PWRs Operation and Maintenance
Raw Water Systems

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Content

1 Summary

An always available cold source is required to safely operate nuclear plants. Moreover, the colder this cold source is, the higher the plant efficiency, which in turn means the more money for the plant owner. These are two strong incentives to maintain raw water systems in good conditions.

To help operators maintaining raw water systems in good shape, this report provides relevant information on how to design, operate, inspect, maintain and repair these systems, and especially the ESWS and cooling towers.

A first section provides comprehensive information on how to design ESWS and cooling towers. The various types of cooling towers are reviewed in this section. Regarding cooling towers' operation, future more stringent environmental constrains may impact the way they are operated to-day.

A second section details raw water treatments, as regards scale formation, corrosion and fouling mitigation. Of course, river and seashore plants concerns are different, therefore, their raw water treatment is reviewed separately.

The third section is the "masterpiece" of the report as reporting the field experience. In this section, a first chapter is relevant to water intake, pumping station and filtering drums. The gear reducer of the circulating pumps has been a big burden in the past. Then, a second chapter is dedicated to concrete pipes with metallic web. Given the original way these pipes are fabricated, they suffer from very specific damages. The third chapter reviews ESWS issues. Although fire-fighting systems share some damage mechanisms with ESWS, they are reviewed separately in the chapter #4. The next chapter, the #5, concerns cooling towers. Cooling towers deserve heavy programs of inspection because there have been several cooling towers collapsing in the past, stressing how serious cooling tower condition monitoring is important. One of the major interests of the last chapter, the #6, is to present an up-to date process for managing raw water systems ageing. It has been successfully applied to a Spanish plant and there is room for further applications.

Given the wide collection of data contained is this document regarding raw water systems design, operation, maintenance and repair, it is a good basis for engineers new in the field of raw water systems operation, to get a broad overview of what has been done on these systems in the past.

2 Introduction

Raw water has a major safety role as acting as cold source for plants. Raw water is used for:

- Cooling the condenser, either in open or in closed circuits;
- Providing water for service water systems;
- Providing water to the Fire Fighting System;
- Providing water to the Auxiliary Feedwater Tank in case of emergency (earlier units).

Second bullet: service water systems at any power plant have one major function which is to cool the multitude of heat exchangers or coolers other than the condenser.

This system is referred to by a variety of names - Service Water, Cooling Water, Salt Water. Sometimes the system is broken into separate building systems as Turbine Building, Auxiliary Building, Reactor Building. Often the system is broken into safety and non-safety portions. For a number of plants, the safety portion is referred to as the Essential Service Water System. The equipment in the safety portion of the system is powered by independent sources, e.g., diesel-driven pumps and diesel generators to supply electrical power.

Components cooled or served by the Service Water System can include:

- Generator hydrogen gas cooler;
- Stator cooling;
- Generator exciter cooler;
- Air compressor aftercooler;
- Component Cooling System heat exchangers;
- Containment fan cooler units;
- Feedwater pump oil and motor coolers;
- Condensate pump oil and motor coolers;
- Turbine oil cooler;
- Heater drains pump oil and motor cooler;
- Diesel generators;
- Circulating pump seal water.

The report starts with some design consideration, chapter #3.

Raw water can be used without any treatment, except filtration, or after chemical treatment for mitigation of solid precipitation, and bacteria or plants development. These chemical treatments will be reviewed in chapter #4.

Raw water systems include filters, pipes, pumps, valves, heat exchangers… Some of these components have experienced field failures. To minimize the failures rate, maintenance programmes have been set which include non-destructive tests, destructive examinations, repairs, refurbishing or replacements. The operating experience along with the maintenance programmes of raw water systems are reported into chapter #5.

Chapter #6 is the conclusion.

3 Some design considerations

3.1 Essential Service Water System

3.1.1 Background

The main role of the ESWS is to cool the CCS. Therefore, the ESWS runs continuously (during power production and during outages), and its operation is twin with the CCS operation:

- In normal operation (mode 1) or at the plant start-up (mode 2; Reactor Coolant Pumps, Chemical and Volume Control System, Reactor Cavity and Spent Fuel Pit Cooling and Treatment System…);
- In hot shutdown conditions (modes 3&4; Chemical and Volume Control System, Reactor Cavity and Spent Fuel Pit Cooling and Treatment System…);
- In cold shutdown conditions (mode 5; Reactor Heat Removal system, Reactor Cavity and Spent Fuel Pit Cooling and Treatment System…);
- During reactor refueling and steam generators inspection (mode 6, Reactor Heat Removal system, Reactor Cavity and Spent Fuel Pit Cooling and Treatment System…);
- In case of accident: safety function (Safety Injection System, Containment Spray System, safety rooms…).

Some remarks:

- The ESWS is tight to the environment, therefore, it needs to comply with the environmental regulatory rules, in the same manner the circulating water does;
- For plants equipped with closed cooling circuits, the ESWS generally supplies makeup water to the cooling towers;
- The ESWS of some EdF 3 loop reactors has a fitting on each train to supply raw water to the auxiliary feedwater tank;
- On some EdF N4 series reactors, the ESWS is a closed circuit cooled by cooling towers with induced draft.

The ESWS being a safety significant system, it must comply with the two following rules:

- Being redundant;
- Being available in any circumstance: on line maintenance should be possible without jeopardizing neither the plant safety nor its availability.

This means ESWS must have at least two independent trains as pictured on (Figure 3-1).

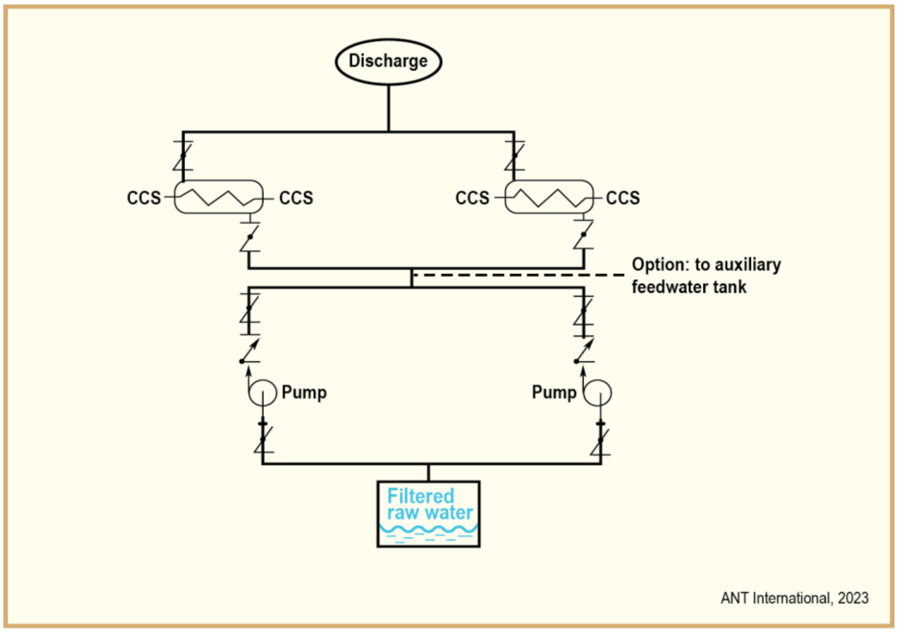


Figure 3-1: ESWS basic principle.

The following design considerations come from the EdF fleet.

3.1.2 Structures upstream ESWS pumps

When there are 2, 4 or 6 units on the same site, ESWS equipment's upstream the pumps are often common to twin units:

- The water intake either into natural environment (river, lake or sea) or in artificial environment (artificial lake, dam) is typically single. If the raw water source is artificial, it must comply with the redundancy and constant availability criteria;
- Structures between the water intake and the prefiltration: if their unavailability risk is not superior to the natural environment one (canal, pond…), they can be assimilated to the natural environment and can be single. However, if they are tunnels or pipes, they must be double in order to allow their online inspection and maintenance;
- Prefiltration installations. Grids can be cleaned by only one trash rake. This trash rake may not be emergency power supplied if its failure does not jeopardize ESWS pumps water feeding, for example because of an oversizing of the grids or little trash production;
- Structures joining the prefiltration installation and the filtration installations. If these two installations are rather distant, these structures are composed of a waterway located immediately downstream the grids, a minimum of two junction tunnels or pipes along with another waterway immediately upstream the filters;
- Filtration installations and structures between these installations and the pumps.
  - The ESWS pumps filters can either be specific to the ESWS or common to other circuits such as the Circulating Water System, or the Conventional Island Closed Cooling Water System;
  - There are two filters per unit;
  - Various connections, not used in normal operation, equipped with valves or sluice gates, allow keeping the two ESWS trains in operation even when one of the two filters is unavailable. This connection can join either the two filters of a same unit or two filters of different units;
  - The filters' mesh is typically 3 mm for the high flow rate screens (rotating drums also used for the CWS) and 1 mm for the low flow rate filters (ESWS specific water supply or units equipped with cooling towers);
  - By design, the filters are oversized as regards their maximal acceptable flow rate and head loss.

4 Raw water treatments

4.1 Why do we need treating raw water?

The main drawbacks of using raw water are:

- Scale formation;
- Corrosion;
- Deposits precipitation;
- Fouling.

Scale formation is the formation of hard and adherent solid deposits on walls, as the result of the precipitation of some particular salts contained into the raw water. The nature and quantity of deposits mainly depend on the water chemical composition. The most popular scales in natural waters are mainly composed of calcium carbonate. In some particular circumstances, scale can be composed of calcium sulphate and/or calcium phosphate.

Electrochemical corrosion of a metal is the transformation of a metal in contact with aqueous solution, from the elementary state to a combined state. The oxidizing-reducing reactions induce metal dissolution and oxides formation. Corrosion rate can be limited by the instantaneous formation of a protective oxide at the metal surface, it is called passivation.

To scale and oxides formation, we can add deposits from various minerals coming from the grounds leached by the raw water (clay, sand, silt…). Depending on their size, these particles can be sorted either into the suspended solids category or into the colloids category.

Fouling car be either from organic origin or from biological origin. Organic material comes from the rain running on the ground and from urban and industrial wastes. Organic material is partially eliminated by clarification, decantation and filtration treatments when raw water is used for demineralized water production. Biological organisms are microorganisms, algae, bacteria and mushrooms which, when developing on walls, can form major masses often with a gel aspect.

4.2 Concerned systems

The concerned systems are:

- Facilities supplying filtered raw water to the units from natural water (intake canal), they are typically gathered into the pumping station;
- Supplied systems:
  - Condenser;
  - Cooling tower in case of closed system, including makeup water pipes;
  - ESWS and CICCWS auxiliary coolers;
  - Circuits containing water to demineralize and miscellaneous circuits: DPWSS, FFWPS, RWS, water to demineralize pretreatment;
- Discharge pipes into the environment (discharge canal);
- All connecting equipment’s: ponds, canals, tunnels, pipes….

4.3 Scale formation mitigation

4.3.1 Sea water

Most of the chemicals contained in sea water are far from saturation to the exception of calcium carbonate.

Calcium carbonate precipitation is enhanced by temperature or salinity increase, by a higher pH and by a pressure drop. Chlorides induce a delay of $CaCO_3$ precipitation and favour an amorphous form precipitation.

In the case of sea water plants, the temperature raise is too limited to trigger any calcium carbonate precipitation. Therefore, neither specific protection, nor chemical of physical treatments are required.

Note that when salt is removed from sea water by reverse osmosis, calcium carbonate precipitation is mitigated by lowering the pH from 8/8.5 down to 6/6.5.

Regarding plants with cooling towers supplied with brackish water, only site tests can assess the calcium carbonate precipitation risk. These tests allow selecting the relevant concentration factor, which means the factor preventing any scale formation along with the use of chemical treatments.

4.3.2 Fresh water

4.3.2.1 Definition

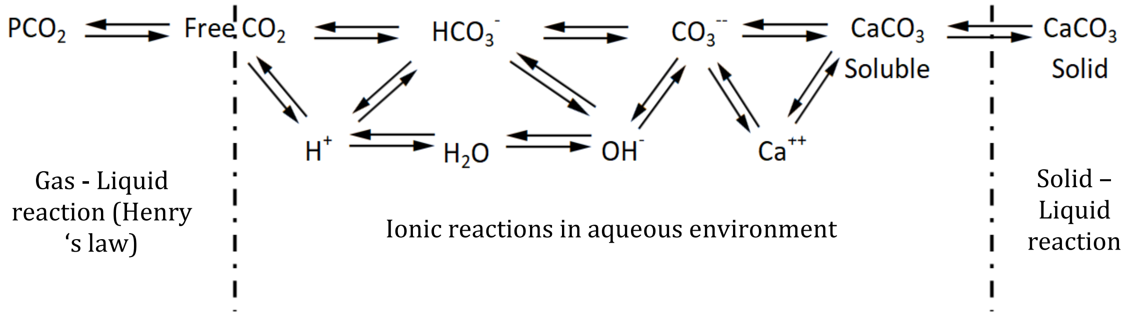
Scale forms from the precipitation of calcium carbonate which has a weak solubility.

In open systems, scale formation risk inside condenser tubes is limited by the implementation of mechanical cleaning, however, in closed systems, this risk is real because of evaporation and of the salts concentration occurring in this type of system.

Inside a cooling tower, the evaporation results in salts' concentration. The tight contact between water and air favours the gases' equilibrium between liquid and gas phases (Henry 's law). The water saturates in air (surface waters, because they are often polluted, are not air saturated) and depletes in CO_2 which is always present in concentrations exceeding the Henry 's law in surface waters.

If all the salts present in river water were very soluble, closed systems could operate with a high concentration factor. The formation of calcium carbonate, the most insoluble salt present into water, limits the concentration factor and determines which quantity of water to take from or to discharge to the river.

Calcium carbonate precipitation results from complicated equilibriums between the calcium and the CO_2 which can be sketched as follows:



Gas – Liquid reaction kinetics is low, but inside a cooling tower where the dispersion is huge, therefore contact surfaces are extended and recirculation rates high (5 to 6 times per hour), this equilibrium quickly occurrs.

Ionic reactions in aqueous environment are almost immediate. Solid – liquid reactions' rates are very low. Therefore, it is the kinetics of this reaction which governs scale formation.

Using the hereabove reactions' constants, we can demonstrate that the equilibrium is reached when the following equation is verified:

Equation 4-1: $$[Ca^{2+}]x[HCO_3-]^2 = Constant$$

equivalent to:

Equation 4-2: $$TH_{Ca}xTAC^2 = Constant$$

Or, given in French rivers, TH and TAC are close:

Equation 4-3: $$TAC = Constant$$

This constant is not different from the limit TAC (TAC_{lim}) which corresponds to the equilibrium conditions of the environment into which we get neither $CaCO_3$ precipitation, nor solubilization under an ionic form. TAC_{lim} is the maximum of the TAC value we can maintain inside the system without risk of $CaCO_3$ precipitation.

4.3.2.2 Scale formation mitigation

4.3.2.2.1 Scale formation risk monitoring

To avoid scale formation, we need to know the limit TAC, in other words, the maximum TAC value that we can maintain in a given system. Its value is determined by site tests.

In the real life, the calcium carbonate precipitation is monitored by measuring the raw water and the system TACs'.

Inside a cooling tower, the evaporation results in a concentration factor determined as follows:

- F = Makeup/Blowdown

In absence of precipitation, this ratio is equal to the following chemical concentration factor:

- F = concentration of a salt not precipitating in the system/concentration of this salt into the raw water

We can then define a theoretical TAC of the system equals to:

- $TAC_{theoretical}$ = F x TAC (raw water)

By comparing this theoretical TAC with the TAC measured into the system, we can check whether or not scale is forming:

- If F x TAC (raw water) > TAC (system), $CaCO_3$ is precipitating, the water is said furring;
- If F x TAC (raw water) = TAC (system), the system is in equilibrium and
- If F x TAC (raw water) < TAC (system), $CaCO_3$ is dissolving, the water is said aggressive; note that could happen only if the system has previously been fouled with $CaCO_3$ scales.

5 Field experience

5.1 Water intake, pumping station and filtering drums

5.1.1 Background

Water intake and pumping station are civil work structures which design, construction and maintenance are quite generic (Figure 5-1 and Figure 5-2). Some areas cannot be drained; however, the operator can perform remote visual examination using underwater robots. The use of underwater robots is efficient to track silt deposition on rafts.

Rotating drum's function is to trap debris that could damage or plug condenser tubes. Filtering drums technology may appear as basic; however, they are unusually huge components (Figure 5-3 and Figure 5-4). Their maintenance mainly targets the bearings and the rotating mechanisms.

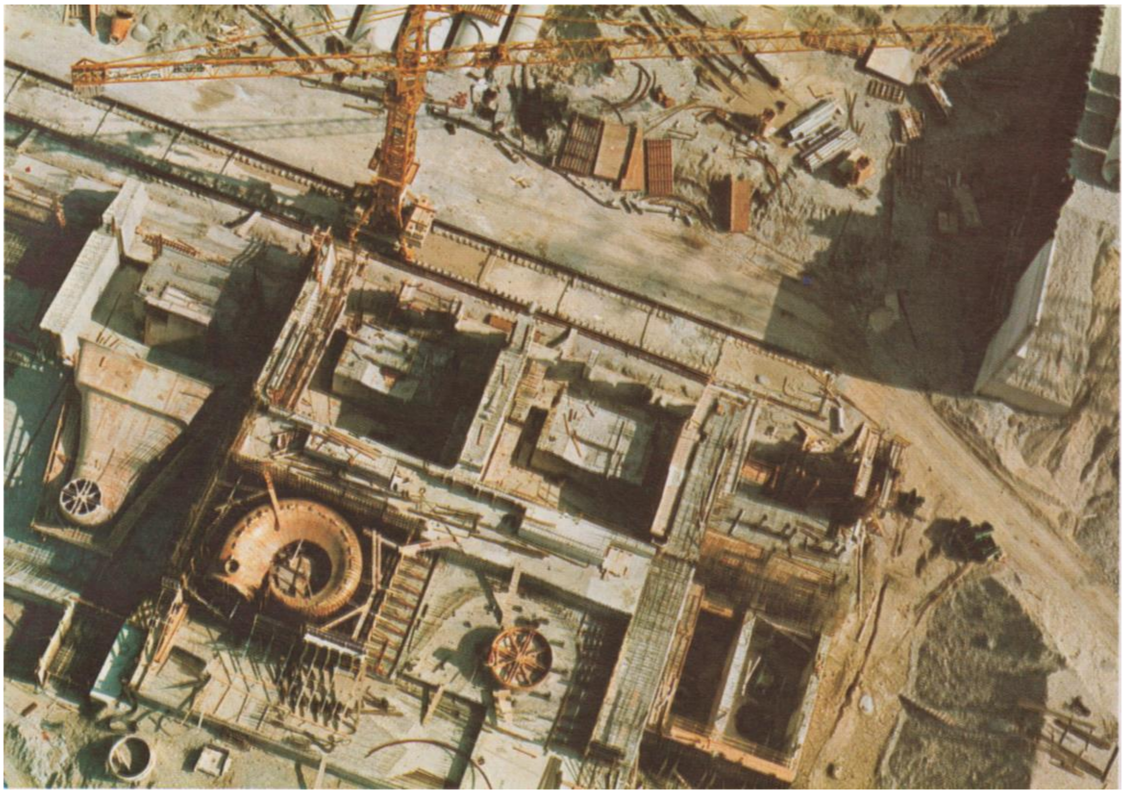


Figure 5-1: View of the lower level of a pumping station (river water) during construction. We can see the three water intake recesses; the crane moves into the future water intake canal connected to the four-water intake concrete cells. We can see the concrete block which is going to support one side of a rotating filtering drum. The water arrives from the back, via the two sides of the concrete block, after having gone through the rotating drum as sucked by the circulating pump. We can see to the left of the picture the housing formwork of a circulating pump, intake side. The water supply is located at the bottom. To the centre, we can see the spiral shape formwork of the outlet cell of a circulating pump. To the right, we can see the recesses of the three pumps of the auxiliary raw water systems; at the back, we can see, behind the crane, the "Bonna" discharge concrete pipes [Dürr, 1978].

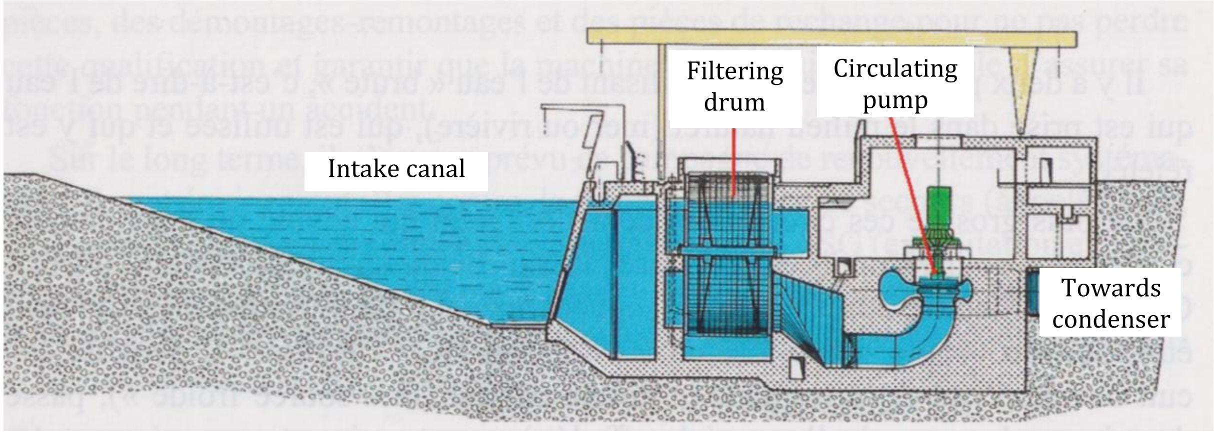


Figure 5-2: Sketch of a typical water intake [Hutin, 2016].

6 Conclusion

Plants being thermodynamic facilities, Carnot's law tells you that they need a cold source to operate. Raw water systems provide this cold source; therefore, these systems are paramount both for the thermodynamic cycle efficiency, which in turns means economics gains and for the plant safety. These are two incentive reasons for maintaining raw water systems in very good condition, with a 100% availability factor.

This report provides a big picture regarding raw water systems, from the design to the operation, to the maintenance and to the repair.

Given their importance in raw water systems, this report focuses on ESWS and cooling towers.

The three major threats for raw water systems are corrosion, fouling and scale deposition. This report describes with a lot of details how to manage corrosion and how to prevent fouling, especially bio-fouling, and scale formation.

Efficient tools exist to maintain a high degree of availability factor of raw water systems, at least, so far. However, given environmental constrains are going to be worse and worse, operators may have to spend more resources and efforts to maintain these high availability factor in harsher and harsher conditions.

7 Industry perspective

Because some raw water systems, and especially ESWS, are safety significant systems, operators should bring a lot of attention to these systems. This report compiles a great set of information about design, construction, operation, inspection, and repair of these systems with focus on ESWS and cooling towers.

More than a half century of experience of running these systems is reported here, therefore, this document should be part of the tools box of any system engineer in charge of raw water systems operation, inspection, maintenance and repair.

This report is the third of a list of a new ANT line of 12 reports about PWRs operation and maintenance:

- Condenser (released at LCC17);
- Feedwater plant and other secondary components – Mechanical components (released at LCC18);
- Raw water systems and cooling towers (released at LCC19),
- Reactor cooling system piping and associated systems (planned release at LCC20).

Planned, with no specific release order:

- Reactor cooling pumps;
- Pressure vessel (including penetrations);
- Steam generators (including blowdown and feedwater);
- Pressurizer (including heaters, valves, surge line, nozzles);
- Pressure vessel internals;
- Control rod drive mechanisms;
- Turbine;
- Main generator.

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Related ANTI reports on PWRs operation and maintenance:

The condenser: a key player for a good feedwater chemistry, François Cattant, LCC 17, 2022.

PWRs Operation and Maintenance - Feedwater Plant and Other Secondary Components – Mechanical Components, François Cattant, LCC 18, 2023.

List of Abbreviations

AFNOR	Association Française de NORmalisation
AFT	Auxiliary Feedwater Tank
AISI	American Iron and Steel Institute
ANTI	ANT International
ASTM	American Society for Testing Materials
CCS	Component Cooling System
cfu	colony forming units
CICCWS	Conventional Island Closed Cooling Water System
CSS	Containment Spray System
CTCS	Condenser Tube Cleaning System
CTFDVS	Cooling Tower Forced Draft Ventilation System
CVCS	Chemical and Volume Control System
CWFS	Circulating Water Filtration System
CWS	Circulating Water System
CWTS	Circulating Water Treatment System
dBA	Acoustic decibel
DC	Direct Current
DPWSS	Demineralisation Plant Water Supply System
EdF	Electricité de France
EPRI	Electric Power Research Institute
ESWS	Essential Service Water System
FBR	Fast Breeder Reactor
FFS	Fire Fighting System
FFWPS	Fire Fighting Water Production System
FFWS	Fire-Fighting Water System
HAZ	Heat Affected Zone
ICFTRS	Intake Coarse Filtration and Trash Removal System
ID	Inside Diameter
MIC	Microbiological Induced Corrosion
MPa	MegaPascal
MT	Magnetic Test

mV	milliVolt
MWe	Mega-Watt electrical
MWt	Mega-Watt thermal
NPP	Nuclear Power Plant
OD	Outside Diameter
PT	Penetrant Test
PVC	PolyVinyl Chloride
PVC	PolyVinyl Chloride
PWR	Pressurized Water Reactor
RCS	Reactor Cooling System
RCP	Reactor coolant Pump
RHR	Reactor Heat Removal system
rpm	round per minute
RWS	Raw Water System
RWTS	Raw Water Treatment System
SEM	Scanning Electron Microscope
SIS	Safety Injection System
SS	Stainless Steel
TA	simple Total Alkalinity: Na and K salts content in French degrees
TAC	full Total Alkalinity (Methyl orange end-point alkalinity of the makeup water in French degrees)
TH	Total Hardness (water)
TH_{Ca}	Calcium concentration in French degrees
UT	Ultrasonic Testing
UTS	Ultimate Tensile Strength
VSCE	Volt referenced to the Standard Calomel Electrode
VT	Visual Testing
YS	Yield Stress

Unit conversion

TEMPERATURE

°C + 273.15 = K **°C × 1.8 + 32 = °F**

T(K)	T(°C)	T(°F)
273	**0**	32
289	16	61
298	25	77
373	**100**	212
473	**200**	392
573	**300**	572
633	360	680
673	**400**	752
773	**500**	932
783	510	950
793	520	968
823	550	1022
833	560	1040
873	**600**	1112
878	605	1121
893	620	1148
923	650	1202
973	**700**	1292
1023	750	1382
1053	780	1436
1073	**800**	1472
1136	863	1585
1143	870	1598
1173	**900**	1652
1273	**1000**	1832
1343	1070	1958
1478	1204	**2200**

Radioactivity

1 Sv = 100 Rem
1 Ci = 3.7×10^{10} Bq = 37 GBq
1 Bq = 1 s^{-1}

MASS

kg	lbs
0.454	**1**
1	2.20

DISTANCE

x (µm)	x (mils)
0.6	0.02
1	0.04
5	0.20
10	0.39
20	0.79
25	0.98
25.4	**1.00**
100	3.94

PRESSURE

bar	MPa	psi
1	0.1	14
10	**1**	142
70	7	995
70.4	7.04	**1000**
100	10	1421
130	13	1847
155	15.5	2203
704	70.4	**10000**
1000	100	14211

STRESS INTENSITY FACTOR

MPa√m	ksi√inch
0.91	**1**
1	1.10