Chapter 2
Clogging of Recirculating Nuclear Steam Generators

Abstract In pressurised water reactors power plants, water is vaporised by the heat extracted from the nuclear reaction by heat exchangers, the *steam generators*. Iron oxide particles produced by the corrosion of the secondary piping get deposited in the steam generators. They gradually obstruct the flow holes of plates inside the steam generators, thus impeding the flow of the secondary fluid. This phenomenon called *clogging* or *blockage* is a major safety and performance concern.

2.1 Pressurised Water Reactor Power Plants

A nuclear power plant is an industrial installation producing electricity from one or more nuclear reactors. In these reactors, nuclear fission chain reactions produce heat that is used to vaporise water. The produced steam is then fed into turbines coupled to an AC generator which produces electricity. This generic principle is shared by several plant designs which differ in the way the nuclear reaction is controlled and the process used to extract heat from the reactor to produce steam. Currently, the most widespread designs are the two-loops *pressurised water reactor* (PWR), the single-loop *boiling water reactor* and the heavy-water *Canada deuterium uranium* reactor. Hereafter, we will focus on the PWR design in which the heat-transfer fluid flowing through the reactor is light water maintained in liquid state by very high pressure.

Figure 2.1 represents schematically a PWR plant. The thick arrow paths represent the *primary water circuit* which flows through the reactor, numbered ⟨1⟩ on the diagram. Orange arrows represent the *hot branch* starting at the reactor outlet, and blue arrows (↗) the *cold branch*, after heat extraction from the primary water. The reactor is a steel vessel containing the reactor core composed of *fuel rod bundles* (⟨2⟩). They are metallic sealed cylinders containing fissile material, generally uranium oxides enriched from 3 up to 5 %. The reactor also includes devices to control the fission reaction, particularly *control rods* made of neutron-absorbing material that can be inserted gradually into the core (⟨3⟩).

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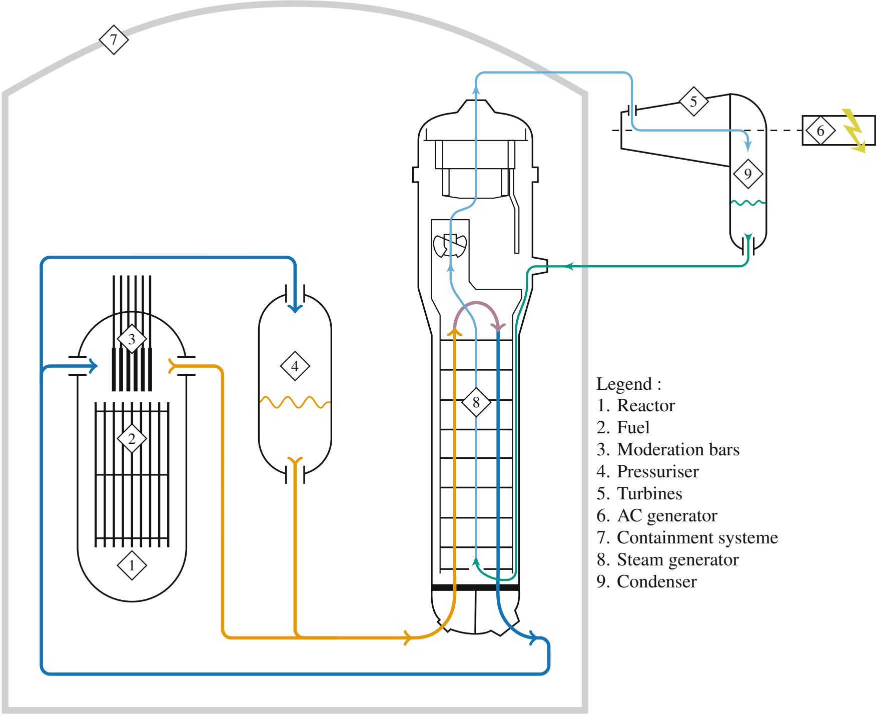

Fig. 2.1 Schematic of a PWR power plant

The pressuriser (4) ensures that the water of the primary circuit is always in liquid state. The temperature of the primary water in nominal regime is, depending on the considered location, between 285.8 and 322.9 °C. The pressuriser maintains it at a pressure of about 155 bar.

Another loop, the *secondary circuit*, is drawn in thin green and sky-blue arrows (↗ and ↗) in Fig. 2.1. It feeds steam to the turbines (5) which drive the AC generator (6) which in turn produces electricity. The change in arrows colour from green to sky-blue indicates vaporisation. Note that the primary and secondary circuits are separated: water that flowed through the reactor never mixes with the water that is vaporised. Only thermal energy is transferred from the primary water to the secondary water through heat exchangers, the *steam generators* (8). The reactor, pressuriser and steam generators are enclosed in a concrete containment (7). The French 900 MW power plants studied in the following comprise 3 steam generators. After expansion in the turbines, the steam coming from the steam generators outlet is condensed into another heat exchanger, the condenser (9). Water flowing out of the condenser is finally heated by a third kind of exchanger, not represented on the diagram, before going back to the steam generator inlet.

The functioning of steam generators and the available measurements are detailed respectively in Sects. 2.2 and 2.3. Section 2.4 presents the degradations caused to iron oxides accumulation on their internal components. The object of this book is to propose a new methodology to diagnose malfunctions caused by one of them, *tube support plate clogging*.

2.2 Functioning of Recirculating Steam Generator

The steam generators are large heat exchangers, approximately 20 m tall and 3.5 m in diameter, in which the secondary water is vaporised by the heat extracted from the primary water.

Figure 2.2 represents a model 51B steam generator. Its main functioning parameters and geometric characteristics are provided in appendix A. A steam generator is composed of a hemispherical header tank (① on Fig. 2.2) separated by a horizontal plate, the tube sheet (②), from a cylindrical vessel approximately 9 m tall (③), which is itself topped by a dome (④). The header tank is divided by a vertical plate (⑤). One half collects the hot water coming from the reactor (⑥). It then flows in a bundle of 3,330 tubes (⑦) through the tube sheet before arriving in the heat exchange area called *riser* (⑧). The tube bundle is the interface between the primary and secondary circuits. The tubes have an internal diameter of 22.22 mm and are 1.27 mm thick. They are U-shaped and pass again through the tube sheet, downwards. The cooled down water is thus poured into the other half of the header tank before flowing back to the reactor (⑨). The primary flow rate is high, about 16,000 th^{-1} or 4,400 kg s^{-1}.

On the secondary side, liquid water is fed into the steam generator from the top of the vessel (⑩). A cylindrical metal sheet, the *tube wrapper* (⑪), separates the outer downcomer (⑫) in which the water flows down, from the inner riser where the tube bundle is located. This separation stops 25 cm above the tube sheet, thus delimiting the circular admission area of the riser. The riser is divided into a hot and a cold leg. The hot leg contains the section of the U-tube where the primary water coming from the reactor is ascending in the riser. The water then flows down, back to the reactor, in the cold leg. The vapour quality of the secondary water increases as it rises in the riser. The driving force causing the circulation in the steam generator is the density difference between the liquid descending by the downcomer and the liquid–steam mixture in the riser: it is a thermosiphon. Due to the U shape of the tubes, the steam generator is a co-current exchanger in the hot leg and counter-current in the cold leg.

At the top of the riser, just above the arched section of the tube bundle (⑬), the vapour quality in nominal regime is around 0.25. The vapour quality needs then to be increased so that the steam reaching the turbine is almost dry because high velocity water droplets would damage its blades. The mixture flows through moisture separators, the swirl vanes (⑭, there are 3 of them in the steam generator studied here), and steam dryers, the chevron separators (⑯), before exiting the steam generator by nozzles located at the dome's top. After this drying process, the steam is saturated with a residual humidity, the moisture carry-over, of less than 0.0025.

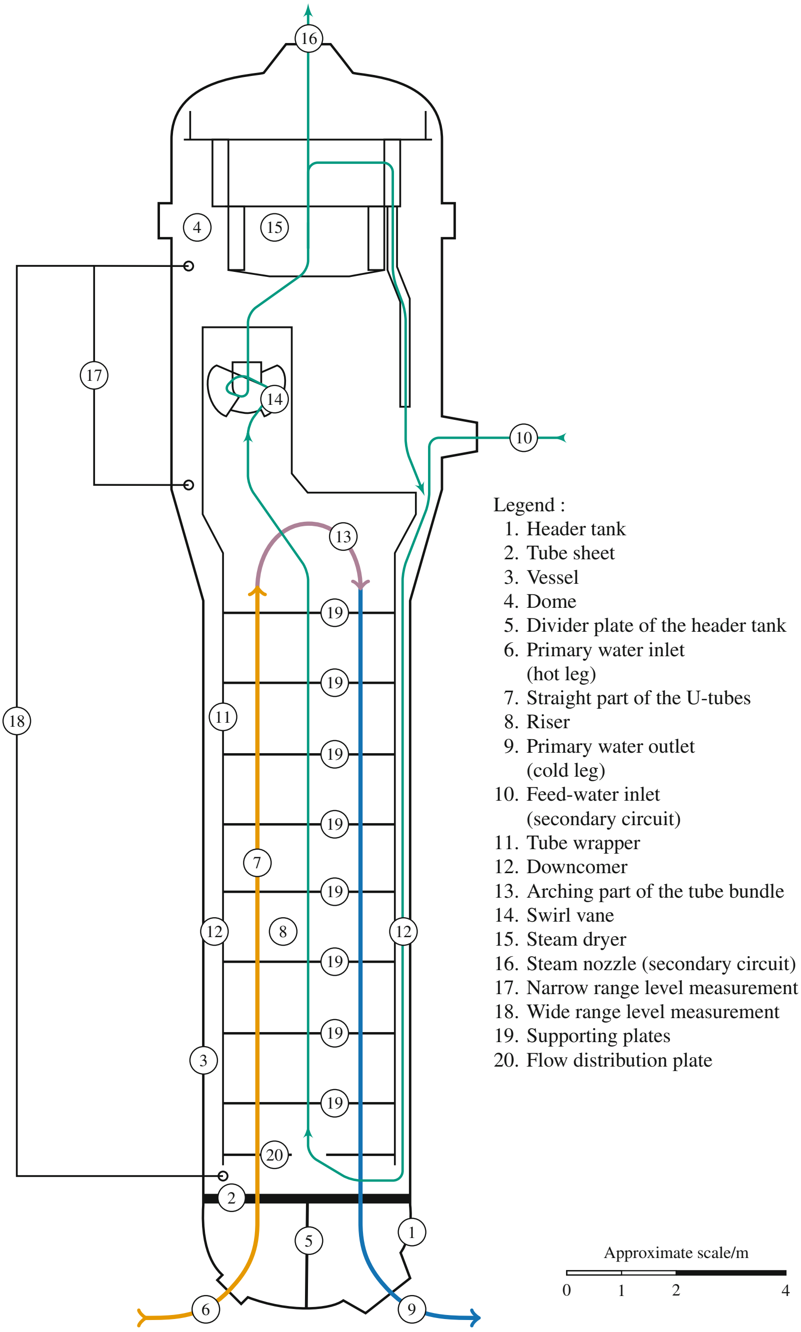

Fig. 2.2 Schematic of a model 51B steam generator in frontal cut

The water collected by the separation devices falls down to the riser or is, for the most part, directed to the downcomer. Hence, the water at the riser inlet is almost saturated and the temperature elevation needed to vaporise it is low, around 15 °C. The *circulation ratio* is the ratio between the total flow rate through the tube bundle over the flow rate of steam exiting the steam generator. In stationary regime, the latter is equal to the feed-water flow rate. The circulation ratio of the 51B steam generator has a nominal value of approximately 4.1, equal to the inverse of the quality at the swirl vanes inlet.

Data collected from 11 French generating units equipped with type 51B or closely related steam generators were used to prepare the examples provided in this book. They belong to 4 plants which, for confidentiality reason, are given nicknames: Armstrong, Bechet, Coltrane and Dolphy. The clogging states of Armstrong and Bechet evolve relatively slowly, while Coltrane and Dolphy have reached very high clogging levels in the past which required chemical cleaning operations. The two pairs also differ in their *chemical conditioning*, a term that will be explain later in Sect. 2.4.2.

2.3 Physical Measurement Near the Steam Generator

Most of the sensor measurements that will be referred to in this book have a sampling rate of 2 s. Depending on the sites and sensor types, some data prior to 2008 were compressed, which increased the deadband and replaced small variations by plateaus.

Table 2.1 provides typical values in nominal regime of the principal measurement available close to the steam generator and their associated uncertainty. As a parry against sensor drift or failure, some of these measurements are made by several sensors simultaneously. These are control measurements available in real-time. Other more precise one-off measurements are made periodically, for instance to control the power transferred by steam generators. They are not used in this book.

2.3.1 Steam Generator Water Level Measurement

Two sensors are aimed at measuring the water level in the steam generator (Roy 1985). The term "level" is used in literally only in the collection area, at the top of the downcomer, just under the feed-water inlet, outside the tube wrapper. Indeed, there is no proper free surface separating liquid water from steam in the riser: the secondary fluid there is a mixture whose quality varies gradually.

The level in the collection area is regulated by the control system. Too low a level could initiate nucleation and lead to vaporisation in the core due to insufficient heat extraction by the steam generators. Conversely, very a high level leads to high humidity in the outing steam which can be damaging to the turbines. The level is

Table 2.1 Typical values and associated uncertainties for the main quantities measured around steam generators (Regaldo et al. 1984; Douetil 2008; Deneux and Favennec 2010)

Measured quantity	Unit	Average value	Uncertainty	Sensors by steam generator
Steam pressure	bar	56.5	1.6	2
			0.5	1
Steam flow rate	$\mathrm{t\,h^{-1}}$	1830	45	2
	$\mathrm{kg\,s^{-1}}$	508.3	12.5	
Feed-water flow rate	$\mathrm{t\,h^{-1}}$	1813	31.3	2
	$\mathrm{kg\,s^{-1}}$	503.6	12.5	
Feed-water temperature	°C	218	3.6	1
Purge flow rate	$\mathrm{t\,h^{-1}}$	50	0.8	1 by generating unit
	$\mathrm{kg\,s^{-1}}$	13.8	0.2	
Purge temperature	°C	182	1.5	1 by generating unit
Primary temperature				
At steam generator inlet	°C	322.9	1.0	4
At steam generator outlet	°C	285.8	0.6	4
Primary flow rate	$\mathrm{t\,h^{-1}}$	15876	612	One-off testing
	$\mathrm{kg\,s^{-1}}$	4410	170	

estimated from the difference between the pressure measured at two different heights. It is thus affected by variations in the fluid density as well as residual pressure drops due to the heterogeneity of the flow in the downcomer.

The *narrow range level* is used to control the feed-water flow rate (⑰ on Fig. 2.2). It is deduced from the pressure difference between the dome and the bottom of the collection area. Except in case of extreme events, such as very fast transient caused by accidental depressurisation, the narrow range level is maintained constant by the control system.

The *wide range level* is measured between the dome and the bottom of the downcomer (⑱ on Fig. 2.2). It is therefore much more sensitive to the temperature and flow rate of the feed-water, as well as to the circulation ratio. It is used only to watch over the level variations during slow transient, especially during manual control at low power load. Indeed, this measurement is not representative of the actual level during faster transients because it is too much affected by dynamic pressure. It is precisely on this effect that the diagnosis methodology presented in this book relies.

2.4 Steam Generators Degradation by Iron Oxides Deposition

Particles and dissolved species produced by oxidation of the secondary components are carried by the feed-water. Part of these corrosion products are eliminated by the purges located at the bottom of the steam generators but most of it circulates in the

Fig. 2.3 A quatrefoil pattern on the pediment of the West door of the Croylan Abbaye in Lincolnshire, England (*Author*: Janice Tostevin)

riser and can be deposited onto the steam generators internal components. Particles are not carried out by steam and therefore accumulate in the steam generators.

The analysis of samples collected in steam generators after several operation cycles by De Vito (2002) and Dijoux (2003) revealed the presence of many chemical species with a clear predominance of one iron oxide, the magnetite, Fe_3O_4. Magnetite is also predominant in sludges collected after chemical cleaning of steam generators (Lebrun and Petit 2006; Tessier and Petit 2006; Lebrun and Petit 2007). The particles concentration is highly dependant on the regime and the chemical conditioning of the secondary circuit, and so is their granulometric distribution, which was only recently assessed for the French fleet (Couvidou 2011). The dissolved species concentration is difficult to estimate and is not precisely known (Pujet 2002).

2.4.1 Tube Support Plate Clogging

The tube bundle is hold by regularly spaced *tube support plates*. The 51 B type steam generators have 8 of them, numbered ⑲ on Fig. 2.2. The plate numbered ⑳ at the bottom of the steam generator is called the *flow partition plate*. It homogenises the velocity of the fluid entering the riser from below. Contrary to tube support plates it has a large opening in its centre of 55 cm in diameter.

The tube support plates are steel plates 30 mm thick, perforated by 6,660 holes through which the tubes pass. Each tube is surrounded by 4 flow holes, called *quatrefoil holes* because they are arranged in a manner reminiscent to the ornamental pattern of the same name (see Fig. 2.3). Figure 2.4 schematically represents a detail of a tube support plate.

The tube support plates are subjected to the *clogging* phenomena, also called *blockage*: quatrefoil holes are gradually obstructed by accumulation of corrosion

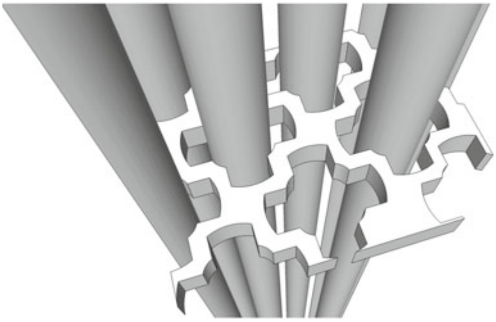

Fig. 2.4 Schematic of the detail of a tube support plate. The quatrefoil holes can be seen around the steam generator tubes (*Author*: Olivier Deneux)

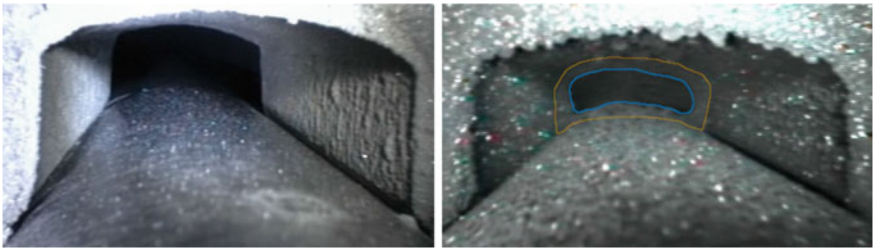

Fig. 2.5 Pictures of a clean (*left*) and a clogged (*right*) quatrefoil hole obtained by endoscopic inspection of upper tube support plates. On the *right picture*, the *outer orange* outline indicates the junction between the deposit and the quatrefoil hole edges. The *inner blue* outline delimits the surface area through which the secondary mixture flows. This pictures are taken from the top and it can be observed that the deposit is located at the bottom of the hole. This is almost always the case for 51B type steam generators

products. Figure 2.5 shows a clean quatrefoil hole on the left, and a clogged one on the right. These pictures where obtained by endoscopic inspection of the upper plate of a steam generator. This technique is described in Sect. 3.1.

The clogging of tube support plates reduces the flow passing section, which increases the singular pressure drop of the fluid going through them. Four main risks caused by clogging were listed by Adobes (2011):

- Perturbation of the velocity field can generate vibrational instabilities threatening the mechanical integrity of the tubes;
- During fast transients, pressure and temperature oscillation can occur and have repercussions on the core;
- Local increases in the dynamic loading of the support plates can break the truss rods holding them;
- A lowering of the circulation ratio, and therefore of the water mass inside the steam generator, can compromise its capacity to extract residual heat after a loss of coolant accident.

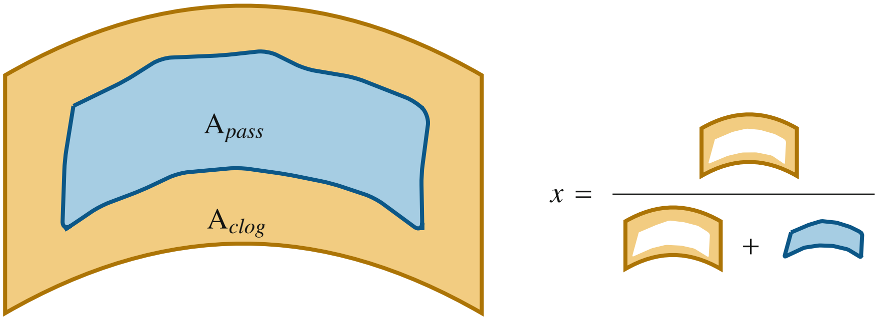

Fig. 2.6 Schema of a clogged quatrefoil. The *outer orange* surface annotated A_{clog} represents the deposit. The *inner blue* surface annotated A_{pass} is the remaining passing cross section. The clogging ratio, x, is equal to the ratio of the blocked area to the total area

The reduction of the passing surface of a quatrefoil hole is accounted by its *clogging ratio*, which is equal to the ratio of the cross section area of the deposit to the area of the hole without clogging:

$$x = \frac{A_{clog}}{A_{hole}} = \frac{A_{clog}}{A_{clog} + A_{pass}} = 1 - \frac{A_{pass}}{A_{hole}}, \tag{2.1}$$

with A_{clog}, A_{pass} and A_{hole} denoting the areas respectively of the cross section of the deposit, of the remaining passage and of the hole without clogging Fig. 2.6.

Fouling is another degradation caused by iron oxides when they deposit upon the surface of the tubes. It increases the thermal resistance of the tubes and consequently degrades the steam generator energetic performance. Plant operators need to gradually increase the opening of the steam line valve at the steam generators outlets to compensate for the lowering of pressure in the dome, until they sometimes reach the maximum opening. This other vast topic will not be treated in this book which focuses on the diagnosis of clogging.

2.4.2 Maintenance and Remediation Operations

Several processes were designed to prevent and mitigate clogging (Lacroix 2012). For instance, increasing the alkalinity of the secondary water can halve the quantity of oxides it carries. This is achieved by adding chemical species to the secondary water: morpholine, ethanolamine ou ammonia (Guivarch and Gay 2010). The pH of the chemical conditioning in use in France ranges from 9.2 to 9.8. However, high pH conditioning is not an option when the secondary circuit includes brass components because of ammoniacal corrosion of copper. Hence, some French units still function at low alkalinity, notably the unit no. 2, 3 and 4 of the Coltrane plant, and no. 1, 2, 3 and 4 of the Dolphy plant (Mercier 2010).

Adding dispersant to the feed-water is believed to allow to evacuate a greater proportion of oxides with the purges. Tests of this process, already in use in some American units, were performed in 2012 in France (Lacroix 2012).

The tube sheet and the lower part of the bundle, under the flow partition plate, are cleaned periodically with high pressure jets so as to avoid stress corrosion cracking of the tube basis. This cleaning technique was tentatively adapted to remove the clogging of the upper tube support plate of the unit no. 4 of Dolphy in 2006, and of the unit no. 3 of Coltrane in 2007. This had only a very limited efficiency for clogging and almost none for fouling of the arched part of the tube. Hence, this technique was abandoned in favour of a global one, *chemical cleaning*.

EDF maintenance strategy distinguishes between *curative* and *preemptive* cleaning. There are several curative cleaning processes which share a common general principle: the dissolution of magnetite deposits by a solution of ethylenediaminetetraacetic acid (EDTA) in presence of an amine and hydrazine at high temperature. Preemptive cleanings last shorter and are conducted under less aggressive chemical conditions at lower temperature. They can remove limited amount of deposited material and need to be performed more often. The target of magnetite removal for a preemptive cleaning is around 500 kg per steam generator, while certain curative cleanings remove more than 4 t of dry material. A simple computation based on the geometric characteristics given in appendix A shows that most of this mass originates from fouling deposits and not clogging. However, important fouling often goes with important clogging as indicated by the monitoring indexes described in the next chapter. Until December 2012 when the work presented here was completed, the greater part of the chemical cleanings carried out in France were curative ones and in the following the term will refer to these.

Chemical cleanings are heavy maintenance operations that are very expensive, especially because they lengthen the offline period between operation cycles. They also produce important volumes of effluents that must be dealt with. Still, steam generator replacements are even more costly, about thrice as much, and heavily constrained by the manufacturing capacity, limited in France to a few units per year. Considering the safety issues raised by clogging and the high cost of the means to counteract it, an efficient maintenance strategy is crucial. Such a strategy requires to be able to diagnose steam generator clogging frequently and reliably.

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