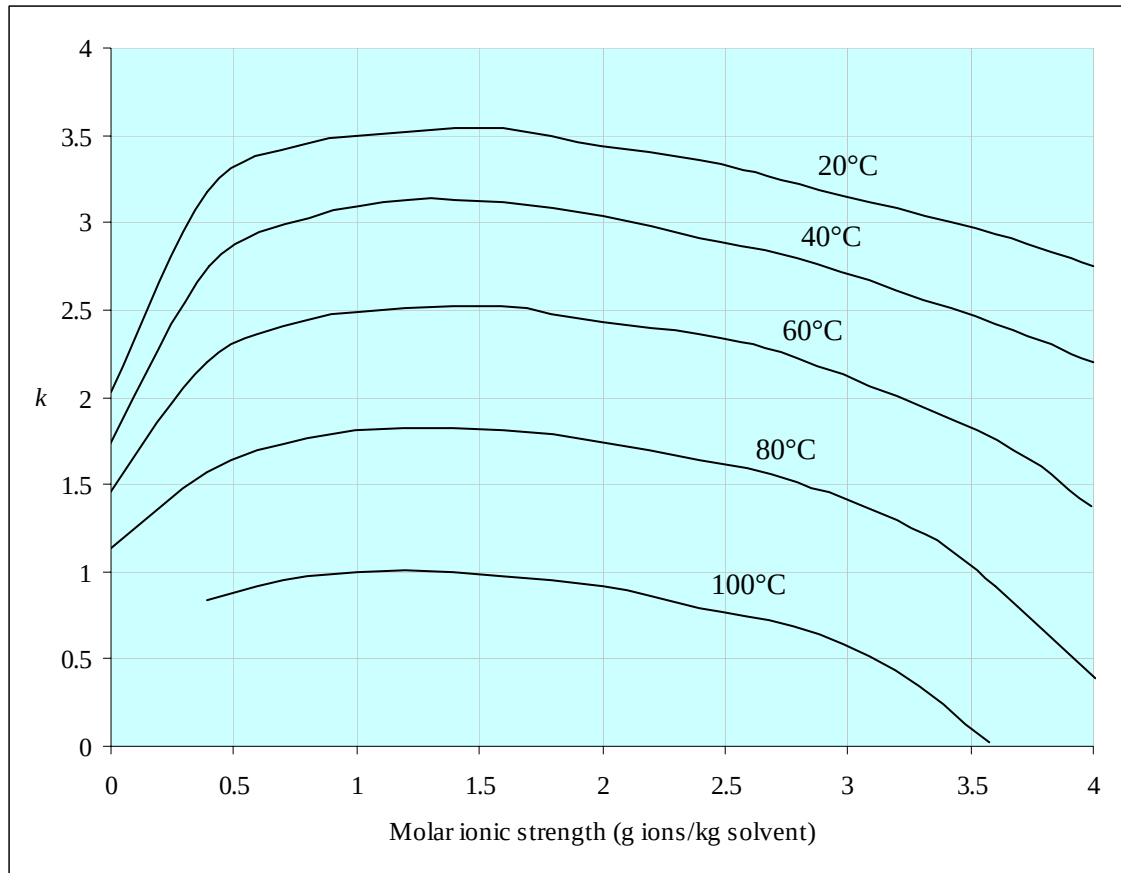
$\text{p(TA)} = -\log_{10} (\text{TA})$ where TA is expressed in equivalent moles of CaCO_3 per litre (note different units to those used in Equation (6.2)), and

k is a constant, the value of which depends on total salt concentration and temperature.

At equilibrium *MSI* is zero, therefore, the above equation reduces to:

$$k = \text{pH} - \text{pCa}^{2+} - \text{p(TA)}. \quad (6.4)$$

The relationship between constant *k*, operating temperature and total ionic strength of the solution is given in Sketch 6.1.



Sketch 6.1 Effect of temperature and ionic strength on k in Equation (6.4)

The molar ionic strength I is:

$$I = \frac{1}{2} \sum m_i z_i^2 \quad (6.5)$$

where the summation is over all ions present and m_i and z_i are the molar concentrations and their charges respectively. Approximately:

$$I \approx 2.5 \times 10^{-5} \text{TDS} \approx 1.6 \times 10^{-5} \Lambda \quad (6.6)$$

where TDS is the concentration of total dissolved solids in mg/litre and Λ is the conductivity in micro-Siemens.

6.2.2 Calcium sulphate (CaSO_4) scaling

Sulphates may precipitate and this propensity for precipitation may be expressed in terms of a *Solubility Index* SI. A negative saturation index indicates a non-scaling condition, a zero index indicates an equilibrium condition, and a positive index indicates that scale may form on the heat transfer surface. Recently, Oddo and Tomson²⁶ developed the following functions for calculating the solubility index of various forms of

calcium sulphate scales:

$$SI = \log_{10} \left\{ [Ca^{2+}] [SO_4^{-2}] \right\} + a_0 + a_1 T + a_2 T^2 + a_3 P + a_4 I^{\frac{1}{2}} + a_5 I + a_6 I^{\frac{1}{2}} T \quad (6.7)$$

The coefficients for various calcium sulphates are summarised in Table 6.1.

TABLE 6.1 Coefficients for Equation (6.7)²⁶

Coefficients	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Gypsum	3.47	1.8×10^{-3}	2.5×10^{-6}	-5.9×10^{-5}	-1.13	0.37	-2×10^{-3}
Hemihydrate	4.04	-1.9×10^{-3}	11.9×10^{-6}	-6.9×10^{-5}	-1.66	0.49	-0.66×10^{-3}
Anhydrite	2.52	9.98×10^{-3}	-0.97×10^{-6}	-3.07×10^{-5}	-1.09	0.50	-3.3×10^{-3}

Free sulphate and calcium ions can be calculated from the following equations, respectively:

$$[SO_4^{-2}] = \frac{-\{1 + K_s(\sum C_M - C_{SO4})\} + \left\{ (1 + K_s(\sum C_M - C_{SO4}))^2 + 4K_s C_{SO4} \right\}^{0.5}}{2K_s} \quad (6.8)$$

$$[Ca^{+2}] = \frac{C_{Ca}}{(1 + K_s[SO_4^{-2}])} \quad (6.9)$$

The parameter K_s in Equations (6.8) and (6.9) is given by:

$$\log_{10} K_s = 2.0052 + 8.1768 \times 10^{-3} t + 3.888 \times 10^{-6} t^2 + 1.552 \times 10^{-8} P, \quad (6.10)$$

$$-2.38 I^{0.5} + 0.58 I - I^{1/3} (2.34 \times 10^{-3} t + 4.16 \times 10^{-2}), \text{ where}$$

t = temperature (°C),

P = total pressure (Pa),

I = ionic strength, molar,

C_{SO4} = total sulphate concentration, molar = (g/l SO_4^{2-})/96,

C_{Ca} = total calcium concentration, molar = (g/l Ca^{2+})/40, and

$$\sum C_M = C_{Ca} + C_{Ba} + C_{Sr} + C_M, \text{ molar.} \quad (6.11)$$

For seawater with the composition given in Table 6.2 at 104°C and 2.96 MPa, Equation (6.11) in conjunction with Equations (6.8)-(6.10) predicts saturation indices of -3.5, -3.4 and -2.7 for gypsum, hemihydrate and anhydrite. This means crystallisation fouling of calcium sulphate will not occur at this temperature and pressure.

TABLE 6.2 Composition of seawater used in example
(Note: this composition differs from that in Table 2.1)

Component	Concentration (mg/l)
Na	8440
K	159
Mg	25
Ca	150
Sr	44
Ba	20
Cl	12555
SO ₄	14
HCO ₃	1418
Calculated ionic strength	0.42 molar

6.3 Thermal Conductivities Of Scales

Values for thermal conductivities for various scales are given in Table 6.3. Also given for comparison is a typical value for biofilm; as will be seen, the scales have much higher thermal conductivity than biofilm. The conductivity of a biofilm is similar to that of a stagnant water layer.

TABLE 6.3 Thermal Conductivities For Biofilm And Scales^{27,28}

	Thermal conductivity (W/m K)
Biofilm (water)	0.63
<i>Scales</i>	
Calcium Carbonate	2.26-2.93
Calcium Sulphate	2.31
Calcium Phosphate	2.60
Magnesium Phosphate	2.16
Magnetic Iron Oxide	2.88
Analcite	1.27

6.4 Parametric Effects On Crystalline Fouling

As was mentioned above, crystalline fouling is strongly affected by temperature. Below 38-66°C, it is minor but can become more serious at elevated temperatures. Crystalline fouling is only slightly affected by water velocity, though very high velocities may tend to shear off crystal deposits. The importance of crystalline fouling relative to other types of fouling will depend on the application. It is usually less important than biofouling for power station condenser applications but may be the dominant mechanism for high wall temperature heat exchangers such as process condensers or finned tube units.

7. CORROSION FOULING

Most metals in their refined form (except for a few noble metals such as gold) are inherently unstable. This instability drives the process of corrosion leading to the reversion of the refined metals to their natural mineral states (e.g., oxides). There are a number of different types of corrosion which include:

- (1) **General or overall corrosion.** Here, a uniform attack over the entire exposed area of a surface occurs. This process can occur over a wide range of temperatures.
- (2) **Pitting corrosion.** This is characterised by highly localised corrosion rates with little or no general corrosion in the areas surrounding the pits.
- (3) **Galvanic corrosion.** When two dissimilar metals are electrically connected in the presence of an electrolyte, the more electrochemically active metal corrodes at an increased rate by giving off electrons. Loraine²⁹ reports experience of galvanic corrosion in aluminium brass tubes. This corrosion occurred over the full length of the 25.4 mm internal diameter, 21 m long tubes but was concentrated nearer the mid length. This was ascribed to the presence of carbon deposits arising from the carbonisation of the drawing process lubricant in the annealing furnace. The carbon deposits were partly burnt off by air oxidation but this was limited in the mid length section by the exhaustion of the oxygen in the annealing furnace air in this zone. This explained why corrosion was more severe in this region. Loraine recommends that tube manufacturers be asked to remove carbon deposits by sand blasting the tube bore and that the delivered tubes be checked (by examining the inner surface using an introscope) to ensure that this process has been effective.
- (4) **Microbiologically-induced corrosion (MIC).** Micro-organisms may form colonies on the metal surface, leading to corrosive conditions in that locality.
- (5) **Stress-corrosion cracking (SCC).** When a stressed metal is exposed to certain types of environment, it may become susceptible to stress-corrosion cracking at stress levels that may be significantly below the yield strength of the material.
- (6) **Hydrogen embrittlement.** Hydrogen embrittlement of noble alloys, particularly titanium, may occur if dissimilar metals (e.g. different materials for baffles and tubes) and wet conditions prevail.

It should be noted that the corrosion of a metal surface leading to an insulating (i.e., fouling) layer on the surface is an essential component in protecting the surface from further corrosion. Thus, oxide films are a *necessary* foulant in many cases. Continued removal of these layers can give rise to further interactions between the metal and the fluid and to continued corrosion either locally or generally. Erosion may aid this process.

In seawater conditions, a variety of corrosion mechanisms occur. Sometimes, these mechanisms are combined, making the corrosion behaviour rather complex. The oxide film on the metallic surface is susceptible to erosion/corrosion. Thus, in bends, T-junctions, etc, the fluid impinging on the surface can erode away the oxide film giving rise to continued corrosion and ultimately penetration of the tube wall. In straight pipes, there is a critical *shear stress* (fluid force per unit area of wall) above which removal of the oxide layer and enhanced corrosion begins to occur. For metals such as titanium, the corrosion/erosion resistance is large but much more severe problems are encountered with copper alloys. This represents an important paradox in considering fouling by seawater; on the one hand, titanium has a high resistance to corrosion/erosion but a high susceptibility to biological fouling. Copper alloys, on the other hand, inhibit biological fouling (see Section 8) but are much more susceptible to erosion/corrosion. Operating such alloys above the critical shear stress will reduce the corrosion fouling factor, but the materials will continue to corrode/erode and this situation is unacceptable. Table 7.1 shows results for critical tubeside velocity and

critical shear stress for copper-based alloys in seawater and Table 7.2, from an alternative source, shows typical accepted maximum tubular design velocities for some copper alloys. It will be noted that, though there is general consistency between Tables 7.1 and 7.2, there are some discrepancies. The lower velocity values should be used when these discrepancies occur. It should also be noted that the normal design velocities for condensers are of the order of 2.0 m/s. A typical minimum velocity to prevent sediment deposition and consequent under-deposit corrosion is 1.0 m/s³⁰.

TABLE 7.1 Critical tubeside velocity and shear stress for copper-based alloy in seawater³⁰

Alloy	Critical Velocity (m/s)	Temperature (°C)	Critical shear stress (Pa)
C12200 Copper	1.3	17	9.6
C68700 Aluminium brass	2.2	12	19.2
C70600 Copper nickel (90 Cu-10 Ni)	4.5	27	43.1
C71500 Copper nickel (70 Cu-30 Ni)	4.1	12	47.9
C72200 Nickel	12.0	27	296.9

TABLE 7.2 Preferred, minimum and maximum tubeside velocities for various materials (Data supplied by Working Party)

Tube material	Preferred design velocity (m/s)	Minimum design velocity (m/s)	Maximum design velocity (m/s)
B111-C68700 Aluminium brass	1.5	1.0	2.2
B111-C70600 Copper nickel (90 Cu-10 Ni)	1.8	1.0	2.5
B111-C71640 Copper nickel (70 Cu-30 Ni)	2.1	1.0	3.0
Carbon steel	1.5	1.0	2.2
Stainless steel/(Super) Duplex	2.5	2.0	4.5
Titanium	2.5	1.5	5.0

For flow inside round tubes, the wall shear stress (τ_w) is readily calculated from the friction factor f as follows:

$$\tau_w = \frac{f \rho v_a^2}{2} \quad (7.1)$$

where ρ is the fluid density (kg/m³) and v_a its velocity (m/s). Friction factor f can be calculated from standard relationships, for instance, the Blasius equation:

$$f = 0.079 Re^{-0.25} \quad (7.2)$$