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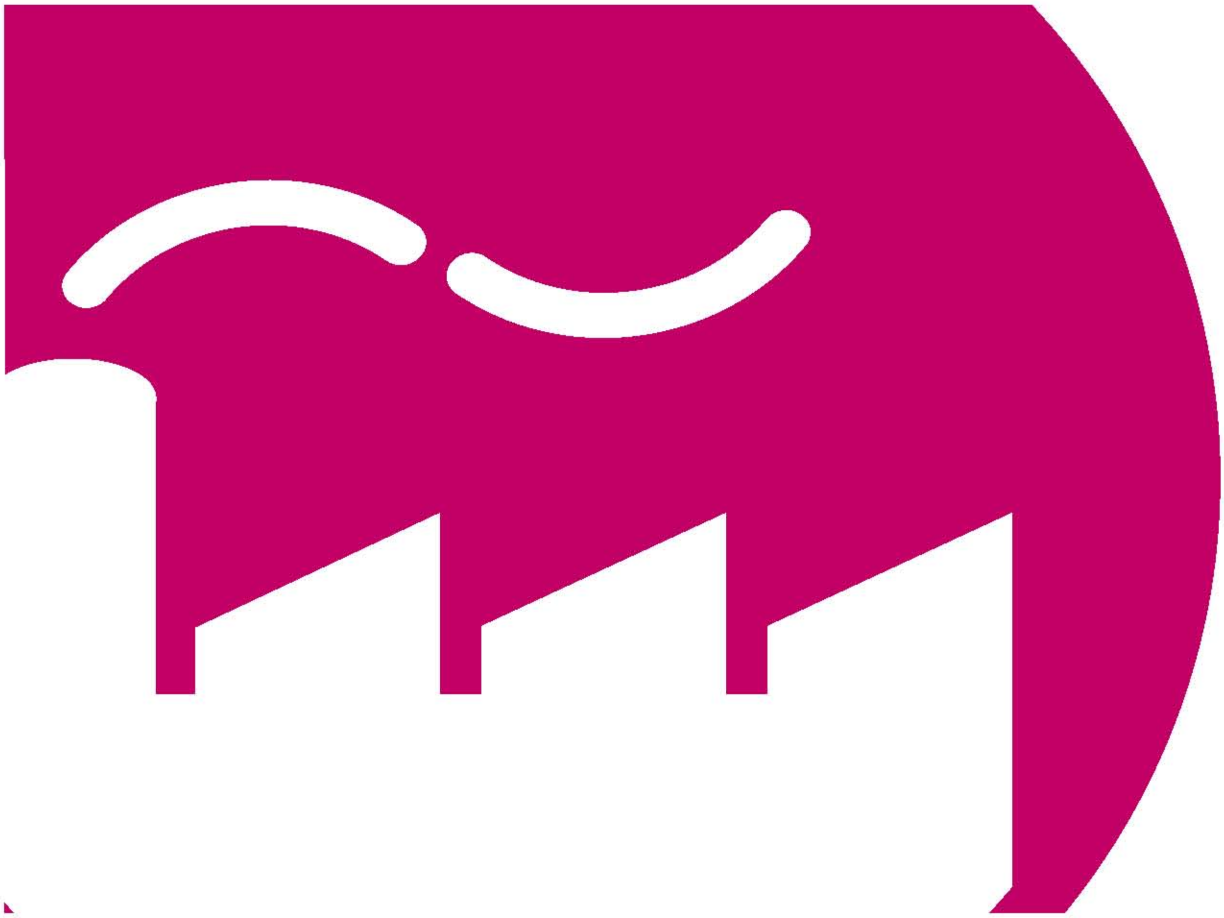

Chemical discharges from nuclear power stations: historical releases and implications for Best Available Techniques

Report – SC090012/R1

The Environment Agency is the leading public body protecting and improving the environment in England and Wales.

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Our work includes tackling flooding and pollution incidents, reducing industry’s impacts on the environment, cleaning up rivers, coastal waters and contaminated land, and improving wildlife habitats.

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This report was produced by the Research, Monitoring and Innovation team within Evidence. The team focuses on four main areas of activity:

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- **Maintaining scientific credibility**, by ensuring that our programmes and projects are fit for purpose and executed according to international standards;
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Miranda Kavanagh

Director of Evidence

Executive summary

This report presents the findings of a survey of non-radioactive chemical discharges from nuclear power stations in the UK, USA, France, and Germany. Plants were selected to represent the two candidate designs for the new nuclear build programme for England and Wales, and also to include plants located on the coast. The candidate designs are the UK EPR™ supplied by AREVA (joint submission with EDF) and the AP1000™ supplied by Westinghouse. Both are based on pressurised water reactor (PWR) technology. This main interpretative report is supplemented by a separate Annex report which contains information on the sites surveyed and their chemical discharge data.

A PWR power plant consists of a water-filled reactor system (the primary circuit) that generates useful heat which is transferred to a secondary circuit via steam generators. Steam in the secondary circuit is used to drive a turbine generator and then condensed using an external source of cooling water, in the same way as in a fossil fuel power station. The chemicals used in the primary circuit are boric acid (used to adjust nuclear reactivity) and lithium hydroxide (used to control pH). Those used in the secondary steam circuit are usually hydrazine (to remove oxygen from the water) and ammonia/amines (to control pH). The final main external water cooling circuit may require dosing with biocides, usually chlorine. There are also other smaller plant systems such as water and waste water treatment plants, all of which use and potentially discharge a range of chemicals, predominantly to water.

Sizewell B is the UK's only current operating PWR power station. Discharge data show that only residual chlorine is present in the outlet of the main cooling water flow at concentrations consistently above those of the inlet, but within the limits of the discharge permit.

Permits for PWR power stations in the USA specify separate limits for discharges from individual plant systems (internal plant outfalls, such as those from waste treatment systems) and for final discharges of cooling water to the environment. Limits for internal outfalls are based on generic US federal regulations that specify concentrations which should be achievable at the 'end-of-pipe' using the Best Available Technology. Those for external outfalls ensure that the final discharges do not cause a breach of federal or state water quality criteria. Some trends can be observed in the data for US plants. Discharges of chlorine vary seasonally, with lower discharges occurring in winter when biofouling is less of an issue. Suspended solids, oil and grease vary depending on plant age or operational factors. Zinc discharges fluctuate due to corrosion of galvanised water systems; in one plant this has required such systems to be replaced by ones made of stainless steel. Operators of several US plants describe regulatory requirements to minimise the use and discharge of hydrazine.

Permits for the French PWR power stations include a common suite of parameters. There are limits for discharges from the main hold-up tanks serving the nuclear reactor systems and allowances for discharges due to shutdown of the reactors for refuelling. All chemical discharges are below these permitted limits; those coming close to exceeding them are nitrogen/ammonium and phosphates. Historical discharge data illustrate that the quantity of chemicals discharged has reduced over time (hydrazine in particular). Site-specific and individual plant factors determine the type of chemicals discharged; for example, the methods used to control the chemistry of the secondary steam plant or the corrosion of plant during maintenance outages and the type of raw water that needs to be treated and purified in order for it to be used in the reactor and steam circuits. There was no clear relationship between discharges of chemicals and reactor output, or between reactors of the same design at different locations.

The regulatory limits in French permits can be used to illustrate differences between chemicals discharged from coastal and inland sites. Limits for chemicals associated with chlorination of once-through seawater cooling systems are specified at coastal sites; these are mainly for total and residual chlorine and by-products of the chlorination process such as bromoform. At the inland sites, there are separate limits for discharges of biocides (mostly monochloramine) and anti-scaling chemicals from cooling towers.

There are only limited data available for chemical discharges from the German PWRs covered in the survey. One plant uses a stripping system to reduce discharges of ammonia to an especially sensitive surface watercourse.

Because of the different regulatory regimes, differences in reporting results and a complex interplay between discharges, plant-specific factors and operational issues, it is not possible to directly compare chemical discharges from the English, US, French and German PWR power stations. It is only possible to state that the main discharges to water are from the steam/secondary systems and the once-through cooling water systems. These are broadly similar to those to water from fossil fuel power stations. Additional chemical discharges related specifically to the nuclear reactor in a PWR power station are of relatively minor importance, although these will be the main source of radioactive discharges. These were the subject of a separate, earlier review (Environment Agency Science Report SC070015/SR1).

The predicted discharges published for the AP1000™ and UK EPR™ designs are all generally consistent with the permit limits currently in force for the current operating PWRs covered in this study.

Across the earlier PWR power stations covered in the survey, the greatest emphasis on applying Best Available Techniques (BAT) for minimising discharges of chemicals is for biocides used in the main external water cooling systems (especially chlorine). Aspects of power plant cooling water systems were the subject of a separate review (Environment Agency Science Report SC070015/SR3). Other areas where use of BAT is emphasised include the use of chemicals to prevent corrosion during maintenance (especially hydrazine), the discharge of chemicals due to the operation of the main steam circuit, and reducing discharges from water treatment plants (at some sites this has acted as a driver for the replacement of ion exchange systems with membrane technologies such as reverse osmosis). Less emphasis is placed on the discharge of chemicals associated with the primary circuit because the boric acid and lithium hydroxide used in the reactor are of low toxicity and discharged in relatively low volumes which are then diluted in any cooling water outfall.

As part of this project, a generic ecotoxicological assessment was completed which assumed discharges at the maximum permitted limits for one of the predecessor plants at a notional coastal location and using once-through seawater cooling. Discharges of chlorine in cooling water and hydrazine are the most likely to come close to environmental criteria. This is consistent with the emphasis placed on the use and discharge of these chemicals identified in the survey of PWR power plants.

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1 Introduction

1.1 Report objectives

The Environment Agency is engaged in a joint project with the Health and Safety Executive[1] to complete a Generic Design Assessment (GDA) of the candidate nuclear power station designs proposed to be built in England and Wales. These new generation nuclear power stations designs include the nuclear reactors and associated power plant systems such as turbines, generators and support systems. An important part of the GDA will be to determine if the candidate designs represent Best Available Techniques (BAT) for reducing radioactive and non-radioactive chemical discharges to a minimum. This process will support the eventual licensing of individual plants at specific locations, if and when they are constructed.

To support these activities and the assessments of BAT in the candidate designs, three major pieces of work were commissioned by the Environment Agency. The first (Environment Agency 2010a) collated and reviewed radiological discharge data. The second (Environment Agency 2010b) reviewed options for cooling water systems. This report is the result of the third piece of work and assesses the non-radioactive chemical discharges.

The projects collated data from a range of nuclear power stations currently operating across the world, including those with design characteristics similar to or incorporated into the candidate designs. The reactors included in these surveys include 'predecessor' designs to the newer 'candidate' designs, although the terms 'Generation II' and 'Generation III+' are more usually applied.

At the time of writing (2011) there are two candidate designs in the GDA process, both of which are pressurised water reactors (PWRs):

- The AP1000™ – a PWR from Westinghouse Electric Company LLC with a net electrical output of 1,117 megawatt electrical [MW(e)]. Net output represents the output to the grid after electrical load in the power plant itself is taken into account.
- The AREVA European Pressurised Water Reactor (EPR™) for the UK – a PWR submitted for GDA jointly by Electricité de France (EDF) and AREVA. The reactor system design is from AREVA, but for construction in the UK, other aspects such as the civil design are based on those of EDF. It is referred to as the UK EPR™ for the rest of this report. It has a net electrical output of approximately 1,600 MW(e).

Because both candidate designs are PWRs, the current survey was confined to power stations with this generic reactor design.

This main interpretative report is organised as follows:

- The rest of the introduction outlines the candidate reactor designs being considered for the nuclear new build programme, then lists the PWR power stations selected to be included in this study from England, the USA, France and Germany. The final part of the introduction provides an overview of PWRs, with emphasis on the chemicals used and potentially

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[1] This report refers to the Health and Safety Executive (HSE). In April 2011 HSE's Nuclear Directorate became the Office for Nuclear Regulation (ONR).

discharged. It also describes auxiliary plant systems that use and potentially discharge chemicals.

- Section 2 provides an overview of the regulatory regimes applied to the discharges of chemicals from PWR power plants in England, the USA, France and Germany. This section also provides an overview of the chemicals covered by discharge permits in each country.
- Section 3 provides a more detailed list of the chemicals used and potentially discharged from PWR power stations. This is based on the detailed descriptions of the predecessor plants provided in the separate Annex report.
- Section 4 describes the main chemicals discharged from PWR power stations and how BAT is being used to minimise their use or discharge. It also provides information on how BAT has been applied in the candidate designs, where this has been specifically highlighted in relevant publications.
- Section 5 compares the discharge limits in the plant permits. It also compares information on actual discharges with the size and capacity of individual PWR plants or, where several individual plants may be located together, the total capacity of the site. The data for this comparison were drawn from the detailed assessments of the predecessor plants given in the separate Annex report.
- Section 6 compares the types of chemicals discharged from PWRs with those discharged from conventional fossil fuel power plants. The aim is to identify which chemical discharges are generic to any form of power plant using a standard steam cycle. This section also compares the actual discharges of chemicals from currently operating PWR power stations with some generic limits that are applied to those from conventional fossil fuel power plants.
- Section 7 consists of an outline ecotoxicity assessment based on the chemical discharges identified in Section 3. It does not replace any site-specific assessments nor does it replace any assessments already carried out for the candidate designs (see Section 1.2.1).
- Section 8 provides an overview and conclusions on a chemical-by-chemical basis and a summary of issues relating to the application of BAT.

As far as possible, technical terms are explained in the main text. A combined glossary and list of abbreviations is provided at the end of the report.

The separate Annex report describes the PWR power plants in England, the USA, France and Germany that were included in the survey and their chemical discharges, and provides a detailed analysis of the discharge data.

1.2 Candidate reactor designs considered in the report

A range of civil nuclear power station designs are currently being offered by vendors for new build projects around the world. Four designs were initially proposed by vendors (or utilities) for the GDA process in England and Wales. Subsequently, the economic simplified boiling water reactor (ESBWR™) offered by GE Hitachi Nuclear Energy International LLV and the heavy water reactor (CANDU) ACR-1000 series offered by the Atomic Energy of Canada Limited were withdrawn from the GDA process. The two remaining candidate designs are the AP1000™ offered by Westinghouse and the UK EPR™, which is a joint submission by EDF and AREVA.

1.2.1 GDA for the UK EPR™ and AP1000™ and site-specific assessments

The GDA reports for the AP1000™ and UK EPR™ summarise their predicted chemical discharges and whether these can be considered as BAT. They include lists and quantities of chemicals that might be stored and used on site, and also discharged to water or to air.

The GDA reports are published on the plant vendors' websites (UK EPR™ 2010a,b,c,d and Westinghouse 2010a). They will be reviewed by the Environment Agency and Health and Safety Executive during 2010 and 2011 as part of the process for the licensing of the designs in England and Wales. These GDA reports are referred to in Section 4.

Some utilities are currently preparing environmental impact assessments to support their proposals for new nuclear power stations at specific locations in England and Wales. These assessments have been published on utilities' websites for public consultation and include site-specific assessment of the impacts of chemical discharges (for example, Hinkley Point C; EDF 2010a).

1.3 Predecessor PWR designs and others considered in this report

The survey objective was to collect information on the chemical discharges from operating PWR power stations. A number of PWRs from across the world were selected to include in this survey based on four main criteria.

- The PWR power plants should include ones from which the main design features of the AP1000™ and UK EPR™ were derived. For the AP1000™, this means including operating Westinghouse PWRs in the USA and Japan, and at Sizewell B in England. For the UK EPR™, it means including EDF's latest N4 design PWRs operating in France and the Konvoi PWRs in Germany. But while existing PWR power plants are generally considered to represent 'Generation II', both the AP1000™ and the UK EPR™ incorporate significant new and evolutionary features representing 'Generation III+' designs. These features are said to include:
    - a standardised design for each type to improve the efficiency of licensing, reduce capital cost and reduce construction time;
    - simpler and more rugged designs, making them easier to operate and less vulnerable to operational upsets;
    - greater availability and longer operating life of typically 60 years;
    - reduced possibility of core melt accidents;
    - greater resistance to serious damage from an aircraft impact;
    - improved use of the reactor fuel including European utility requirements regarding ability to use mixed plutonium–uranium oxide fuel (MOX).

- There was a need to establish any pro-rata relationship between chemical discharges and the numbers of reactors on a single site or electrical output. By considering sites with more than one reactor, other constraints on chemical discharges might be highlighted, such as the need to co-ordinate discharges from the individual reactors over time or if one or more reactors are shutdown for refuelling or maintenance.
- Once-through seawater cooling is used at most existing UK nuclear power stations and it is likely that it would be used for most of any new generation plants. Therefore coastal PWR power stations in the USA and France were selected. Chemical use and discharges from coastal and inland sites will differ, because different chemicals are used in the cooling water systems and because of different constraints in discharging chemicals to sea and to more sensitive inland watercourses. There could be greater pressure to either recycle chemicals or direct them to a solid waste stream, rather than discharging to a sensitive inland watercourse. Differences in the cooling method could have a more significant influence on chemical discharges than those due to differences in plant design or vendor.
- The PWR plants should also include those covered in the earlier survey of radiological discharges (Environment Agency 2010a).

1.4 AP1000™ predecessors and other US PWR plants selected for the study

The Westinghouse AP1000™ is based partly on features of pre-existing Westinghouse PWR reactors, but with newly designed safety protection systems –the aim being that, in the event of faults, the safety systems will allow mainly passive cooling and shutdown of the reactor. This has reduced the complexity of the safety systems, and the numbers of pumps and valves compared with existing Westinghouse designs, thus improving reliability and reducing maintenance requirements. The Westinghouse AP1000™ design has also been simplified by reducing the number of steam generators from four to two, while still maintaining a high electrical output that offers economies of scale. The design also allows for a modular method of plant construction. In January 2006, the US National Certification Committee approved the AP1000™ design for use in the USA. Four AP1000™s are currently being constructed at Sanmen in China.

Sizewell B is the only operating PWR in the UK. The reactor is based on a Westinghouse design known as SNUPPS (standard nuclear unit power plant system) initially designed in the 1970s, but with additional redundancy and diversity in some of the safety systems. It is owned and operated by British Energy (part of the EDF Group) and is the only UK reactor that can be considered a predecessor to the AP1000™. A full description of the plant is given in Annex A2.

Of the 103 nuclear power plants in the USA, 69 are PWRs and the rest are boiling water reactors (BWRs). A shortlist of AP1000™ predecessor PWRs and other Generation II designs was drawn up (Table 1.1). A full description of each plant is provided in the separate Annex report, with the relevant sections referenced in Table 1.1. A location map is shown in Figure 1.1.

Several Combustion Engineering plants were included in the survey. These have two heat transfer loops compared to the four used in the Westinghouse plants (for details see Section 1.6.1). They were included to increase the number of coastal US sites. Chemical operations in the two designs would be expected to be broadly similar and differ on a plant by plant, rather than design basis (Section 1.6).

Furthermore, significant chemical discharges take place from the secondary and auxiliary plant systems, which are supplied by a range of different manufacturers and not necessarily by vendors who supply the main reactor system. Including alternative predecessor plants ensures that variations in chemical discharges due to differences in these other plant systems were covered in the survey.

In Japan, a single Westinghouse three-loop 780 MW(e) plant was built at Takahama at the same time as similar Mitsubishi three-loop units. This was considered to be a useful smaller seawater-cooled predecessor, but no data on chemical discharges could be obtained and it is not discussed further.

Table 1.1 AP1000™ predecessors and others from the USA

Plant	Site overview	Plant type
Beaver Valley, Pennsylvania (A3.2)	Inland site with twin reactors with cooling towers. Make-up from the Ohio River.	Westinghouse three-loop design
Byron, Illinois (A3.3)	Inland site with twin reactors with cooling towers. Make-up from the Rock River.	Westinghouse four-loop design
Comanche Peak, Texas (A3.4)	Inland site with twin reactors. Inland cooling water reservoir (Squaw Creek).	Westinghouse four-loop design
Seabrook, New Hampshire (A3.5)	Single reactor site. Seawater cooling via 3 km culverts to the Atlantic Ocean.	Westinghouse four-loop design
Salem, New Jersey (A3.6)	Twin reactor site. Seawater cooling from Delaware Bay, Eastern Atlantic seaboard.	Westinghouse four-loop design
San Onofre, California (A3.7)	Twin reactor site (but with individual plant permits). Seawater cooling from the Pacific Ocean.	Combustion Engineering two-loop design
Diablo Canyon, California (A3.8)	Twin reactor site. Seawater cooling from Diablo Creek and Pacific Ocean.	Westinghouse four-loop design
Millstone, Connecticut (A3.9)	Twin reactor site. Both use seawater cooling from Long Island Sound connected to Eastern Atlantic seaboard.	Combustion Engineering two-loop and a Westinghouse four-loop design
St Lucie, Florida (A3.10)	Twin reactor site. Seawater cooling from eastern Atlantic seaboard.	Combustion Engineering two-loop designs
Calvert Cliffs, Maryland (A3.11)	Twin reactor site. Seawater cooling from Chesapeake bay, eastern Atlantic seaboard.	Combustion Engineering two-loop designs

1.5 EPR™ predecessors and other French PWR plants selected for the study:

The UK EPR™ is modelled on the most recent AREVA N4 reactors in France, notably those using four steam generators but with a four-system safety architecture based on the German Siemens Power Generation Division Konvoi design. Penetrations through the bottom of the reactor pressure vessel are avoided and there is an improved neutron shield within the reactor pressure vessel to maximise use of the reactor fuel. Like the AP1000™, the UK EPR™ also uses fewer valves, pumps, tanks and heat exchangers than its immediate predecessors and there is enhanced protection against aircraft impact and earthquakes.

Four EPR™ reactors are currently being built in Finland, France and China. However, the UK EPR™ jointly proposed AREVA and EDF specifically for the UK includes some individual design features used by EDF in its French power stations.

The standardised PWR reactor designs in France include:

- 900 MW(e) three-loop plants (CPY/CP2/CP1). Thirty-four of these reactors are in operation, mostly constructed in the 1970s and the early 1980s. They drew on some aspects of Westinghouse designs but with wholly French supplied (Framatome/Alstom) plant systems.
- 1,300 MW(e) four-loop plants. Twenty of these are in operation, built between the 1980s and mid 1990s (P4 Westinghouse license and related P′4 French designs but all with Framatome/Alstom plant systems). As well as using four main coolant loops, the main design change includes a double concrete shelled primary containment with vented annulus instead of the single steel lined shell used in the initial 900 MW(e) designs.
- 1,450 MW(e) four-loop plants, representing the latest wholly French design (N4) with Framatome (now AREVA NP)/Alstom plant systems. There are four of these at two separate inland sites of Civaux and Chooz.

Note the EPR™ is by AREVA (NP), which was created in 2001 by the merger of Framatome (now AREVA NP), Cogema (now AREVA NC) and Technicatome (now AREVA TA).

The current assessment initially considered the N4 designs at Civaux and Chooz. To give greater coverage of other PWR power station sites in France, the twin P′4 reactor sites at Golfech and Penly were included, as well as PWR plants at French coastal sites and those where several individual plants are located within one sites.

The final list for the French PWR power stations covered in the survey is given in Table 1.2 and a location map is shown in Figure 1.2. A full description of each plant is provided in the Annex report, with the relevant sections referenced in Table 1.2.

Table 1.2 EPR™ predecessors and other PWR power plants in France

Plant	Site overview	Basis for inclusion
Civaux (A5.1.1)	Inland site with two N4 reactors. Cooling tower with make-up from Vienne River.	EPR™ predecessor
Chooz (A5.1.2)	Inland site with two N4 reactors. Cooling tower with make-up from Meuse River.	EPR™ predecessor
Golfech (A5.1.3)	Inland site with two P′4 reactors. Cooling tower with make-up from Tarn River.	1,300 MW(e) four-loop plant
Penly (A5.1.4)	Coastal site with two P′4 reactors. Seawater cooling from the English Channel.	1,300 MW(e) four-loop plant
Flamanville (A5.1.1)	Coastal site with two P4 reactors. Seawater cooling from the Bay of Biscay.	Coastal site with four-loop plants
Paluel (A5.1.6)	Coastal site with four P4 reactors. Seawater cooling from the English Channel.	Larger coastal reactor site
Gravelines (A5.1.7)	Coastal site with six CPY reactors. Seawater cooling from the English Channel.	Multiple reactor coastal site

With respect to the Konvoi aspects of the EPR™ design, these are specific to a suite of German plants, including Neckarwestheim 2 and Isar 2. These are all situated inland, with water for the main cooling systems drawn from rivers and augmented by cooling towers. Therefore they are less representative of the situation for new nuclear build in England and Wales than the French coastal sites. Furthermore the design features in the Konvoi plants, while partly incorporated into the AREVA EPR™, are not ones that would have significant effects on the use or discharge of chemicals. Although these German plants were considered in this study, less emphasis was placed on them than the French N4 and coastal sites. Details of the two German Konvoi predecessors are given in the Annex report Sections A7.1 and A7.2.

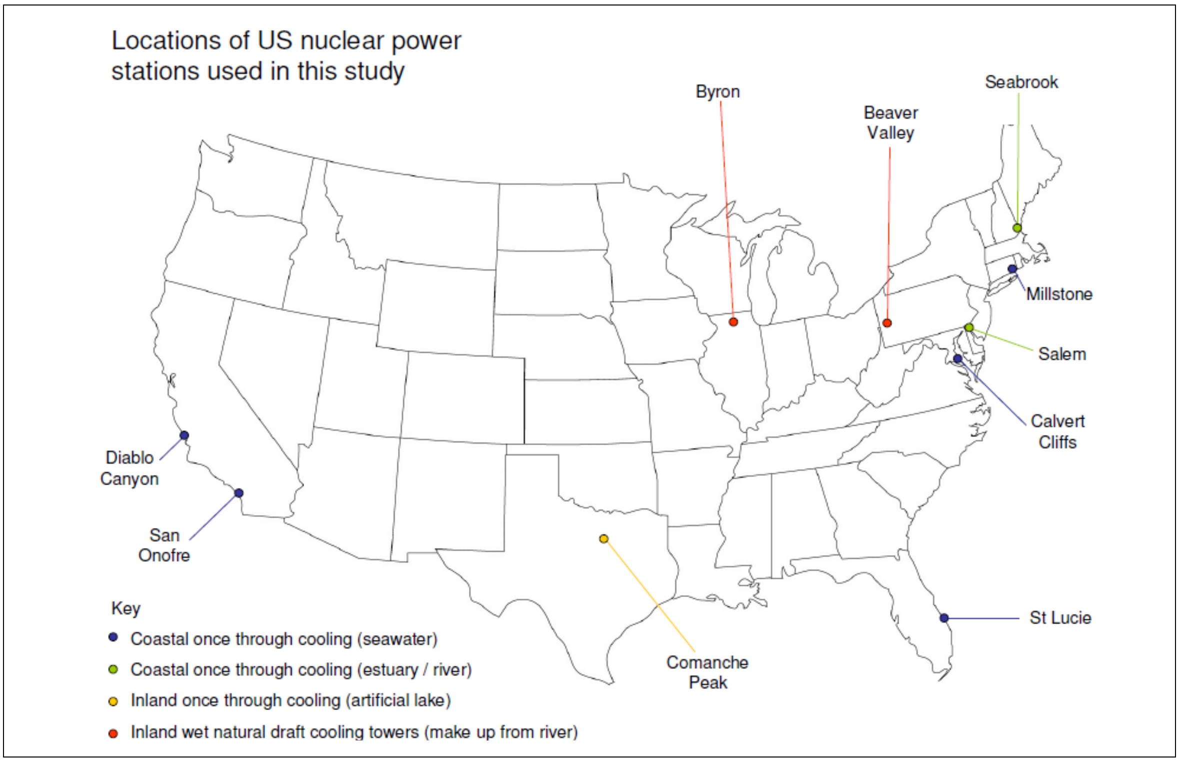

Figure 1.1 Location map of plants in the USA (AP1000™ predecessor plants and others at inland and coastal locations)

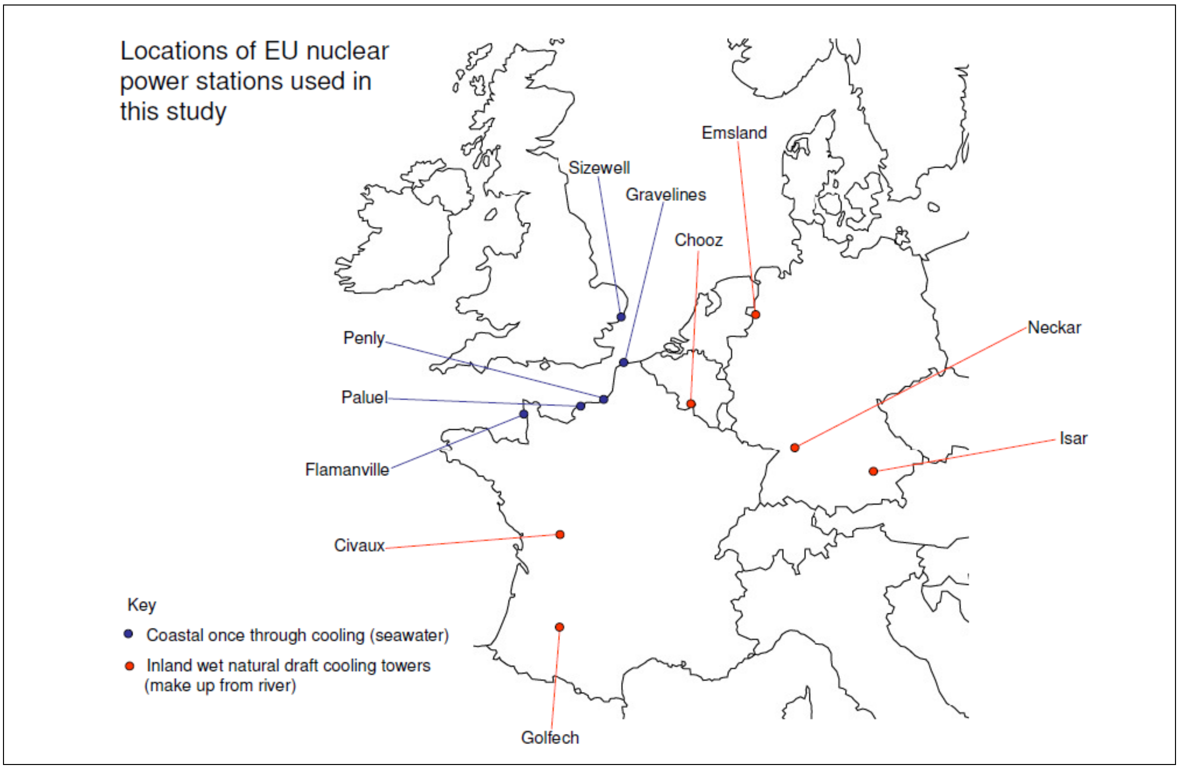

Figure 1.2 Location map of EPR™ predecessors and other PWR power plants in the EU (Sizewell is AP1000™, the remainder are French and German designs)

1.6 Features of the generic PWR design and chemical discharges

This section describes the main features of PWR technology that is the basis for both the AP1000™ and the UK EPR™, with an overview of chemicals that are used and potentially discharged – particularly to water. Further details are given in the later sections of the report and, for the individual PWR power plants covered in the survey, in the Annex report.

1.6.1 Reactor primary circuit

The central part of the PWR is the primary circuit and nuclear steam supply system (NSSS), illustrated in Figure 1.3. The reactor pressure vessel is connected to one of two, three or four heat transfer loops, each with its own separate steam generator and circulating pump. The numbers of heat transfer loops in the designs covered in the current study are given in Tables 1.1 and 1.2. The UK EPR™ has four heat transfer loops and the AP1000™ has two (but to retain an economic output, each of these has a larger capacity than those in the EPR™). The primary circuit is housed within the main concrete containment building. This area of the power station is sometimes called the 'nuclear island'.

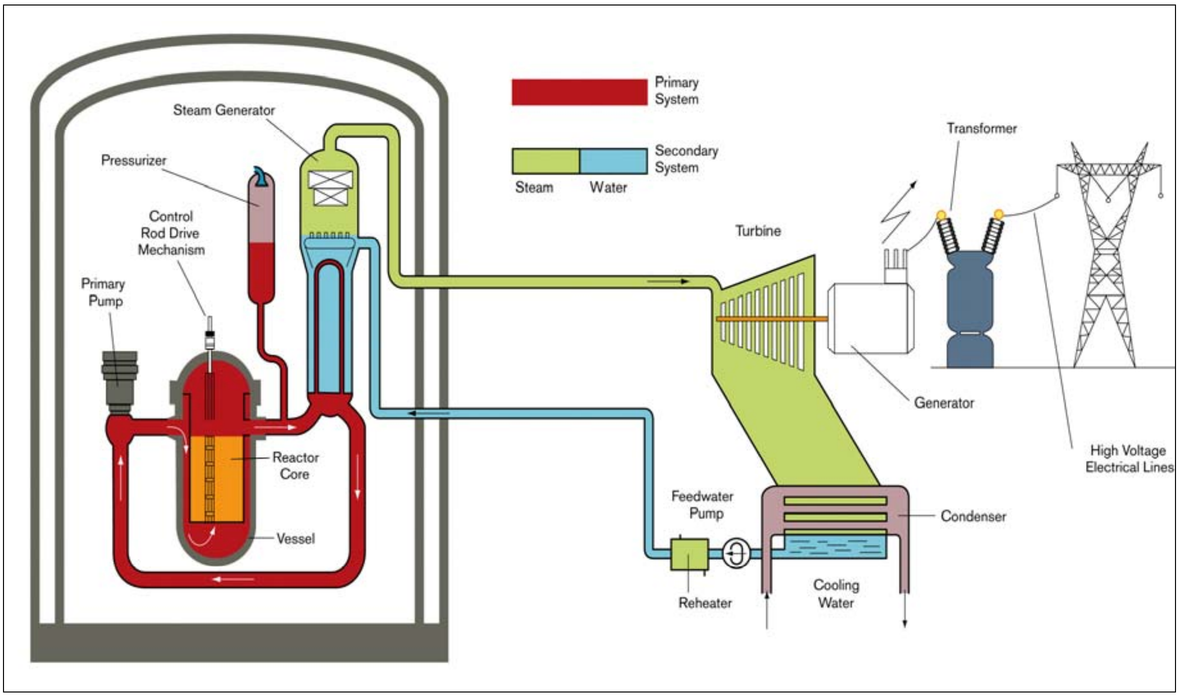

Figure 1.3 Simplified schematic of a PWR reactor showing a single heat transfer loop (primary circuit) and the secondary or steam circuit and its turbine generator (source AREVA EPR™)

The primary reactor circuit of a typical PWR has a volume of between around 250 and 350 m^3 and is filled entirely by water dosed with up to 2,000 mg/l of boron in the form of boric acid (H_3BO_3). This borated water is called reactor coolant (shown in red in Figure 1.3) and together with the control rods (shown penetrating the upper part of the reactor in Figure 1.3) provides the necessary control on nuclear reactivity in the reactor core (shown in orange in the figure). Boric acid used to control nuclear reactivity in this way is sometimes called a ‘chemical shim’. The coolant is also dosed with lithium hydroxide (enriched in the lithium-7 isotope) to act as a pH control agent (about 3–4 mg/l).

Pumps in each heat transfer loop move the borated coolant through the reactor core, where it picks up heat, to the steam generators. From here it passes through hundreds of narrow tubes, transferring this useful heat to the secondary steam circuit. The coolant is then returned to the reactor core to be reheated. The temperature of the water in the circuit is of the order of 325°C during operation. The pressure in the circuit prevents the coolant from boiling. The reactor pressuriser is a single smaller vessel in the reactor circuit connected to one of the heat transfer loops, where steam is allowed to form to accommodate small changes in water volume due to changes in reactor power.

To compensate for the effects of fuel burn-up over a normal 12–18 month fuel cycle, there is a need to dilute the boric acid in the primary circuit from an initial concentration of about 2,000 mg/l to a few mg/l. This is done by bleeding or ‘let-down’ of primary circuit coolant and its replacement by pure make-up water (using smaller piped connections to one of the heat transfer loops). As well as boric acid, the coolant let-down will contain small amounts of radionuclides that originate from the reactor core or fuel. These are removed, as far as possible, by treating the let-down using ion exchange and filtration in the radioactive waste treatment systems. The resulting residual solution of boric acid could be discharged to the environment, processed to recover the boric acid and purified water (to reuse in the primary circuit during the next fuel cycle) or treated to form a solid waste. Alternative strategies involve using boric acid artificially enriched in the boron-10 isotope; this is discussed in detail in Section 4.

During reactor start-up and shutdown, small amounts of hydrazine and hydrogen peroxide may be added to the reactor circuit. These are minor compared with boric acid. They are mostly destroyed as the system is heated up and therefore are not discharged to the environment.

1.6.2 Secondary or steam circuit

Heat from the primary side of the steam generators is transferred through the steam generator tube bundle into an entirely separate, water-filled, secondary or ‘steam’ circuit (shown in blue in Figure 1.3). Steam is used to turn the turbine generator to produce electricity (shown in green in Figure 1.3). This part of a PWR power station is sometimes called the ‘conventional island’ since it operates in the same way as a fossil fuel power station.

To minimise corrosion in the steam circuit, it is initially filled using high purity feedwater. Usually this needs to be dosed with chemicals continually to maintain purity. Hydrazine (at about 0.1 mg/l) is normally used to remove residual levels of dissolved oxygen. pH is controlled by dosing with ammonia and/or volatile amines such as ethanolamine, morpholine or more complex, so-called ‘advanced amines’ (all at about 10 mg/l). Ammonia or amines dissociate in the steam and water to form a range of pH-controlling species (such as ammonium, NH_4^+, RNH_3^+). Hydrazine also breaks down to ammonia. This use of hydrazine and ammonia/amines is called an ‘all volatile treatment’ (AVT). It differs from the phosphates that were used historically (and remain in use in some conventional plants) and the filming amines that can be used to form a protective film on boiler and steam side surfaces.

A range of alternative strategies have been developed to control the chemistry of the water in the steam circuits of PWRs, usually to address plant specific issues of corrosion. These could affect the type of chemicals that need to be discharged. However, AVT (or variations on AVT) remain the most commonly used and are mostly likely to be applied on the new candidate designs (Odar and Nordmann 2010; UK EPR™ 2010a and Westinghouse 2010a).

The secondary circuit generates mechanical energy for the turbine generator by drawing the steam under low pressure into a large-scale tubed condenser where it is converted back into water. Large pumps then return this condensate to the steam generators via a condensate polishing plant (CPP) (Section 1.6.3) and the chemical dosing points. The tubes in the main condenser carry a continuous flow of cooling water. The primary requirements in the design of the condenser are to maximise the transfer of heat from steam to the external cooling water, and to minimise any possible leaks of the external cooling water into the steam circuit, which could otherwise adversely affect water chemistry in the circuit and increase corrosion. External cooling water is usually supplied to the condenser from the sea, a river or a lake.

Once through seawater cooling

PWR power stations using seawater cooling for the main steam circuit can generally employ a ‘once-through’ system where seawater is pumped through a culvert, passed through the condenser and then discharged through a separate culvert back to the sea. Typical flow volumes for a single plant are of the order of 3–5 million m^3 per day. These systems normally require chemical dosing to minimise infestation by films of algae or colonies of shellfish (biofouling). This is usually achieved by dosing the inlet to the cooling water system with chlorine, although proprietary biocides to control site-specific organisms may also be required.

Chlorine used to control biofouling is usually generated by electrolysis. It forms a range of oxidising species in the once through cooling water as it flows into the main condenser, including hypochlorous acid (HOCl), hypochlorite (OCl^-) and free chlorine, as well as some organic by-products of chlorination such as bromoform ($CHBr_3$) or chloramines.

Some oxidants remain in the discharge of main cooling water and further chlorinated by-products can be formed. The subsequent fate of these in the receiving water depends on physical processes of mixing, dilution, volatilisation and chemical ones of oxidation and photo-degradation.

Plant operators must adjust the rate of chlorination so that it is sufficient to control biofouling (the so-called 'chlorine demand') and yet minimise the discharge of oxidants and chlorination by-products in the final receiving water. Bromine, chlorine dioxide and ozone are alternative but less frequently used oxidising biocides. Use of biocides may only be required seasonally, especially when water temperatures rise above about 10°C in summer months.

Inland water cooling and cooling towers

PWR power stations using river water to cool the main condenser generally require the additional use of cooling towers. These recirculate and independently cool some of the cooling water flow, so minimising the thermal load on the river. Cooling towers reduce the total volume of water that needs to be withdrawn from a river, typically to about five per cent of that required in a once through system.

Most plants use natural draft, wet cooling towers. In these, the cooling water from the main condenser is dispersed through an open packing system within a concrete tower with a hyperbolic profile. The packing system (consisting of splash bars or a system that forms a film of water) maximises the surface area of water open to the air. Packing systems in older towers were made of timber but modern ones use combinations of concrete supports and plastic. Vents in the base of the tower allow cool air to enter, which then passes up through the packing system. The water is cooled mainly by evaporative cooling, but partly by direct heat transfer. The resulting water vapour frequently appears as a plume from the top of the tower (sometimes called drift or windage). Some water has to be rejected more or less continuously (called blowdown) and replaced by fresh water from the river or lake (called make-up) to compensate for losses due to evaporative cooling and to maintain the quality of the water in the cooling tower circuit. A simplified flow circuit is shown in Figure 1.4.

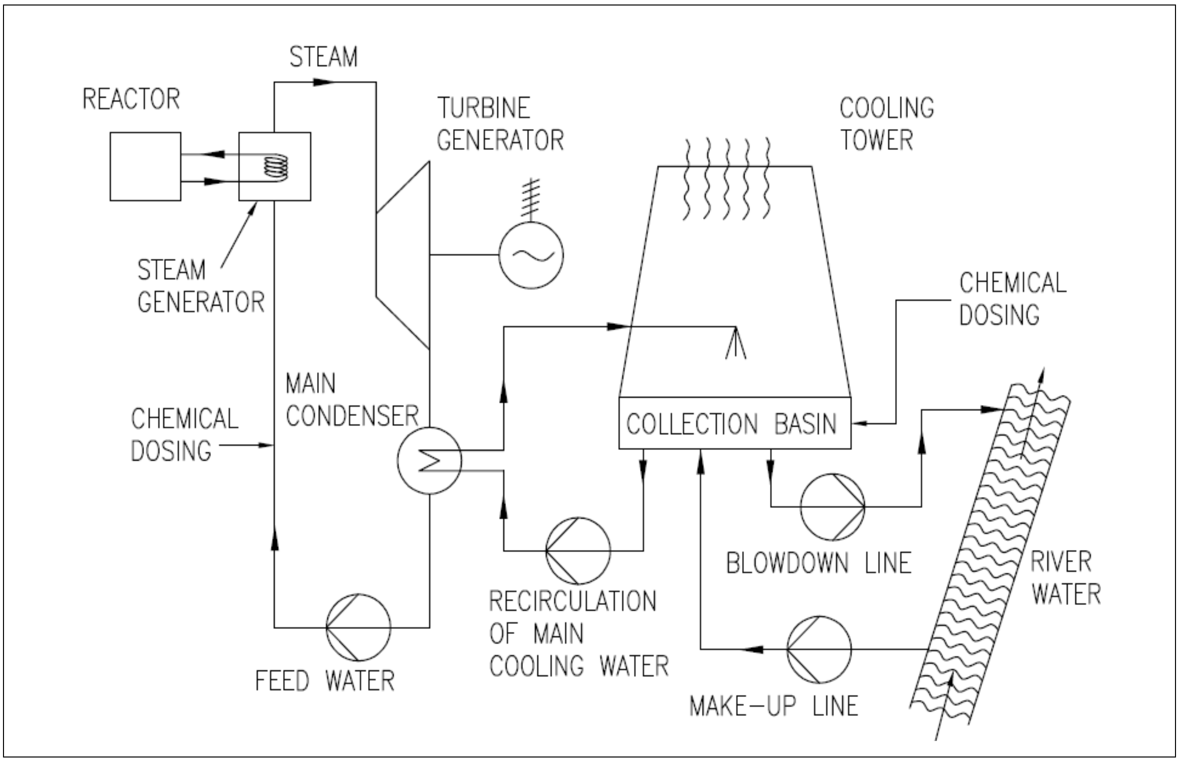

Figure 1.4 Simplified wet cooling tower showing water path to condenser and make-up and blowdown to the external cooling water source

Cooling tower systems also require chemical dosing to control biological activity. Usually chlorine or other oxidising biocides are used, although non-oxidising biocides such as metabolic inhibitors such as gluteraldehyde or isothiazolin can be used. Dosing is required to prevent the build-up of algal films and organisms in the main condensers. It may also be required to minimise the levels of potentially harmful microbes (such as Legionella) in the blowdown returned to the river or lake, and in the airborne drift from the tower.

Cooling tower circuits usually also require additional chemical dosing to control any build-up of sediments in the collection basins or of hard scale (calcium sulphate, carbonate or phosphate) in the pipework or condenser tubes. This involves continuous or intermittent use of dispersants (usually polymers) and anti-scale chemicals (acids and chelating agents) that together ensure that the saturation indices for salts of concern are not exceeded. More details are provided in Environment Agency (2010b).

1.6.3 Auxiliary plant systems in the PWR

In any PWR, the main plant systems (reactor and steam circuit) are supported by auxiliary systems which store, use and in some cases discharge chemicals. Any aqueous discharges from these internal sources (sometimes called internal plant outfalls) are of relatively small volume (up to a few hundred m^3 per day). They are usually directed initially to hold-up tanks for monitoring and checking to ensure they comply with the relevant site permit limits, before being discharged on a batch basis. These discharges are then usually directed to the main cooling water flow or to the cooling tower blowdown, because this allows for maximum dilution of chemicals (and radioactive constituents) prior to discharge to the environment. The main auxiliary plant systems are described below.

Radioactive waste handling facilities

These handle, treat, store and discharge radioactive wastes from various areas in the nuclear island. They include systems for handling gaseous, liquid and solid wastes. The main chemical waste in liquids consists of boric acid from the reactor circuit. The liquids may also contain detergents and other complex chemicals from other plant systems that generate active aqueous effluent.

The main treatment processes used are ion exchange and filtration. The primary objective of treatment is to remove traces of radioactive materials from the effluents, rather than any non-radioactive chemicals. Ion exchange systems and filters are also used to treat borated water used in the fuel storage ponds.

In contrast to those used in the non-radioactive areas of the PWR plants, the ion exchange resins and filters from the radioactive waste treatment system are always directed to a solid radioactive waste route, rather than being regenerated for reuse.

Condensate polishing plant

This maintains the purity of the water in the secondary (steam) system, usually using deep-bed ion exchange resins and/or filters.

Deep-bed ion exchange resins are regenerated at intervals to allow them to be reused, using acid (usually sulphuric) and alkali (usually sodium hydroxide). Although ion exchange resins may be used in other plant systems, those in the condensate polishing plant are usually the largest and so their periodic regeneration can be a major source of chemical effluents. These effluents will be dominated by any excess sulphuric acid and sodium hydroxide used in the regeneration process, as well as salts of sodium, calcium and chloride removed from the resins during regeneration. Excess acid and/or alkali are normally neutralised in large neutralisation tanks prior to discharge. The effluents may also contain ammonia or amines and the breakdown products of hydrazine that the resins tend to take up from the secondary circuit water flows. Periodic backwashing and cleaning of any special filters used in certain designs of polishing plants can generate effluents containing dissolved or suspended solids.

Difficulties associated with maintaining the required high purity of the water used in the main steam circuit will determine the size and capacity of the condensate polishing plant and the frequency of regenerating the ion exchange resins or backwashing of filters. These in turn depend on the initial quality of the feedwater or ingress of external cooling water through any small leaks in the condenser. External cooling water ingress is a more significant issue for plants using once-through seawater cooling because seawater contains high levels of salts that are especially detrimental if they enter the main steam circuit and then reach the steam generators.

Other treatment systems have been developed for condensate polishing, including pre-coat filter demineralisers. These consist of a small volume of fine grade ion exchange resin coated onto a filter support system. Once the resin is exhausted, it is backwashed from the filter and then generally rejected as a solid waste, rather than being regenerated. Because the small volume of resin used has only a limited capacity, these systems are only suitable where limited treatment of the condensate in the steam circuit is required, in particular where there is only very minor ingress of impurities from the external cooling water flow through any leaks in the condenser (Tavares and Applegate 2008).

Some French PWRs do not have condensate polishing plants. Instead, they rely on the fact that most impurities in the steam circuit tend to accumulate in the feedwater in the steam generators. These plants therefore rely wholly on steam generator blowdown treatment systems to maintain the quality of water in the steam circuit.

Steam generator blowdown

Although precautions are taken to maintain high purity of water in the main steam circuit, there can be a tendency for any impurities that do occur to be carried forward and become concentrated in the steam generators. Solid corrosion products from the main condenser can also behave in this way and accumulate as sludge in the steam generators. These materials could cause corrosion of the tubes and increase leaks of primary circuit coolant into the steam circuit, as well as limiting the life of the plant.

Build-up of impurities in the steam generators can be minimised by either continuous or intermittent blowdown of water from the steam generator. This blowdown contains impurities that can be removed in a small dedicated steam generator blowdown plant using ion exchange or membrane technologies (Section 4.3.6). The purified blowdown can then be returned to the main steam circuit. If it is still of insufficient quality, it is rejected as an aqueous waste stream containing impurities such as sodium, chloride, ammonia and other dosing chemicals used in the steam circuit. If there have been any small leaks from the primary to secondary circuit, it may also contain traces of radioactive material (mainly tritium). If discharged, the blowdown water is replenished using fresh make-up water.

Many French PWR plants rely on these systems to maintain the quality of the water in the secondary steam circuit and do not have separate condensate polishing plants. The current design for the UK EPR™ relies on this strategy (UK EPR™ 2010e). The AP1000™ design retains a condensate polishing plant (although of smaller size and capacity than on some earlier PWRs) in addition to a steam generator blowdown system (Westinghouse 2010b). The use of titanium condenser tubes reduces the need for condensate polishing by the reducing the chance of ingress of external cooling water (containing high levels of salts) into the main steam circuit.

Raw water treatment plant

This purifies raw water (from boreholes or utility supplies) to a sufficient quality for use in the various plant systems. It may employ standard ion exchange methods or membrane technologies (such as reverse osmosis). Depending on the quality of the raw water, additional treatment steps may be needed such as coagulation, settling and filters to remove iron, organic carbon or nitrates – all of which can produce their own particular aqueous waste streams. Regeneration of ion exchange systems will produce effluents contain excess acid and alkali as well as salts and suspended iron originally present in the raw water.

Seawater can be used in plant systems if it is treated in a desalination plant using reverse osmosis followed by final polishing in a small-scale ion exchange plant. This generates a waste stream consisting of brine.

Laundry, decontamination workshop, laboratories

Clothing that may be contaminated by low levels of radioactivity is generated when workers access potentially active areas in the nuclear island of the PWR. This clothing may be disposable but much may also be washed in an on-site active laundry to make it suitable for reuse. Some operators may use off-site contractors for their laundry. An on-site active laundry will generate aqueous effluents containing proprietary detergents plus small amounts of radioactive material.

Some items like pumps may be decontaminated in an on-site decontamination workshop to avoid build-up of activity or to allow them to be more serviced safely. This is done using decontamination solutions consisting of detergents, acids and proprietary cleaning systems. Active samples may also be analysed in on-site laboratories that generate small amounts of aqueous effluents containing a range of chemicals.

The aqueous effluents from these facilities containing detergents, acids, alkalis and proprietary cleaning chemicals will generally be directed to the radioactive waste treatment systems for decontamination prior to discharge. Again, the primary objective is removal of small amounts of radioactive materials, rather than any extensive chemical treatment. Further details are given in Section 4.

Diesel and standby generators

These use diesel fuel and lubricating oil, which need to be stored to minimise any leaks to water. The diesel engines will also use coolants and anti-freeze agents, which may require intermittent flushing and renewal. The resulting effluents may contain water soluble corrosion inhibitors and anti-freeze including molybdate or zinc phosphonate, scale and corrosion inhibitors, alkalinity controllers, anti-foams and glycol-based anti-freeze. Proprietary mixtures are designed to minimise environmental impacts if they need to be discharged.

The standby generators will be the main source of chemical discharges to air. These will consist of carbon dioxide, sulphur and nitrogen oxides, and particulates or soot. These diesel plants are relatively small and, in the absence of emergency use, emissions to air take place only during periodic testing.

Auxiliary plant cooling water systems

Larger electric motors on pumps and the plant heating, ventilation and air conditioning (HVAC) systems all require cooling using individual (so-called ‘local’ to plant) chiller units. These carry a flow of circulating cooling water, which itself is cooled by an external source of water via a central heat exchanger. The circulating water requires chemical dosing to prevent corrosion and build-up of biofilms (these can act as a focus for microbiological corrosion of the underlying steel pipework).

The complexity of these systems and the variety of plant components made of different materials makes control of corrosion and biofouling more difficult than in the main cooling water system serving the turbine generators. Chromate based inhibitors (potassium chromate, K_2CrO_4) were used, but due to their toxicity, they have been mostly replaced by ones based on molybdates (MoO_4) or a sodium nitrite borax mixture ($NaNO_2/Na_2B_4O_7$). In systems using copper, tolytriazoles are also used. Most chemicals are used as proprietary mixtures that include a range of inhibitors plus biocides, preservatives and dye tracers that are described in the relevant material safety data sheets (MSDS).

Corrosion inhibitors in these systems are not routinely discharged but may need to be managed if the systems are purged, or for certain maintenance requirements. In these circumstances they may appear in certain aqueous effluents and discharges.

Site run-off and stormwater, sewage effluents, oily effluents

Like any large power station, PWRs cover large areas of land, much of which are hard-standing, car parking areas or roof areas. Rain and storm water run-off from these needs to be managed. The main contaminant from car parks is oil, which is removed using oil–water separators. Other constituents include sediments, biological material (that gives rise to a biochemical oxygen demand in any receiving water), zinc (from galvanised or zinc-based roof coatings) and other heavy metals.

Plants may rely on local municipal sewage services or they may have a dedicated on-site sewage plant. Effluents will be dominated by sediment and biological material.

All mechanical plant systems, especially in the turbine hall, will use lubricating and hydraulic oils. These have to be stored and transferred. They are not discharged in aqueous effluents, but small leaks and spills inevitably occur which need to be considered and managed.

1.6.4 Refuelling and maintenance in PWRs: wet lay-up of plant systems

At intervals of between 12 and 18 months, a PWR power station needs to be shutdown to allow the reactor to be refuelled. Shutdown periods usually last about four weeks. During this time there can be increased transfer of used coolant containing boric acid around the auxiliary systems and also transfer of boric acid dosed water used to store used fuel in the storage ponds. This can increase the discharges of aqueous effluents dosed with boric acid through the radioactive waste treatment system. At intervals, larger purges of boric acid may be required from the fuel storage ponds. These are also treated to remove radioactive material prior to discharge.

Maintenance on other plant systems is carried out during reactor shutdown periods. This means that some water-filled systems can become temporarily stagnant and oxygen can enter, so corrosion can become more of a problem. Frequently there is a need to carry out additional chemical dosing of plant during these periods – called 'wet lay-up'. Corrosion is initially minimised by ensuring the water used to fill plant systems contains low levels of corrosive ions such as chloride. Levels of dissolved oxygen are reduced from about 8 mg/l (normally present in water in contact with air) to less than 0.1 mg/l, usually using hydrazine. However, the oxygen-scavenging ability of hydrazine become less effective at low temperatures, so either the concentrations of hydrazine in the plant systems need to be increased appreciably or the hydrazine needs to be replaced with alternative oxygen scavengers. Occasionally even this is inadequate and phosphate-based or other corrosion inhibitors need to be used.

Once the period of wet lay-up comes to an end, these potentially large volumes of chemically dosed water need to be managed. This usually involves simple treatments (such as to destroy hydrazine) followed by discharge. This may require special arrangements in the site permits.

1.6.5 Chemical discharges to air from cooling towers

The updraft of air through a wet cooling tower can carry water vapour and entrained droplets out of the top of the tower. These can appear as a visible plume, called drift, especially in colder weather. In older towers, losses due to drift can be as much as 0.2 per cent of the recirculating flow. These losses could reduce the number of cycles that a given volume of water in the circuit can be reused for to as few as 5–10, even ignoring any requirements for blowdown from the cooling tower collection basin.

Therefore significant make-up to the system from a river or reservoir would be required. In newer designs, losses due to drift have been reduced to less than 0.05 per cent of the recirculating flow, allowing the number of cycles a given volume of water in the circuit can be reused for to as many as 50–100 and so reducing the need for make-up. Reducing evaporative losses in this way can also reduce the visual impacts of drift.

As evaporative cooling takes place, some of the dosing chemicals fractionate into the airborne drift from the tower. There may be some leaching of copper-based preservatives used in the wooden support structures of some older cooling towers. Even where these have been replaced with more modern concrete and plastic splash bars, there can remain issues due to carryover of biological materials into the airborne drift.

As drift moves across the surrounding areas, dry and wet deposition of the drift and contaminants can occur, which can then pass into vegetation, soil and water. These effects are extensively documented but not usually covered as specific issues in reports of discharges from plants using cooling towers. Chemical dosing needs to be adjusted and balanced to minimise the impacts of the airborne drift, while at the same time minimising the impacts of dosing chemicals in the blowdown water discharged into surface watercourses (Environment Agency 2010b).

These issues and the presence of visible drift are largely avoided in dry cooling towers and other types such as mechanical draft. However, the capacity of these is usually limited and, with a few exceptions, they are not usually used in large-scale power plants.

1.7 Chemical discharges during construction and commissioning of the PWR

This report describes chemical discharges associated with normal operations of the PWR nuclear island and auxiliary plant. This includes normal operation at power and those associated with the periodic refuelling of the reactor and certain maintenance operations (Section 1.6.4).

The construction and final decommissioning of the reactor plant will produce additional chemical discharges from the site, potentially extending over several years. For example, with up to several thousand more site workers during construction, there will be a need for many more toilet facilities and foul water systems than those required for the several hundred workers on-site during the operational phase. The GDA for the AP1000™ and the UK EPR™ both address how these arise and will be managed during the construction of these reactors and power stations in the UK. They are not addressed in this report.

2 Regulatory regimes and permit systems in the UK, USA, France and Germany

2.1 UK regulatory regime

In the UK, the operation of larger sites using or storing nuclear materials is regulated under the Nuclear Installations Act 1965. Each site operates under a set of licence conditions issued under this Act by Her Majesty's Nuclear Installations Inspectorate, which became part of HSE's Nuclear Directorate.[2] Discharges of radioactive and chemical materials from such sites are regulated under permits in England and Wales by the Environment Agency, and in Scotland by the Scottish Environment Protection Agency (SEPA). The permits were originally issued under the Radioactive Substances Act 1993 (RSA93) with separate permits covering the discharge of non-radioactive chemicals under the Water Resources Act 1991.

The Environmental Permitting Regulations were introduced in 2007, combining the Pollution Prevention and Control and Waste Management Licensing regulations in England and Wales. In 2010, the scope of the Environmental Permitting Regulations was widened to include radioactive substances, water discharges and groundwater activities. For any new nuclear power station in England or Wales, the discharges of radioactive and chemical substances would be permitted under the Environmental Permitting (England and Wales) Regulations 2010.

The UK has only one PWR reactor that is used to generate electricity, namely Sizewell B, situated on the coast of the North Sea in Suffolk. This plant was originally issued with a permit in the mid-1980s, largely based on the approach already adopted for the UK's gas-cooled reactors. Since then a number of reassessments, mainly of radioactive discharges, have been carried out in support of periodic re-authorisation under the requirements of RSA93. There have been considerable changes in permitting of chemical discharges since Sizewell B was authorised and permits for new nuclear power stations could be very different. The chemical discharge limits are based on the difference in concentration measured between the inlet and the outlet back into the sea for the pollutants listed in Table 2.1. Further details of the permit and chemical discharges for the Sizewell B PWR power station are given in Annex A2.

Table 2.1 Pollutants covered by chemical discharge limits at Sizewell B

Pollutant	Reason for presence in chemical discharge
Total residual oxidants	Chlorination of the once through cooling water system
Ammonia	As nitrogen and use of ammonia in the steam circuit for pH control
Nitrite	Use as a corrosion inhibitor in certain closed circuit plant systems (may require occasional purging)
Boron	Use of boric acid in the primary reactor circuit and sodium tetraborate as a corrosion inhibitor in closed circuit plant systems

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[2] This document refers to the Health and Safety Executive (HSE). In April 2011 HSE's Nuclear Directorate became the Office for Nuclear Regulation (ONR).

2.2 US regulatory regime

In the USA, liquid and gaseous wastes from the radioactive waste treatment systems in all nuclear power stations are regulated by the US Nuclear Regulatory Commission (NRC). However, chemical and other discharges to water and to air are regulated separately by permits issued by the US Environmental Protection Agency (USEPA). Issue of the permits is in accordance with the National Pollutant Discharge Elimination System (NPDES) established under the US National Environmental Protection Act.

One of the consequences of this regulatory regime is that some chemicals within the radioactive discharges, notably boric acid in primary circuit let-down, may not be fully captured by the permitting system. Plant operators and regulators generally come to an agreement on how this apparent gap may be addressed on a site-by-site basis.

In the first stage to obtaining an NPDES permit, plant operators will prepare a report on site operations (usually including a site-wide water balance) and the chemicals to be stored, used and discharged, much in the manner of an Environmental Impact Statement. Generally, discharges and sources of liquid waste are separated into:

- **Internal outfalls**. These are usually low volume discharges that come from specific plant areas or plant systems. Discharge limits on internal outfalls ensure that reliable analysis and monitoring can be carried out before they become diluted in the cooling water. It also allows better demonstration that Best Available Techniques or Best Management Practices (see below) are being used to minimise the discharges at source.
- **External outfalls**. These are outfalls that discharge directly into the environment. The most important are the large volumes of water associated with once-through seawater cooling systems and blowdown from cooling towers. Some US sites also have separate external outfalls due to cooling water associated with the smaller service water systems.

The operator’s report or ‘fact sheet’ is submitted to the regulatory agency. In most states, the authority to regulate chemical discharges is delegated to the state environmental agency, with oversight from the federal EPA. The main caveat is that the state regulations have to be at least as stringent as the federal ones and, in many cases, they are more restrictive. Only a few states are not delegated with this authority, and in these cases, the permit application is assessed directly at the federal level.

The most important of the federal requirements governing discharges is the US Clean Water Act (CWA). Under this, the primary requirement governing discharges from large-scale steam generating plants (nuclear and otherwise) is the Code of Federal Regulations (CFR) Title 40, Part 423 (Steam Electric Power Generating Point Source Category) [40 CFR 423].

CFR Title 40 Part 423 specify a range of parameters for the waste streams of a generic power plant. They cover internal and external discharges with limits based on what should be achievable ‘at end-of-pipe’ using Best Available Techniques (BAT) and Best Management Practices (BMP). Some of the generic waste streams specified in CFR 40 are only relevant to fossil-fuelled plants. Those relevant to processes in a PWR plant are:

- once through cooling water;
- recirculated cooling water (in cooling tower circuits at inland plants);
- metal cleaning wastes (from periodic cleaning of the steam generators and decontamination and other maintenance facilities);

- steam generator blowdown;
- low-volume sources.

The range of parameters is relatively limited and, in most cases, the limits giving guidance that Best Available Techniques are being achieved are similar in discharges from the different generic processes. These so-called 'technology based' limits are summarised in Table 2.2.

Table 2.2 Generic parameters covered in 40 CFR 423

Parameter	Daily maximum (mg/l)	30-day average (mg/l)
Total residual chlorine	0.2	n/s
Free available chlorine	0.5	0.2
Total suspended solids	100	30
Oil and grease	20	15
Copper	1.0	1.0
Iron	1.0	1.0
Chromium	0.2	0.2
Zinc	1.0	1.0
USEPA priority pollutants (a selection of 126 metals and organic materials used or previously used in a range of industries and of particular concern from the standpoint of human or environmental toxicity)	Always to be reported as 'not detected'	Always to be reported as 'not detected'

Permit discharge limits may also be based on 'Water Quality Based Effluent Limits' (WQBELs). These are usually applied to the final discharges of the main cooling water to the environment after any discharges from internal plant outfalls have joined it. WQBELs take into account mixing in the river, lake or reservoir, and are calculated to make sure that the discharges do not cause any environmental standards in the receiving water to be exceeded.

Typical WQBEL parameters included in the permits for the US PWR power plants include hydrazine, trace metals, ammonia, amines, site-specific biocides and limits based on toxicity testing (often for local species of interest). Certain pollutants, such as those on the USEPA priority list, are required to be reported as 'not detected' when using a specified sampling and analytical technique, rather than as less than a numerical limit.

The permits may also include generic bans on discharges of 'any pollutant that may cause or contribute to an impact on aquatic life or pose a substantial hazard to human health or the environment due to its quantity or concentration' or blanket bans on specific groups of chemicals. Blanket bans usually include polychlorinated biphenyls (PCBs; previously used in transformers but now discontinued) and dioxins and/or those in a separate 40 CFR listing (40 CFR 122.42) that includes acrolein, acrylonitrile, nitrophenols and antimony.

The permits must be renewed every five years. Six months prior to the renewal date the plants submit analytical data for the listed pollutants and requests for any changes they require to the permit. In some renewals, plants will request removal of parameters from the permit if long-term monitoring has consistently shown values below detection.

2.2.1 A note on BAT in the USA

In the USA, discharges must be made in accordance with BAT and BMP. These are similar in meaning to these concepts in the UK:

- **Best Available Treatment Technology**. This is the technology-based standard of the Clean Water Act and is defined as the Best Available Technology Economically Achievable for privately owned treatment works. Effluent limit guidelines reflect the best performance technologies for a particular pollutant or group of pollutants, or for a category or class of point sources, that are economically achievable.
- **Best Management Practices (BMP).** These are schedules of activities, prohibitions of practices, maintenance procedures and other management practices to prevent or reduce the discharge of pollutants to waters. BMPs include treatment requirements, operating procedures, structures, devices and/or practices to control plant site run-off, spillage, leaks, sludge or waste disposal, or drainage from raw material storage. USEPA publishes guidance on the development of BMP Plans (USEPA 1993), which sites are required to produce and update. For many PWR power plants, these deal with thermal and flow impacts of cooling water on biota in receiving waters.
- **Best Professional Judgment.** This method is used by the permitting agency to develop NPDES permit conditions on a case-by-case basis, using all reasonably available and relevant data.

2.2.2 Summary of parameters in US PWR plant permits

The chemical parameters included in the permits for the US PWR power plants included in the current assessment are summarised in Table 2.3. The data have been assembled and filtered from the USEPA website (Annex A4) and cover parameters with limits and those where only monitoring is specified.

Table 2.3 indicates the cooling systems employed by the US PWR power plants. It suggests there are no significant differences in the permits for sites with once-through cooling or with cooling towers. This is because parameters in the permits are based on the federal requirements of CFR 40 Steam Generating Plant (Table 2.2) plus what may be demanded by state-specific regulatory bodies, independent of plant location. For example, the table shows, while they employ once-through seawater cooling, there is a more extensive set of parameters specified in the permits for the plants at San Onofre and Diabolo Canyon in California than, for example, the plant at Salem in New Jersey, which also uses once-through seawater cooling.

Further information on the permits and discharges from the US PWR power plants are given in Annex report sections A3 and A4.

Table 2.3 Summary of parameters in US plant permits and reports

	Beaver Valley	Byron	Comanche Peak	Seabrook	Calvert Cliffs	Millstone	Salem	San Onofre	Diablo Canyon	St Lucie
Once through cooling (O) or cooling towers (C)	**C**	**C**	**O**	**O**	**O**	**O**	**O**	**O**	**O**	**O**
Chlorination										
Free available chlorine	■		■	■		■			■	■
Total residual chlorine	■	■	■	■	■	■	■	■	■	
Bromine chloride						■		■		
Free available oxidants										■
Total residual oxidants								■		
Solids										
Settleable solids						■		■	■	
Total dissolved solids	■		■							
Total suspended solids	■	■	■	■	■	■	■	■	■	■
Other parameters										
Ammonia	■				■	■	■	■	■	
Biochemical oxygen demand five-day (BOD_5)								■		
Total organic carbon (TOC)	■							■		
Chemical oxygen demand (COD)						■	■			
Faecal coliforms	■	■						■		
Colour	■									
Total cyanide	■							■	■	
Dimethylamine										■
Hydrazine	■	■				■		■	■	■
Hydrogen peroxide								■	■	
Nitrite and nitrate								■		
Oil and grease	■	■	■	■	■	■	■	■	■	■
pH	■	■	■	■	■	■	■	■	■	■
Total phosphorus	■									■
Salinity								■		
Specific conductance						■				
Turbidity								■		
Physical parameters										
Flow through plants	■	■	■	■	■	■	■	■	■	■
Water temperatures	■	■	■	■	■	■	■	■	■	■
Metals										
Aluminium	■									
Antimony								■		
Arsenic	■							■		
Boric acid (boron)								■		
Cadmium				■						■
Chromium (hexavalent)		■		■				■		
Chromium total	■	■				■			■	
Copper	■	■	■	■	■	■	■	■	■	■
Iron	■	■	■	■		■		■	■	■
Lead		■		■		■		■	■	
Lithium						■			■	

	Beaver Valley	Byron	Comanche Peak	Seabrook	Calvert Cliffs	Millstone	Salem	San Onofre	Diablo Canyon	St Lucie
Once through cooling (O) or cooling towers (C)	C	C	O	O	O	O	O	O	O	O
Manganese	■									
Mercury								■	■	
Nickel		■		■		■		■	■	
Selenium								■		
Silver								■	■	
Thallium								■		
Titanium									■	
Zinc	■	■		■		■		■	■	
Biocides										
Aldrin, dieldrin, benzene hexachloride (BHC), heptachlor, etc.								■	■	
Clamcontrol	■				■					
Tributyl tin								■		
Toxicity tests (various)			■	■		■	■		■	■
Cleaning chemicals										
Citric acid, EDTA, formic acid, oxalic acid						■				
Surfactants						■				
Others										
PCBs								■	■	
Volatile organic compounds (VOCs) (USEPA list)								■		
Semi-VOCs (USEPA list)								■		

Notes: This table has been produced using downloaded and filtered data from the USEPA website. Plants may produce separate reports that may cover additional parameters monitored on an intermittent basis.

2.3 French regulatory regime

Nuclear power plants in France are regulated by the state organisation ASN (Autorité de Sûreté Nucléaire). One of ASN's stated objectives is 'the limitation of the dispersion of radioactive or chemical substances resulting from the nuclear activities to be achieved by strict control on discharge of effluents and management of waste'. This therefore covers radioactive materials as well as chemical ones. ASN states that any impacts of radioactive and chemical discharges on human health and the environment must be as low as reasonably achievable (ALARA). This integrated approach is reflected in the permits for the French plants.

Although the acronym BAT is not used, the introductory text in each discharge permit for the French PWR plants states that 'All steps must be taken in the design, construction, maintenance and operation of site facilities, in particular the use of best available technology at an economically acceptable cost, to reduce water consumption and impact of discharges.' According to the permits, the requirements for achieving this include the following generic approaches:

- Facilities where waste liquids originate must be designed, operated and maintained to maintain flow and make the discharged activity and quantity of chemical effluents as low as reasonably possible.
- Different categories of waste (radioactive, non-active, biological, chemical) should be collected as close to the source as possible and subjected to appropriate treatment before mixing with each other or with the final effluent.
- The facilities for treatment must be designed to cope with changes in the characteristics of the inflows, including during start-up or shutdown of the reactor or other systems.

The regulatory activities of ASN take account of the main French legal framework for the management of water resources. These include the 1992 Water Law and the 2006 Water and Aquatic Environment Law (which transposes the Water Framework Directive into French law).

ASN notes that this integrated approach across radiological, chemical and thermal discharges is different to many other countries where such discharges are regulated separately, as for example in the USA (Section 2.2).

2.3.1 Summary of parameters in French plant permits

Most sites in France have two or more reactor power plants, but the permits cover radiological and chemical discharges from the site as a whole rather than from individual reactors. Most limits in the permits are expressed in terms of mass flows (kg) within specific time periods of two hours, daily and annually. There are a few additional limits expressed as maximum allowable concentrations in the final hold-up tanks prior to discharge, in the main discharge canal (cooling water culvert) or in the mixing zone in the receiving water body. Limits on concentrations in the final hold-up tanks allow operators to time and co-ordinate discharges into the final cooling water culverts so that limits in these and in the final receiving waters are not exceeded. The permits for all the French sites cover a common suite of parameters which are summarised in Table 2.4.

Table 2.4 Parameters covered in permits for French plants

Parameter	Plant sources and comments
Boron	Primary circuit let-down. Also emergency and other shutdown and fuel systems. In more recent permits, limits are changed from gross site values to lower values with additional allowances for specific plant operations.
Lithium	Primary circuit let-down. Not specified in all permits.
Hydrazine	Secondary circuit and wet lay-up. Subject to greatest changes as permits are updated.
Amines	Morpholine and ethanolamine for some plants only
Ammonium (NH_4^+)	Specified for tanks serving the nuclear island (pH control in main steam circuit) with separate limits for other sources (such as water treatment) and for plants using monochloramine for cooling towers. Note that ammonium is a different chemical species with significantly lower environmental impacts than free dissolved ammonia (NH_3).
Morpholine and/or ethanolamine	pH agents used in the main steam circuit (selected plants).

Parameter	**Plant sources and comments**
Detergents	Site laundry and decontamination workshops.
Phosphates	Detergents and phosphate corrosion inhibitors used for wet lay-up.
Total phosphorus	Includes organic species.
Chemical oxygen demand (COD)	Specified in most permits.
Suspended materials	Site run-off and other plant sources. Specified in all permits.
Total metals	In all permits a single limit is given for total metals specifically from the nuclear island (including zinc, copper, manganese, nickel, chromium, iron, aluminium, lead).
Iron, copper, aluminium	In some permits separate limits are given for these metals in discharges from the nuclear island but more generally are for those from the demineralisation or other auxiliary water treatment plants.
Total residual oxidants, total residual chlorine	Specified for coastal plants using once through cooling and some inland plants using monochloramine treatment for cooling towers.
Free chlorine	Specified in permits for some inland plants using monochloramine treatment.
Organic species adsorbable on activated carbon	Specified in permits for some inland plants. Covers by-products of chlorination or monochloramine treatments.
Bromoform	Specified in permits for some coastal plants. Assumes this is the main trihalogenated by-product of chlorination.
Nitrites, nitrates	Specified in permits for inland plants using monochloramine treatments.
Hydrocarbons	Mainly specified effluents for general plant areas and storm water run-off.
Polyacrylates	Dispersants specified for cooling tower systems for some inland plants.
Biochemical oxygen demand, Kjeldahl nitrogen	Mainly specified in discharges from waste water or sewage treatment works.

Some of these parameters are only associated with discharges from the nuclear island routed through the radioactive waste treatment systems, or from the main steam circuit routed via large holding tanks in the turbine hall. For these parameters, the permits list a single discharge limit for routine operations with additional allowances for when the reactor and steam systems are shutdown. These allowances cover the necessary additional flows of chemically dosed water into the treatment systems and discharges during shutdown periods (Section 1.6.4).

When parameters arise from several different sources and discharge through different routes, several different limits may be specified in the permit. This is mainly the case for suspended solids and hydrocarbons. These may have separate limits specified for discharges from the nuclear island and from other site areas. There are also separate limits for the discharges from the raw water treatment plants.

All the permits for the French PWR plants and sites also specify a range of generic requirements including:

- no impacts on the colour of the receiving waters;

- for coastal sites, an absence of impacts on flora and fauna outside a zone extending for 50 m around the point where discharge of the once through cooling water takes place;
- no visible films from hydrocarbons – permits generally state that oil separators serving open areas such as parking must be capable of accommodating flow from severe storm events occurring once every ten years and lasting for ten minutes;
- no odour from samples immediately after they have been collected nor after they have been incubated at 20°C for 24 hours;
- limits on sodium and chloride, generally for discharges from water treatment plants;
- limits on BOD_5 for effluents discharged from general waste water treatment plants (dealing with foul water or from workers accommodation areas);
- requirements for extensive ecological surveys and assessments (for example, Lampert et al. 2007 covering those for the plant at Paluel).

Further details of the permits and limits applied at the French power plant sites and the discharges of chemicals are given in Annex report sections A5 and A6.

2.4 German regulatory regime

Germany's nuclear power programme uses a combination of BWR and PWR reactors, as well as some prototype or experimental reactors. Some larger facilities such as the five PWRs at Greitswald have been shutdown but a significant number of PWR power stations remain in commercial operation. Neckarwestheim and Isar 2 are examples of PWRs based on the Siemens/KWU design, features of which have been incorporated into the UK EPR™. They were therefore included in the current survey.

Nuclear reactors in Germany are regulated by the German Nuclear Safety Standards Commission (KTA), the Reactor Safety Commission (RSK) and the Commission on Radiological Protection (SSK). Chemical and radioactive discharges are regulated at the national level by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. At the local level they are regulated by individual state bodies which issue permits for discharges.

Since German Unification in 1989, the arrangements have led to a somewhat fragmented regulatory regime with differing requirements in different German states. For this reason, a new regulatory regime came into force in March 2010 with the German federal government being wholly responsible for conserving and protecting water resources, as well as the control and issue of discharge permits.

Further details of the permits and limits applied at the German predecessor sites and the discharges of chemicals are given in Annex report section A7.

3 Chemical discharges from PWR plants in the survey

An overall summary of the main chemicals in use and potentially discharged from the PWR power plants covered in the current study is provided in Table 3.1. It is based on information collated from the plant surveys included in the Annex report.

Table 3.1 lists the main bulk chemicals used. It is not intended to provide an exhaustive list of all the chemicals that might be used across a site as a whole. It is not possible to define all the proprietary systems that any plant may use, although most will contain one or more of the individual chemical types in the table as their main active ingredient. The table also lists several metals that are not normally discharged or used (such as mercury and lead) but which could be potential contaminants.

The final column notes if the chemicals are included in the Generic Design Assessments for the UK EPR™ or AP1000™. Within this column, 'n/s' indicates that the chemical is not specified within GDA documents; however, these chemicals may well be present either individually or within proprietary mixtures on the operating plant.

Table 3.1 provides an overall list of chemicals used and potentially discharged from:

- **Primary reactor circuit and connected systems**. These are confined to boric acid and lithium hydroxide. Active effluents from the site laundry or plant drains may contribute a range of other chemicals such as complexing agents. All these will initially pass through the radioactive waste treatment systems prior to final discharge.
- **Main steam circuit and auxiliary plants.**
    - Additives in the main steam circuits and used for the all volatile treatments such as hydrazine, amines and ammonia. The amines dissociate and form ammonia and a series of hydrolysis products, some of which will be taken up on ion exchange resins in the condensate polishing plant or steam generator blowdown systems. The dominant species released when these are regenerated is ammonium (NH_4^+).
    - Chemicals in effluents from the regeneration of ion exchange resins, backwashing of filters and other routine procedures in the raw water and waste water treatment systems. These are mainly neutral salts of sodium, calcium and magnesium. Discharges are on an intermittent but regular basis.
    - Additives used for the wet lay-up of plant systems during maintenance. These are mainly phosphates but also include hydrazine and a range of alternatives such as carbohydrazide. These may be recycled or discharged at the end of the maintenance period.
    - Additives in coolants used in recirculating and service water systems. Some plants use chromate-based systems, others molybdates or nitrite borax mixtures. Minor additives are likely to include chemicals to prevent build up of scales and dispersants. These are only discharged when the systems are flushed or renewed.
    - Residues of oil and hydrocarbons from small spillages or areas where fuel is stored. These would be discharged after treatment through oil water separators.

  - Acids, complexing agents and heavy metals from the periodic cleaning of plant systems or of the main steam generators.

- **Main cooling water circuits, once-through seawater or recirculating cooling towers**.

Table 3.1 Summary chemical listing

	Application	Comments	Discharges	GDA
Primary circuit				
Boric acid	Primary circuit activity control.	Used in all plants in the primary circuit and in safety systems and fuel storage ponds.	Internal discharges diluted to very low levels in final discharges. Mass discharged up to about 10,000 kg/year per reactor.	EPR™ and AP1000 ™
Lithium hydroxide	Primary circuit pH control.	Used in all plants.	Mass discharged in the range of 10–100 kg/year.	EPR™ and AP1000 ™
Other active areas				
Surfactants	Used in site laundry and decontamination workshops.	Mostly proprietary types for specific water and washing conditions.	Treated through radioactive waste plant. May be discharged in kilogram quantities but can be reduced using biotreatments. Contribute to phosphates in discharges. Mass discharged in the range 200–1,000 kg/year.	EPR™ and AP1000 ™
Complexing agents, e.g. EDTA	Used in site laundries and decontamination solutions for plant systems.	Used in proprietary systems and mixtures.	Mass discharged in the range of 100–1,000 kg/year per reactor.	n/s
Citric acid (decontamination agent)	Used in site laundries and decontamination solutions for plant systems.	Used in proprietary systems and mixtures.	Mass discharged in the range of 100–1,000 kg/year per reactor.	n/s
Oxalic acid (decontamination agent)	Used in the periodic cleaning of steam generators.	Used in proprietary systems and mixtures.	Intermittent discharges on a less than annual basis only. May be handled via off-site contractors.	n/s
Other circuits				
Hydrazine	Secondary circuit oxygen control. Wet lay-up of plant systems during shutdown and maintenance.	Used in all plants with some changes in limits allowed. Significant worker health hazard.	Attention in French and US plants on reduction in discharges of hydrazine. Unstable and breaks down to ammonia, nitrogen and water. Mass discharged 10–100 kg/year	EPR™ and AP1000 ™
Carbohydrazide	Secondary circuit oxygen control	Alternative to hydrazine identified in some US predecessor plants.	Breaks down to water, carbon dioxide and nitrogen oxides. Mass discharged about 10–100 kg/year.	n/s

	Application	Comments	Discharges	GDA
Ammonia	Secondary circuit pH control plus other sources. Monochloramine treatment in wet cooling towers.	Used in the secondary steam circuit in most plants either directly dosed or as a breakdown product from hydrazine. Also originates from use of hydrazine in wet lay-up of plant systems and from regeneration of ion exchange reins in steam generator blowdown systems.	Neutralised in plant to form ammonium sulphate (NH_4^+). Major contributor to total nitrogen in discharges. Mass discharged 100–10,000 kg/year.	EPR™ and AP1000™
Hydrogen peroxide	Used to treat hydrazine and in small amounts for reactor operations and other plant systems.	Only small amounts used. Decomposes readily to water and oxygen.	Used in small amounts only. Decomposes readily to water and oxygen Mass discharged less than 10–100 kg/year.	EPR™ and AP1000™
Ethanolamine	Alternative to ammonia for pH control in steam circuit.	Alternative to ammonia for pH control in the main steam circuit.	May be discharged from regeneration of condensate polisher resins or from condensate. Mass discharged about 1,000–2,000 kg/year.	EPR™
Morpholine	Alternative to ammonia for pH control in steam circuit.	Main alternative to ammonia for pH control in the main steam circuit.	May be discharged from regeneration of condensate polisher resins or in surplus condensate. Mass discharged about 1,000–2,000 kg/year.	EPR™
Sarcosine (2-methylamino acetic acid)	Alternative to ammonia for pH control in steam circuit.	Not identified as applied at plants in current scope	May be discharged from regeneration of condensate polisher resins or in surplus condensate.	n/s
5-Aminopentanol	Alternative to ammonia for pH control in steam circuit.	Not identified as applied at plants in current scope	May be discharged from regeneration of condensate polisher resins or in surplus condensate.	n/s
Aminomethyl propanol	Alternative to ammonia for pH control in steam circuit.	Not identified as applied at plants in current scope	May be discharged from regeneration of condensate polisher resins or from condensate.	n/s
3-Methoxypropylamine	Alternative to ammonia for pH control in steam circuit.	Neutralising amine in combination with hydrazine to prevent corrosion in steam condensate systems or in other low solids aqueous systems.	May be discharged from regeneration of condensate polisher resins or from condensate.	n/s
Pyrrolidine	Alternative to ammonia for pH control in steam circuit.	Neutralising amine in combination with hydrazine to prevent corrosion in steam condensate systems or in other low solids aqueous systems.	May be discharged from regeneration of condensate polisher resins or from condensate.	n/s
Sulphuric acid	Used to regenerate cation exchange beds in water treatment plants and as anti-scale treatment in	Used at all plants covered in the study. Main agent to control (neutralise) pH of discharges to meet usual pH target range of 6–9.	Used in large quantities but neutralised prior to discharge to form neutral salts of calcium, magnesium or sodium sulphate. Mass discharged 5,000 to >10,000 kg/year.	EPR™ and AP1000™

	Application	Comments	Discharges	GDA
	cooling towers		Larger amounts discharged from cooling tower circuits.	
Sodium hydroxide	Used to regenerate anion ion exchange resins.	Used at most plants. Main agent to control (neutralise) pH of discharges to meet usual pH target range of 6–9.	Used in large quantities but neutralised prior to discharge to form neutral salts of sodium.	EPR™ and AP1000 ™
Hydrochloric acid	Used for regeneration of ion exchange resins and cleaning agent.	More rarely used than sulphuric acid.	Would generally be neutralised prior to discharge.	n/s
Sodium carbonate	Cleaning agent and builder used in detergents etc.	Common chemical additive.	Likely to be neutralised prior to discharge to form neutral sodium salts.	n/s
Sodium phosphate	Corrosion inhibitor for wet lay-up of plant systems.	Used where hydrazine cannot be used.	Main contributor to inorganic phosphates in discharges.	EPR™ and AP1000 ™
Sodium hexametaphosphate	Corrosion inhibitor for wet lay-up of plant systems.	Used where hydrazine cannot be used.	Main contributor to inorganic phosphates in discharges.	EPR™
Sodium nitrite	Corrosion inhibitor in auxiliary plants.	Alternative to chromate and molybdate as a corrosion inhibitor.	Infrequent discharges only during flushing of plant systems. Mass discharged about 100–5,000 kg/year	n/s
Borax (sodium tetraborate)	Corrosion inhibitor in auxiliary plants.	Alternative to chromate and molybdate as a corrosion inhibitor.	Infrequent discharges only during flushing of plant systems. Mass discharged about 100–5,000 kg/year.	n/s
Potassium chromate	Corrosion inhibitor in auxiliary plant systems.	Used at only a few plants. Now superseded by other types.	Infrequent discharges only during flushing of plant systems. Mass discharged about 50 to 1,000 kg/year.	n/s
Sodium molybdate	Corrosion inhibitor in auxiliary plant systems.	Used in plant systems , cooling circuits etc	Infrequent discharges only during flushing of plant systems.	n/s
Methoxypropylamine	Corrosion inhibitor in auxiliary plant systems.	Identified at Seabrook, Diablo Canyon, Millstone	Infrequent discharges only during flushing of plant systems.	n/s
Benzotriazole	Corrosion inhibitor mainly for copper systems.	Used in small copper based systems only. Copper systems are very rarely connected directly to primary plant systems.	Infrequent discharges only during flushing of plant systems.	n/s
Tolytriazole	Corrosion inhibitor mainly for copper systems.	Identified at Byron and Diablo Canyon only.	Infrequent discharges only during flushing of plant systems.	AP1000 ™
Amino trimethylene phosphonic acid	Complex corrosion inhibitor typical of proprietary systems.	Example of a proprietary scale inhibition, corrosion inhibition, chelating agent system	Infrequent discharges only during flushing of plant systems.	n/s

	Application	Comments	Discharges	GDA
Hydroxyphosphono-carboxylic acid	Complex organic anti-scale, corrosion inhibitor typical of proprietary systems.	Example of a proprietary multi-functioning anti-scale and corrosion inhibitor.	Intermittent discharges during flushing of plant systems but potential more continuous discharge from cooling tower circuits.	n/s
Amino trimethylene phosphonic acid (AP)	Typical organic phosphonate anti-scale and corrosion inhibitor	Example of a proprietary multi-functioning anti-scale and corrosion inhibitor also used in cooling towers.	Intermittent discharges during flushing of plant systems but potentially more continuous discharge from cooling tower circuits.	n/s
Brine	Outflow from membrane treatments of seawater.	Identified in plants using membrane technologies for treating seawater for use in the plant.	Already present in seawater but would be an issue for discharges to freshwater	n/s
Ferric chloride	Flocculant in used in treatment of waste water.	Used in raw and waste water treatment.	When used as flocculant, mostly directed to solid non-radioactive waste.	n/s
Aluminium chloride or sulphate.	Flocculant in used in treatment of raw water.	Used in some raw water treatment plants	When used as flocculant, mostly directed to solid non-radioactive waste.	n/s
Cresyl phosphate	Hydraulic fluid	Stored on site and used for hydraulic fluid	Only in faults or spillages.	EPR™
Cooling water				
Chlorine	Once through seawater cooling systems. Usually added via an electrolysis system or dosed as sodium hypochlorite.	Monitored in discharges via tests that usually measure total residual oxidants rather than chlorine itself. Discharge is common to non-nuclear and fossil fuelled power plants.	Controlled in once-through cooling water systems in accordance with usual cooling water BAT (see Section 4.3.9). Limits in the range of 0.1–0.5 mg/l; a flow of five million m^3 /day, equivalent to about 200,000 kg/year per reactor.	EPR™ and AP1000™
Chlorine dioxide	Used in some seawater cooling systems	Not identified as used in the PWR plants covered in the current survey.	Not identified in the plants covered in the survey.	n/s
Bromoform/bromine compounds.	No use identified	By-product of chlorination.	Varies according to chlorination and local conditions. Limits of the order of 0.05 mg/l and mass limits around 5,000–11,000 kg/year.	EPR™ and AP1000™
Polyacrylic acid (dispersant)	Dispersant used in cooling towers and waste water treatment.	Used in cooling tower circuits	Continuous discharge associated with cooling water. Mass limits 1,000–2,000 kg/day.	n/s
Organic phosphonates	Corrosion and anti scale chemicals	Used in proprietary multi-functioning anti-scale and corrosion inhibitors in cooling tower circuits.	Identified for some US plants.	n/s
Corrosion products				
Copper	Additional use as biocide and in anti-foul coating in cooling towers. Some	Trace metal from corrosion of auxiliary plant but also biocide.	Likely to be diluted to very low concentrations in cooling water flows. Limits likely to be based on environmental quality	EPR™

	Application	Comments	Discharges	GDA
	older plants use copper condenser tubes that can leach copper.		standard in any receiving water.	
Zinc	Primary circuit additive at µg/l levels only.	Trace metal from corrosion of auxiliary plant systems and galvanised plant areas (such as roofing). Primary circuit additive used at very low concentrations only.	Likely to be removed in waste systems as particulates and/or ion exchange systems prior to discharge and then further diluted in main cooling water. Run-off is likely to be the main source of zinc in discharges.	EPR™ and AP1000™
Nickel	No use as an additive identified.	Trace metal from corrosion of stainless steels used in plant systems.	Not likely to appear in discharges in detectable levels.	n/s
Manganese	No use as an additive identified.	Trace metal from corrosion of stainless steels used in plant systems.	Not likely to appear in discharges at detectable levels.	n/s
Iron	Added as a coagulant in some water treatments.	Corrosion product from carbon steel auxiliary plant systems. From raw water treatment.	Mostly removed in waste systems and solid oxide/hydroxide precipitate (that will also scavenge other trace metals.	n/s
Chromium	Normally only used as chromate corrosion inhibitor.	Trace metal from corrosion of stainless steel plant	Mostly removed in waste systems and solid oxide/hydroxide precipitate (that will also scavenge other trace metals.	n/s
Lead	No use as an additive identified.	Trace metal mostly from impurities in plant systems and other bulk additive chemicals.	Mostly removed in waste systems and solid oxide/hydroxide precipitate (that will also scavenge other trace metals.	n/s
Mercury	No use as an additive identified.	Identified as a potential impurity in sodium hydroxide in one US plant. (Diablo Canyon)	Not likely to appear in discharges at detectable levels.	n/s
Other parameters				
Chlorinated hydrocarbons	Solvents used on site in small quantities only.	Likely to be controlled at source and will occur in effluents only due to accidental spillages.	Fugitive discharges only, i.e. due to small leaks.	EPR™
Leaching from antifouling coatings	Identified in some cooling tower systems.	Most toxic types replaced by other systems (see Section 7.2.6). Some cooling towers use concrete supports and do not require anti-foul coatings.	Fugitive discharges only, i.e. due to small leaks.	n/s
pH	General water/waste water quality parameter.	Mostly specified in the range of 6–9 in permits.	Water/waste water quality parameter.	EPR™ and AP1000™
Chemical oxygen demand (COD)	General water/waste water quality parameter.	Specified for waste systems from nuclear island	Water/waste water quality parameter.	EPR™ and AP1000™
Biochemical oxygen	General water/waste water	Specified for foul water systems only.	Specified for support plant only. Not for the	EPR™

	Application	Comments	Discharges	GDA
demand (BOD)	quality parameter.	Other sources include backwash water from cooling water systems (screens and debris filters).	nuclear island.	and AP1000 ™
Suspended solids	General water/waste water quality parameter.	Suspended solids removed in settling basins or filters in treatment plants. May consist of ferric or aluminium oxides. Suspended solids from other plant areas will consist of grit and solids from settling basins or coarse screens.	Specified in all permits. Mass discharges of 1,000–10,000 kg/year per reactor.	EPR™ and AP1000 ™
Oil and hydrocarbons	Used in plant systems, especially turbine hall and standby diesel generators. Present in run-off from parking and service areas.	Generally treated using oil water separators.	Specified from auxiliary plant and run-off only.	EPR™ and AP1000 ™
Herbicides/pesticides	Used to control site vegetation.	Outside areas only.	Fugitive discharges only. Most types now biodegradable. Noted in some US plant permits.	n/s

4 Main chemical discharges and use of BAT in PWR plants and candidate designs

4.1 Introduction

Section 1.6 described the individual plant systems in a PWR power station that use and potentially discharge chemicals to air and water. The review of operating PWR power stations (in Section 3 and the Annex report) identified many different chemicals that are used. However, only a few of these chemicals are used on a large-scale or will potentially be present in routine discharges to water. This section provides further detail on the more important chemicals and describes aspects of Best Available Techniques (BAT) that are either applied or are potentially available to minimise the discharges and any associated environmental impacts.

4.2 Background to the concept of BAT

The Integrated Pollution Prevention and Control (IPPC) Directive 96/61/EC aims to minimise pollution from point sources throughout the European Union by applying a unified approach across Member States. A key principle central to implementing IPPC is the application of BAT to minimise discharges of waste to air, water and land. Strictly, radioactive discharges from nuclear power stations are regulated under separate regulations but the Environment Agency (2010c) has stated that BAT must also be applied to minimise radioactive discharges:

> 'BAT are the means by which an operator optimises the operation of a practice in order to reduce and keep exposures from the disposal of radioactive waste into the environment as low as reasonably achievable, economic and social factors being taken into consideration (ALARA). That is, where an operator uses those techniques which represent BAT then they will be taken to have met the requirements of optimisation and ALARA'.

There is no equivalent specific definition for chemical discharges from any form of power installation, other than a generally stated aim of achieving:

> 'A high level of protection to the environment taken as a whole by, in particular, preventing or, where that is not practicable, reducing emissions into the air, water and land'.

Most UK technical guidance on what is considered as BAT in each industrial sector covered by IPPC is based on the sector-specific BAT Reference Documents (BREFs). These are agreed between EU Member States and industry. They explain what should be implemented in a particular type of industrial plant to ensure that the overall objectives of BAT are met, which are minimal environmental impacts, taking account of costs and local factors.

Certain auxiliary plant systems in nuclear power stations, notably the larger standby emergency diesel generators, are regulated under IPPC and subject to a standard set of BREFs that govern how discharges should be minimised. However, discharges of chemicals from the nuclear island are not covered and there are no universally agreed methods considered BAT for minimising such discharges (like there are for discharges to air and water from large-scale fossil fuel power plants). For this reason, the term BAT is not fully applicable to nuclear plants, although the emphasis for chemical discharges is always on the preventative techniques of:

- minimising the use of chemicals or substituting for less hazardous ones;
- containment and engineering controls and general good housekeeping;
- segregating chemicals and waste streams to allow optimised and tailored treatments prior to discharge;
- abatement and treatment followed by analysis and monitoring;
- preventative maintenance;
- training and inspection procedures and implementation of Environmental Management Systems (ISO 14001).

The preventative measures with minimisation at source are always preferable to 'end-of-pipe' technologies or 'dilute and disperse'.

Permitting of plants under IPPC is gradually being replaced by the Environmental Permitting Regulations (2010) regime, which includes both radioactive and non-radioactive discharges (Section 2.1). However, the overall requirements, especially with respect to application of BAT, will remain broadly the same.

4.3 BAT for specific chemicals

This section provides an overview of the techniques used at the PWR plants covered in the current study that are used to minimise the use or discharge of specific chemicals in accordance with the principles of BAT.

4.3.1 Boric acid

Boric acid is a major additive in the primary circuit coolant of all PWRs and is central to controlling nuclear reactivity during all stages of reactor operation (Section 1.6.1). Boric acid is prepared and stored as a concentrated solution (usually about 7,000 mg/l boron). During refuelling of the reactor or during shutdown, the boron concentration in the reactor coolant needs to be maintained at about 2,000 mg/l. This is then reduced to about 1,500 mg/l to allow the reactor to be brought to criticality (reactor start-up) and to start generating useful heat. To compensate for fuel burn-up over a 12–18 month fuel cycle, the concentration is progressively reduced to essentially zero (burn-up refers to the consumption of the fissionable uranium-235 in the fuel, coupled to the build-up of fission products that gradually reduce its efficiency). This is done by let-down of the borated coolant into the waste treatment systems and replacing it with purified make-up water. Large volumes in excess of 250 m^3 of boric acid in aqueous solution (also containing low mg/l levels of ^7LiOH and traces of radioactivity, mainly tritium) need to be managed and handled over each fuel cycle.

Some PWRs are operated in a load following mode, where reactor power and station electrical output are altered to respond to changes in demand from the electrical grid. This can be done by changing the concentrations of boric acid in the coolant, by using the reactor control rods or by a combination of both. French plants currently use control rods for load following without the need to alter the concentrations of boron in the primary circuit. This strategy would be used in the AP1000™ if load following was adopted (see Section 2.6.3 in Westinghouse 2010a). If plants were to choose to adjust reactor power for load following by changing the concentration of boric acid in the coolant, they will need to manage surplus reactor coolant containing boric acid.

Avoiding the need to shut down and then re-start the reactor part way through a fuel cycle will avoid the need to increase the boron in coolant to 2,000 mg/l and subsequently diluting it to allow start-up. Ensuring that impurities in the coolant (radioactive ones and others such as chloride or silica) are maintained at low levels minimises the need for let-down of coolant into the waste systems.

For the boric acid solutions that do arise over each fuel cycle, a survey of the current PWR plants (Annex report sections A2 to A5) and a separate study by Bates and Pick (1996) show that there are several approaches to ensure that waste borated reactor coolant is minimised in accordance with the principles of BAT. These are outlined below.

Evaporation of coolant to recover the boric acid and water

Some plant designs include a dedicated on-site boric acid evaporator system that treats the let-down by evaporation to recover the boric acid as a concentrate (usually at about 7,000 mg/l) and also to produce a purified distillate. Both of these can be reused later in the fuel cycle or during subsequent fuel cycles. The UK EPR™ has this type of system (see Section 1.1.2.1 in UK EPR™ 2010c). The system incorporates degassing of the distillates to remove gaseous activity that may be carried over during evaporation. However, recycling in this way can be constrained by several factors:

- The boric acid recovered can be of insufficient quality (for example with respect to chloride or other impurities) to allow it to be reused in the primary circuit. Moreover, tritium can build up in the distillates which could cause excessive worker dose when reused (mainly from inhalation of tritiated water vapour released from water storage tanks or fuel ponds). This would not be maintaining doses to workers in the plant ALARA. Because of this, the UK EPR™ also allows for discharge of the distillates and concentrates as waste.

- There can be build-up of radioactive material (especially cobalt-60) in the evaporator plant. This will result in high doses to maintenance workers which again may not be consistent with ALARA. There have also been problems with the reliability of some evaporators due to corrosion by the high levels of boric acid that build up in the concentrates.

- During the later parts of the fuel cycle, the concentration of boric acid in the reactor coolant falls to only a few mg/l and the volumes of let-down to be treated increase appreciably. This may require the evaporator to be run almost continuously to recover boric acid concentrates containing a useful concentration of 7,000 mg/l boron. This consumes significant energy and operator effort and may not be cost-effective. An alternative strategy is to only use the evaporator during the initial parts of the fuel cycle when the let-down contains higher levels of boric acid (more than about 1,000 mg/l) and then discharge the more dilute let-down produced later in the fuel cycle.

There is little information on the use of evaporators in the plants covered in the survey. Most information suggests that, even where they have been installed, their use is not generally favoured and alternative strategies for managing borated coolant over the fuel cycle are used.

Use of ion exchange systems

Some plants are equipped with a boron thermal regeneration system. These use special ion exchange resins to remove boron from the primary coolant towards the end of each fuel cycle; the treated effluent can then be returned to the reactor as part of the overall boron dilution process. This minimises the need to discharge used coolant and the need to use fresh make-up water. The special resins are passed through a tailored thermal cycle to release the boric acid as a concentrate, which can be stored and used in the next fuel cycle (or rejected as waste). The resins can then be reused. This technology is installed and used at Seabrook and various other US PWRs.

An alternative method of ion exchange is to use a standard deep bed resin (that cannot be regenerated) to remove boron from the primary circuit let-down during the later parts of the fuel cycle when boron concentrations have fallen to between 50 and 300 mg/l. The treated effluent can then be returned to the reactor system as make-up. Once the ion exchange bed becomes exhausted (saturated by boron), it is treated as a solid low-level radioactive waste stream. This approach has been used at Calvert Cliffs and St Lucie; however, the used resins appreciably increase the amounts of low level radioactive waste generated. Some French plants have dedicated anion exchange beds used for this operation (although no information was available for those included in the current survey; Annex A5).

Discharge of boric acid

Even though plants may be equipped with evaporators or ion exchange systems, operational problems (such as increased worker doses) or problems with increased amounts waste may prevent them from being used.

In these cases, an option is to treat the let-down in the radioactive waste systems (to remove fission products by ion exchange and activation products by filtration) and then discharge the resultant effluent containing boric acid and traces of tritium (which cannot be removed by treatment) in to the environment. Discharge is invariably with the main cooling water to maximise dilution. The operation is controlled to ensure that discharges of radioactive material in the effluent (in particular, tritium) remain well below the relevant limits in force.

The AP1000™ generic design assumes that the final hold-up tanks contain a maximum of 2,700 mg/l boron and that this is discharged at 22.7 m^3 per hour into the once-through seawater cooling of 136,000 m^3 per hour. Therefore the boron concentration in the cooling water would be increased by only 0.45 mg/l for only 128 hours per year. This boron discharge is considered negligible in relation to the Environmental Quality Standard (EQS) for boron in seawater of 7 mg/l and the background concentration of boron in seawater of about 4.5 mg/l (Mance et al. 1988). Westinghouse claims that treating the effluent to remove activity then discharging it (containing boric acid) to sea is BAT, rather than its recovery by evaporation (see Section 3.3.4.2 in Westinghouse 2010a). For this reason, the AP1000™ does not include an evaporator plant for the recovery of boric acid from waste streams.

Sizewell B has a boric acid evaporator but to date the practice has been to discharge the surplus borated reactor coolant to sea rather than recycle it. Concentrations of boron in the discharge from this procedure have consistently remained well below the discharge limit of 1 mg/l (see Annex A2).

There are no readily available data for the US plants, although several record discharges of boric acid from the radioactive waste system (such as St Lucie and Diablo Canyon, Annex A4) but without detail on whether it constitutes all of the let-down or only a portion that has not been recycled. Fact sheets for Seabrook and Byron present calculations that show discharges of boric acid (even to inland water sources) will have no impact on boron limits in the receiving waters after dilution in the cooling water outfalls (Annex A3.3 and A3.5). None of the US permits or fact sheets mention any problems or issues with the discharge of boric acid (compared with the greater attention paid to those of hydrazine, see Section 4.3.3).

For the French plants covered in the survey, it is not always clear whether boric acid is recycled or discharged. However, mass discharges of boric acid are always below any limits that are in the site permits (Annex A5.4).

Direction of boric acid to a solid waste stream

At some inland plants, it is not permitted to discharge boric acid as an aqueous waste stream. Therefore it may need to be recovered by evaporation then directed to a solid waste route, usually using cement or a polymer for encapsulation. Adding magnesium oxide or hydroxide followed by calcium oxide or hydroxide will form a gel-like material, which can then be more readily mixed with cement. An alternative for concentrates containing up to 30 per cent boric acid is to use sodium metasilicate before mixing with cement. This alternative is not used at any of the PWR plants covered in this current survey, but it is practised at some inland Russian PWR plants.

Use of boric acid enriched in boron-10

Only the boron-10 isotope is involved in controlling nuclear reactivity in a PWR, via the $^{10}B(n,\alpha)^{7}Li$ reaction. The natural abundance of the boron-10 isotope is about 19.8 per cent, with the remainder of boron being boron-11. Using boric acid artificially enriched in boron-10 can achieve the same control over nuclear reactivity, but using a lower concentration of boric acid. This is called enriched boric acid (EBA). There are a number of operational advantages in the use of EBA (EPRI 2001):

- It allows the pH of the coolant to increase, which then reduces the transport of corrosion products (such as cobalt-60) and so reduces radiation doses to plant workers. It also reduces the tendency of solid deposits to form on the fuel (which can affect reactivity or cause other operational problems).
- It increases safety shutdown margins when mixed oxide (MOX) cores or more highly enriched fuel are used in the reactor.

EBA is sometimes considered as a BAT approach to reactivity control. Seven of the most recent Siemens PWRs, including the EPR™ predecessor Neckarwestheim, have been converted to operate with EBA containing 27–30 per cent boron-10. EBA has been proposed for the EPR™ but not the Westinghouse AP1000™.

The main disadvantage of using EBA is that it is much more expensive than boric acid of natural isotopic composition. To minimise costs, a number of management options have been developed in plants where EBA is used. These include:

- only using EBA in the systems that are directly connected to the primary circuit during normal operation at power. Back-up and fuel storage systems which do not require regular flushing are filled with boric acid of normal isotopic composition. This technique is used at Millstone (Annex A3.9).
- recycling through the conventional boric acid evaporators in the radioactive waste plant (as in the UK EPR™), through a boron thermal regeneration system, or through a membrane (reverse osmosis) system, recently developed for this purpose in the USA.

As well as the benefits associated with the reactor itself, there will be reduced discharges of boric acid to the environment. Additional maintenance and worker dose issues will need to be considered on a case-by-case basis.

4.3.2 Lithium hydroxide

Lithium hydroxide is used to control pH in the primary coolant at concentrations of up to about 3–4 mg/l (Section 1.6.1). It is artificially enriched in the lithium-7 isotope to minimise the formation of tritium from lithium-6. Over the fuel cycle there is some uptake of lithium in the ion exchange beds, although most plants use resins that are already supplied in the lithium-7 form to avoid this. Lithium-7 will be present in any reactor coolant discharged from the primary circuit to control concentrations of boron, therefore it appears in a number of downstream systems and discharges.

Although lithium hydroxide enriched in lithium-7 is expensive, only relatively small amounts are used at reactor start-up and concentrations are not sufficient to make its recovery (such as by special ion exchange resins) economically viable. Furthermore, recovered material would contain unacceptably high levels of chemically similar fission products such as caesium-137. In the final discharge to the environment, lithium is present at very low concentrations, is already present in seawater and has low toxicity (Section 7).

For these reasons, all the PWR plants covered in the current survey consider that BAT for the management of this primary circuit additive is to discharge it in aqueous effluents or, if boric acid is recovered as a solid waste stream in the radioactive waste evaporators, to direct it to this solid waste route as well.

4.3.3 Hydrazine

Most discharges of hydrazine originate from its use as an oxygen scavenger and pH control agent in the main steam circuit (Section 1.6.2) or in plant systems subjected to wet-lay up during shutdown or maintenance (Section 1.6.4). Hydrazine reacts with dissolved oxygen:

$$N_2H_4 + O_2\,(aq) \rightarrow 2H_2O + N_2(gas)$$

and may decompose to ammonia which controls pH:

$$2N_2H_4 \rightarrow 2NH_3 + N_2 + H_2 \text{ and then } NH_3(aq) + H_2O \leftrightarrow NH_4^+ + OH$$

Hydrazine is stored as a 35 per cent weight solution. It is used as a dilute aqueous solution (about 0.1 mg/l) during operation of the main steam circuit to maintain dissolved oxygen concentrations below 0.005 mg/l. During wet lay-up and maintenance it is used in plant systems at concentrations of up to 100 mg/l. A soluble catalyst is sometimes added to increase the rate of reaction between hydrazine and dissolved oxygen in cold water systems.

Across the plants included in the survey, BAT to minimise discharges of hydrazine involves the following:

- Minimising the need for hydrazine dosing at source. This includes ensuring that, prior to use, the levels of dissolved oxygen in the main steam circuit water have been reduced as far as possible to below normal saturation conditions (about 8 mg/l O_2). Dissolved oxygen can be removed using physical degassing, bubbling nitrogen or steam through the water to displace oxygen (sparging), or by heating and retaining the water under a low pressure. Re-absorption of oxygen by stored water can be avoided by using nitrogen blankets or floating membranes that cover water surfaces in storage tanks. Ingress of air into the plant systems is prevented.

- Gas separation technology could potentially be used as a replacement for traditional atmospheric degassers and also for de-aeration of make-up water prior to its use in the steam circuit of PWRs (DTI, 2006).
- Degassing methods are never sufficient to reduce levels of dissolved oxygen to the very low values required for secondary circuit operation or wet lay-up. Only chemical dosing can be used for this. Hydrazine might be replaced by alternative oxygen scavengers. A number of plants in the USA, such as Byron, note the potential use of carbohydrazide (Annex A3.3). The chemical name for this is 1,3-diaminourea [$CO(NHNH_2)_2$], and unlike hydrazine, it is a solid and is less toxic to workers. However, there is no evidence that carbohydrazide is currently approved for use at any of the plants for the secondary circuit at power and it would not rival the worldwide experience available in the use of hydrazine in standard all volatile treatment of PWR systems. It may be more suitable for replacing hydrazine in the less critical conditions of wet lay-up. Alternatives to hydrazine were not noted in the permit data for the French PWR plants (Annex A5).
- Other alternatives to hydrazine have been considered in literature but were not identified in any of the PWR plants covered in the current survey.
- Accidental discharges of hydrazine can be minimised by preventing leaks or spillages and ensuring that excessive quantities are not stored on the site. Minimising the size of storage facilities for hydrazine on site will also reduce requirements that could arise under the Control of Major Accident Hazards (COMAH) Regulations.

There is extensive guidance on the use of hydrazine for the wet lay-up of plant systems (especially steam generators) by the US Electrical Power Institute (EPRI 2005). BAT is to initially use high quality water to fill the plant systems to minimise the potential for corrosion (especially by chloride). Then hydrazine is generally maintained above 75 mg/l to keep dissolved oxygen concentrations at less than 0.1 mg/l. For the UK EPR™, wet lay-up of the steam generators during shutdown is based on a baseline concentration of about 75 mg/l, with 7 mg/l additional hydrazine for every day the plant system is shut-down (see Section 2.2.2.10.2 Chapter 6.2 in UK EPR™ 2010c). Then it can either be drained to the turbine hall sumps or left in the steam generators for start-up, when it will be converted entirely to ammonia (about 20 kg) and mostly discharged to air via the condenser extract system.

Concentrations of hydrazine used for wet lay-up are clearly much higher than used in doing the main steam circuit at power (about 0.1 mg/l). Intermittent discharges from this activity may be a larger source of hydrazine than those from the operation of the main steam circuit at power.

Alternatives to hydrazine for wet lay-up and tested by EPRI (2005) include carbohydrazide and di-ethyl hydroxylamine (DEHA). These are noted in the permits for several of the US plants covered in the current survey, although with little information on actual application or plant experience. The EPRI report concludes that:

> 'However, breakdown products such as carbonates have caused many plant operators to return to dealing with the high concentrations and discharge limitation issues of hydrazine'.

Salem's steam cycle improvement plan (Annex A3.6) includes replacing a number of treatment chemicals, including hydrazine, with methoxypropylamine, polyacrylic acid and ammonium chloride. Other alternatives for corrosion control in cold water circuits include molybdate, azoles, ammonium benzoate, phosphonates, polyphosphates and biodegradable polymers. Some of these involve high levels of dissolved solids and would not be suitable for use on a PWR nuclear island.

Options for on-site treatment of dilute solutions of hydrazine discharged from plants after wet lay-up include oxidation using 30 per cent hydrogen peroxide (H_2O_2). This has reduced discharges of hydrazine from Millstone by over 50 per cent and allowed the limit for hydrazine in the relevant internal outfall to be reduced from 75 to 37 mg/l (Annex A3.9). Some plants, such as Beaver Valley, suggest using sodium hypochlorite to oxidise excess hydrazine because this provides additional biocidal activity in the treatment tanks. The UK EPR™ proposes to destroy hydrazine in the final hold-up and sentencing tanks prior to discharge. The AP1000™ documentation notes that hypochlorite will be used to treat accidental spills of hydrazine in the turbine hall prior to these being washed to the turbine hall sumps for discharge.

Some US plants do not highlight hydrazine as being an issue. This may be because they assume that hydrazine is decomposed entirely into ammonia, ammonium and water and therefore any final aqueous discharges contain only negligible levels of residual hydrazine.

4.3.4 Ammonia (ammonium), morpholine, ethanolamine

Ammonia and amines are stored as concentrates (up to 35 per cent ammonia) but used in the plants as dilute solutions, typically between 1 and 100 mg/l. Ammonia and amines are mainly used in the secondary steam circuit. Some ammonia will arise from decomposition of hydrazine used in secondary circuit treatment and in the wet lay-up of plant systems (Sections 1.6.2 and 1.6.4).

Most ammonia should be retained in the water phase of the steam circuit. However, some remains in the steam/volatile phase and may be discharged to air via the condenser extract system (a vacuum system that assists in maintaining the condenser at low negative pressure to help draw in the steam from the turbines). Aqueous ammonia will be taken up by the ion exchange beds in the condensate polishing plant or in the steam generator blowdown treatment system until the concentrations reach equilibrium with the circulating water. When the ion exchange resins are regenerated, the ammonia is released mainly as ammonium sulphate. The proportion of ammonia (NH_3) and the less environmentally harmful ammonium ion (NH_4^+) in the final plant effluents depends on the equilibrium between:

$$NH_3\,(aq) + H_2O \leftrightarrow NH_4^+ + OH^-$$

The equilibrium shifts to ammonia when the pH is above about 9.0 and to ammonium at lower pH. Generally speaking, at pH 8.0, the proportion as NH_3 is around 10 per cent or less. At a pH slightly above 9.0, the proportion is about 50 per cent. The equilibrium shifts in favour of ammonia with increased temperature. Under the pH conditions specified in the plant permits, and the pH range that effluents are neutralised to prior to discharge (between 6 and 9), the dominant species will be ammonium. As internal plant effluents are mixed with the main cooling water, the lower temperatures and pH values closer to 7 will increase the dominance of ammonium. This is why ammonium is the species specified in the permits for all French plants (Annex A5.2.4).

BAT to minimise discharges of ammonia will be to minimise its use at source, that is, by implementing control measures to maintain the quality of feedwater in the secondary circuit and by minimising the use of hydrazine for dosing and wet-lay up of plant systems (Section 4.3.3 and also Odar and Nordmann 2010). Operators at most plants covered in the current survey appear to consider that dilution is BAT for minimising discharges of ammonia, as well as ensuring that the pH of the effluent is close to neutral, so that the less toxic ammonium ion (NH_4^+) is maintained as the dominant chemical species. However, specific ammonia treatments proposed include the following:

- Electro-deionisation to remove ammonia from steam generator blowdown prior to it being directed to the steam generator blowdown ion exchange units. The concentrate containing the ammonia can then be reused in the feedwater, although the primary objective is to avoid premature saturation of the ion exchange beds by ammonia and so reduce the generation of a potential solid radioactive waste stream (Goffin and Calay 2000). Electro-deionisation is proposed for the steam generator blowdown system in the AP1000™ (Section 4.2.2.2 in Westinghouse 2010a), although it is not clear if it is specifically for ammonia or for other impurities in the blowdown.
- With respect to end-of-pipe abatement methods, Neckarwestheim has a specialised system for steam stripping of ammonia from effluents from the condensate polishing plant and steam generator blowdown system (Annex A7.1). This is required partly due to higher than normal levels of ammonia used to control the chemistry in the steam circuit (so-called 'high all volatile treatment') coupled to especially stringent limits on the discharge of ammonia and ammonium into the Neckar River.

There is no specific information on BAT for abatement of ammonia discharges to water from conventional power plants. Most information relates to using ammonia for scrubbing flue gas or controlling nitrogen oxides (NOx) in burners (Environment Agency 2002). However, bioremediation has been proposed to reduce levels of ammonia in water from the washing and immobilisation of flyash.

Amines may be added to secondary side coolant to control pH act in the same way as ammonia, that is, by acting as a weak base that partially dissociates into the main pH controlling species. An example is ethanolamine:

$$(OH)CH_2CH_2NH_2 + H_2O \leftrightarrow (OH)CH_2CH_2NH_3^+ + OH^-$$

The main advantage is that the amine and its conjugate remain more fully in the water phase which increases protection against corrosion (EPRI 1997). As the condensate passes through ion exchange beds (in the condensate polishing plant or in the steam generator blowdown system), the positive charged base is taken up by the cation bed (displacing H^+). When the beds are regenerated using sulphuric acid, it is released again as the free amine. Small amounts of the organic amines may decompose in the steam circuit to form traces of organic acids (mainly acetic and formic). However, the main effluents are dilute solutions of the amines released from the cation beds during regeneration. This is reflected by limits for morpholine or ethanolamine in the permits for the French PWR plants, where these amines are used for controlling secondary circuit chemistry (Annex A5.1.1 to A5.1.7).

Operators select the types of amines to use based on their efficiency in preventing corrosion. Plants with copper in the steam circuit, especially those with copper condenser tubes, need to use morpholine because ammonia cannot be used in copper-based systems. There is less consideration of the relative toxicity or environmental impacts of different amines in the final discharges.

Amines may also be used in conjunction with hydrazine and ammonia for wet lay-up of the steam generators. Use of ethanolamine and morpholine for wet lay-up at concentrations between 30 and 150 mg/l is noted for the UK EPR™ (UK EPR™ 2010c).

BAT for minimising discharges of amines will centre on minimising the use amines at source by maintaining the purity and quality of the feedwater in the secondary circuit, and minimising the frequency the ion exchange resins in the condensate polishing plant (or steam generator blowdown system) are regenerated, which otherwise acts as a source of amine discharges. Some end-of-pipe treatment methods identified for amines in effluents from nuclear plants include the following:

- Electrolytic destruction of amines in effluents from PWR plants in Korea. Operational experience on the plants suggests the process is not very efficient and consumes large amounts of energy, so it may not be BAT (Rhee et al. 2007).
- A US patent (Rhee et al. 2009) describes a method to capture ethanolamine from the steam circuit side of nuclear/conventional power plants by evaporation. The resultant concentrate containing the amines is then treated in anoxic and aerobic digestion tanks, forming carbon dioxide and nitrogen. This leaves an aqueous waste stream that has a lower oxygen demand and total nitrogen content, and lower toxicity.

These techniques could probably only be applied to the relatively concentrated solutions of amines arising from internal plant outfalls rather than the much more dilute solutions after effluents are mixed with larger flows of main cooling water. They have not been identified as being used on any of the plants covered in this survey.

4.3.5 Regeneration chemicals (sulphuric acid and sodium hydroxide)

Large-scale cation and anion (or mixed) ion exchange beds are used for treating raw (towns) water and in the condensate polishing plants of many PWR power plants. Smaller scale ion exchange plants may be used, for example, in the steam generator blowdown lines (Sections 1.6.2 and 1.6.3).

The resin beads in these beds eventually become exhausted. When this happens, the impurities they are meant to remove from the feedwater start to appear in the treated water (called ‘breakthrough’). The resins then have to be regenerated using acids and alkalis, usually sulphuric acid and sodium hydroxide at concentrations between 2 and 6 per cent. Once the ion exchange beds are regenerated, they are backwashed to remove any unspent acid/alkali and the salts that have been released from the resins (mostly those of calcium, sodium and magnesium from the cation and chloride and sulphate from the anion resins). This leaves the resins in a refreshed form ready for reuse. A simplified scheme showing use of anion and cation resins in separate beds is shown in Figure 4.1. Some systems use anion and cation resins in mixed beds that require separating into the two resin types for regeneration, after which the resins are again mixed together.

The spent acid and alkali and back washings are neutralised in tanks to between pH 6 and 9 (as specified in the permits). If required, flocculation is used to remove sediments and fines that may have been washed from the resins. The final neutral salt solutions are then discharged, usually via the main cooling water flow or cooling tower blowdown. These processes are identical to those used on the raw water and condensate polishing systems in fossil fuel power plants.

BAT for the use of sulphuric acid and sodium hydroxide starts with correct storage and spillage control, and ensuring that only the minimum quantities required for normal operation are stored on-site. Minimising the consumption of purified make-up water will reduce the need for frequent regeneration of ion exchange beds used to treat raw water. Some plants implement stringent water management plans and operators of US

PWR plants are required to submit a water balance as part of their permit application (for example, Byron Annex A3.3). Using a source of raw water that requires minimal treatment to make it suitable for use in the plant will also contribute to minimising discharges from any raw water treatment system.

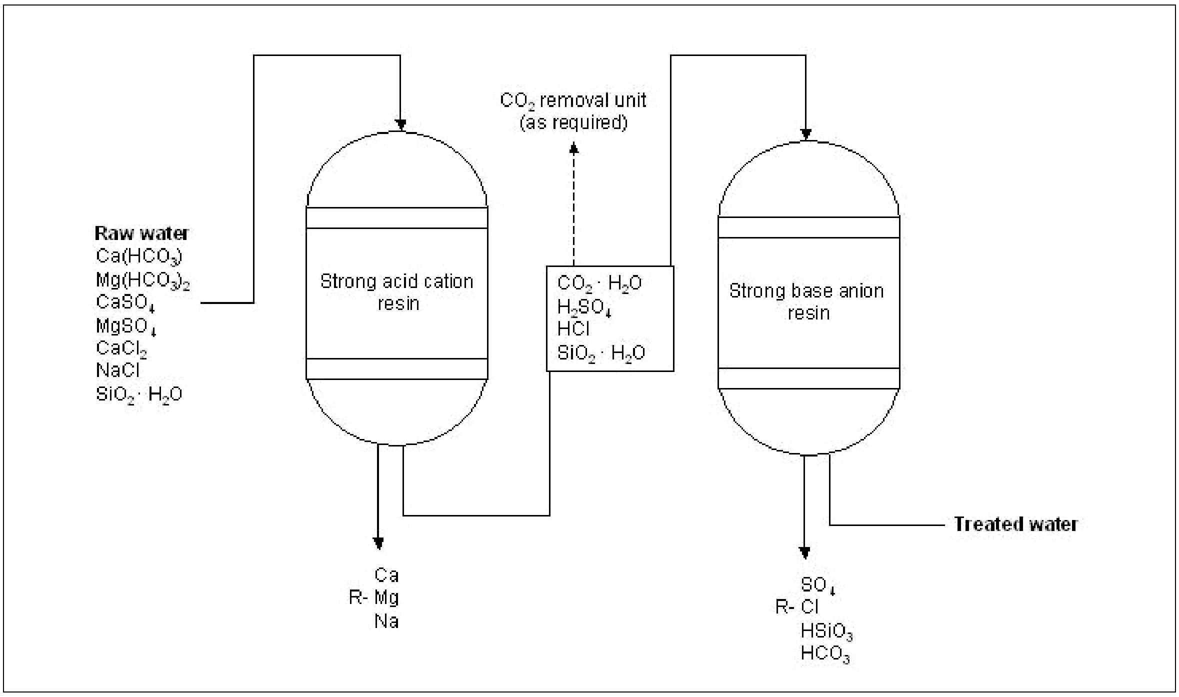

Figure 4.1 Simplified outline of the regeneration of cation and anion exchange resins in raw water or condensate polishing plant

Starting with and then maintaining high purity feedwater during the operation of the main steam circuit will reduce the need to regenerate ion exchange beds in the condensate polishing plant and therefore minimise the discharge of chemicals from this process. Most plant operators specify that feedwater in the steam circuit must always have a conductivity of less than 0.08 µS/cm and concentrations of Na^+, SO_4^- and Cl^- less than 2 µg/l Therefore it is crucial to minimise leakage of cooling water through the main condenser tubes and into the steam circuit. Use of titanium tubes in the main condensers at Sizewell and most other coastal plants has minimised this problem. This means that condensate polishing plants only need to be used occasionally at start-up, or with reduced throughput, and in turn the resins require regenerating less frequently and fewer chemical effluents are generated.

By reducing the need for full flow condensate polishing, large capacity deep bed ion exchange systems may no longer be required. Instead pre-coat systems can be used., These only require a small volume of resin which, when exhausted, is more usually rejected as a solid waste rather than being regenerated (Tavares and Applegate 2008). Many French plants have decided to avoid having a large-scale condensate polishing plant altogether, instead relying on a smaller steam generator blowdown system to treat the feedwater in the steam circuit. This will be implemented in the UK EPR™ (UK EPR™ 2010e).

Using new types of ion exchange resins in deep bed systems can also reduce the need for regeneration. An example is the ultra-low chloride resins used at Millstone, which have greatly increased the service life and the volume of condensate that can be treated before the resins need regenerating (Annex A3.9 and Yarnell 2008). Changing the types of resins that are used is relatively easy to implement compared with changes to the design of a condensate polishing plant.

Build-up of ammonia or amines in the ion exchange beds in condensate polishing plants can lead to early exhaustion of the resins and the need for frequent regeneration. To avoid this, some plants use a smaller front-end or so called ‘guard bed’ that preferentially absorbs these secondary circuit additives. As this smaller bed becomes exhausted, it can be regenerated using smaller amounts of acid and alkali than would be required for the main beds, which can then remain in service for a longer period of time. Other alternatives to the problem of early exhaustion of ion exchange beds due to secondary circuit additives are:

- use of high capacity strong acid cation resins that provide longer run lengths prior to the breakthrough of amines and so reduce the need for regeneration and its associated waste effluent;
- use of proprietary cation beds that are already in the ammonia (or appropriate amine) form.

In the USA, some contractors offer a service to take ion exchange resins off-site for regeneration. This will avoid the need to store bulk quantities of acid and alkali on-site, and will reduce site discharges from regeneration. The procedure obviously requires plant operators to have two sets of resins – one being in use and one being off-site and regenerated by the contractor (EPRI 2004). The new raw water treatment plant at Hinkley Point B regenerates its ion exchange resins off-site in order to reduce site discharges and maintenance effort.

Other recent developments in secondary circuit design ensure that the quality of the feedwater is correctly maintained and corrosion is minimised, contributing to achieving BAT and reducing the discharge of chemicals (Murau and Schottler 2005). Some assessments suggest that these secondary side discharges contribute up to 40 per cent of overall chemical emissions to water from conventional power plants. Improvements in secondary circuit design are essential to achieving the ‘zero emissions’ concept (Section 6.4). New developments include, for example, ‘advanced cascading blowdown’ or ‘on-demand condensate polishing’ where, rather than being used in deep beds, ion exchange resins are injected directly in to the condensate flow as and when required, and are then recovered by hydrocyclones (EPRI 2004). These features were developed after the PWR plants covered in the current survey were designed and built (in the 1970s and 1980s). There may be some opportunities to use them in the conventional steam-side of future nuclear power plants (EPRI 2006). However, unlike simple substitution of resin types (discussed by, for example, Yarnell at Millstone), they involve more fundamental changes to plant design which may be more difficult and costly to implement.

Ion exchange beds are also used in PWRs for treating aqueous radioactive waste streams, notably in the chemical and volume control system (that treats primary circuit coolant) and the radioactive waste systems. These beds are mostly less than about 1 m^3 in volume and, because they handle active materials, they are not regenerated for reuse. Instead, when exhausted they are mobilised by backwashing and then directed to the solid radioactive waste treatment systems. Filters in the radioactive systems are also directed to a solid waste route, rather than being cleaned and reused.

4.3.6 Use of membrane technologies for raw water treatment

Use of membrane technologies (such as reverse osmosis) to prepare make-up water reduces the need for ion exchange and has been implemented on some US plants, such as Beaver Valley and Seabrook (Annex A3.2 and A3.5). Treated water from membrane plants usually still requires final polishing by ion exchange, but using much smaller systems. Note that membrane technologies are not generally applicable to condensate polishing (where the replacement technology for deep bed ion exchange units is to use ion exchange resins in alternative configurations, as described in Section 4.3.5; see DTI 2006).

A multi-flow deionisation plant, which also employs a polyamide reverse osmosis unit, was installed to treat raw water at Hinkley Point B in 2004. The treatment also involves using activated charcoal to remove trace organics from the raw water (which could otherwise affect water chemistry in boilers). Figure 4.2 shows a view of this plant with the storage tanks and membrane modules.

Some membrane systems can treat seawater, which might be BAT for reducing the consumption of scarce water resources drawn from utility suppliers or groundwater (extracting groundwater from coastal aquifers can exacerbate saline intrusion). The waste stream from these is brine. Discharge of brine can be a problem from large desalination plants used to supply public water, but would probably be less of an issue for any smaller scale plant used to supply treated water to a power plant site.

Figure 4.2 Membrane plant for raw water treatment at Hinkley Point B (supplied and installed by GE Water and Process Technologies)

Point Beach, although not covered in the current survey, is a PWR plant where older deep bed ion exchange systems for the treatment of raw water have been replaced with membrane filters and reverse osmosis units. This is claimed to have reduced effluent production by about 60 per cent, which has reduced operating costs and improved the quality of the feedwater used for the reactor and steam systems (Sundstrom and Weynberg 2005).

The AP1000™ design for the UK includes two 100 per cent reverse osmosis units operating in series for primary demineralisation, and two 100 per cent electro-deionisation units for secondary demineralisation of raw water for make-up supplies to all plant systems (see Section 2.7.3 in Westinghouse 2010a). It also uses electro-deionisation to treat the steam generator blowdown (a membrane treatment that is made more effective by the application of an electrical charge across the membrane; see Section 4.2.2.2 in Westinghouse 2010a).

The decision to use these systems for raw water treatment would need to be made on a case-by-case basis, taking account of the type of water to be treated, the cost of the plant, its reliability and maintenance requirements as well as the chemical discharges from its operation. Membrane technologies are not entirely effluent-free. Seabrook (Annex A3.5.1) notes a requirement to continuously dose its system with proprietary chemicals to prevent scale build-up. The AP1000™ proposes to use polyphosphates for this. Nevertheless, operators of US plants such as Beaver Valley (and Point Beach) note that less waste effluent is produced from raw water treatment when using membrane technologies compared to when using deep bed ion exchange systems.

4.3.7 Oil and grease

Within the nuclear reactor system itself, the largest amounts of oil are used in the main reactor circuit coolant pumps. This needs to be changed at intervals. The used oil is potentially active (mainly due to cobalt-60) and is managed via a suitable radioactive oil waste treatment route. Traces of oil and grease in discharges are mainly from the turbine hall, auxiliary plant systems (especially standby diesel generators) and rainwater run-off from car parking and other open plant areas (Section 1.6.3). These sources are similar to those from conventional fossil fuel power plants.

Most plant permits specify an absence of floating films of oil in discharges. They are also limits on the concentration of entrained or emulsified oil droplets present in suspension.

For areas storing fuel oil or diesel, BAT include providing secondary containment and bunds. These need to be of an appropriate size to accommodate any breach of the tank or pipework. Valves and pipes must have suitable locks and underground pipes need to be pressure tested for leaks. Some permits (such as Byron, Annex A3.3) note the availability or continuous use of skimmers and booms around final discharge points to contain spillages or oil films, especially from discharges due to stormwater.

Permits for most US PWR plants include stormwater management plans as part of their overall approach to BAT for minimising discharges of oil and grease in run-off from parking or oil storage areas. For French plants, the permits specify installation of systems that are capable of managing oily run-off resulting from one in ten year stormwater events. These systems will include interceptors (where initial separation of oil and water can take place) and oil–water separators (which treat the aqueous effluent prior to discharge). Interceptors can intercept larger accidental spills before they reach a discharge point.

All the plants included in this survey use oil–water separators as BAT for abatement of low levels of oil and grease in plant effluents (notably from the turbine hall). Oil–water separators are included in the designs for the AP1000™ and UK EPR™. The design and performance of these vary. All oil–water separators rely on gravity separation and floatation of what are normally immiscible mixtures of water and hydrocarbons. When hydrocarbons are mixed in water (for example due to the presence of surfactants), other methods may be required to clean up the effluent such as flocculation, induced air floatation, ultrafiltration or biological treatment. None of these were identified in the descriptions of the PWR plants covered in the current survey.

Vendors for the AP1000™ and UK EPR™ have presented extensive information to demonstrate application of BAT for the storage of oil and lubricants for the large emergency standby diesel generators. Examples include:

- appropriate design of oil and fuel storage areas including permanent fuel stores, delivery areas and temporary storage areas for intermediate bulk containers (IBCs) and drums containing oil or other additives such as anti-freeze;

- incorporating sumps and retention areas for oily water, such as arising from fire fighting;
- appropriate design and construction of subsurface structures and sumps;
- maintaining the condition and coating of hard surfaces in all areas associated with the diesel plant and fuel storage facilities to prevent oil and spills soaking through.

The UK EPR™ requires the storage of 4,000 litres of cresyl phosphate (see Chapter 3.3 in UK EPR™ 2010a). This is an organophosphate hydraulic fluid and oil additive containing a mixture of *ortho*-, *meta*- and *para*-cresyl groups (sometimes abbreviated to TOCP). It is a hazardous material that requires particular attention to avoid spillages. Again, no routine discharges in water should be expected.

Monitoring for discharges of oil and grease probably depends more on the sampling and analytical methods used than any other parameter. The US plants dataset includes a range of analysis methods. These include the initial extraction of oil and grease using different solvents (Freon, carbon tetrachloride) with subsequent analysis of the extract using infra-red spectrometry, gravimetric analysis or gas chromatography. The results obtained using these different methods can vary significantly. Fact sheets for the US plants covered in this survey show frequent discussion of the methods that should be used to give the most consistent results (such as USEPA Method 1664A) and note that the method should be specified in the final plant permit.

An example where the method has had effects on the results reported for hydrocarbons is at Salem (Annex A3.6). Until about 2007, levels of hydrocarbons in two internal outfalls varied from being not detected to up to 30 mg/l. Around 2007 a change in the analysis method has given results consistently quoted as ‘less than 5 mg/l’, which represents the detection limit of the new applied technique.

4.3.8 Suspended solids

These consist of insoluble materials held in aqueous suspension. They can be removed from effluents by physical means such as gravity settling (with or without the aid of flocculants) or by filtration. They originate from plant systems, building structures and roofing areas, open site areas or areas where construction is being carried out.

Suspended solids in the primary coolant consist of corrosion products and, since these may be radioactive (mainly due to cobalt-60), they must be removed in the primary circuit clean-up system using special cartridge filters. Filter ratings are selected to ensure maximum retention of the particulates to prevent them moving into downstream systems (where they would give rise to worker dose) and eventually discharges. The German PWR Isar 2 uses electromagnetic filters to remove particulates. BAT for the abatement of particulates from the reactor systems aims to reduce radiological, rather than non-radiological impacts on water or ecosystems (Section 1.6.3).

Other plant systems are made mainly of carbon or other low alloy steels. Particulates from these will be dominated by iron corrosion products (rust). Formation of rust and other corrosion products is minimised by chemical dosing during operation, wet lay-up and maintenance. This ensures that plant systems achieve their design life. Any iron oxides that are mobilised when the systems are flushed out are either collected in settling tanks and/or removed from effluents using coarse (mesh) and fine filters. For example, the French plants incorporate 5 and 25 μm filters and there are also coarse filters in the discharge path from the hold-up tanks serving the nuclear island and turbine areas. Similar filters are specified for the AP1000™ and the UK EPR™.

Several US plant operators note that settling of suspended solids can be enhanced (reducing the levels of solids in effluents) by using coagulation and flocculation coupled with settling and filtration. These techniques may be required to manage sediments from the overflow from large collection basins under wet cooling towers. However, permits for the French inland plants suggest that BAT in these plant areas is to carry out continuous dosing with dispersants to reduce the build-up and accumulation of sediments in the cooling tower collection basins and ensure their continuous removal in the cooling tower blowdown.

Sediments and bulk solids will also originate from cooling water intake screens. Backwashing will generate large sized solid and mostly putrescible or biodegradable waste, which may need to be disposed of to landfill or by incineration.

Particulates from roofs of buildings are minimised at source by using corrosion-resistant or other roof coating systems. For coastal sites, there may also be a need to minimise fouling of roof areas by seabirds. This could act as a source of run-off containing solids and with a high biochemical oxygen demand.

Suspended solids in run-off from open ground areas are minimised at source by maintaining hard standings and by emptying interceptors and catch-pots regularly. Areas that need free drainage should be covered by shingle rather than loose soil or sand. Other areas of soil are grassed or covered by vegetation. Areas where construction is taking place (such as temporary roadways) will need specific controls to avoid erosion and formation of run-off containing high levels of sediment.

4.3.9 Biocides and control of biofouling

At some plants, flow rates combined with natural scouring by suspended materials is sufficient to prevent any initial build-up of biofilms, colonisation by shellfish and associated fouling in the main cooling water systems (such as at Salem). However, the majority of PWR plants need to take action to minimise the build-up of biofilms or other biological activity in the main cooling circuit, including the intake culverts and the cold side of the condensers on the turbine generators. These growths would otherwise reduce flow and create localised conditions where corrosion becomes more likely (Section 1.6.2). The plant systems requiring this protection are the same as those in fossil fuel power plants.

There is extensive guidance on what contributes to BAT for the control of biofouling (European Commission 2001a, Environment Agency 2010b). An overview of this is provided below, but with emphasis on what has been established for the PWR power plants covered in this survey.

Figures 4.3 and 4.4 show the effects of build-up of the common mussel (*Mytilus edulis*), which is the most common problem in plants around the UK.

Figure 4.3 Mussel infestation in a main cooling water culvert (drained for maintenance) (By permission of KEMA)

Figure 4.4 Mussel infestation at the entry to the cooling tubes in the main condenser (By permission of KEMA)

Control of biofouling in once-through seawater cooling systems

For once-through systems, control of biofouling starts with correct design of the main cooling water system. This includes minimising the susceptibility of plant systems to corrosion, which could lead to leaks in the condensers. The emphasis is on the condenser tubes; previously copper and copper nickel alloys were used which offer their own biocidal effect on the cooling water. But because the release of copper from these cannot be actively controlled, they are no longer favoured but still remain applicable to specific water conditions. Now titanium tubes are preferred, and because the tubes are thinner, heat transfer and thermal efficiency are improved. Titanium tubes are used at most of the plants covered in this survey and for the AP1000™ and UK EPR™. Calvert Cliffs (Annex A3.11) is an example of a US plant where older copper condenser tubes were replaced with titanium, which decreased the levels of copper discharged (although the driver for replacement is likely to have been operational issues such as leaks rather then the relatively minor copper leaching).

Chemical dosing in once through seawater systems needs to take account of IPPC guidance and local site-specific conditions. IPPC for industrial cooling systems (European Commission 2001a) suggests that, for seawater cooling systems, levels of free residual oxidants in the discharge of less than 0.5 mg/l (with a 24-hour average of 0.2 mg/l) demonstrate that chlorination is being carried out in accordance with BAT. This will vary depending on whether the dosing regime is continuous or discontinuous. These values are consistent with those in US CFR 40 for total residual chlorine (0.2 mg/l daily maximum) and free available chlorine (0.5 mg/l daily maximum and 0.2 mg/l 30-day average). The data for Sizewell B (Annex A2) and for the US plants that use once through seawater cooling (Annex A3) show that those operators are able to meet these requirements. The process of restricting chlorination on a seasonal basis (when water temperatures are above about 10°C and infestation becomes more likely) is illustrated by datasets for US plants such as Calvert Cliffs and Seabrook (Annex A4).

A summary of the *generic* chlorination regimes for the UK EPR™ is shown in Table 4.1, including the halogenated by-product bromoform. It shows the levels of chlorination of the main once through cooling water system, with additional dosing limited to 10 non-consecutive days per year. Shock treatment is only applied to smaller service water systems, and is required to cover their greater complexity and presence of dead legs.

Table 4.1 is summarised from Section 5.4.3.3 in UK EPR™ PCER Chapter 3.4 (UK EPR™ 2010a). The expected and maximum concentrations of total residual oxidants (TRO) and bromoform are ‘realistic values for the expected discharge based on the experience of existing units’. Chlorine dosing would be adjusted for any specific site. The use of exceptional chlorination on non-consecutive days is consistent with practice at the US plants covered in this survey.

Table 4.1 Expected and maximum values for parameters associated with chlorination on the UK EPR™

	Total residual oxidants	**Bromoform**
Normal chlorination 0.5 mg/l every 30 seconds	Expected at outlet 0.14 mg/l	Expected at outlet 0.0027 mg/l
	Maximum at outlet 0.5 mg/l	Maximum at outlet 0.02 mg/l
Exceptional chlorination 1 mg/l for up to 10 non-consecutive days per year	Maximum at outlet 1.0 mg/l	Maximum at outlet 0.04 mg/l
Service water system Shock chlorination at 6 mg/l	Maximum at outlet 0.72 mg/l	Maximum at outlet 0.0244 mg/l

Although the plan for Hinkley Point C (EDF 2010a) is to install a chlorination plant, it should never need to be used because the scouring effect of sand should prevent biofouling (similar to the US plant Salem, see Section A3.6). The effects of chlorination are considered in its environmental assessment, which conservatively assumes that the concentration of chlorine at the outlet is equal to the concentration at the inlet – should the situation arise where the site had to use chlorination.

The Environmental Report for the AP1000™ suggests dosing once-through cooling water at the inlet with 0.2 mg/l chlorine (hypochlorite), applied only seasonally when water temperatures are above 10°C. In this case, the expected residual chlorine in the discharge is about 0.197 mg/l (Westinghouse 2010a, Section 4.2.5.1). The report notes that with dosing tailored to exact local and seasonal conditions, total residual oxidants in the discharge as low as 0.05 mg/l may be achievable. This is consistent with the low levels of residual chlorine recorded in some US plants (such as 60 µg/l in once through cooling water from Calvert Cliffs). The report also notes chlorine dosing of the smaller service water systems but with no figures quoted for the dosing regime. There are no predictions for concentrations of bromoform in discharges from the AP1000™, although there is an extensive list of potential chlorination by-products and reference to the fact that these will be site-specific and depend on the types of organic material already present in the water.

Levels of chlorine and/or total residual oxidants reported in discharges from once-through seawater cooling systems can depend on the analytical method used. For example, field methods may only be designed to ensure that cooling water in the discharge culverts is below a limit of 0.1 mg/l. Analysis using laboratory techniques allows actual concentrations to be reported. This could explain some of the differences in levels of residual oxidants reported in discharges from some of the US plants. A useful summary is provided by Harp (2002).

Halogenated by-products are formed as a result of chlorination. These include trihalogenated organics such as bromoform ($CHBr_3$) and more complex ones that are termed 'adsorbable on charcoal' (AOX) in French permits. The compounds formed depend on the type of organic carbon already present in the cooling water (Jenner et al. 1997, Environment Agency 2010b). Permits for coastal French plants give limits for bromoform while inland sites give limits for AOX (Annex A5). The limits for AOX are generally consistent with the IPPC guideline value of 0.15 mg/l (end-of-pipe) considered to demonstrate BAT (Annex VI in European Commission 2001b).

Although trihalogenated organics can be removed from water using activated charcoal (used to treat drinking water), this is unlikely to be considered as BAT for treating large flows of once through cooling water. BAT to minimise the discharges of halogenated organic materials relies on tailoring the chlorination regime to site-specific conditions, and understanding the organic carbon present in the cooling water (Jenner et al. 1997).

BAT in cooling systems includes ensuring that chlorination is applied only when required, that is, according to the season, the water temperature or when problematic species appear in the local area. A recent development is pulse chlorination (Polman and Jenner 2002, Jenner et al. 2004). This involves introducing chlorine at short intervals and in concentrations adapted to the longer term colonisation and short-term feeding behaviour of mussels and clams (the main problem species in most seawater systems). It is claimed to reduce the use and impacts of chlorine by over 50 per cent compared to standard longer term dosing regimes (Polman and Jenner 2002).

A number of techniques are available to treat chlorinated water. They use chemical dosing, usually sodium thiosulphate or sodium sulphite, which are applied to water held in tanks on a batch basis, by continuous dosing into the flow or combinations of both (Norecol et al. 1997). The hypochlorite is converted to sodium chloride and oxygen. These techniques are considered in the AP1000™ report (Section 4.2.5.1 in Westinghouse 2010a) and discussed at length by Wilde and Shealy (1992) for treating smaller discharges from experimental reactors in the USA. However, these are unlikely to be considered as BAT for the cooling water flows from a large-scale power plant.

Maintenance of systems can involve remote mechanical cleaning of the condenser tubes and flow path using foam balls or brushes. In the larger parts of the cooling water system such as the culverts, the entire system might be drained and then cleaned manually using high pressure water jet washing (as shown in Figure 4.3).

Control of biofouling in cooling tower systems

Design features to minimise the effects of biofouling in wet cooling towers centre on using biofilm-resistant packing. Older designs used timber supports and splash slats to distribute the cooling water through the tower; these were generally treated with paints or preservatives containing copper chromate arsenate or tri-*n*-butyl-stannane oxide (*bis*-tributyltin oxide). They are now not generally considered to represent BAT because of leaching of the copper, arsenic or tin. More modern and acceptable alternatives for timber supports include other copper-based systems such as copper quaternary ammonium. However, most modern designs avoid using timber altogether. The plant at Byron, for example, uses concrete structures to support plastic splash slats. These are also less susceptible to clogging and so increase cooling efficiency.

US plants routinely use chlorination to control biofouling in cooling towers. However, French inland plants like Chooz and Golfech generally use monochloramine (NH_2Cl), although the main emphasis appears to be minimising the discharge of waterborne pathogens such as Legionella, rather than control over biofouling. Dosing by monochloramine is achieved by initial dosing of water with chlorine followed by dosing with ammonia. While monochloramine is the main product formed, it is accompanied by low levels of dichloramine ($NHCl_2$), trichloramine ($NHCl_3$) and organic chloramines; the relative amounts of which depends on the initial ratio of ammonia to chlorine, the pH and the temperature. These secondary products have less disinfection power than monchloramine.

Some of the advantages of monochloramine treatment are:

- monochloramine produces lower concentrations of disinfection by-products (especially trihalomethanes, THM) because it is less reactive with natural organic matter compared with chlorine;

- monochloramine provides longer lasting protection than chlorine and for this reason is sometimes applied as a secondary treatment step after primary treatment with chlorine;
- monochloramine may be more effective for certain microbes such as Legionella. There is, however, contradictory information on the relative efficiency of monochloramine compared with chlorine in cooling towers; some studies suggest its slower action makes it less effective.

Where blowdown from cooling towers takes place to especially sensitive surface waters, ultraviolet (UV) light may be used to control biofouling. This is being investigated for the French inland site at Civaux (Annex A5.1.1).

As an alternative using biocides in cooling towers, microbes and slimes can be removed from the circulating water by diverting a small proportion of the flow through a deep-bed sand filter (side stream biofiltration). Chemical dosing is then only required when especially difficult conditions arise. This option is not applicable to the much larger flows of water in a once-through cooling water system.

Alternative treatments

Alternative biocide treatments are available but some are only applicable to the smaller re-circulating or service water cooling systems:

- Other oxidising biocides – ozone, hydrogen peroxide (used at Isar 2) or peracetic acid. The environmental effects are expected to be less harmful then halogenated biocides, but their application needs special care and they tend to be more costly and not applicable in all situations.
- Non-oxidising biocides: These are metabolic inhibitors and are usually only applied to cooling tower systems or closed loop recirculating cooling circuits. They include isothiazolones, dibromo-nitrilopropionamide, glutaraldehyde and quaternary ammonium compounds. Some are acutely toxic and are often not readily biodegradable, although there are some which hydrolyse or are degraded by other mechanisms. The AP1000™ report notes use of ammonium chloride as an algicide in the service cooling system (see Table 4.2-2 in Westinghouse 2010a), although it is not clear if this is actually in the form of a quaternary ammonium system (commonly known as 'polyquats').
- Byron uses a copper ionics system as an alternative to chlorination but only for specific species (zebra mussels; Annex A3.3). Copper condenser tubes are usually resistant to biofouling but are no longer considered BAT because the slow release of copper cannot be controlled by the operator.
- Specific biocides should be used for certain species or seasons. The main example of this identified in the US plants is 'Clamcontrol' used for Asiatic clams. This is an alkyl phosphonium chloride salt (containing the PH_4^+ ion).

Use of biocides also needs to take account of the Biocidal Products Directive 98/8/EC. This involves a simple screening assessment that compares additives in terms of their relative aquatic impacts, followed by a site-specific assessment.

In very specific circumstances, alternatives to using chemical biocides include thermal back-flushing, osmotic shock or mechanical cleaning. These are usually applied after biofilm build-up when colonisation has taken place. Plant permits suggest that thermal back-flushing and other shock-type treatments are very constrained in time and frequency. This means operators have to prevent initial infestation and colonisation of their cooling water systems as much as possible.

For larger species, such as fully grown fish or mammals, exclusion techniques include strobe lights, air bubble curtains, sound deterrents, low-flow intakes and offshore ‘Gunderboom’ nets. For individual animals that do enter the initial part of the cooling circuit, there are collection and return systems (mostly for larger fish that may be important to the local economy). Details are provided in Environment Agency (2010b).

Summary on BAT applied to control of biofouling

IPPC guidance for large-scale industrial cooling emphasises that BAT for cooling water treatments and systems is highly dependent on the site-specific conditions systems (European Commission 2001a, Environment Agency 2010b). This is reflected in the wide range of methods and chemical treatments identified in the PWR plants covered in this study. Even for the most common technique of chlorination, a range of concentrations and dosing regimes are used. This is reflected in the advice that British Energy provides to each of its nuclear plants (British Energy, 2006). Predicted discharges for the AP1000™ and UK EPR™ will therefore be notional and will need to be adjusted in accordance with BAT to meet site-specific conditions. Discharge limits and reporting need to take account of the analytical method and detection limits.

4.3.7 pH

The pH of discharges from internal outfalls will be dictated by the presence of either strongly or weakly ionised acids or alkalis. Strongly ionised mineral acids like sulphuric acid or alkalis such as sodium hydroxide (used to regenerate ion exchange resins) have a high buffering capacity and affect the pH of even large volumes of water in external outfalls. Weakly ionised acids and alkalis (such as citric acid used in decontamination solutions) have a low buffering capacity and will have a less significant impact on the pH of the external outfalls.

For all the PWR plants covered in this survey, BAT for controlling discharges to within pH 6–9 is neutralisation with a suitable acid or alkali, followed by testing and then discharge. Neutralisation will cause iron and other metals to precipitate, and therefore may need to be accompanied by settling and filtration to remove suspended solids prior to final discharge (Sections 4.3.8 and 4.3.13).

4.3.8 Detergents

Detergents will appear in aqueous discharges from on-site laundries used to treat active clothing or decontamination workshops (Section 1.6.4). BAT for detergents is to select types that have low environmental impacts (for example those that are biodegradable) and following the manufacturer’s recommendations regarding quantities, concentrations, pH and temperature conditions when using proprietary systems. Detergent systems will also need to be selected to ensure that they do not introduce foam into the discharge and receiving water.

The UK EPR™ report states that the detergents used will be biodegradable commercial products, containing no EDTA (ethylene diamine tetra-acetic acid) or phosphates (see Section 5.3.1.5 in Chapter 3.4, UKEPR™ 2010a). Decon 9 is a common proprietary decontamination agent used in laboratory applications and contains anionic and non-ionic surface active agents, stabilising agents, alkalis, non-phosphate detergent builders and sequestering agents.

There is no indication of the treatment of detergents in discharges from any of the plants in this survey, apart from relying on dilution or discharge to standard sewage treatment (to reduce biochemical oxygen demand).

A standard technique to destroy organic matter in effluent is the Fenton process. This uses hydrogen peroxide and an iron catalyst to oxidise organic contaminants and has been tailored to meet the conditions met in effluents from active laundries, reducing biochemical and chemical oxygen demand by up to 90 per cent (Vilve et al. 2009). Ultrafiltration has been proposed to treat effluents from a laundry serving a nuclear site. This removes active particulates and allows recovered wash solutions and detergents to be reused. The efficiency may be limited by microbiological fouling of the membranes and difficulties ensuring suitability of the recovered solutions for reuse. There might also be an additional dose to workers involved in the maintenance of these systems. Organic-rich solutions from active plant laundries may also be treated using electro-oxidation with titanium oxide as the surface catalyst or treatment with ozone in conjunction with ultra-violet light (Vilve and Sillanpaa 2010).

4.3.9 Phosphorus and phosphates

Use of phosphate to control pH in the main steam circuits of PWRs during operation at power has been entirely replaced by all volatile treatments (AVT) using ammonia and amines (Section 4.3.3). However, phosphates and polyphosphates remain in use for the wet lay-up of auxiliary plant systems during maintenance or reactor shutdown, because AVT cannot be used due to the ingress of oxygen from air (Section 1.6.4). They also originate from anti-scale and other chemical treatments in cooling water circuits and from the discharges of decontamination solutions containing detergents. Discharge limits are specified in the permits for all French plants with additional allowances for reactor shutdowns. Analysis of the discharge data for phosphates from the French plants suggests they come close to the limits in force (Annex A5.2.5).

Operators of PWR plants covered in the current survey appear to rely on minimising the use of phosphates or other phosphorus species at source, then dilution in the main cooling water outfalls as BAT for minimising discharges and environmental impacts. Where discharges must be reduced to the absolute minimum, phosphates can be removed from water using precipitation using lime, alum or hydrated aluminium sulphate, all of which produce a final solid waste form (Lenntech 2010). None of the plants covered in the current survey appear to employ these treatment methods.

4.3.10 Corrosion products and heavy metals

This section gives a brief overview of BAT applied to discharges of corrosion products and heavy metals from the plants covered in the current survey and the UK EPR™ and AP1000™ candidate designs.

Iron

The primary circuit of PWRs is made of stainless steel and thus is not susceptible to corrosion that would produce measurable iron corrosion products in discharges. The main secondary steam circuit is made of low alloy steels; corrosion is minimised by all volatile treatment (Section 1.6.2).

During normal load operation, total concentrations of iron in the feedwater will usually be below 5 µg/l. Higher levels up to 200 µg/l may occur when the secondary steam system is disturbed during plant start-up. Most of this iron will be removed in the condensate polishing plant and it may be mobilised when the resins are backwashed during regeneration. BAT to minimise iron in the effluents from this process will be settling in the neutralisation tanks prior to discharge. During initial commissioning, concentrations of iron in effluents from the secondary steam system can reach 2 mg/l and may require specific treatment or allowance in the permit.

Some iron in the steam circuit may be carried forward to the steam generators and appear either in the blowdown, or when cleaning of these is carried out by ‘sludge lancing’ or chemical cleaning. BAT to minimise discharge of iron from these activities is the use of specialist contractors who are able to capture the effluents containing dissolved or suspended iron and treat them, usually as a solid low radioactive waste.

Iron in particulate form will originate from the corrosion of carbon steel pipework and vessels in auxiliary plant systems. BAT will be to minimise corrosion at source, but then ensure that any oxide particulates only form as and when required in specific water treatment steps (such as in neutralisation basins of filter plants) so that they can be directed to a solid waste route instead of appearing in the final effluents.

Iron can also occur in raw water and is taken up in the various treatment steps in any raw water treatment plant. It is released when filters or ion exchange beds are backwashed or regenerated. Suspended iron in the effluents may require specific removal steps such as flocculation and coagulation, which again ensure that iron is retained mainly as a solid waste.

Permits for most of the French plants covered in this survey include limits on the discharge of iron from raw water treatment plants; these are usually significantly larger than for iron from other plant sources and depend on the amount of iron present in raw water (Annex A5.2.6).

Copper

Only a very few plant systems in any PWR use copper or copper-based alloys. Older plants may have copper cooling tubes in the main condenser in the turbine system or in other heat exchangers (for example the smaller ones that serve the service water systems).

Where copper is used in the main condenser, BAT is to control the chemistry in the main steam system so that corrosion and loss of copper from the tubes is minimised. The most important precaution is to avoid the use of ammonia, which would attack and dissolve the copper and carry it forward to the condensate polishing plant and steam generators where it would cause corrosion. Some leaching of copper from the side of the tubes exposed to cooling water (sea or river water) can occur and again BAT will be to ensure correct treatment of the main cooling water, avoiding for example the use of monochloramine. Residual leaching of copper provides a significant biocidal effect for the main cooling water flow and may significantly reduce the need for chlorination.

Titanium condenser tubes are much less susceptible to corrosion on the steam side of the circuit and the main cooling water side than copper ones. Most modern PWRs using once-through seawater cooling use titanium tubes as BAT. Not only does this avoid leaching of copper, but it also minimises the chances of leaks of main cooling water into the main steam circuit (Section 1.6.2).

At some plants where titanium tubes are installed, electro-ionisation cells producing low levels of copper are used to control biofouling in the main external cooling water circuit (Section 4.3.9). BAT to minimise unwanted environmental impacts from dissolved copper is to only use it as and when required, with monitoring to ensure levels of copper in the cooling water are at the minimum concentration needed to control colonisation by algae. This is shown by the seasonal and intermittent discharges of copper from this system used at Byron (Annex A3.3).

There has been increased regulatory attention in the USA to the leaching of copper preservatives from wooden supports used in older style wet cooling towers, which can then appear in the cooling tower blowdown. Options for removal of copper (and other metals) from these non-contact cooling waters prior to discharge include (Christopherson and Howell 2007):

- clarifiers and media filtration;
- electro-coagulation and media filtration;
- filtration and ion exchange;
- membrane processes using microfiltration or ultramicrofiltration (reverse osmosis is not usually suitable for primary metals removal as it is not tolerant to suspended solids).

None of the designs covered in the current study note use of these methods for treatment of cooling water blowdown, either because leaching of copper has not become an issue or because the towers are of a newer design and use concrete and plastic splash bars and support systems. It is unlikely to be an issue for new plants on coastal sites, which will most likely employ once-through seawater cooling.

Zinc

Only a few systems in a PWR use zinc as a primary structural metal; it is mainly used for galvanising in auxiliary plant systems, especially heating and ventilation plants. Zinc forms the base for a range of corrosion-resistant paints (usually zinc phosphate or zinc silicate).

Leaching by rainwater and stormwater run-off will be the main source of zinc in aqueous effluents. Treatment of water and discharges from these sources to remove sediments or in the neutralisation tanks will help reduce zinc via precipitation. Any remaining zinc will be reduced to low values during dilution with the main cooling water outfall to well below the background in seawater (1–5 µg/l, although higher in estuary water) or the EQS (40 µg/l for seawater but as low as 8 µg/l in freshwater).

Operators of some US plants, such as Beaver Valley, have replaced zinc and galvanised water systems (especially water-cooled chillers used in air conditioners in plant and domestic areas) with stainless steel ones to minimise the leaching of zinc into the final discharges (Annex A3.2).

Some PWR plant operators have started to add small levels of zinc to the primary circuit coolant (this is proposed for the AP1000™ and the UK EPR™). The zinc is added as zinc acetate depleted in the (natural) zinc-64 isotope, which could be activated in neutron flux to zinc-65. It is incorporated into the oxide film between the metal (stainless steel or nickel-based alloy) and the coolant. The films become more stable, inhibiting corrosion and reducing incorporation of radioactive corrosion products such as cobalt-58 and cobalt-60. This helps further reduce any effects of corrosion of the stainless steel pipework in the reactor circuit, notably localised stress corrosion cracking (SCC) of weld zones or other sensitive areas. The amounts of zinc added are very low (in the order of 5 grams per day) and will be mostly removed by the ion exchange beds in the primary coolant clean-up systems prior to passing into the waste systems. It will not have an overall effect on the concentrations of zinc in the final aqueous discharges (see Section 2.6.6 in Westinghouse 2010a).

Chromium, manganese and nickel

Small amounts of these metals originate from corrosion of primary circuit stainless steel and nickel alloys used in the steam generators. The total concentrations in the primary circuit coolant are expected to be in the range of 1 to 10 µg/l. There are some marginally higher concentrations of some of these metals in effluents from the condensate polishing plants at some US plants (for example as at Millstone, Annex A3.9).

BAT is to minimise at source by optimal control of coolant pH and by correct co-ordination of the boron with lithium. Any corrosion products that do arise are likely to be radioactive (due to cobalt-60, manganese-54, etc.) and BAT is then to remove these in the primary coolant clean-up system. The correct cartridge filters need to be chosen to maximise their removal in treatment systems. Consequently, only very small amounts reach down-line waste treatment systems, where further removal of corrosion products is carried out.

Larger amounts of chromium will occur in any wet systems using chromates as corrosion inhibitors. Some plants suggest BAT is to replace these corrosion inhibitors with less toxic materials, for example, nitrite borax at Sizewell B (Annex 2). Chromates are still used at some plants if they are insisted upon by plant designers and vendors. Where this is the case, BAT to minimise discharges is likely to centre on minimising spillages and the need for system make-up or purging. When the solutions do need to be refreshed, they will need to be directed to a suitable treatment route, possibly to specialist contractors off-site.

4.3.11 Other chemicals

Sulphate and chloride

Sulphate and chloride are the main components present in raw water that may appear in discharges after treatment (carbonate species are usually converted to carbon dioxide and degassed, or are otherwise neutralised). Sulphate is formed as sodium sulphate when sulphuric acid is neutralised with sodium hydroxide. The largest discharge of sulphate from the French plants is from sulphuric acid used for anti-scale in cooling towers (Section A5.2.9). Sulphate and chloride are of relatively low ecotoxicity. The main issues will be to ensure they are discharged as neutral salts (rather then in acid solutions). High levels of chloride in brine from reverse osmosis may require further assessment in discharges.

Biochemical and chemical oxygen demand (BOD and COD)

Permits for French and several US plants include limits on biochemical and chemical oxygen demand. Both the BOD and COD tests are a measure of the potential oxygen-depletion effect of a waste stream on a receiving water body. The BOD test measures the oxygen demand of biodegradable pollutants whereas the COD test measures the oxygen demand of biodegradable pollutants plus that of non-biodegradable oxidisable pollutants (such as ammonia and nitrite). Discharge limits are mainly applied for waste water from auxiliary plant systems and stormwater run-off. Effluents with the highest levels of BOD or COD will probably be washings from cooling water intake screens or from the active laundry.

In some industries, large volumes of effluent with high BOD and COD capacities require special treatments. BAT for the smaller volumes from a PWR site will involve minimising at source any oxidisable materials in site run-off, removing solids in settling systems and then ensuring that certain effluents (such as foul water) are directed to sewage treatment prior to discharge. Special oxidation techniques for organic materials such as detergents were noted in Section 4.3.11, but their use was not identified in the PWR plants covered in this survey.

Proprietary systems

These cover a very wide range of types and quantities of chemicals used, including those discussed in the previous sections sold individually or in modified mixtures such as detergents containing phosphates and preservatives. Examples include chemicals used in the main cooling water systems in cooling towers (hardness and scale controllers, anti-foams) proprietary cleaning solutions and biocides. Ensuring these are used and discharged in accordance with BAT will involve:

- purchase in accordance with the exact requirements of the plant in terms of type and quantity;
- understanding of additives or other trace chemicals (such as preservatives) present in the systems that may have additional side effects and impacts;
- availability of the correct data and Material Safety Data Sheets (MSDS);
- correct storage and controls being available in case of spillages;
- use in accordance with the manufacturer's instructions by trained and experienced personnel, according to written plant procedures and management controls;
- correct segregation at source and then direction of the used solutions through the appropriate waste management route in the plant or, if necessary, via an off-site contractor;
- correct disposal of surplus material.

All these issues and precautions are described in detail in the respective reports supporting the AP1000™ and UK EPR™, including storage volumes, tank systems, portable tanks (so-called TOTE® tanks) spillage controls and adherence to requirements under the Control of Major Accident Hazards Regulations (UK EPR™ 2010a–d, Westinghouse 2010a).

PCBs

Use of polychlorinated biphenyls (PCBs) in electrical equipment has been largely discontinued. Where old equipment still contains insulating oils based on PCBs, operators are required to replace them (or the equipment) with more acceptable alternatives. The maximum limit for residual levels of PCBs remaining in insulating oils in the UK is generally around 5 mg/l. PCBs are on the USEPA list of priority pollutants, and for this reason, US plants permits state that no discharge of PCBs in water is allowed. PCBs are not mentioned in the permits for the French plants.

Overall, BAT for minimising any discharge of PCBs in aqueous effluents or run-off will be ensuring completion of any PCB replacement programme, and correct storage and disposal of older plant that may have contained PCBs. Note that oil–water separators would not be sufficiently effective in removing very low levels of PCBs from aqueous effluents prior to discharge (Section 4.3.7).

Toxic materials and carcinogens, USEPA 126 priority pollutants

This generic group of chemicals covers a potentially wide listing. The UEPA priority pollutant list contains chemicals that have been or are still used in a range of industries. The list includes volatile hydrocarbons and chlorinated solvents (some of which are now banned under the Montreal Protocol), polyaromatic hydrocarbons (some of which are by-products of combustion and found in, for example, sump oil) and plasticisers. Metals in the list include arsenic, antimony and cadmium.

These chemicals are not expected to be used in PWR power plants; for example, solvents used for degreasing or refrigerants in chiller units would all be expected to comply with latest EU requirements on avoiding specific chlorofluorocarbons (CFCs). Metals such as lead and cadmium are used only in very small amounts in batteries. Antimony used to be used in pump seals, but is no longer due to problems of activation (forming the isotope antimony-125). Similarly, none of these chemicals would be expected to occur in aqueous discharges from the nuclear island or auxiliary systems on a PWR site.

Most US plant permits suggest that BAT is to ban the use of all materials that appear on the USEPA priority lists of pollutants or, where these have been used previously, use less hazardous substitutes.

At a few US plants, stormwater run-off appears to be a common source of trace metals on the USEPA priority list in discharges, such as antimony (for example Beaver Valley, Annex 3.2). Together with the presence of oil and grease, this has been a driver for the implementation of stormwater management plans on many of these sites. Demonstrating BAT to minimise discharges of these pollutants is mostly based on them not being detected in the effluents when using standard methods for analysis.

Given the very low concentrations of pollutants after dilution in the cooling water, any further demonstration of BAT would need to be based on the results of effluent toxicity tests. These are discussed in Section 7.4.

4.4 BAT for discharges to air

The main direct discharges to air from a PWR power plant site will come from:

- water vapour (visible drift) from cooling towers at inland sites;
- testing and any use of the emergency diesel standby generators;
- fuel burnt in the auxiliary boilers used to supply steam for HVAC systems and for frost protection of water storage tanks situated outside buildings (steam may also be used for some smaller steam driven emergency turbine pumps);
- systems used to maintain low negative pressure in the main condenser.

The requirements for BAT to minimise emissions to air from cooling towers include the following:

- Reducing drift and water vapour that appear in the plume from the tower. This includes using drift eliminators within the tower and locating cooling towers away from nearby buildings or topographical features that could affect the drift and cause its ‘grounding’. Drift eliminators abruptly change the direction of airflow within the tower, imparting centrifugal force to separate water from the air and return it to the cooling water circuit. Drift eliminators therefore also minimise losses of water from the cooling circuit and reduce the need for fresh make-up water and blowdown.

- Avoiding hazardous or toxic materials in the cooling tower packing (asbestos or copper and arsenic based timber treatments) to minimise fugitive emissions in the drift.
- Correct use and application of biocides in the cooling tower system to minimise risks from airborne pathogens, especially Legionella.

All the PWR plants covered in the survey, the AP1000™ and the UK EPR™ are all equipped with at least two standby diesel generators. IPPC guidance generally applies to combustion equipment, including diesel generators, with a thermal capacity greater than 20 megawatts thermal [MW(th)]. There is no readily available information on the power of diesel generators at the plants covered in the current survey. Fact sheets for the US plants and permits for the French sites make no specific mention of emissions to air or regulatory requirements for diesel generators. In the GDA for the AP1000™, Westinghouse states that the maximum thermal power of each standby diesel generator is 12.9 MW(th), which falls below the threshold of combustion devices subject to permitting under IPPC. The UK EPR™ includes four backup diesel generators, each rated at 17.6 MW(th) and two further emergency backup generators of 6 MW(th). The GDA report notes that, as these total 50 MW(th), they would be covered under IPPC and it therefore includes an extensive assessment of how BAT would be achieved to minimise emissions from these plant systems (UK EPR™ 2008).

In summary, the case for BAT involves:

- Operational feedback from the French plants that shows that diesel, rather than gas-fired turbines, are BAT with respect to safety, reliability and rapid start-up for emergency use in the event of loss of normal external and/or internal electrical supplies.
- Design of the diesel engines according to modern practice with, for example, crankcase extraction systems.
- An optimised maintenance programme. In particular, as for all large diesels, there is a need to avoid build-up of hard carbon and glaze in the cylinder bores. This usually occurs only after prolonged periods of running at low speeds or low loads, so is not normally an issue for standby systems.
- Use of low sulphur fuel (for example A2/D fuel with less than 0.1 per cent sulphur as per British Standard 2869).
- Simplified antifreeze based on glycol and water.
- Management of all waste materials.

More importantly, the diesel generators would only be used for specific emergencies so would only be operated occasionally for testing (EDF states that the annual running time for testing for each plant on a twin EPR™ reactor site would be around 20 hours). For all these reasons, end-of pipe abatement methods are unlikely to be considered as BAT. Any impacts due to small emissions to air would be minimised by directing the exhaust to stacks with an appropriate height of about 20–30 m, and by use of the correct fuel and maintenance procedures.

Heating and ventilation systems will vent air from plant areas to air. These systems are fitted with high efficiency particulate air (HEPA) arrestors (HEPA filters). These ensure that air from potentially radioactively contaminated plant areas is filtered prior to discharge. No significant chemical discharges are expected to be associated with these systems. Some might be a potential source of Legionella and BAT for these would be appropriate chemical dosing and a regular maintenance and testing regime.

Large-scale electrical switchgear systems in the substations of electrical plants sometimes use sulphur hexafluoride (SF_6) in ‘gas insulated switchgear’. Sulphur hexafluoride is a potent greenhouse gas with a long-term effect that is 22,800 times greater than that of carbon dioxide. Fugitive emissions should be minimised, and some equipment suppliers have suggested using alternative fluid insulators, but none offer the overall advantages in terms of performance and safety (low toxicity) of SF_6. IPPC guidelines only cover leakage from already installed equipment; there are no recommendations for emissions from maintenance or from the manufacture or installation of new equipment (Olivier and Bakker 2003).

Operating PWR plants usually include small-scale encapsulation plants that convert liquid and some solid wastes into immobilised solid waste forms. Some of these are dedicated on-site facilities, whereas others store the solid waste until arrangements are made to bring a mobile plant on to the site. Cement or polymers are used to encapsulate the wastes. Cementation plants may require permitting under IPPC. The process may result in some minor fugitive emissions of cement dust or polymer fume to air, but these would normally be captured in the filters of the local ventilation plants.

5 Relationship of permit limits and discharges to reactor power and size

This section discusses whether there is any relationship between the permitted discharge limits and the actual discharges for selected groups of chemicals. Chemical discharges do not generally depend on plant size or capacity, although they may relate to the numbers of individual plants on a single site location.

A review of the relationship between discharges of radioactive substances and the size and capacity of the plants has already been published (Environment Agency 2010a) and is summarised below:

- Fission products (such as tritium and caesium-137) are formed in the fuel. The quantity of fission products depends on the amount of fuel in the reactor (and therefore on the capacity of the reactor), the load factor (the proportion of time the reactor is at power) and the burn-up of the fuel that is achieved (the proportion of the uranium-235 that is actually used to produce useful heat, some portion always being unusable and left in the fuel when it is removed from the reactor). However, the amounts of fission products finally released into the aqueous environment will depend on many plant-specific factors such as the number of fuel pins that might leak fission products into the coolant and how this coolant is routed and treated in the radioactive waste treatment systems.

- Activation products (such as cobalt-60 and manganese-54) are formed from small amounts of corrosion products and the reactor surfaces. The amount of activation products generated initially depends on the neutron flux in the reactor, and then on reactor power and load factor. The actual discharges will depend on how the activated materials are released from reactor surfaces, their movement into downstream waste treatment systems and whether the plant operators choose to direct them to a solid waste route (in the form of filters, ion exchange beds) or discharge them to the environment.

5.1 Chemicals from the primary reactor circuit

Boric acid and lithium hydroxide ($^{7}LiOH$) are the main non-radioactive chemicals used in the primary reactor circuit of a PWR. The typical inventory of boric acid at the start of a fuel cycle (assuming a circuit volume of 250 m^3 and a concentration of 2,000 mg/l) is of the order of 500 kg and that of lithium hydroxide (assuming a concentration of about 3 mg/l) is about 0.75 kg.

The discharge limits for boric acid and lithium hydroxide at the French plants are partly related to the size and numbers of reactors on each site (Annex A5.2). However, for boric acid in particular, the permits contain additional allowances and headroom for when the reactors are shutdown, tanks and systems require periodic emptying, and when the reactors use more highly enriched fuel (Annex A5.2.1).

Coolant containing boric acid is discharged at the end of the fuel cycle because the large volumes of primary circuit let-down may be of insufficient quality to allow any recovery of boric acid by evaporation or are too dilute to make evaporation economically viable (Section 4.3.1). Tanks containing concentrated boric acid (up to 7,000 mg/l as boron) may need to be emptied if the quality is insufficient to use in the primary circuit. All these factors will mask any simple direct relationship between plant capacity or number of reactors on a single site with the discharge limits in force for boric acid.

Assessment of the actual discharges of boric acid from the French plants (Annex A5.4) suggests that these are typically 20–40 per cent of the site limits and depend on operational conditions such as the amounts that are recycled versus those discharged. In future, they would also depend on any proposed use of enriched boric acid ($H^{10}BO_3$) or changes to accommodate use of mixed plutonium and uranium oxide fuel.

5.2 Chemicals from the secondary steam plant and auxiliary plant circuits

The secondary steam systems on all PWRs and the methods of controlling water/steam chemistry are, in all important respects, identical to those used in many fossil fuelled plants. The main requirement is to maintain control over levels of dissolved oxygen and pH using an all volatile treatment (Section 1.6.2).

The limits for discharges of hydrazine from the French sites with several reactors (such as Paluel and Gravelines) show some relationship to site size and capacity. However, each French site has additional allowances for reactor shutdowns when additional hydrazine is used for wet lay-up of secondary plant systems. The actual discharges of hydrazine are mostly less than about 30 per cent of the site limits in force and have decreased over time in response to improved operational practice and regulatory pressure (Annex A5.4). Concentrations of hydrazine in internal plant discharges can be intermittent or erratic, such as in the steam generator blowdown lines at St Lucie or Millstone. These relate to operation of specific plant systems and could have a similar impact on the discharges of hydrazine in the final external outfalls (Annex A5.3).

The amount of hydrazine discharged depends more on site-specific issues such as how wet lay-up is applied, for how long and the concentrations needed to control the levels of dissolved oxygen and the pH of the solutions rather than on plant size or overall site electrical output capacity. The concentrations of hydrazine required can vary from a few mg/l up to several hundred mg/l, depending on the site-specific issues of corrosion that each individual plant needs to address. The concentrations of hydrazine discharged will also depend on whether plant operators destroy hydrazine before discharge, for example, Millstone treats used wet-lay solutions with hydrogen peroxide to destroy the hydrazine prior to discharge.

The amounts of other secondary side chemicals used and discharged (mainly ammonia and amines) might be expected to depend on the volume of water and steam and therefore on the overall size and capacity of the turbine generators in each plant. However, the final discharges will depend on the complex reactions these additives undergo in the steam circuits and treatment systems, and how these are operated on a site-specific basis. For example, ammonia in the steam circuit is taken up on the ion exchange resins in the condensate polishing plants. When these are regenerated, ammonia is released predominantly as the ammonium ion (NH_4^+). Some plants rely on the decomposition of hydrazine as the main source of ammonia for controlling pH in the steam circuit, rather than actual dosing with ammonia.

Gravelines (with six reactors) has higher discharge limits for ammonium compared to the twin reactor sites using morpholine such as Chooz and Golfech. However, data in Annex A5 show that the actual discharges of ammonium and morpholine from French sites show no significant correlation with plant size or site capacity. At Gravelines, the actual discharges depend on the relative use of ammonia and morpholine to control pH in each of the six reactors. There are much less data on discharges of ammonia from the US sites, with those from Salem showing rather erratic changes over time that cannot be related to available operational data.

Overall discharges of chemicals used in the secondary steam circuits of PWR plants will depend on:

- the pH regime applied in the secondary steam circuit;
- how much dosing is required to control plant-specific corrosion issues and how the condensate polishing plant is operated;
- how plant systems in wet lay-up are managed;
- discharges of amines will depend on any in-plant decomposition and how the breakdown products behave in the condensate polishing plant;
- treatments of hydrazine prior to discharge.

Phosphates are used for wet lay-up of plant systems when the ingress of oxygen cannot be controlled and it is not possible to use hydrazine. Discharges of phosphate depend on how much plant needs to be laid up, the frequency of shutdowns and site-specific issues of corrosion. Phosphates will also be discharged from their use in cooling towers.

Discharge limits for metals show some relationship to the numbers of plants on each site for the French plants (Annex A5.2.6). Actual discharges are less than 15 per cent of the limits and do not vary across the sites. Discharges from the hold-up tanks serving the nuclear island will depend on plant-specific issues of corrosion and on how the waste treatment plants are operated. Discharges of iron will depend on if it is used as a flocculant during waste water treatment, or if raw water supplies contain dissolved or particulate iron (which is removed then discharged during the backwashing of filters or ion exchange systems). All these processes are independent of the electrical or thermal capacity of the reactor systems.

Several US plants show discharges of zinc due to corrosion of galvanised plant systems that have changed over time. At Beaver Valley, a step change occurred when zinc-plated plant systems were replaced by stainless steel. Again, these changes are independent of the electrical capacity of the reactors.

5.3 Chemicals used in the main cooling water systems

The main chemicals used in cooling water systems are biocides, with chlorine being the most common biocide used. At plants with closed circuit cooling towers, corrosion inhibitors, polymer dispersants and anti-scale and anti-foams are also used.

Discharge limits in the permits for chlorine from French plants using once-through seawater cooling show some relationship to plant size, with the multiple-reactor sites at Gravelines and Paluel having the largest discharge limits. Data for Sizewell B and the US plants show that the actual discharges of chlorine (and total residual oxidants) are seasonal and vary according to site-specific requirements (Annex report Sections A2 and A3). These include limits on the frequency that chlorination may be applied, or the number of plants on any one site that can be treated by chlorination at any one time, or whether use of shock treatment is allowed. Some coastal sites such as Salem in the

USA and Hinkley Point B in the UK do not need to carry out chlorination at all (see Annex report A3.6.1).

Discharge limits and actual discharges of biocides across all the different types of site, cooling systems and environmental conditions will therefore be largely independent of plant capacity.

5.4 Overview of relationship of limits and discharges to plant size and capacity

The assessment for French plants (Annex A5) suggests that mass limits for the chemicals discharged in water make some allowance for the numbers of individual PWR plants on each reactor site, notably for the larger multiple reactor sites at Paluel (four reactors) and Gravelines (six reactors). On the other hand:

- All the French sites have additional discharge limits to accommodate wet lay-up, maintenance and reactor shutdowns or the periodic emptying and flushing of specific plant systems. How and when these allowances are used may depend on a range of external factors which are not readily related to plant capacity.
- Limits in permits may need to change over time. In most cases, they become more stringent either as plant operators are able to draw on more extensive operating experience or in response to downward pressure on the limits by the regulators.
- Relevant concentration limits and quality standards must be met in the water body receiving the discharges, regardless of the number of reactors or the plant capacity. This is particularly relevant to chlorine dosing in once-through cooling water systems at multiple reactor sites, where environmental criteria for total residual oxidants commonly represent a limiting factor on the dosing regime applied (see Section 7.3.4).
- The main bulk chemical discharges (apart from those associated with biocides in cooling water) come from the secondary steam plant or other support systems rather than the nuclear island. Mass flows and changes in discharges from these conventional areas of a PWR, where the most significant site-specific and individual plant operational issues arise, will override any simple pro-rata relationship with thermal power of the reactor system or total electrical output capacity of the plant or site.
- Discharges of biocides from the main cooling water systems or iron from raw water treatment plants can depend on a range of seasonal or site factors, rather than anything related to reactor operations or power output.
- Unlike radioactive materials, discharge of chemicals from auxiliary plant systems will continue when the reactor is shutdown.

For all these reasons, within the power range of the current operating or proposed candidate designs considered in the current study [1,000–1,500 MW(e)], there is no straightforward relationship between the limits in force for chemical discharges from the nuclear island or from auxiliary plant systems and either the capacity of any individual plant. Neither is there any straightforward relationship between the actual discharges made and plant capacity or numbers of individual plants on multiple reactor sites.

6 Comparison of discharges of chemicals from PWR and fossil fuel power plants

This section of the report compares chemical discharges from nuclear PWR power plants with those from conventional (fossil fuelled) power plants. It also describes some aspects of the newly developing field of ‘zero emissions’ technologies that might be applicable to PWR plant systems. Chemical emissions to air are discussed first, since this is where the most significant differences lie between nuclear and fossil fuel power plants.

6.1 Chemical emissions to air

PWR power plants generate electricity from useful heat produced by nuclear fission. Conventional power plants burn fossil fuels to generate electricity, producing carbon dioxide (CO_2) as the main waste product. Minor waste products from burning fossil fuels include:

- sulphur and nitrogen oxides (so-called SOx and NOx);
- halogen gases;
- particulates (containing carbon, organics and metals);
- ash;
- waste from treating (scrubbing) flue gases to remove sulphur dioxide (mostly comprising calcium sulphate).

Extensive work has been carried out to compare the impacts due to the emission of greenhouse gases (notably carbon dioxide) from nuclear and conventional fossil fuel plants. An example of a quantitative assessment of whole cycle impacts (including mining and processing uranium ore, construction, operation and waste management) has been carried out for Sizewell B (British Energy 2008). This concludes:

> ‘The total emissions of CO_2 from electricity generated at Sizewell B power station, calculated on a lifecycle basis, are estimated to be 5.5 g/kWh. This compares to operational emissions of CO_2 from a typical UK coal plant and a typical gas power station, of around 900 g/kWh and 400 g/kWh respectively. CO_2 emissions from Sizewell B are dominated by the extraction and construction phase, which are responsible for 31 and 40 per cent of all CO_2 emissions respectively’.

The Sizewell B assessment also showed that about 78 per cent of emissions of SOx and 90 per cent of NOx are from the extraction of uranium ore and from the production of steel and concrete at the construction phase. When averaged by unit electricity generated, the levels of SOx and NOx emitted from all operations associated with the construction and operation of Sizewell B were lower than those from an average fossil fuel plant.

There is no consensus or international agreement on what constitutes overall BAT for generating electrical power in terms of carbon dioxide and other gaseous emissions.

The UK's energy policy is designed to address the twin challenges of climate change and security of energy supply. In support of this the White Paper, *Meeting the Energy Challenge*, sets out the UK Government's view that nuclear, as an affordable, dependable and safe form of energy, should be part of the UK's future low-carbon energy mix (BERR 2008).

The only processes on a nuclear power station site that are powered by fossil fuels are oil-fired auxiliary boilers or standby diesel generators (discussed in Section 4.4).

6.2 Chemical emissions to water

Conventional and nuclear power plants both use a process to convert useful heat into work using water as the working fluid in a closed loop (called a Rankine Cycle). Heat is supplied by fossil fuelled boilers or a nuclear reactor at one end of the closed loop, and is removed from the other end by the main condenser that rejects the heat to the environment via an external cooling water source. The temperature difference and phase changes (steam to water) provide power to drive the turbine generator.

The main water flows in conventional and nuclear plants, and the chemical issues that must be addressed, are similar and cover:

- Water flows in the main steam circuit. To control corrosion, all plants need to condition the water in this circuit using chemical dosing. Many conventional plants still use solids treatments such as phosphates, polymer and sulphite, although all volatile treatments (which are standard in a PWR) using hydrazine/ammonia are also employed.
- Condensate polishing and regeneration of ion exchange resins in the condensate plant. All power plants need to ensure that, after the steam has passed through the turbine and been converted to water in the main condenser, the final resultant condensate is of adequate quality to be reused in the hot end of the main steam circuit (that is to the main boilers or steam generators). This is usually achieved using ion exchange on a continuous or intermittent basis, although alternative membrane purification technologies can also be used. A typical layout of a deep bed system in a fossil fuel plant is shown in Figure 6.1. There is some opportunity to remove any accumulated impurities in the steam generators of PWRs by continuous or intermittent blowdown – a process that is not possible in the once-through boilers used in most conventional power plants. The blowdown water will contain high levels of salts and solids but will be of a relatively small volume.
- Water flows through the main external cooling water system. The major water flows for conventional and nuclear plants are associated with the cold end of the Rankine cycle, whereby heat carried by steam through the turbine has to be transferred to the environment via a condenser cooled using seawater or via cooling towers. These systems invariably need chemical dosing to prevent biofouling. Usually chlorine is the main biocide used, sometimes combined with bromine or other biocides (see Section 4.3.9). After passing through the main condenser, the discharges from this part of the plant contain residues of these chemicals and by-products such as halogenated hydrocarbons. Chemical discharges from cooling towers in PWR (see Section 4.3.9) and fossil fuel power plants will also be similar.

The effluents from preparing purified boiler make-up water are similar for PWR and conventional power plants. Raw water treatment systems are used to prepare the large quantities of high purity water required for the main boilers. These use ion exchange resins and filters, possibly with coagulants and settling basins, and therefore produce similar aqueous waste streams. Some plants may use membrane systems (see Section 4.3.6).

Similar effluents from waste water treatment are produced at PWR and conventional power plants. These treat waste water from internal plant systems using ion exchange, membrane technologies, filtration, settling and pH adjustment. Apart from traces of radionuclides that may pass through the radioactive treatment systems in PWR plants, the overall bulk chemical composition and environmental impacts to be managed will be similar and include:

- Effluents from leaks of oil and oily effluents from oil storage areas.
- Cleaning liquids used to clean and maintain boilers in fossil fuel plants and decontaminate PWR plant systems (such as the steam generators). These may contain mineral or organic acids, alkalis, alkali phosphates, iron oxides in suspension and complex corrosion inhibitors. They are treated on-site or taken off-site by specialist contractors for treatment elsewhere.
- Stormwater and run-off from parking and hard surfaced areas (carrying oil and silt) and the large areas of roofing.
- Effluents from laundry systems containing detergents. These are likely to be lower at conventional power plants compared to PWRs because there is no need to treat potentially active items.

Figure 6.1 Standard deep bed condensate polishing plant (resin vessels) in a fossil fuel power station – similar systems are used in many PWR power plants (see Section 1.6.3) (By permission of Graver Water Systems LLC)

Conventional fossil fuel power plants may produce potentially major chemical discharges to water that PWR or other types of nuclear plants do not, such as:

- drainage and run-off from fossil fuel storage areas – these will be dominated by suspended solids, hydrocarbons and sulphurous or iron-rich leachates from the mineral pyrite (FeS_2) which is usually present in coal;
- water from the quenching of ash from the boilers;
- aqueous effluents from ‘clean coal’ technologies, including those used for washing of coal to remove sulphur prior to combustion;
- aqueous effluents from wet scrubbing of flue gases to remove sulphur or nitrogen oxides or, for example, halogen acids or trace organics.

Extensive information on methods that are considered BAT to minimise the impact of these discharges is available in the literature and is covered in Environment Agency (2002).

6.3 Comparison of limits demonstrating BAT for the EU combustion sector with US CFR 40 Part 423 limits and data for the PWRs in the survey

There are two main guidance documents that apply to BAT for large-scale [greater than 50 MW(th)] conventional power plants in the UK. The Environment Agency IPPC Sector Guidance Note (Environment Agency 2002) covers combustion activities and the IPPC Reference Note on the Application of Best Available Techniques (BREF) (European Commission 2001a) covers industrial cooling water systems.

There is no equivalent guidance for the nuclear sector in Europe. As a PWR plant shares many features with a conventional fossil fuel power plant (such as the turbine generator and cooling water circuit), operators will need to take account of these BAT guidance documents, especially for cooling water treatment (see Section 4.3.9).

In the USA, the Code of Federal Regulations CFR 40 Part 423 covers nuclear and fossil fuel steam generating plant used for the production of electricity (see Section 2.2).

The guidance values from the BREF note and CFR 40 Part 423 are compared in Table 6.1. BREF notes apply mainly to final discharges whereas the CFR 40 covers the final outfall and a range of internal outfalls from specific plant systems (such as steam generator blowdown). Data for discharges of chemicals from US PWR plants covered in this survey are also included in Table 6.1 (summarised from Annex A4), though the quality and extent of data in the table reflects what is available from the USEPA website. Table 6.1 shows:

- Discharges of chemicals associated with chlorination of cooling water (free and total residual oxidants), pH, suspended solids and oil and grease conform closely to discharge limits given in CFR 40 and the IPPC guidance for large combustion plants.
- The concentrations of total residual oxidants in main cooling water flows vary across the plants from 0.002 mg/l for Comanche Peak to 0.14 mg/l for Beaver Valley. There are also considerable differences in the trends over time, which reflect how chlorination is applied to meet site-specific issues of biofouling and permit limits.
- Concentrations of heavy metals tend to be higher from internal outfalls and in a few cases come close to BAT (especially zinc). However, interpretation is limited by the quality of the reported analytical data; trace metal

concentrations (apart from zinc) are always low and close to the analytical detection limits. There may also be issues associated with sample collection and preservation methods, for example, samples that have been filtered and acidified will give different results to those that have not been pre-treated.

- Discharges of ammoniacal nitrogen from some plants appear to come close to IPPC guidance limits. However, there are very little data on the relative amounts of ammonium and ammonia in discharges from US plants. Data for the French PWR sites also suggest discharges of ammonium can often come close to discharge limits.

It is not possible to compare the data for the French PWR plants in this section because it is expressed as mass discharges (in kg) rather than concentrations discharged (Annex report Sections A5 and A6).

Table 6.1 IPPC combustion and large-scale cooling and CFR 40 values for BAT and selected data for US plant discharges (mean of daily maximums, mg/l)

		Suspended solids	**Ammoniacal nitrogen**	**Cadmium**	**Mercury**	**pH**	**Free chlorine**	**Residual oxidants**	**Oil and grease**	**Copper**	**Chromium**	**Iron**	**Zinc**
IPPC combustion		**1–10**	**5**	**0.01**	**0.005**	**5-9**	**n/s** [1]	**n/s**	**10** [3]	**n/s**	**n/s**	**n/s**	**n/s**
IPPC cooling systems (*24-hour mean*)		**n/s**	**n/s**	**n/s**	**n/s**	**n/s**	**n/s**	**0.1–0.5 (*0.2*)**	**n/s**	**n/s**	**n/s**	**n/s**	**n/s**
CFR 40 Daily maximum (*30–day mean*)		**100 (*30*)**	**n/s**	**n/s**	**n/s**	**6-9**	**0.5 (*0.2*)**	**0.2**	**20 (*15*)**	**1 (*1*)**	**0.2 (*0.2*)**	**1 (*1*)**	**1 (*1*)**
Beaver Valley	Main [2]	–	0.39	–	–	8.27	0.16	0.14				2.37	0.06
	Others	18.4	5.87	–	–		0.01	0.02	6.09	0.15		0.79	11.1
Byron	Main	5.5	–	–	–	8.1	–	0.15	1.01	0.008	–	–	0.3
	Others	20.7	–	–	–	9.2	–	0.07	–	–	–	–	–
Comanche Peak	Main	6.6	–	–	–	7.4	–	0.0002	–	–	–	–	–
	Others	13.8	–	–	–	8.2	–	3.5	–	0.02	–	0.11	–
Seabrook	Main	4.85	–	–	–	7.79	–	0.01	–	–	–	–	–
	Others	3.1	–	–	–	7.71	–	n/d	1.45	–	–	–	–
Salem	Main	6.72	–	–	–	7.79	0.1	–	2.2	–	–	–	–
	Others	–	9.89	–	–	7.79	0.1	–	2.2	–	–	–	–
San Onofre Unit 2	Main	–	0.4	0.004	–	–	–	0.094	7.2	0.016	0.012	–	0.017
	Others	18.3	–	–	–	7.2	–	–	8.25	0.56	–	–	0.03
San OnofreUnit 3	Main	–	0.4	0.004	–	–	–	0.090	9.34	0.016	0.011	–	0.015
	Others	16.6	–	–	–	8.1	–	–	–	0.9	–	0.1	0.031

		Suspended solids	Ammoniacal nitrogen	Cadmium	Mercury	pH	Free chlorine	Residual oxidants	Oil and grease	Copper	Chromium	Iron	Zinc
IPPC combustion		**1–10**	**5**	**0.01**	**0.005**	**5-9**	**n/s** [1]	**n/s**	**10** [3]	**n/s**	**n/s**	**n/s**	**n/s**
IPPC cooling systems (*24-hour mean*)		**n/s**	**n/s**	**n/s**	**n/s**	**n/s**	**n/s**	**0.1–0.5** **(*0.2*)**	**n/s**	**n/s**	**n/s**	**n/s**	**n/s**
CFR 40 Daily maximum (*30–day mean*)		**100** **(*30*)**	**n/s**	**n/s**	**n/s**	**6-9**	**0.5** **(*0.2*)**	**0.2**	**20** **(*15*)**	**1** **(*1*)**	**0.2** **(*0.2*)**	**1** **(*1*)**	**1** **(*1*)**
Diablo Canyon	Main	–	60.0	0.045	0.005	7.9	6.9	0.06	–	0.002	–	–	0.006
	Others	–	–	0.002	0.001	–	–	–	–	0.031	0.003	–	0.043
Calvert Cliffs	Main	–	–	–	–	–	–	0.06	–	0.006	–	–	–
	Others	10.7	2.4	–	–	8.6	–	0.1	5.9	0.18	–	–	–
St Lucie	Main	–	–	–	–	–	–	0.03	1.38	–	–	–	–
	Others	2.88	–	–	–	–	–	–	–	0.027	–	0.11	–

Notes: 1 n/s = not specified

[2] 'Main' refers to main cooling water flow. 'Others' is based on selected data for internal plant outfalls.

[3] The value of 10 mg/l oil and grease is based on a limit proposed by the Environment Agency for conventional plant.

6.4 Zero discharge concepts and power plant design and operation

There is increasing pressure on operators of all thermal steam generating plants to reduce their impacts on water resources in terms of:

- initial use of water;
- thermal and other amenity impacts;
- avoidable losses of water or heat from the plant.

Overall requirements are becoming more stringent; examples include entrainment issues associated with once-through cooling water systems and reducing discharges of hydrazine. Permits for the US plants increasingly emphasise recycling effluents and minimising discharges.

These restrictions have driven the development of technologies based on the concept of ‘zero discharge’ – sometimes called ‘totally effluent free’ (TEF). Most technologies fail to fully meet this objective, requiring some input of fresh water and producing some effluents. There may be a policy to direct effluents to a route with less environmental impact such as to a solid waste rather than discharge to water or air (Hansen 2010).

Implementing zero discharge technology means giving priority to the collection and recycling of drains and leaks. For PWRs, this implies recycling of all primary let-down and water from drains through the radioactive waste systems, including using evaporators to recover the boric acid. Some plants covered in this survey have features that go a significant way to meeting this objective, but operational constraints may prevent it from being achieved, such as managing tritium and worker doses during maintenance of the evaporators (see Section 4.3.1).

The largest discharges to water from all the plants covered in this survey, and from the candidate reactor designs, are those associated with the main external cooling water.

For plants using cooling towers, meeting the zero discharge objective will involve preventing loss of water in drift and minimising the need for blowdown from the cooling tower collection basin, therefore reducing the need for fresh make-up water. Dry cooling towers would go some way towards achieving this; they are currently used on some conventional power plants but have a limited cooling efficiency. An alternative might be hybrid dry/wet system (EPRI 2009) but detailed cost–benefit analysis would be required on a site-by-site basis. The only dry or hybrid type towers identified in the predecessor plants covered in this survey are at Neckarwestheim (Annex A7.1).

At plants using once through seawater cooling systems, it has been shown that operators are able to control chlorination and its impacts (see Section 6.3). At the US plants, the effects of entrainment of fish or even mammals (such as seals) in the cooling water systems and the thermal impacts of discharge seem to be the greater drivers towards zero withdrawal and discharge of cooling water. Section 316(b) of the US Clean Water Act requires that the location, design, construction and capacity of cooling water intake structures reflect the best technology available for minimising adverse environmental impact.[3] In response, some states (including California and New York) have proposed that coastal PWR plants should replace once through seawater cooling systems with cooling towers. At the time of writing (2010), final decisions on how this part of the Clean Water Act should be implemented (if at all) remain to be finalised.

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[3] http://water.epa.gov/lawsregs/lawsguidance/cwa/316b [Accessed August 2011]

The Palo Verde plant in Arizona is probably the only PWR power plant to date to have adopted and gone a significant way to meeting the overall objectives of a zero discharge policy. It uses 100 per cent reclaimed grey/brown water (76 million m^3 per year) from Phoenix and surrounding cities, which is stored in an 80-acre reservoir and used for make-up to the cooling tower circuits.

There are significant design, operational and maintenance issues associated with adopting a zero discharge policy such as problems with reliability and increased costs and maintenance. For a nuclear plant, increased maintenance could increase radiation doses to workers and, for any systems supporting the reactor, there could be significant safety case issues to address. An example is recycling of boric acid through evaporators (see Section 4.3.1). All decisions would need to be supported by an ALARP assessment. Zero discharge is more likely to be adopted for the secondary steam circuits and sought as a target in other plant systems such as recycling of laundry effluents or minimising flushing and discharges of cooling water circuits.

Overall, the conclusions from this overview are as follows:

- Zero discharge concepts are in an early stage of development and would only be applied for PWR plant systems where significant cost and environmental benefits can be identified.
- The effectiveness of a zero discharge concept would need to be established on a site-by-site basis. What might be appropriate for one plant or site might not be effective or appropriate elsewhere.
- At each stage in the design and operation of the plant, a detailed cost–benefit analysis would be needed before implementing a zero discharge strategy. For a PWR, additional ALARP studies would be required as well as revisiting the Safety Cases covering operation and accidents.

7 Outline ecotoxicity assessment for chemical discharges

Assessment of the effects of discharges from nuclear power stations on the environment has tended to focus on radiological impacts. However, increasing attention is being paid to the impacts of non-radioactive chemical materials. This is reflected in the detailed assessments on the storage, use and discharge of chemicals carried out in support of the licensing of the PWR candidate designs (UK EPR™ 2010a–d, Westinghouse 2010a).

This section provides an overview of some of the approaches adopted to assess the effects of non-radioactive discharges and a generic ecotoxicological assessment. It considers only discharges to water during a normal operational phase and assumes use of a once-through seawater cooling system. A totally different assessment would be required for any plant using cooling towers.

Additional assessments for impacts due to construction (where sediments, suspended solids, oil and hydrocarbons are likely to be the more significant issues) are in progress for specific sites (for example, EDF 2010a). This section does not cover impacts due to chemical releases to air (see Section 4.4).

7.1 Regulatory background

Discharges of specific substances to surface waters are controlled under the Dangerous Substances Directive (DSD) 2006/11/EC and the Water Framework Directive (WFD) 2000/60/EC. This control includes:

- designated dangerous substances;
- designated priority substances;
- designated priority hazardous substances;
- any other potentially polluting, toxic, bioaccumulative, carcinogenic, teratogenic or persistent substances.

Regulating these discharges protects the environment and human health, complies with EU requirements and minimises loads discharged to the environment.

The Dangerous Substances Directive specifies two lists of dangerous substances. List I covers substances that are particularly toxic and persistent, and which may tend to accumulate in the environment, while those substances in List II are still toxic but to a lesser degree. The Directive will be repealed in 2013. In England and Wales, it has already been replaced in part by The River Basin Districts Typology Standards and Groundwater threshold values (Water Framework Directive) (England and Wales) Direction 2010.

The Water Framework Directive provides a basis for a more recent and holistic approach to water management across Europe. It expands the scope of water protection to all bodies of water, surface water and groundwater, with the aim of achieving ‘good status’ by 2015. Its requirements include classifying all water bodies in terms of their chemical and biological quality.

Under the Water Framework Directive, priority substances (regarded as harmful) and priority hazardous substances (regarded as extremely harmful) are referred to as Annex X substances. They are identified, together with their EQS, in the Environmental Quality Standards Directive 2008/115/EC. This includes some substances formally specified under the Dangerous Substances Directive. A further category, known as ‘specific pollutants’, are referred to as Annex VIII substances and are defined as pollutants that are released in significant quantities in a particular country.

A list of specific pollutants and dangerous substances is provided in Table 7.1. Substances that may be discharged from a PWR power plant (identified in this survey) are listed alongside these categories.

Table 7.1 Overview of classes of pollutants and substances discharged from PWR plants covered in the survey

WFD specific pollutants (Annex VIII)	Substances discharged from PWRs
Organohalogen compounds and substances that may form such compounds in the aquatic environment	Trihalomethanes formed by chlorination of cooling water. Specified in permits for French plants as bromoform and AOX. Trihalomethanes are on the USEPA pollutant list.
Organophosphorus compounds	Organophosphates and phosphonates. Some use in anti-scale and corrosion inhibitors, but will be selected on the basis of low environmental impact. Cresyl phosphate hydraulic fluid.
Organotin compounds	Used in older types of cooling towers but not identified in any plants in this survey.
Substances and preparations, or the breakdown products of such, that have been proved to possess carcinogenic or mutagenic properties or properties which may affect steroidogenic, thyroid, reproduction or other endocrine-related functions in or via the aquatic environment	Generally covered in US plant permits by requirements to avoid use or discharge of ‘any pollutant that may cause or contribute to an impact on aquatic life or pose a substantial hazard to human health or the environment due to its quantity or concentration’. French plant permits note prevention of impacts on aquatic flora and fauna.
Persistent hydrocarbons and persistent and bio-accumulative organic toxic substances	Permits include limits on hydrocarbons and discharges of oil. French permits note avoidance of bioaccumulative chemicals.
Cyanides	No direct uses identified.
Metals and their compounds (note lead and nickel are WFD Priority Substances)	All permits cover trace and heavy metals that are mostly discharged only as minor corrosion products (not usually used as additives).
Arsenic and its compounds	Not generally used on plants. Use of arsenic compounds is avoided in cooling towers.
Biocides and plant protection products	Limits on chlorination in accordance with BAT. Limits in use of proprietary systems at US plants.
Substances which contribute to eutrophication (in particular nitrates and phosphates)	Limited in all plant permits.
Substances that have an unfavourable influence on the oxygen balance (and can be measured using parameters such as BOD and COD)	Permits for French plants deal with water treatment plants and limits on COD and BOD.

WFD specific pollutants (Annex VIII)	**Substances discharged from PWRs**
Materials in suspension	CFR 40 parameters in US permits and covered in all French plant permits (matières en suspension or MES).
Additional substances listed in DSD	**Chemicals potentially discharged**
Mercury and its compounds (note mercury is a WFD priority substance)	No direct uses identified. Impurity only.
Cadmium and its compounds (note cadmium is a WFD priority substance)	No direct uses identified. Impurity only.
Persistent synthetic substances that may float, remain in suspension or sink and which may interfere with any use of the waters	French and US plant permits note avoidance of floating oil films or substances that may affect biota in the receiving waters. Specify ecological surveys and some specify ecotoxicity testing.
Substances that have an effect on the taste and/or odour of water	French plant permits note no odour on samples after incubation at 20°C. US plant permits note no effects on taste or smell.
Toxic or persistent compounds of silicon and substances that may cause the formation of such compounds in water	No direct uses identified.
Non-persistent mineral oils and hydrocarbons of petroleum origin	Permits include limits on hydrocarbons and discharges of oil.
Fluorides	No direct uses identified. Impurity only.

7.2 Details of specific pollutants and List I and List II substances

The chemicals discharged from PWR plants (Table 3.1) that are covered by the WFD or fall under List I or List II of the DSD are summarised in Annex Table A8.1 and below.

In the primary circuit, boric acid could be a specific pollutant (and fall under List I) because it is toxic for reproduction. It could be a specific pollutant (and fall under List II) under the category metals and compounds. Lithium hydroxide is not a specific pollutant, nor does it fall under List I or List II.

Secondary circuit additives such as phosphates and nitrites are specific pollutants (and List II substances) mainly they could contribute to eutrophication. Free ammonia is toxic to marine biota (but ammonium is less so). Hydrazine could be a specific pollutant (and List I) because it is a presumed carcinogen.

Corrosion product metals such as manganese, copper, chromium and zinc are specific pollutants (and List II substances). Nickel and lead are priority substances (and fall under List II). The permits for the plants covered in this survey do not specify the use or discharge of mercury or cadmium (priority substances and List I) or arsenic (specific pollutant and List II).

Chlorine used as a biocide in once-through seawater systems reacts to form chlorinated hydrocarbon by-products. Chlorinated hydrocarbons fall into the organohalogen group of substances and are therefore specific pollutants and List I substances.

Oils and lubricants would be specific pollutants and List I substances if they were persistent. Non-persistent hydrocarbons would be List II substances. Cresyl phosphate proposed to be used for the UK EPR™ is probably the most hazardous of the oils identified in this survey. There are no data on the storage or use of cresyl phosphate in the AP1000™ design.

Apart from boric acid, discharges of specific pollutants take place primarily from the conventional side of the PWR plant, that is, from the main steam circuit, once-through cooling water system or from certain maintenance activities. These will also be associated with discharges to water from a conventional fossil fuel plant (see Section 6.2). These conclusions are broadly consistent with the information published for the AP1000™ (see Table 2.9-5 in Westinghouse 2010a).

7.3 Generic ecotoxicological assessment

7.3.1 Approach

The generic approach to an ecotoxicity assessment is to calculate the concentrations of pollutants in the environment due to point or diffuse discharges. These environmental concentrations are then compared with water quality criteria such as Environmental Quality Standards (EQS) or other relevant criteria such as background environmental concentrations.

The approach adopted for assessing the effects of discharges of pollutants to surface water in England and Wales is described in Horizontal Guidance Note H1 (version 2.2, Environment Agency 2011, in press). These assessments support applications for discharges made under the Environmental Permitting (England and Wales) Regulations (2010) and implement the WFD requirement to ensure that permit discharge limits do not cause EQS to be exceeded in the receiving waters.

The Horizontal Guidance Note describes methodologies for establishing environmental concentrations of pollutants from 'simple' and 'complex' discharges to water.

Simple discharges

Annex (d) of the H1 Guidance Note covers 'simple discharges'. These are defined as continuous discharges over time, where all the components have been identified, the toxicity and environmental effects of individual chemicals is documented and the combined effects can be estimated by simple addition.

For discharges to coastal waters and lower estuarine waters, the overall approach is as follows:

- Calculate the end-of-pipe concentrations in the final discharge, then those in the environment due to dilution in the receiving water (river, estuarine or coastal). This is calculated using the site-specific 'initial dilution' to yield the 'process contribution' (PC in µg/l) to the receiving waters.
- Compare the PC values for each substance released against the relevant EQS. Releases can be 'screened out' from further consideration where the PC is less than 4 per cent of the EQS Maximum Allowable Concentration (MAC) or EQS Annual Average (AA). This does not take into account the background concentration of the substance or the environmental quality of the receiving water. This threshold is based on a judgement that the PC is unlikely to contribute to the EQS being exceeded by a margin over and above that due to natural variations that may already occur. Where EQS

values have not been established, other criteria are used (see Section 7.3.3).

Complex discharges

Annex (e) of the H1 Guidance Note covers ‘complex discharges’. These are discharges where there is no available information on the safe levels or aquatic toxicology of the likely combination of chemicals in the discharge, even if there is information on the individual chemicals. These assessments are also used if the receiving water is especially sensitive or if the simple approach has not allowed a discharge to be ‘screened out’ on the basis of negligible impacts. The approach is also required to assess the impacts of intermittent discharges, especially stormwater or combined sewage overflows. The PC values are again compared with relevant environmental quality criteria, but the method may also include an assessment on whether the discharge causes greater than 10 per cent deterioration in background concentrations already present. It may also require a direct toxicity assessment (DTA) (see Section 7.4.1).

Applying the generic approach to discharges from a PWR

For discharge of chemicals from a PWR site with two or more reactors, it might be expected that chemicals will be discharged from holding tanks on a batch basis. These will include chemicals originating from the primary circuit (boric acid), those from the turbine hall (containing secondary steam circuit additives) or those from water treatment plants. The solutions of corrosion inhibitors that may be used during the wet lay-up of plant for maintenance would also be discharged intermittently. Therefore discharges would consist of mixtures of chemicals varying over time and according to whether the reactor is shutdown for refuelling. For a multiple reactor site they could vary according to the phase of operation of each reactor (see Section 1.6.4).

According to Annex (e) of the H1 Guidance Note, these circumstances may require a ‘complex’ assessment. However, discharges from the holding tanks on a coastal PWR site will generally be made into the once-through seawater cooling flow which is of the order of five million m^3 per day per reactor. Overall this would make them more like a continuous discharge rather than a series of intermittent discharges.

The main chemicals in cooling waters are biocides, such as chlorine and chlorination by-products (CBP). Even though most plants carry out biocide dosing intermittently, again the large flow of cooling water will make the discharge of biocides approximate to a continuous, rather than a batch or intermittent, discharge.

Given this, a simplified approach assuming continuous discharge has been applied for this generic assessment, as per Annex (d) of the H1 Guidance Note. This assumption is consistent with the approach normally taken for assessing the radiological impacts of aqueous discharges from a PWR power plant to water (which uses a different assessment tool called PC CREAM). That is, although the discharges take place from the holding tanks on a batch basis, they appear in the environment as a continuous background component in the main cooling water.

7.3.2 Generic screening assessment

This section describes a screening ecotoxicological assessment for discharges of chemicals from a notional coastal UK site, with two PWRs based on an outline predecessor design, each of 1,500 MW(e) capacity, and using once-through cooling water.

Tables 3.1 and A8.1 show that a wide range of chemicals have been identified as being used and potentially discharged from a PWR power plant. However, the permits and fact sheets for the plants covered in this survey, and the assessments for the candidate designs, suggest that a common suite of routine bulk chemicals are used in the primary and steam circuits and larger auxiliary systems (see Section 4).

This assessment is based on the mass discharges of these routine bulk chemicals from the twin reactor site at Flamanville at the limits in the permit over periods of two hours, daily and at the annual limit. The assessment conservatively assumes that chlorine does not decay as it travels through the plant, that is, the concentration of chlorine in the outlet is the same as the inlet. Chlorine decay models are available (such as Wang et al. 2008), but they require site-specific data such as temperature and flow rate.

Some chemicals were additionally included in the assessment as follows:

- To include the potential use of secondary amines and their subsequent discharge, ethanolamine and morpholine were included at the mass limits shown in the permit for the twin coastal reactor site at Penly (Annex A5.2.4).
- The mass discharge of hydrazine was taken from the AP1000™ (370 kg per year per reactor). This was included as it is a larger amount than is specified in permits for the French sites (or for the UK EPR™).

The mass discharge limits for total metals (2 kg per two hours, 3 kg per day and 190 kg per year) were converted into mass fluxes for the individual metals (aluminium, copper, chromium, iron, manganese, nickel, lead and zinc) using the ratios for the UK EPR™ (also see Annex A5.2.6).

These mass discharge values used in this generic ecotoxicity assessment are shown in the first column of Table 7.3 at the end of this section. The mass discharges were converted into end-of-pipe concentrations by assuming mixing in a main cooling water flow for a single reactor of five million m^3 per day (based on the discharge at Sizewell B and similar values at US coastal sites). This is equivalent to 10 million m^3 per day for a twin reactor site.

The end-of-pipe concentrations were further processed to allow comparison with relevant environmental criteria (see Section 7.3.3) as follows:

- Boric acid (H_3BO_3) was converted to boron.
- It was assumed that 10 per cent of the ammonium (NH_4^+) discharged was converted to the free ammonia form (NH_3). The ionised NH_4^+ is relatively harmless to aquatic organisms. EQS relate to the more harmful unionised dissolved ammonia (NH_3). The equilibrium between these two species depends on salinity, temperature and pH in the mixing zone where the discharge occurs. A figure of 10 per cent conversion to ammonia is a standard assumption used for screening assessments (USEPA 1989).

Annex (d) of the H1 Guidance Note recommends using the following equation to calculate process contributions:

$$PC_{(water)} = (RC \times 1{,}000) / ID$$

where:

PC is the process contribution (µg/l) to the receiving water;

ID is the site-specific initial dilution; and

RC is the release concentration in the effluent (mg/l).

Discussions with the Environment Agency (Timmis R, personal communication, August 2010) suggest this approach was developed for low discharge flows and may not applicable to large cooling water flows from a twin reactor coastal site. Furthermore, there is no site-specific data available with which to estimate the initial dilution for a generic PWR reactor discharge.

Instead, a simple dilution factor of 10 was applied to the end-of-pipe discharges. This is based on a number of Canadian and US studies (Health Canada 2010). Health Canada (2010) also states that the European Centre for Ecotoxicology and Toxicology of Chemicals for the Chemical Industry uses a generic dilution factor of 10 in its local exposure models.

The calculated process contributions are included in Table 7.3.

7.3.3 Environmental Quality Standards and other environmental assessment criteria

Following the H1 guidance, the next step is to compare the calculated PCs with relevant environmental criteria – preferably Environmental Quality Standards (EQS). The most up-to-date EQS for England and Wales are given in The River Basin Districts Typology, Standards and Groundwater Threshold Values (Water Framework Directive) (England and Wales) Direction 2010.[4] The EQS for any dangerous substance not identified under the Water Framework Directive will continue to apply until the Dangerous Substances Directive is repealed. If no EQS is available, the PC can be compared to natural background concentrations and/or ecotoxicity data. In any site-specific assessment, this should to take into account any sensitive local species and results of habitat surveys.

Several EQS values may be established for a pollutant, for different types of water body (inland, surface waters, saline waters and groundwater) and to take into account the natural chemistry of the water. Maximum Acceptable Concentrations (MAC) EQS account for acute impacts of a pollutant and Annual Average (AA) concentrations take account of longer term, chronic effects. Some EQS are applicable to surface waters in the European Union, while others are specific to the United Kingdom. Some are statutory EQS and others are non-statutory EQS.

Table 7.3 and Table A8.1 in the Annex Report list the available EQS values for the chemicals used or potentially discharged from the plants covered in this survey. There are no EQS established for many of these chemicals.

Ecotoxicity data were reviewed as follows to enable the relative toxicity of the chemicals to be considered.

- Chronic toxicity data expressed as the no observable effect concentration (NOEC). This is the highest concentration of a pollutant, found by experiment or observation, that causes no alterations of morphology, functional capacity, growth, development, or life span of target organisms distinguishable from those observed in a normal control population under the same conditions (but in the absence of the pollutant). Where this needs to be extrapolated to a 'real' population, a safety factor of between 10 for longer term effects or up to 1,000 for shorter term acute effects may need

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[4] http://archive.defra.gov.uk/environment/quality/water/wfd/classification.htm [Accessed August 2011]

to be applied. This more stringent limit is called the Predicted No Effect Concentration (PNEC).

- Acute toxicity data expressed as the lethal concentration that causes death (resulting from a single or limited exposure) in 50 per cent of the treated population of a specific species [abbreviated to LC(50)]. Low LC(50) values mean the substance it toxic even at low concentrations. LC50 values are of limited use in ecotoxicity studies because they only measure acute effects and do not account for long-term effects on the population such as ability to reproduce.

Ecotoxicity data as NOECs and LC(50)s for chemicals used or potentially discharged from the candidate designs is included in Annex Table A8.2 and in Table 7.3.

Where possible, the PC contributions are compared to statutory EQS for saltwater bodies. Where these are not available, non-statutory EQS, freshwater EQS or other benchmarks are used.

There are no EQS or other benchmarks available for hydrazine, ethanolamine and morpholine (secondary circuit additives). However, in support of the proposed twin UK EPR™ power station at Hinkley Point C, EDF commissioned experimental studies to establish PNECs (EDF 2010a). The results are summarised in Table 7.2.

To assess the effects of the discharge of ballast from tankers to coastal waters, a PNEC for bromoform of 7.1 µg/l has been derived (IMO 2009, Annex 4, page 21, Environmental risk assessment). However, the natural background levels of trihalogenated organics and some AOX compounds can be tens of µg/l (European Commission 2010a, Environment Agency 2010b).

Table 7.2 Proposed PNEC values for chemical parameters based on EDF research and reviews

	Acute marine PNEC	Chronic marine PNEC
Hydrazine	0.004 µg/l	0.0004 µg/l
Ethanolamine	160 µg/l	160 µg/l
Morpholine	28 µg/l	17 µg/l

Note: Source: Table 17.5, EDF (2010a)

The EQS for detergents in Table 7.3 conservatively assumes they consist entirely of EDTA complexing agent, for which EQS are available. However, EDF states that EDTA will not be used in the UK EPR™ (see Section 4.3.11).

It is useful to compare process contributions with natural background concentrations and these are listed in Table 7.3. These will depend on a range of factors (such as pH, suspended sediment), and because they differ significantly between coastal and open ocean waters, should be determined on a site-specific basis.

7.3.4 Results of the assessment

The generic assessment assumes that the chemicals discharged from a notional twin PWR site are at the discharge limit, diluted in 10 million m^3 per day cooling water flow and are further diluted by a factor of 10 in the mixing zone of a coastal water body. The calculated concentrations in this mixing zone were compared with EQS or other environmental criteria (summarised in the final columns of Table 7.3).

The H1 assessment allows ‘insignificant releases’ to be screened out by establishing if they are so small that they are unlikely to cause significant impact on the receiving water. Substances cannot be screened out from the assessment where:

- process contribution discharges at the limit that are greater than 4 per cent of the available EQS;
- any process contributions exceed the LC(50) or PNEC.

These are highlighted in red in Table 7.3 and summarised below.

Total residual oxidants

Process contributions for two hourly, daily and yearly discharges of total residual oxidants exceed 4 per cent of the EQS. The process contribution from two hourly and daily discharges slightly exceeds the EQS of 10 µg/l. Therefore total residual oxidants cannot be screened out from this H1 assessment.

This issue of total residual oxidants associated with chlorine dosing at assumed maximum generic limits is well recognised (see Section 4.2.5.1 in Westinghouse 2010a and Section 2.5.3.1 in UK EPR™ 2010f). The impacts are addressed through operational controls (already in place at UK coastal sites) and chlorination only according to site-specific requirements. This will reduce discharges of chlorine and the resultant process contributions in accordance BAT (see Section 4.3.9). The following also need to be considered:

- The comparison does not take into account the fact that the saltwater EQS of 10 µg/l for chlorine is based on the 95th percentile concentration. Concentrations above the EQS can occur, providing the 95th percentile is not exceeded.
- The toxic effects of total oxidants vary according to the exact chemical species that contribute to total residual oxidants (hypochlorous acid and hypochlorite), which are dependent on temperature and pH.
- Residual oxidants are naturally degraded in the environment. Taylor (2006) reported half-lives of some chlorinated by-products: bromoform (26 hours), dibromochloromethane (17 hours), dichlorobromomethane (9 hours) and dibromoacetonitrile (14 hours).

Further guidance is available in European Commission (2001a).

Hydrazine

The process contributions for hydrazine (based on the annual discharge from the AP1000™ at a notional site) exceed the PNEC values established by EDF – most significantly for the short-term releases. This was also identified in the environmental assessments carried out for Hinkley Point C (EDF 2010a). However, the following should be noted:

- The process contribution calculated for hydrazine assumes no on-site treatment prior to discharge. Any on-site pre-treatment of hydrazine, such as that proposed for the UK EPR™ or already implemented at the US plant at Millstone could significantly reduce the predicted process contributions.
- The assessment assumes hydrazine is diluted in the environment by a factor of 10 from the end-of-pipe concentration. A further reduction in

concentration would occur due to hydrolysis or any microbiological degradation of the hydrazine.

- The conservative values for the PNEC of hydrazine are based on studies by EDF and include a safety factor of 100. Only the two-hour discharge would exceed the LC(50) of 0.8 µg/l or the lowest NOEC of 0.5 µg/l from the review of ecotoxicity data (Annex report Table A8.1).

Phosphate

The two-hourly process contribution for phosphate (14 µg/l) slightly exceeds the most stringent USEPA criterion of 10 µg/l specified to limit algal growth and eutrophication. The daily process contribution (1.5 µg/l) is greater than 4 per cent of this criterion. Therefore phosphate cannot be screened out from this H1 assessment.

However, the values of phosphate calculated here are unlikely to cause eutrophication in near coastal or estuarine environments because nitrogen is likely to be a limiting factor for algal growth.

Ammonia

The two-hourly discharge of ammonia (0.96 µg/l) is slightly greater than 4 per cent of the EQS (21 µg/l), so ammonia cannot be screened out from this H1 assessment.

The process contribution for ammonia was calculated based on 10 per cent of ammonium (NH_4^+) being present as ammonia (NH_3). In the pH and temperature conditions of a coastal mixing zone, the proportion of ammonia is likely to be lower, which would reduce the process contribution for ammonia.

Background concentrations of free ammonia in some UK coastal waters may be of the order of 15 µg/l (Newell 1967).

Summary

Of the chemical discharges from a generic twin reactor site at the assumed limits, total residual oxidants and hydrazine cannot be screened out from the generic assessment. Discharges of these chemicals might therefore need to be considered as a priority in a more detailed dispersion modelling or ecotoxicological assessment.

The assessment needs to take account of the following factors:

- The process contributions are based on discharges at the limits shown in the first columns of Table 7.3. Data for French sites (Annex A5) show that for most parameters, actual discharges are mostly less than the limits. This would reduce actual process contributions and any associated exceedance of environmental criteria.
- The dilution factor of 10 that was applied to the end-of-pipe concentrations is a notional one and would depend on a range of site and seasonal factors.
- The environmental criteria used are generic. They would need to be reassessed for any individual site where more sensitive features or species might be present (such as local fishing resources).

- This assessment covers the routine bulk chemical discharges identified from the PWRs included in this survey. It does not include all possible chemicals that are used and which could appear in discharges to water.
- The assessment does not cover discharges of hydrocarbons present as residues after treatment of effluents through oil–water separators. EQS are available for some volatile hydrocarbons (such as xylenes) but not for heavier fractions in lubricating oils. Manufacturers of oil–water separators routinely claim that they should produce an aqueous stream containing less than 10 mg/l of oil.
- The assessment does not cover thermal impacts or those due to chemical or biochemical oxygen demand.

7.3.5 Persistent, Bioaccumulative and Toxic (PBT)

As well as the relatively simple impacts on a receiving water and sensitive species due to a discharge, there may also be a need to consider if, even if the impacts are negligible, there could be longer term impacts due to accumulation of chemicals as they pass along the food chain or if they gradually accumulate in the environment. Criteria for persistence, bioaccumulation and longer term toxicity are defined in Annex XIII of the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulations. They can be summarised as follows:

- A persistent substance is one that has a half-life in marine water higher than 60 days and in marine sediments higher than 180 days.
- A substance is considered bioaccumulative when the bioconcentration factor is higher than 2,000.
- A toxic substance is one where the long-term NOEC for marine and freshwater organisms is less than 0.01 mg/l or the substance is classified as carcinogenic, mutagenic, or toxic for reproduction, or there is other evidence of chronic toxicity.

Data are provided in the Annex Table A8.2 for persistence, bioaccumulation and toxicity for chemicals used or potentially discharged from PWR power plants. The basic information in this table suggests that none of the substances discharged would likely to be persistent and bioaccumulative and toxic. However, this would need to be underpinned at any specific site by a fuller PBT assessment.

7.4 Ecological assessments (direct toxicity and whole effluent toxicity tests)

EQS values and other environmental criteria can only be used to give a prediction of general environmental impacts. They may not be relevant to local species or water chemistry conditions. If concentrations of a chemical along the discharge route are very low, this can introduce significant unknowns into any calculated or measured process contributions in the receiving water. This has already been shown for heavy metal discharges from the US plants (Annex A3). For these reasons, operators of PWR plants covered in the current survey are routinely required to carry out effluent toxicity tests (see approach for ‘complex’ discharges, Section 7.3.2).

7.4.1 Sizewell B and Direct Toxicity Assessment

Discharges from the Sizewell B PWR are subject to periodic toxicity tests, although the results from tests are not available. According to the H1 Guidance Note, the discharge of a ‘complex’ effluent requires a direct toxicity assessment (DTA) to be performed.

Direct Toxicity Assessment (DTA) is a process of measuring the environmental hazard (toxicity) of a discharge and assessing the whole effluent toxicity using standardised aquatic toxicity tests (Environment Agency 2006). In essence, DTA integrates the additive, synergistic and antagonistic effects of chemical substances in ‘complex’ effluent, including any breakdown products that may also be present. DTA gives a more comprehensive assessment of the potential environmental impact of chemical discharges compared to the ‘simple’ effluent assessment (Section 7.3.4).

DTA measures the acute toxicity of effluents using a suite of ‘tried and tested’ aquatic ecotoxicity tests. Such tests have been developed as ‘bioanalytical’ surrogates representing groups of organisms likely to be found in the aquatic environs (plants, invertebrates). In the UK, current DTA tests employ the following species:

- **Inhibition of algal growth:** For the freshwater environment *Pseudokirchneriella supcapitata* and for the saline environment *Skeletonema costatum.*
- **Immobilisation of invertebrates**: For the freshwater environment *Daphnia magna* and for the saline environment Oyster Embryo Larval Development or *Tisbe battagliai* mortality tests (Environment Agency 2010d).

The DTA approach is very similar to the US whole effluent toxicity approach.

7.4.2 US plants and whole effluent toxicity tests

Whole effluent toxicity tests are performed by the majority of US plants to determine whether a dilute effluent sample adversely affects the survival, reproduction or growth of test organisms.

Chronic and acute toxicity tests are performed at Comanche Peak, Seabrook and San Onofre. The test organisms vary:

- Comanche Peak uses water fleas (*Ceriodaphnia dubia*) and fathead minnows (*Pimephales promelas*).
- Seabrook uses inland silverside (*Menidia beryllina*), mysid shrimp (*Mysidopsis bahia*) and sea urchins (*Arbacia punctulata*).
- San Onofre uses red abalone (*Haliotis rufescens*), giant kelp (*Macrocystis pyearifera*) and topsmelt silverside (*Atherinops affinis*).

For most of the US plants covered in the survey, the permits specify that whole effluent toxicity tests should be carried out every quarter. On the basis of consistently negative results, the regulator may agree that plants can reduce the frequency of testing to twice per year.

7.4.3 French PWR sites

Operators of the French PWR sites carry out monitoring of phytoplankton and zooplankton. This monitoring surveys:

- species variation in space and time;
- number and nature of the species;
- active chlorophyll;
- total weight of the chlorophyll-containing matter.

Fish and shellfish such as sole, bristling (*Sprattus sprattus*) and grey prawns are monitored for variation in time and space along with those species that live in sand in intertidal areas. Whole effluent toxicity tests are also carried out. Extensive reports are available in French (for example, Lampert et al. 2007).

Table 7.3 Results of generic ecotoxicology assessment

	Mass release kg			**End of pipe concentration mg/l**			**PC µg/l (d)**			**Statutory saltwater EQS**	**Other benchmarks**	**LC50 (c)**	**NOEC (c)**	**PNEC acute**	**PNEC chronic**	**Concentration in seawater (k)**
	2 hrs	**24 hrs**	**year**	**2 hrs**	**24 hrs**	**year**	**2 hrs**	**24 hrs**	**year**	**µg/l**	**µg/l**	**µg/l**	**µg/l**	**µg/l**	**µg/l**	**µg/l**
Discharge from the nuclear island																
Boric Acid **(e)**	2,500	7,000	40,000	5.2E-01	1.2E-01	1.9E-03	**52**	**12**	**0.19**		7,000 **(m)**					4,500
Lithium	1	4	4	6.0E-04	3.8E-04	1.2E-06	**0.06**	**0.04**	**0.0001**							170
Hydrazine	7	9	150	8.6E-03	9.0E-04	4.1E-05	**0.86**	**0.09**	**0.004**			0.8	0.5	0.004	0.0004	
Detergents	160	200	1,800	1.9E-01	2.0E-02	4.9E-04	**19**	**2**	**0.05**		4,000 **(h)**					
Ammonia (unionised+ionised)	80	100	20,000	9.6E-03	1.0E-03	5.5E-04	**0.96**	**0.1**	**0.05**	21		57	11			15
Nitrogen	70	175	n/d	8.4E-02	1.8E-02	n/d	**8.4**	**1.8**	n/d		2,520 **(f)**					
Phosphates	120	150	2,000	1.4E-01	1.5E-02	5.5E-04	**14**	**1.5**	**0.05**		10 **(g)**					
Phosphorus	40	50	700	4.8E-02	5.0E-03	1.9E-04	**4.8**	**0.5**	**0.02**							
Chemical Oxygen Demand	120	150	n/d	1.4E-01	1.5E-02	n/d	**14**	**2**	n/d							
Total Metals	2	3	190	2.4E-03	3.0E-04	5.2E-05	**0.2**	**0.03**	**0.01**							
Suspended Solids	100	120	19,400	1.2E-01	1.2E-02	5.3E-03	**12**	**1.2**	**0.5**		25,000 (i)					
Discharge from raw water treatment																
Iron	5	50	10,500	6.0E-03	5.0E-03	2.9E-03	**0.60**	**0.50**	**0.29**	1,000						1.3
Sulphate	1,100	2,400	250,000	1.3E+00	2.4E-01	6.8E-02	**132**	**24**	**7**							
Suspended Solids	25	55	14,000	3.0E-02	5.5E-03	3.8E-03	**3.00**	**0.55**	**0.38**		25,000 (i)					
Discharge from chlorination																
Residual Oxidants	100	1,200	110,000	1.2E-01	1.2E-01	3.0E-02	**12**	**12**	**3**	10						
Bromoform	10	120	11,000	1.2E-02	1.2E-02	3.0E-03	**1.2**	**1.2**	**0.3**	(10)				7.1**(j)**		
Individual metals																
Aluminium	0.18	0.27	17.0	2.1E-04	2.7E-05	4.7E-06	**0.02**	**0.003**	**0.0005**							1
Copper	0.01	0.02	1.3	1.7E-05	2.1E-06	3.6E-07	**0.002**	**0.0002**	**0.00004**	5						0.1
Chromium	0.28	0.42	26.8	3.4E-04	4.2E-05	7.3E-06	**0.03**	**0.004**	**0.0007**		4.7 **(l)**					0.08
Iron	1.19	1.78	112.7	1.4E-03	1.8E-04	3.1E-05	**0.1**	**0.02**	**0.003**	1,000						1.3
Managense	0.11	0.17	10.6	1.3E-04	1.7E-05	2.9E-06	**0.01**	**0.002**	**0.0003**							0.2
Nickel	0.02	0.02	1.4	1.8E-05	2.3E-06	3.9E-07	**0.002**	**0.0002**	**0.00004**	20						0.2
Lead	0.01	0.02	1.0	1.2E-05	1.5E-06	2.6E-07	**0.001**	**0.0002**	**0.00003**	7.2						0.02
Zinc	0.20	0.30	19.2	2.4E-04	3.0E-05	5.3E-06	**0.02**	**0.003**	**0.0005**	40						0.01
Other substances (a) (b)																
Morpholine	n/d	78	1,150	n/d	7.8E-03	3.2E-04	n/d	**0.78**	**0.03**			28,000	5000	28	17	
Ethanolamine	n/d	22	620	n/d	2.2E-03	1.7E-04	n/d	**0.22**	**0.02**			15,000	1,770	160	160	
Hydrazine	n/d	n/d	740	n/d	2.0E-04	n/d	n/d	n/d	**0.02**			0.8	0.5	0.004	0.0004	
Ammonia	n/d	n/d	25,700	n/d	7.0E-03	n/d	n/d	n/d	**0.70**	21		57	11			

For notes see over

Key to Table 7.3 and Notes:

Mass releases are based on chemicals discharged at mass limits from a generic twin reactor coastal site. Discharges are mostly based on a combination of French operating plants (as only these provide data on mass discharges), but use the predicted hydrazine discharges from the AP1000™ report.

EQS in (µg/l)

a) Annual discharges for morpholine and ethanolamine based on limits for the coastal plant at Penly.

b) Additional discharge of hydrazine of 740 kg/year based on UK AP1000™ Environmental Report, Table 4.2-2.

c) LC(50) is acute toxicity. NOEC is the no observed effect concentration. PNEC is the predicted no effect concentration. All are as µg/l.

d) The PC concentrations are compared with the 4 per cent value of the EQS or other benchmarks. Actual values are compared with LC50 and NOEC. Exceedances are shown in red.

e) Discharges of boric acid (H_3BO_3) are converted to boron (B) for calculating PC and comparison with benchmarks.

f) Benchmark for nitrogen is based on total value for nitrogen in the Water Framework Directive for 'good status' in medium turbidity coastal water (180 µmol/l).

g) Benchmark for phosphate is based on USEPA 1986 data that states that algal blooms are unlikely at or below 10 µg/l. This was used because there are no alternative standards for phosphate in seawater.

h) Benchmark for detergents is based on worst case scenario of all consisting of EDTA with non-statutory EQS for salt water of 4,000 µg/l (MAC). EDTA use is being phased out.

i) Benchmark for suspended solids based on EU freshwater quality standard of 25 mg/l.

j) Benchmark for bromoform based on International Maritime Organization (IMO) data.

k) Metals concentrations from Schwochau (1984), boron concentration from Mance et al. (1988), ammonia concentration from Newell (1967).

l) Benchmark for chromium is annual mean freshwater EQS for Cr(III)

m) Benchmark for boron is UK statutory guidance for boron in saltwater

n/d indicates not defined.

This is provided as a generic example for a notional coastal reactor site. More detailed assessments would be required for a specific reactor site and local conditions.

8 Conclusions and overview

8.1 Permits and regulatory regimes

Discharges of chemicals and radioactive substances from nuclear power plants in England and Wales are regulated by the Environment Agency and in France by the Autorité de Sûreté Nucléaire. In the USA, chemical discharges are regulated by a federal or state delegated body under the overall control of the US Environmental Protection Agency while radioactive discharges are regulated by the US Nuclear Regulatory Commission.

Permits for the selected operating PWRs in all three countries emphasise the use of Best Available Techniques (BAT) to minimise discharges of radioactive materials and chemicals and therefore their impacts on ecosystems and human health.

Limits for discharges of chemicals from the UK's only PWR at Sizewell B cover a relatively small set of parameters in the main cooling water outfall. The limits are expressed in terms of the difference in concentrations measured between the inlet of the cooling water system and the final outlet.

The permits for the US sites include limits for chemicals discharged from internal outfalls or plant systems prior to their entering the main cooling water flow; such an approach can demonstrate application of BAT at source rather then at end-of-pipe. The limits are based on generic values that are applied across all large steam-generating plants in the USA. The permits have additional limits for the concentrations of chemicals in the final main cooling water outfalls, again based on generic values that apply to all large-scale US power plants. These cover a narrower suite of parameters including suspended solids, oil and grease, and chemicals present following chlorination. The US plants are required to monitor other parameters such as trace metals or USEPA priority pollutants in the internal and/or final external cooling water outfalls. End-of-pipe limits for these additional parameters are frequently based on a substance not being detected when analysed using a specified method. There are also requirements for whole effluent toxicity tests.

Limits for the discharge of chemicals from French sites are based on mass limits discharged from the final holding and sentencing tanks that serve the nuclear island and turbine systems. Limits apply to discharges over two hours, daily and annually. They are supplemented by limits on the maximum concentrations allowed in the tanks or in the final discharge routes or in the holding ponds at coastal sites through which discharges finally pass to sea. The approach allows plant operators to optimise the timing and co-ordination of discharges and to minimise their impacts. There are also allowances for additional discharges to cover reactor shutdowns or for the wet lay-up of plant required during maintenance. Separate limits cover discharges of chemicals from once-through seawater cooling systems or from cooling towers, and also chemicals discharged from the raw water and sewage treatment plants on each site.

8.2 Parameters in permits and discharge data

This section highlights the main issues identified in the permits and discharges of chemicals. They are dealt with in the order of importance and the regulatory emphasis placed on them in currently operating plants. Although a matter of judgement, the following listing is suggested:

- Biocides in main cooling water systems, especially chlorine used in once through seawater cooling systems. Other impacts due to large cooling water flows such as thermal impacts and entrainment are also important. These are dealt with in a separate report (Environment Agency 2010b).
- Hydrazine in effluents that arise from the wet lay-up of plant systems for the purposes of maintenance.
- Ammonia and amines used in the secondary steam circuit.
- Hydrocarbons in rain and stormwater run-off.
- Phosphates and phosphorus compounds, including phosphorus-based corrosion inhibitors, anti-scale chemicals and detergents.
- Proprietary systems. Many of the chemicals listed above are likely to be sourced as proprietary systems that contain a range of other additives.
- Trace and heavy metals, including corrosion products and metallic impurities present in some bulk chemicals.
- Chemical discharges specifically from the reactor primary circuit and radioactive waste treatment systems, that is, boric acid and lithium hydroxide. These are the only chemicals used and potentially discharged that are specific to a PWR nuclear power plant. The other chemicals considered above are all ones that might be expected in discharges from a fossil fuel power plant. Based on their chemical properties and environmental impacts, boric acid and lithium hydroxide attract less regulatory scrutiny. However, discharges containing these chemicals from the primary circuit and radioactive waste systems are still strictly regulated because they contain the bulk of the radioactive substances in discharges from any PWR plant – the subject of a separate study (Environment Agency 2010a).

8.2.1 Biocides in main cooling systems

All the operating plants use cooling water drawn from external sources for the main condensers that serve the turbine generators. External cooling is either by seawater or water drawn from lakes, reservoirs or rivers and augmented by cooling towers.

Screens and other mechanical devices are used to exclude larger biota from the cooling systems. Smaller organisms or planktonic materials are too small to be mechanically excluded, but once they enter the systems they can colonise and cause a range of operational problems. They are therefore controlled by dosing the cooling water with chemical biocides.

In all the plants using once-through seawater cooling, the standard biocide is chlorine. At some US plants, metabolic inhibitors for specific or alien species are occasionally used. This survey shows that the issues and problems associated with using biocides at PWR plants and the controls required to meet BAT are consistent with those in other large-scale electrical generating plants at coastal locations. The main issues identified in the current report are as follows:

- Based on simple conservative discharges at maximum limits, levels of residual chlorine discharged could come close to environmental limits. However, operational experience and guidance is available to allow site operators to maintain dosing at the minimum required to protect the plant while ensuring minimal environmental impacts of the cooling water.

Relevant guidance is given in, for example, British Energy's Operational Memorandum (British Energy 2006) or the IPPC BREF for large-scale cooling systems (European Commission 2001a). The dosing regimes specify the maximum concentrations allowed, the frequency of dosing, and seasonal and water temperature factors to be considered.

- For sites with several separate reactors plants, there is a need to co-ordinate the timing of chlorination in each one so that the total discharges of residual chlorine to the receiving water do not exceed guidance values.
- Chlorination of cooling water forms a range of halogenated by-products that vary according to site-specific conditions.
- Due to certain local conditions, some coastal plants are able to operate without chlorination at all, though this is exceptional.
- Detection limits and data reported for total residual oxidants in cooling water outfalls can depend significantly on the analysis methods used.

In all the operating plants using cooling towers, more complex site-specific issues of biofouling need to be addressed. French sites use monochloramine (a combination of ammonia and chlorine), although one site retains chlorine, with future options including use of UV light mainly to control Legionella. US plants with cooling towers use chlorine and other oxidising biocides such as bromine, but also list a wider range of proprietary systems for site-specific problems.

8.2.2 Hydrazine

Hydrazine is used as an oxygen scavenger in the main steam circuit (as part of standard AVT) and during wet lay-up of some plant systems. Hydrazine is stored as a concentrate (about 35 weight per cent). Concentrations used in the main steam circuit are about 0.1 mg/l. Concentrations of up to 100 mg/l are used in aqueous solution for wet lay-up. Operators of the US plants indicate that it is the concentrated solutions used in wet lay-up that have the greatest impacts on final discharges and are therefore the most difficult to manage in accordance with BAT.

Depending on the temperature and pH in the plant systems, the hydrazine decomposes to ammonia (which provides control over pH). Hydrazine and any ammonia formed will undergo complex interactions with ion exchange resins in treatment plants. The final concentrations of hydrazine and its breakdown products in discharges from different plant systems in a PWR are difficult to predict.

Hydrazine solutions used for wet lay-up cannot be reused and must either be discharged directly or treated. Standard treatments are to destroy residual hydrazine as far as possible using hydrogen peroxide or hypochlorite.

Permits for all the French sites include mass limits on discharge of hydrazine with additional allowances for discharges from wet lay-up or during reactor shutdown. Most US plants have limits applied to internal and, in some cases, external outfalls. Limits in discharges have become generally more stringent over time in response to concerns over the toxicity of hydrazine and potential hazards to plant workers handling it.

Actual discharges of hydrazine from French sites are mostly below the limits in force and generally show a downward trend over the past decade. There is no correlation between either limits or discharges with the size of individual plants or number of plants on a single site. This is because limits and discharges depend on how secondary steam plant and wet lay-up is managed and how plant-specific corrosion issues are dealt with. Any correlation with plant size or capacity will also be masked by treatments plant operators might use to destroy hydrazine prior to its discharge.

A generic assessment assuming discharge at the maximum limits for a twin reactor coastal site suggests that concentrations of hydrazine in the final mixing zone could exceed a predicted no effect concentration (PNEC) established in support of the licensing of the UK EPR™.

In response to concerns over hydrazine, there is extensive published information on alternative oxygen scavengers. However, there is no readily available experience on the use of these alternatives in the operating conditions of the main steam circuit of PWRs and none to rival the historical experience gained with hydrazine. Extensive work would be required before such alternatives could be considered for this especially critical application. Data from the US plants and EPRI publications suggest the greater emphasis in the USA is on establishing suitable alternatives to hydrazine for use in wet lay-up of plant systems, when the most concentrated solutions are used although discharged intermittently. However, there is evidence that, after using these alternatives, operators have had problems and reverted to using hydrazine.

8.2.3 Ammonium salts (NH_4^+) and ammonia (NH_3)

Ammonia is used as a pH control agent in the main steam circuit in some plants and also arises from decomposition of hydrazine. Some plants also use proprietary organic ammonia species as corrosion inhibitors and especially algicides and alternative biocides in closed circuits or cooling towers.

In the main steam circuit, ammonia can be taken up by ion exchange beds in the condensate polishing plant (or those in the steam generator blowdown system). When regenerated, these ion exchange beds will release the ammonia (NH_3) mainly in the form of ammonium ions (NH_4^+). Ammonia is converted to predominantly ammonium when effluents are neutralised to the range specified in the plant permits (6–9). Low temperatures and a pH around 7 in the receiving water will ensure that the less toxic ammonium form is the dominant chemical species. The analytical method is critical in distinguishing between these two species and in setting limits. Some methods measure total nitrogen that ensures both ammonia and ammonium are included but do not distinguish between them. Limits and discharges for some French sites are given as ammonium but in others as ‘ammonium as total nitrogen’. There is much less consistent data on limits and discharges for ammonium and ammonia from the US sites.

Mass limits for discharges of ammonium show some correlation with the number of plants on site, but there are additional allowances for operational requirements such as reactor shutdowns. Actual discharges from some French sites come close to the limits.

While neutral pH and dilution are the main means for ensuring BAT is used to minimise discharges of ammonia (and retain most as the less toxic ammonium ion), some plants remove ammonia from process streams using electro-deionisation or steam stripping. These are not, however, suitable for treating large volumes of dilute solutions of ammonia/ammonium and so therefore need to be applied at source.

The results of the generic assessment (Section 7.3.4) suggest that short-term process contributions of ammonia could come close to exceeding EQS, but by only a small margin and depending on dilution factors and the conversion of ammonia to ammonium. The calculated process contributions are comparable to background concentrations of ammonia in seawater.

8.2.4 Amines

Amines may be used as alternatives to ammonia or in combination with ammonia to control pH in the secondary steam circuit of PWRs. The advantage of amines is that they have better retention in the water phase, so improving the control of pH and further reducing corrosion and the potential transport of iron corrosion products from the feedtrain into the steam generators.

The most important amines for the PWR plants covered in this survey are morpholine and ethanolamine. During operation, the amines are taken up by ion exchange resins in the condensate polishing plant and released when the resins are regenerated. Free amines can appear in the final plant discharges. Minor breakdown products include acetates and glycolates.

Limits for the discharge of amines from French sites depend on the number of plants on each site and on how individual plants are operated with allowances for shutdowns and maintenance. Actual discharges of amines are less than the discharge limits and depend on a range of operational factors and chemical behaviour as amines pass through the waste treatment systems. There are little or no data on actual discharges of amines from US plants.

Some methods have been established to treat effluents containing amines, but none were identified as being applied in the PWR plants covered in the survey.

Assessment of the environmental impacts of discharges of amines is limited by uncertainty over concentrations in the final discharges and by the limited availability of environmental criteria or benchmarks.

8.2.5 Hydrocarbons

All PWR plants store and use fuel oil, lubricating oils and hydraulic oils. The largest amounts of stored fuel oil are for the standby diesel generators (used for back up in emergencies) and auxiliary boilers (used to supply steam for heating and frost protection). The largest volumes of hydraulic oil used are in the turbine systems.

BAT to minimise the entry of oil into aqueous discharge routes is to ensure correct design and operation of the oil storage facilities and training of personnel involved in the delivery and use of the oils. There is a wide range of information on the precautions that should be used. These include avoiding ingress of rainwater into oil storage areas (to minimise generation of oily run-off), using correctly sized bunds to contain larger leaks, and having control kits available to mop up any smaller spills. Any oily water that does arise from oil storage areas is treated in oil–water separators. At all the sites covered in this survey, these appear to reduce the concentrations of oil in water sufficiently to allow the final aqueous effluent to be discharged without further treatment.

Other potential sources of oils and hydrocarbons include leaks from vehicles or accidental spillages in parking and construction areas. Oily water will be carried into drains by rain and run-off. BAT to minimise discharges of water containing oil from these sources is to use interceptors (that can handle large accidental spills) and oil–water separators to handle smaller leaks and the low background concentrations of oil that tend to occur in run-off.

All the plants covered in the survey have limits for concentrations of hydrocarbons in water discharged from internal or external outfalls. Further reductions (in accordance with BAT) are limited by the efficiency of oil–water separators. The limit for oil in water at Sizewell B is 5 mg/l. For US plants, the generic limit for hydrocarbons in water is

15 mg/l (30-day average) or a maximum value of 20 mg/l. Limits for French sites range from 0.3 to 5 mg/l for oil in water discharged from internal plant outfalls to 0.02 mg/l in cooling water culverts and 0.005 mg/l in the mixing zone in any final receiving water. Permits for all the plants note there must be no visible films of oil on the final discharges of aqueous effluents. The Environment Agency has set a limit of 10 mg/l for oil in aqueous discharges from the Little Barford Power Station in Cambridgeshire.

Permits for some US plants include limits on US priority pollutants present as components or impurities in certain types of oil (for example xylene, benzene, polyaromatic hydrocarbons). The limits for these pollutants are usually based on their not being detectable in the discharge when analysed using a standard USEPA method.

Actual concentrations of oil in water discharged from internal and external outfalls in US plants are below the limits in force. However, several US plants highlighted issues associated with historical spillages of oil on the sites that remain to be managed. There are no available data for concentrations of oil in discharges from either Sizewell B or the French sites.

Environmental impacts of discharges of small amounts of oils in aqueous effluents or from spillages would depend on the type of oil. There are environmental benchmarks for volatile components (such as benzene), but these will only be present in petrol (gasoline) and do not occur in the heavier types of lubricating or hydraulic oils.

8.2.6 Detergents

Detergents are used in the active site laundries but also in the decontamination of plant systems and general plant areas. All detergents are proprietary systems containing surfactants, sequestering agents, pH controllers, stabilising agents and builders. Used in aqueous solution in active areas, effluents containing detergents will usually be discharged via the radioactive waste treatment systems. The main objective is removal of the active material (such as cobalt-60) rather than any chemical treatment.

Minimising discharges of detergents and their environmental impacts will involve selecting types that are biodegradable and using them in accordance with the manufacturer’s instructions. It will also involve ensuring that effluents containing detergents are correctly routed through the waste treatment systems.

Some tailored treatment processes have been identified for destroying the organic components of detergents in aqueous effluents. They include oxidation (Fenton process) or ultrafiltration to recover detergents for reuse. None were identified as being used in any of the PWR designs considered in this survey.

Limits for detergents are only specified in the permits for the French PWR sites. There is some correlation between the limits and the numbers of power plants on each site and additional allowances for reactor shutdowns, both of which reflect larger numbers of workers and amounts of potentially contaminated clothing that need to be washed. The actual discharges of detergents are below the limits in force.

There are no readily available environmental criteria or benchmarks against which to assess discharges of detergents. The environmental impacts of a discharge will depend on the types of detergents used. Over the past decade, the formulation of detergents has been changed to minimise their environmental impacts. For example, the use of EDTA in industrial detergents has been largely discontinued. A conservative assessment based on the use of EDTA in a detergent and discharged at the limit for a twin reactor site showed the final process contribution would not exceed the EQS.

8.2.7 Inorganic phosphates

Solutions of sodium phosphate salts are used for the wet lay-up of plant systems where hydrazine cannot be used for operational reasons. Phosphates are also used as permanent corrosion inhibitors in some service water systems. Aqueous effluents containing inorganic phosphate will be discharged via the turbine hall or other sumps or neutralising tanks rather than via the radioactive waste treatment systems.

There are some treatments for removing phosphate from water, but these are generally used only where the water is for potable use or where there are especially stringent limits on the discharge of phosphate. None of the plants covered in this survey treat solutions of phosphate prior to discharge. All the plants consider BAT to be minimising at source and diluting to acceptably low values in the main cooling water flow.

Limits for the discharge of phosphates from French sites show some relationship with the number of reactors on each site, reflecting the amount of auxiliary plant requiring intermittent wet lay-up. There are also allowances to cover increased discharges of phosphate during reactor shutdowns and maintenance. The actual discharges of phosphate from some of the French plants come close to the discharge limits. There is no data relating to discharges of phosphate from the US sites.

The main environmental impact of phosphate is that it is a nutrient for algal growth, which can potentially cause eutrophication. The results of the generic assessment (Section 7.3.4) suggest that short-term discharges of phosphate at the maximum limit from a twin reactor coastal site could marginally exceed a USEPA criterion that is meant to protect against eutrophication. However, longer term discharges do not exceed this value. In addition, the effects of phosphate on algal growth depend on other conditions in the receiving water such as turbulence and the availability of other nutrients.

8.2.8 Phosphorus, organophosphates and phosphonates

Phosphorus is present in discharges with phosphates, but may also occur as organic phosphorus. The most important additives containing organic phosphorus are phosphonates, identified as being used at some US plants. These are used as corrosion inhibitors and to prevent the build-up of scale in water treatment systems, including those using membrane technologies and cooling towers. Phosphonates have complex compositions that include a central phosphate group augmented by aliphatic and aromatic organic groups. Most are only available as proprietary formulations and are used in some detergents.

Minimising the impacts of these chemicals in accordance with BAT will depend on site-specific issues, but will involve use in accordance with the manufacturer's instructions. Their subsequent fate and behaviour due to any deliberate or accidental discharges will depend on their formulation and type.

Some types of organophosphates such as cresyl-phosphate are used as hydraulic oils or oil additives. Preventing accidental spillage or discharge of these oils will employ the same methods as applied to the other hydrocarbon oils stored and used on site.

8.2.9 Proprietary chemical systems

Many of the chemicals described in the previous sections are purchased by plant operators as proprietary systems from commercial suppliers and manufacturers. With the exception of secondary plant additives (ammonia, hydrazine and secondary amines), these purchased materials will usually contain a range of tailored additives such as preservatives and dyes, or inert materials that act as bulking agents or carriers.

Corrosion inhibitors used in closed circuit systems, anti-scale chemicals, and dispersants and coagulants used for cooling or other water treatments all tend to consist of especially complex mixtures; their details should be obtained from the relevant Materials Safety Data Sheets (MSDS).

BAT for the use of these materials is to ensure purchase only from accredited suppliers and then ensure correct storage and use by qualified personnel in accordance with the instructions. Discharge into plant systems must be made only in accordance with local plant operating instructions.

8.2.10 Metals

Iron, chromium, manganese and nickel make up the stainless steel (greater than about 10 per cent chromium) and low alloy steel (less than 10 per cent chromium) used in the reactor, the main steam circuit and the auxiliary plant systems. Corrosion of these can give rise to small amounts of these metals in solution and in particulate form.

The main issues to be addressed are the potential effects of corrosion on the design life of the plant and the appearance of activated corrosion products (such as manganese-54) in any final discharges. The ecotoxicological effects of the small amounts of these metals discharged are of lesser concern. Copper, aluminium and zinc are used in only a few systems that are in contact with water.

Limits for metals in discharges from the US plants are mostly based on the generic list for large power plants (copper, iron, chromium and zinc) and those in the USEPA priority pollutant list (such as arsenic and antimony). Limits on the discharge of metals from the nuclear island and turbine systems in the French sites are based on single mass values that cover a common suite of aluminium, lead, copper, chromium, iron, nickel, manganese and zinc. There are separate limits for the discharge of iron and copper (and in some cases aluminium) from raw water treatment plants.

BAT to meet the design life of the plant and to minimise the production of activation products in the primary circuit and the concentrations of metals in the final discharges all require correct chemical dosing of water in the plant systems to control the pH and levels of dissolved oxygen to minimise corrosion. Any particulate or dissolved metals that are formed are removed by filtration or ion exchange in the waste treatment systems.

The use of mercury, lead and cadmium is specifically avoided in PWR plant systems. Any very low concentrations in discharges will be due to the presence of these metals as impurities in bulk chemical additives. Correct specification and sourcing of these will ensure that the levels of impurities they contain are acceptably low.

At some US plants, the concentrations of some metals (such as nickel or mercury) are higher in discharges from specific plant systems due to localised corrosion or their presence as impurities in the bulk chemicals used for dosing. The concentrations are reduced by treatment and dilution prior their reaching the main cooling water outfall and the environment. The concentrations of these metals even in internal plant outfalls are always close to the analytical detection limits.

Discharges of zinc in effluents from certain plant systems and in the final cooling water outfalls from the US sites are consistently higher than any of the other metals. This is due to leaching of zinc from galvanised components or from certain types of protective paints. In some cases, the concentrations of zinc have fallen over time as these systems have become covered in a passive zinc oxide coating. In other cases, the concentrations of zinc have continued to exceed discharge limits; at these plants operators have had to replace galvanised components with stainless steel.

Zinc is added to the primary circuit coolant at a few PWR plants and in some cases copper is used as a biocide in cooling circuits. The concentrations of zinc and copper used in these applications are very low (less than 0.1 mg/l) and subsequent discharges are small and readily accommodated within discharge limits already in place.

Iron and smaller amounts of copper can occur in the waste effluents from raw water treatment plants. These will depend on the types of raw water being treated or on how the treatment plants are operated, such as the frequency of backwashing filters or ion exchange beds where iron and copper tend to accumulate. Larger amounts of iron in these effluents are removed by neutralisation and settling in tanks prior to the clarified effluent being discharged.

In some older plants, small discharges of copper can come from leaching of copper alloys used in the main condensers. In most of the coastal PWR sites included in this survey, this has been avoided by the use of titanium tubes in the main condensers.

The results of the generic assessment (Section 7.3.4) show concentrations of metals in any main cooling water outfall will be too low to be detected by most routine analytical methods. The predicted short and long-term process contributions (based on maximum limits for a twin reactor coastal site) are below both EQS and typical natural background concentrations. The effects of the metals in the discharges would therefore probably need to be established using whole effluent toxicity tests.

8.2.11 Boric acid

Boric acid is used in the primary circuit of all PWR power plants. Over a fuel cycle there is a need to reduce initial concentrations of boron from about 2,000 mg/l to essentially zero via ‘let-down’ of the primary circuit coolant and its replacement by fresh make-up water. The main strategies to treat surplus borated water to ensure compliance with BAT are minimising waste at source and minimising final discharges, while taking account of practicalities and costs. These strategies are as follows:

- Evaporation to recover the boric acid (and distillates) in a special site facility that may allow the boric acid concentrates and purified water to be reused on the plant.
- Evaporation of the boric acid but directing it to a solid waste route (and the distillates to an aqueous discharge route).
- Discharge of all the surplus coolant containing boric acid to the cooling water outfall.
- Use of enriched boric acid (boric acid artificially enriched in boron-10, which is the isotope responsible for the control over reactivity in the reactor core).
- Use of a specialised ‘boron thermal regeneration system’ that selectively removes boron from effluent and then, when taken through a tailored thermal cycle, releases it as a concentrate. Or use other ion exchange systems that instead of being regenerated are directed to a solid waste route.

The choice of which of these strategies is adopted (and whether evaporators or other systems for the recovery of boric acid are actually incorporated into the plant design in the first place) depends on the following:

- Location of the plant. Plants at coastal locations can discharge boric acid without having a significant impact on the concentrations already normally present in seawater (about 4.5 mg/l). Inland plants are less likely to be able to discharge boric acid to freshwater surface watercourses.
- Doses incurred by workers due to maintenance of boron recycling facilities or due to the presence of tritium and other radioactive impurities in any recovered boric acid or associated distillates that might be reused in the plant.
- The point in the fuel cycle at which the boric acid solutions arise. It is more economic and practical to recover the relatively concentrated solutions of boric acid that arise at the start of each fuel cycle. Discharge of the more dilute ones that arise later in the cycle is less practical because they are more difficult and costly to treat by evaporation.

The mass limits for discharge of boric acid from the French sites show some correlation with reactor capacity and numbers of reactors on any particular site. There are additional allowances for reactor shutdowns and the flushing or emptying of certain plant systems that handle boric acid or the use of more highly enriched fuel.

Mass discharges of boric acid from the French PWR sites covered in this survey are below actual limits in force. Concentrations of boric acid in cooling water discharges from the coastal plants at Sizewell B or in the USA are low and difficult to measure against the background concentrations of boron in seawater. They are well below the saltwater EQS for boron. There are less data on discharges from plants at inland sites, although at several US ones operators have demonstrated that they are able to discharge boric acid without compromising limits for boron in the river water receiving the discharge. Some inland sites use evaporators to concentrate boric acid then direct it to a solid waste disposal route.

8.2.12 Lithium hydroxide

The pH of the primary circuit coolant in all PWRs is controlled by adding low concentrations (2–4 mg/l) of lithium hydroxide, artificially enriched in the lithium-7 isotope to minimise the formation of tritium due to lithium-6. Over a fuel cycle some lithium accompanies boric acid in the ‘primary circuit let-down’.

Generally, the concentrations of lithium in effluents are very small. Although it is an expensive additive, the small amounts used (a few kilograms in each fuel cycle) mean there are no incentives for the recovery and recycling of the lithium-7 hydroxide. Any lithium-7 hydroxide recovered would also probably be too contaminated by fission products (such as ceasium-137) to allow it to be reused safely.

There are limits in permits for the French PWR sites for the mass discharge of lithium, although with no allowances for shutdowns. Discharges of lithium from the plant systems will have concentrations of just a few mg/l, which will be diluted further in the cooling water system to levels well below those naturally present in seawater (about 0.17 mg/l). There are no available EQS for lithium. There are no data for discharges of lithium from the US plants covered in this survey.

8.3 BAT issues, conventional plant and toxicology assessments

Most of the chemicals used at operating PWR plants are used for exactly the same purposes and in similar quantities as at fossil fuel power plants. They include:

- additives to water in the main boilers and turbine systems;
- biocides used in the once-through cooling water systems;
- corrosion inhibitors and anti-scale chemicals used in cooling towers;
- corrosion inhibitors used in smaller closed circuit cooling systems;
- cleaning chemicals.

The only additional chemicals used in a PWR power plant but not in a fossil fuel power plant are boric acid and lithium hydroxide. These are used for dosing the water in the primary reactor circuit.

Chemical emissions to air from PWR and fossil fuel plants are significantly different. Emissions from fossil fuel plants will be dominated by carbon dioxide, sulphur oxides and nitrogen oxides. Extensive studies have been carried out on the abatement of these discharges in accordance with BAT. The only emissions directly to air from a PWR power plant are from the relatively small auxiliary boilers and the occasional testing of the standby diesel generators. Depending on the size of these oil-fuelled systems, these emissions may be subject to regulatory control and therefore require a BAT assessment for permitting.

With respect to chemical discharges to water from the PWRs covered in this survey, a number of issues relating to BAT have been identified where further work might be useful. Prioritising these is a matter of judgement but based on the results of the current study they are as follows:

- Biocides used and then discharged from once through seawater cooling systems, likely to be favoured for PWR plants located at coastal sites in England and Wales (or discharges from wet-type cooling towers if they were used). The setting discharge limits needs to take account of differences in detection limits between different analytical methods.
- Corrosion inhibitors used in the wet lay-up of plant systems. Hydrazine is the main additive used to prevent corrosion during wet-lay up, but there have been investigations into alternative chemicals to remove dissolved oxygen from water and so inhibit corrosion. It is difficult to establish which of these, if any, are actually being used on operating plants. EPRI reports suggest that, even where these alternatives have been used during wet lay-up, problems have caused plant operators to return to the use of hydrazine and manage the issues of discharge.
- Discharge of hydrazine that has been used in the main steam circuit at power. Concentrations of hydrazine used in the main steam system are lower than used in wet lay-up. A few US plants note possible alternatives to the use of hydrazine for the main steam circuit of PWRs. However, it is doubtful if anything could rival the operational experience gained over many years with hydrazine.
- Design and operation of condensate polishing plants and use of new resin technologies. There is extensive information on the design and use of condensate polishing plants and the impacts this can have on the use of

fresh make-up water and the discharge of chemicals. New designs for these plant systems are central to meeting any 'zero discharge' approach. Some of the new available ion exchange resins can improve the performance and reduce discharges from condensate polishing plants without the need for extensive changes in plant design. These issues may be of less significance in the newer plant designs because they have a much reduced need for condensate polishing.

- Use of membrane technologies for water treatment. Some US plants, candidate designs and currently operating nuclear plants in the UK use membrane technologies to treat raw water or aqueous effluents within the plant. These technologies include reverse osmosis and electro-dialysis.
- Management of stormwater. Data for some of the US PWR plant sites show that run-off from stormwater may contain higher levels of certain pollutants than any other source on a PWR site. The design of drain systems and the management of effluents from these will be central to ensuring that discharges of stormwater are in accordance with BAT.
- Problems associated with the methods used for sampling and analysis of chemicals in plant effluents, especially of trace metals, oils and hydrocarbons. Results can vary significantly depending on the methods used, which makes comparison across plants difficult.
- Documenting data on chemical discharges. This survey suggests there is less emphasis on collation and cross-site comparison of chemical discharges from the PWR power plants than for radioactive substances.

The generic impacts of discharges of chemicals to water from a PWR can be assessed using current methodologies. These are used routinely to assess the impacts of discharges from fossil fuel plants in order to demonstrate compliance with the requirements of both the EU Water Framework Directive and Integrated Pollution Prevention Control Directive. The concentrations of most chemicals in the cooling water discharged from a PWR will be very low. Only biocides are likely to be measurable by routine methods of analysis.

Estimating concentrations of chemicals in discharges based on mass and the total volume of effluent is subject to some uncertainty, which makes comparison with environmental criteria (like EQS) difficult. Some chemicals discharged may undergo complex decomposition or other reactions that are poorly understood. Environmental criteria have not been established for every chemical that may be discharged, although natural background concentrations (where available) can give an indication of the potential size of impact a discharge might have. For all these reasons, assessments of environmental impacts of chemical discharges from a PWR may need to be supported by ecological surveys and direct toxicity assessment that includes any species of local importance.

References

This list of references also covers those given in the Annex to this report.

BATES, J. C. and PICK, M., 1996. *CVCS resin management procedures: options for Sizewell B,* in Proceedings of BNES International Conference on the Water Chemistry of Nuclear Reactor Systems 7, Vol. 1, pp. 81-90.

BERR, 2008. *Meeting the Energy Challenge. A White Paper on Nuclear Power.* CM 7296. London: HMSO; Department for Business, Enterprise and Regulatory Reform. Available from: http://www.official-documents.gov.uk/document/cm72/7296/7296.pdf [Accessed August 2011].

BRITISH ENERGY, 2006. *British Energy Operational Memorandum (BEOM). The control of marine fouling*. BEG/SPEC/ENG/BEOM/006 [British Energy/EDF internal document].

BRITISH ENERGY, 2008. *Environmental product declaration of electricity from Sizewell B nuclear power station*. *Technical report.* A study for British Energy undertaken by AEA Environment and Energy.

CHRISTOPHERSON, D. and HOWELL, C., 2007. Copper removal from cooling tower blowdown. *The Analyst*, Winter 2007, 14 (1).

DRIRE and DIREN, 2008. *Les Rejects Liquids du CNPE de Gravelines et de la SOMANU à Maubeuge*. *Nord de Calais*. IRE 2008 Nucléaire, pp. 297-302.

DRUELLE, P., 2001. Civaux NPP: Engineering triumphs on two fronts, *Inside WANO*, 9 (3), 5-7. Available from: http://www.wano.org.uk/WANO_Documents/Inside_WANO/Vol9No3/Vol9No3_E.pdf [Accessed August 2011].

DTI, 2006. *Water Treatment for Fossil Fuel Power Generation*. Technology Status Report TSR026. London: Department of Trade and Industry.

EDF, 2010a. *Hinkley Point C, EDF Energy Public Consultation (Stage 2). Environmental Appraisal Volume 2*. Available from: http://hinkleypoint.edfconsultation.info/Preferred_Proposal_Documents/Environmental%20Appraisal/Volume_2/Environmental%20Appraisal-%20Volume%202%20MAIN%20MENU.pdf [Accessed August 2011].

EDF, 2010b. EDF annual station reports [in French]. Available from: http://energie.edf.com/nucleaire/environnement/resultats-mensuels-de-la-surveillance-45714.html [Accessed August 2011].

ENVIRONMENT AGENCY, 2002. *IPPC Sector Guidance Note. Combustion Activities*. V2.03 27.07.05. Bristol: Environment Agency. Available from: http://publications.environment-agency.gov.uk/PDF/GEHO1205BJYG-E-E.pdf [Accessed August 2011].

ENVIRONMENT AGENCY, 2006. *Integrated Pollution Prevention and Control (IPPC). Guidance on the use of Direct Toxicity Assessment in PPC Impact Assessments*. Version 1. Bristol: Environment Agency. Available from: http://publications.environment-agency.gov.uk/pdf/SCHO0106BKDP-e-e.pdf [Accessed August 2011].

ENVIRONMENT AGENCY, 2010a. *Study of Historical Nuclear Reactor Discharge Data*. Science Report SC070015/SR1. Bristol: Environment Agency. Available from:

http://publications.environment-agency.gov.uk/PDF/SCHO0509BQAM-E-E.pdf [Accessed August 2011].

ENVIRONMENT AGENCY, 2010b. *Cooling Water Options for the New Generation of Nuclear Power Stations in the UK*. Science Report SC070015/SR3. Bristol: Environment Agency. Available from: http://publications.environment-agency.gov.uk/PDF/SCHO0610BSOT-E-E.pdf [Accessed August 2011].

ENVIRONMENT AGENCY, 2010c. *Radioactive Substances Regulation: Assessment of Best Available Techniques (BAT).* Bristol: Environment Agency.

ENVIRONMENT AGENCY, 2010d. *MCERTS for Laboratories Undertaking Direct Toxicity Assessment of Effluents. Register of Approved Laboratories.* Bristol: Environment Agency. Available from: http://www.environment-agency.gov.uk/static/documents/Business/MCERTS_for_DTA_Approved_Labs_List.pdf [Accessed August 2011].

ENVIRONMENT AGENCY, 2011 (in press). How to comply with your environmental permit. Horizontal Guidance Note H1 Annex (d) and Annex (e). H1 Environmental Risk Assessment. Version 2.2.

EPRI, 1997. *PWR Advanced Amines Applications. Revision 2.* Report TR-102952-R2. Prepared by Pedro Point Technology, Pacifica, California.

EPRI, 2001. *An Evaluation of Enriched Boric Acid in European PWRs*. Technical report 1003124. Palo Alto, CA: Electric Power Research Institute.

EPRI, 2004. *On Demand Condensate Polishing. An Innovative Approach to Maintaining Condensate Purity*. Technical report 1011275. Palo Alto, CA: Electric Power Research Institute. Available from: http://mydocs.EPRI.com/docs/public/000000000001011275.pdf [Accessed August 2011].

EPRI, 2005. *Pressurized Water Reactor Steam Generator Lay-up: Corrosion Evaluation.* Interim report. Technical Report 1011774. Palo Alto, CA: Electric Power Research Institute. Available from: http://mydocs.EPRI.com/docs/public/000000000001011774.pdf [Accessed August 2011].

EPRI, 2006. *Condensate Polishing State of Knowledge Assessment. Technology Needs for Fossil Plants*. Technical Report 1010181. Palo Alto, CA: Electric Power Research Institute. Available from: http://mydocs.epri.com/docs/public/000000000001010181.pdf [Accessed August 2011].

EPRI, 2009. *Application of Dry Cooling in Nuclear Power Plants. Proposal for Advanced Cooling Technologies supplemental project*. Palo Alto, CA: Electric Power Research Institute. Available from: http://mydocs.EPRI.com/docs/AdvancedCooling/Task_Nuclear.pdf [Accessed August 2010].

EUROPEAN COMMISSION, 2001a. *Integrated Pollution Prevention and Control (IPPC). Reference Document on the Application of Best Available Techniques to Industrial Cooling Systems*. Available from: http://eippcb.jrc.es/reference/cv.html [Accessed August 2011].

EUROPEAN COMMISSION, 2001b. *General Administrative Framework Regulation on Minimum Requirements for the Discharge of Waste Water. Excerpt of Appendix 31: Water Treatment, Cooling Systems, Steam Generation.*

GILBERT, R. and LAMARRE, C., 1988. Thermal stability of morpholine in the steam water cycle of CANDU-PHW nuclear power plants. *Canadian Journal of Chemical Engineering*, 67 (4), 646-651.

GOFFIN, C. and CALAY, J. C., 2000. Use of continuous electro-deionisation to reduce ammonia in steam generator blowdown of PWR nuclear power plants. *Desalination*, 132 (1-3), 249-253.

HANSEN, T., 2010. Zero-sum game? [online], Power Engineering, 7 January 2008. Available from: http://www.powergenworldwide.com/index/display/articledisplay/335138/articles/power-engineering/volume-112/issue-7/features/zero-sum-game.html [Accessed August 2011].

HARP, D. L., 2002. *Current Technology of Chlorine Analysis for Water and Wastewater*. Hach Technical Information Series, Booklet No. 17. Loveland, CO: Hach Company. Available from: http://www.hach.com/cms/documents/pdf/LIT/L7019-ChlorineAnalysis.pdf [Accessed August 2011].

HEALTH CANADA, 2010. *Priority Substances List. Statement of the Science Report for Ethylene Glycol. Appendix B: Justification for Generic Dilution Factors.* Ottawa: Health Canada. Available from: http://www.hc-sc.gc.ca/ewh-semt/pubs/contaminants/psl2-lsp2/ethylene_glycol/ethylene_glycol_6-eng.php [Accessed August 2011].

IMO, 2009. *Report of the Eighth Meeting of the GESAMP Ballast Water Working Group. 59th Session (MEPC 59/2/16).* London: International Maritime Organization. Available from: http://www.komeri.re.kr/userfile/board/160/MEPC_59-2-16%5B1%5D%20Review%20Report%20of%20the%20GESAMP.pdf [Accessed August 2011].

JENNER, H. A., TAYLOR, J., VAN DONKA, M, and KHALANSKI, M., 1997. Chlorination by-products in chlorinated cooling water of some European coastal power stations. *Marine Environmental Research*, 43 (4), 279-293.

JENNER, H. A., POLMAN, H. J. G., and VAN WIJCK, R., 2004. Four years experience with a new chlorine dosing regime against macrofouling. *VGB Power Technology*, 9, 28-30.

LAMPERT, L. et al., 2007. *Surveillance Ecologique et Halietique du Site Electronuclaire de Paluel. Annee 2007.* Rapport RST LERN 08/01. EDF 5100-CSQ-4200112517.

LENNTECH, 2010. Phosphorous removal from wastewater [online]. Available from: http://www.lenntech.com/phosphorous-removal.htm [Accessed August 2011].

MANCE, G., O'DONNELL, A.R., and SMITH, P.R., 1988. *Proposed Environmental Quality Standards for List II Substances in Water – Boron*. Technical Report TR 256. , Medmenham: WRc.

MÜRAU, P, and SCHÖTTLER, M., 2005. *Low Emission Water/Steam Cycle – A Contribution to Environment and Economics*. Erlangen, Germany: Siemens Power Generation. Available at: http://www.energy.siemens.com/fi/pool/hq/energy-topics/pdfs/en/combined-cycle-power-plants/1_Low_Emission_Water.pdf [Accessed August 2011].

NEWELL, B. S., 1967. The determination of ammonia in seawater. *Journal of the Marine Biological Association,* 47, 271-280.

NORECOL, DAMES & MOORE and ENKON ENVIRONMENTAL LIMITED, 1997. *Chlorine Monitoring and Dechlorination Techniques Handbook*. Prepared for the Greater Vancouver Regional District Drinking Water Treatment Program. Available from: http://www.metrovancouver.org/about/publications/Publications/ChlorineMonitoringDechlorinationHandbook.pdf [Accessed August 2011].

ODAR, S. and NORDMANN, F., 2010. *PWR and VVER Secondary System Water Chemistry. PWR and VVER Secondary System Water Chemistry*. Skultuna, Sweden: Advanced Nuclear Technology International. Available from: http://www.antinternational.com/fileadmin/Products_and_handbooks/SSWC/SSWC_Sample_Report.pdf [Accessed August 2011].

OLIVIER, J. and BAKKER, J., 2003. *Global Emission Sources of Greenhouse Gas Emissions from Industrial Processes: Sulphur Hexafluoride*. Good Practice and Uncertainty in National Greenhouse Gas Inventories. IPCC's Task Force on National Greenhouse Gas Inventories. Available from: http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/3_9_Global_Sources_Industrial_Processes_SF6.pdf [Accessed August 2011].

POLMAN, H. J. G., and JENNER, H. A., 2002. Pulse Chlorination®: the Best Available Technique in macrofouling mitigation using chlorine. *Power Plant Chemistry*, 4 (2), 93-97.

RHEE, I. H., AHN, H. K. and JUNGETA, H. J., 2007. *Recovery process with ion exchange and evaporation.* In Proceedings of the 9th WSEAS International Conference on Simulation, Modelling and Optimization. Available from: http://www.wseas.us/e-library/conferences/2009/budapest/SMO/SMO02.pdf [Accessed August 2011].

RHEE, I. H., CHO, D. C., PARK, B. G., AHN, H. K., JUNG, H. J., HYUN, J.T., HUH, N. S., TOON, M.H. and HAN, H. K., 2009. *Advanced treatment method of ethanolamine-wastewater based on physico-chemical and biological coupling process*. US Patent 7,550,086. Available from: http://www.patentgenius.com/patent/7550086.html [Accessed August 2011].

SCHWOCHAU, K., 1984. Extraction of metals from sea water. *Topics in Current Chemistry*, 124, 91-133. Available from: http://www.springerlink.com/content/y621101m3567jku1/fulltext.pdf [Accessed August 2011].

SUNDSTROM, G. and WEYNBERG, D. M. 2005. *Membrane filtration improves water quality at Point Beach Nuclear Power Plant.* International Water Conference. 2005, Paper IWC-05-15.

TAVARES, A and APPLEGATE, R. A., 2008. *Condensate polishing for nuclear and supercritical plants for the 21st century.* International Water Conference Paper, Paper IWC-08-02. Available from: http://www.gravertech.com/PDF/Product_Sheets/IEP/CondensatePolishingIWC0802.pdf [Accessed August 2011].

TAYLOR, C. J. L., 2006. The effects of biological fouling control at coastal and estuarine power stations. *Marine Pollution Bulletin*, 53, 30-48.

UK EPR™, 2008. PPC Application. Generic information for the UK EPR™ diesel generators. UKEPR™-0004-001.

UK EPR™, 2010a. PCER Chapter 3. Aspects having a bearing on the environment during the operational phase. UKEPR™-0003-030. Issue 02. 66 pages. Available from:

http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/Show.asp?P=290&L=EN&ID_CAT=1.3 [Accessed August 2011].

UK EPR™, 2010b. PCER Chapter 4. Aspects having a bearing on the environment during the construction phase. UKEPR™-0003-040. Issue 00. 11 pages. Available from:
http://www.epr-reactor.co.uk/scripts/ssmod/publigen/content/templates/Show.asp?P=290&L=EN&ID_CAT=1.3 [Accessed August 2011].

UK EPR™, 2010c. PCER Chapter 6.2. Details of the effluent management process. UKEPR™-0003-062. Issue 03. 57 pages.

UK EPR™, 2010d. PCER Chapter 6.3. Outputs for the operating installation. UKEPR™-0003-063. Issue 03. 176 pages.

UK EPR™, 2010e. UK EPR™ Pre-construction safety report. Chapter 10. Main steam and feedwater lines.

UK EPR™, 2010f. PCER Chapter 12. Non-radiological impact assessment. UKEPR™-0003-120 Issue 02. 128 pages. Available from: http://www.epr-reactor.co.uk/ssmod/liblocal/docs/PCER/Chapter%2012%20-%20Non-radiological%20Impact%20Assessment/Chapter%2012%20-%20Non-radiological%20Impact%20Assessment.pdf [Accessed August 2011].

USEPA, 1989. *Ambient Water Quality Criteria for Ammonia (Saltwater*). EPA 440/5-88-004. Washington, DC: US Environmental Protection Agency. Available from:
http://www.epa.gov/waterscience/criteria/library/ambientwqc/ammoniasalt1989.pdf [Accessed August 2011].

USEPA, 1993. *Guidance Manual for Developing Best Management Practices (BMP).* EPA 833-B-93-004. Washington, DC: US Environmental Protection Agency, Office of Water.

WANG, J-T., CHEN, M-H., LEE, H-J., CHANG, W-B., CHEN, C-C., PAI, S-C. and MENG, P-J., 2008. A model to predict total chlorine residue in the cooling seawater of a power plant using iodine colorimetric method. *International Journal of Molecular Sciences*, 9 (4), 542-553.

WESTNGHOUSE, 2010a. Westinghouse AP1000™ Safety, Security and Environmental Reports — PDF library [online]. Available from:
https://www.ukap1000application.com/doc_pdf_library.aspx [Accessed August 2011].

WESTINGHOUSE, 2010b. Westinghouse AP1000™. Design document. Chapter 10. Steam and Power Conversion System. Available from:
https://www.ukap1000application.com/doc_pdf_library.aspx [Accessed August 2011].

WILDE, E. W. and SHEALY, R. L., 1992. Chlorination and de-chlorination of nuclear reactor cooling water. *Water Research*, 26 (4), 539-545.

VILVE, M., HIRVONEN, A., and SILLANPAA, M., 2009. Effect of reaction conditions on nuclear laundry water treatment in the Fenton process. *Journal of Hazardous Materials*, 164 (2-3), 1468-1473.

VILVE, M. and SILLANPAA, M., T. 2010. The influence of reaction conditions in the oxidation of organic compounds of nuclear laundry water by ozone. *Water Science and Technology*, 61, 2557-2561.

YARNELL, P. A. 2008. Development of ion exchange resins with ultra low residuals for condensate polishing applications. IEX 2008 conference papers [online]. Available from:
http://www.soci.org/News/Separation-IEX-2008 [Accessed August 2011].

Abbreviations and Glossary

As far as possible, technical terms and abbreviations have been explained in the text. The following lists some of the less frequently used abbreviations and technical terms.

Term	Explanation
ALARA and ALARP	The **ALARA** (As Low As Reasonably Achievable) principle requires that radiation exposures should be kept 'As Low As Reasonably Achievable (ALARA), economic and social factors being taken into account'. The ALARA principle requires the employer to provide systems (engineered means, operational means and protective equipment) to reduce the radiation dose until or unless the cost of implementing those measures (in time, trouble or money) is considered to be greater than the risk that would thereby be averted. The **ALARP** (As Low As Reasonable Practicable) principle is unique to British law. It requires the employer to provide systems (engineered means, operational means and protective equipment) to reduce the radiation dose until or unless the cost of implementing those measures (in time, trouble or money) is considered to be grossly disproportionate to the risk which would thereby be averted. In practice this requires the employer to go beyond the requirements of the ALARA principle in reducing dose.
AOX	Frequently defined in permits for French plants (**organiques halogenes adsorbables**). AOX is the abbreviation of the sum parameter for water-soluble adsorbable organic halogens in which 'A' stands for adsorbable, 'O' for organic and 'X' for the halogens chlorine, bromine and iodine. It has been correctly used for true AOX constituents (DDT and its metabolites, PCBs, etc.) but also misused for non-adsorbable OX-compounds, mostly high molecular organohalogens in plants and even for inorganic compounds. In the test, a effluent sample is passed through activated carbon to adsorb organic substances. After the carbon has been washed to remove inorganic halides, it is combusted and the gaseous products are analysed for total halogens. In most effluents, the halogen ('X') component of AOX is almost entirely chlorine. AOX is used because of its repeatability, comparative ease of use and low cost compared with other methods for the complex compounds such as PCBs, trichlorophenols, etc.
ASN	**Autorité de Sûreté Nucléaire** (French Nuclear Safety Authority), an independent administrative authority set up by law 2006-686 of 13 June 2006 concerning nuclear transparency and safety (known as the 'TSN law'). Tasked, on behalf of the French state, with regulating nuclear safety and radiation protection in order to protect workers, patients, the public and the environment from the risks involved in nuclear activities. It also contributes to informing the citizens. For more information, see: http://www.french-nuclear-safety.fr/index.php/English-version/About-ASN
AVT	**All volatile treatment**. A process used to treat the water in a boiler and turbine system with chemicals that prevent corrosion but which can appear in both the steam and water phases and none of which form solids in any dry-out zone.
BAT	**Best Available Techniques**. The Integrated Pollution Prevention and Control Directive (IPPC) 96/61/EC applies the concept of Best Available Techniques (BAT) to the integrated control of pollution to air, water and soil. It defines BAT as the most effective and advanced stage in the development

Term	Explanation
	of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and the impact on the environment as a whole: • ‘Techniques’ shall include both the technology used and the way in which the installation is designed, built, maintained, operated and decommissioned. • ‘Available’ techniques shall mean those developed on a scale which allows implementation in the relevant industrial sector, under economically and technically viable conditions, taking into consideration the costs and advantages, whether or not the techniques are used or produced inside the Member State in question, as long as they are reasonably accessible to the operator. • ‘Best’ shall mean most effective in achieving a high general level of protection of the environment as a whole.
Burn-up	**Burn-up** is a term used to refer to the consumption of uranium-235 in nuclear fuel by fission coupled to the build-up of fission products. Both these effects eventually require a pressurised water reactor (PWR) to be shutdown so that fuel that has reached its burn-up limit can be removed and replaced by fresh fuel. Any fuel that has not reached its maximum burn-up may be moved in the reactor (so-called core shuffling). The period during which this is carried out is sometimes called a reactor outage.
BWR	**Boiling water reacto**r. A nuclear heat supply system where steam is generated in the primary circuit and transferred to the secondary circuit directly, without the use of a intermediate heat exchanger (steam generator).
BOD	**Biochemical oxygen demand.** The amount of oxygen consumed by aerobic micro-organisms to allow them to fully decompose the organic matter in a sample of water, sewage, etc. It is a ‘umbrella’ measure of organic pollutants that can be utilised by micro-organisms.
CANDU	CANDU (**CANada Deuterium Uranium**) reactor. A pressurised water reactor that uses heavy water (deuterium) as a moderator. This reduces the requirements to enrich uranium for use as a fuel. The heavy water only acts as a moderator. Normal light water of normal isotopic composition is still used as the main heat transfer medium, as in standard PWRs.
CBP	**Chlorinated by-products**. Chlorination of water produces a wide range of by-products as well as free dissolved chlorine. These include chloramines (compounds of chlorine and nitrogen), halogenated organic compounds (mainly chloroform, tri- and tetrachloroethylene and 1,1,1 –trichloroethane), chlorophenols and chlorobenzenes. If other man-made organic materials such as detergents are present, even more complex organic materials may be formed such as halogenated alkylphenol polyethoxycarboxylates.
COD	**Chemical oxygen demand**: The measurement of the amount of oxygen required for the complete chemical oxidation of organic pollutants to carbon dioxide, water and ammonia. The basis for the COD test is that nearly all organic compounds can be fully oxidised to carbon dioxide with a strong oxidising agent (potassium dichromate) under acidic conditions. It is therefore an ‘umbrella’ test for organic and some inorganic pollutants.
COMAH	**Control of Major Accident Hazards Regulations.** COMAH apply mainly to the chemical industry, but also to some storage activities, explosives and nuclear sites, and other industries where threshold quantities of dangerous substances identified in the Regulations are kept or used.

Term	Explanation
	COMAH sites have a responsibility to establish on-site safety systems in respect of their operations, which includes the responsibility to have in place effective on-site emergency plans. Additionally, the COMAH Regulations place responsibilities for off-site contingency arrangements on local authorities. The extent of control depends on whether the site is a Tier 1 or Tier 2 COMAH site, itself depending on the types and volumes of chemical stored. Nuclear sites will generally minimise the quantities and types so they do not fall under Tier 1 (or even Tier 2) requirements.
CPP	**Condensate polishing plant**. A plant system within the turbine generators. It treats water/condensate from the condenser to remove impurities that may have entered the system, prior to the water being returned to the boilers or steam generators.
CWA	**US Clean Water Act.** The Clean Water Act is the primary federal law in the USA governing water pollution. The Act established the goals of eliminating releases of high amounts of toxic substances into water, eliminating additional water pollution by 1985, and ensuring that surface waters would meet standards necessary for human sports and recreation by 1983. The Clean Water Act does not directly address groundwater contamination. Groundwater protection provisions are included in the Safe Drinking Water Act, Resource Conservation and Recovery Act, and the Superfund Act.
DPD	**N,N-diethyl-*p*-phenylenediamine.** The testing procedures adopted internationally for free and combined chlorine residuals are versions of the DPD procedure developed and refined in the 1940s and 1950s by Dr Tom Palin in the UK. The DPD test solution will turn reddish in the presence of chlorinated water. If the chlorine level is excessively high (25–30 mg/l or more), the colour in the sample will be bleached and the sample will turn clear suggesting no chlorine. The test may be carried out using portable test kits or by laboratory titration. Reliable results require testing in accordance with the instructions and taking account of the effects of turbidity, etc.
EQS	**Environmental quality standards.** EQS are concentrations in surface waters that are used to assess the risk of chemical pollutants to the health of aquatic plants and animals. The method for deriving EQS is set out in the Water Framework Directive (Annex V) and involves testing the toxicity of the substance on aquatic biota. EQS for priority and priority hazardous substances are set at a European level (Directive 2008/105/EC).
Feedwater and feedtrain	Steam from the turbine generators in a thermal power plant is collected and condensed in the main condenser. It is then withdrawn and past though a number of treatment steps and then a series of pre-heaters and pumps that constitute the **feedtrain**. After passage through this it can be returned for reuse as **feedwater** for the steam generators. This cycle is repeated until either the plant is shutdown, or some water in the circuit is rejected and replaced by fresh make-up water.
Fugitive emission	Pollutant released into air from leaks in equipment, pipe lines, seals, valves, and not from the usual sources such chimneys, stacks and vents.
GDA	**Generic Design Assessment**. To be considered for new nuclear build in England and Wales, companies submitted information on their reactor and power station designs to the regulators and for public consultation. The information is examined rigorously by the regulators, who then issue reports on their findings confirming whether they judge a design to be acceptable in terms of all of the relevant UK and international requirements. For more information, see http://www.hse.gov.uk/newreactors/index.htm

Term	Explanation
HVAC	**Heating, ventilation and air conditioning systems**. Systems that operate in all parts of the power plant to control ambient conditions. The objective is to ensure conditions in these plant areas are maintained to allow safe and comfortable working conditions for workers and ambient conditions that allow reliable operation of other plant systems. HVAC systems also route airborne chemical and radioactive contamination out to the environment.
Lay-up	Maintenance of plant systems can cause stagnant or cool water or other working fluids that allow conditions to develop where corrosion can become an issue. To prevent this there is a need to increase the chemical dosing to well above that normally employed (for example increased levels of hydrazine from 1 to over 100 mg/l) or even introduce an entirely new and separate chemical dosing regime. These activities are sometimes called 'wet lay-up' or just '**lay-up**'. Once maintenance is completed, the stage of lay-up is brought to an end and the plant returned to normal operating conditions.
mg/l and µg/l	**Milligrams per litre.** One milligram is one thousandth of a gram (10^{-3}) **Micrograms per litre**. One microgram is one millionth of a gram (10^{-6})
MW(th) and MW(e)	**Megawatts (millions of watts) thermal and megawatts electrical.** The thermal power of any power station or PWR is a measure of the thermal power output of the reactor. Only a proportion (usually about 30–35 per cent) of this thermal or heat output is converted into useful electrical energy. The final electrical out put is measured in megawatts of electrical power. A PWR with a thermal output of about 3,300 MW(th) will have a final electrical output of about 1,500 MW(e). The overall efficiency depends on a number of factors, including the temperature of the cooling water (the colder this is, the greater the thermal efficiency and power output). In any power plant, there are many areas requiring electric lighting and pumps driven by large electric motors. This constitutes the 'house load' that is supplied from the plant itself and, in a PWR, may be of the order of 20–80 MW(e). The useful output to the grid after taking into account this internal load is the net electrical output.
NRC	**US Nuclear Regulatory Commission.** Created as an independent agency by Congress in 1974 to enable the nation to safely use radioactive materials for beneficial civilian purposes while ensuring that people and the environment are protected. The NRC regulates commercial nuclear power plants and other uses of nuclear materials, such as in nuclear medicine, through licensing, inspection and enforcement of its requirements. For more information, see: http://www.nrc.gov
NSSS	**Nuclear steam supply system**. The parts of a nuclear power station that produce the useful heat used to raise steam for driving the turbines and electrical generator.
PC	**Process contribution**. The area of water where discharges of aqueous effluents from a power plant or installation take place is called the 'mixing zone'. There will be a background concentration of chemicals and pollutants (natural and historic man-made). Any addition to this background from the site is called the process contribution. It is used to assess the additional environmental impacts of the site.
PNEC	**Predicted no-effect concentration**. The concentration below which exposure to a substance is not expected to cause adverse effects to a species.
PWR	**Pressurised water reactor**. A nuclear heat supply system where the water in the primary circuit remains under pressure and cannot boil. Heat from this is transferred to the main steam circuit via a intermediate heat exchanger

Term	Explanation
	(steam generator). The water also acts as the moderator for the reactor. However, because it is of normal isotopic composition (so-called 'light water') it has a limited moderating efficiency and the uranium fuel has to be enriched in the uranium-235 isotope in order that fission and a chain reaction can be achieved and maintained.
Reactor shutdown and outages	As fuel reaches its maximum burn-up, its efficiency falls and some of this fuel needs to be removed from the reactor and replaced by fresh fuel. This requires the reactor to be brought to a full cold **reactor shutdown** (with the coolant close to normal temperature and containing at least 2,000 mg/l boron). The reactor vessel is then opened up by removing the head package to allow access to the internal core and fuel elements. Several metres of water in the refuelling cavity provides radiation protection for the workers involved in the remote operations required to remove and replace the fuel. Once the fuel is replaced, entirely underwater, the reactor head is replaced, the fuelling cavity is drained down and the reactor made ready for re-start. The period over which all these operations take place is sometimes called a **reactor outage**.
RSK, SSK and KTA	**Reaktor-Sicherheitskommission:** German Reactor Safety Commission **Strahlenschutzkommission**: German Radiological commission **Kerntechnischer Ausschuß**: Nuclear Safety Standards Commission. Chief regulators in Germany responsible for nuclear safety of the country's 19 nuclear plants at 14 locations. These independent expert commissions advise the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety on questions of nuclear safety and radiation protection.
SOx and NOx	**NOx and SOx** are the terms used to indicate oxides of nitrogen (NO, NO_2, N_2O_2, etc.) and oxides of sulphur (SO_2, SO_3, etc.) when discussing air pollution rather than specify any one of the family or list them all. They are produced from the combustion of fossil fuels, either due to impurities in the fuel or high temperature reactions between oxygen and nitrogen in the air during the combustion process. They contribute to acid rain, air pollution and ozone depletion.
SNUPPS	**Standardised nuclear unit power plant system.** Refers to a four-loop PWR reactor design produced by Westinghouse in the 1970s. The design was developed for four US utilities, and plants were built at Callaway and Wolf Creek. The UK plant at Sizewell B was also based on SNUPPS but with significant modifications, such as a passive emergency boration system.
SCC and PWSCC	**Primary water and stress corrosion cracking**. Stainless steels in nuclear reactors are resistant to general surface corrosion, but may be susceptible to localised corrosion, especially stress corrosion cracking (SCC), where chloride and sulphate become concentrated in any small cracks. The corrosion process then causes the cracks to grow in depth, further exacerbating the concentration and corrosion process at the base of these cracks. Areas that have been welded may be especially susceptible to this process. To prevent it happening, water and dosing chemicals must be of very high purity. However, some types of chemical dosing (such as with zinc) are recognised as helping avoid the process or stop it where it may have already started.
THM	**Trihalomethanes.** Compounds commonly formed as by-products in water subject to chlorination and with the general formula of ($CH_xHalogen_X$). They include chlorinated hydrocarbons such as chloroform ($CHCl_3$) and bromoform ($CHBr_3$). See also chlorinated by-products (CBPs).

Term	Explanation
TRO	**Total residual oxidants.** Chlorination of water produces a range of substances with a strong oxidising capacity that include hypochlorous acid and hypochlorite as well as residual free chlorine and (especially in seawater) bromine. These all offer a strong biocidal effect on the water as it flows through the plant, preventing build-up of biofilms, etc. However, some of these compounds remain in the water when it is discharged back into the environment, causing undesirable environmental impacts. A measurement of the total residual oxidants in the water offers an indication of the residual impact due to dosing with chlorine. Another advantage of total residual oxidants as a measure of residual effects of chlorination is that it can be carried out using a single test that captures all of the various oxidising species and therefore their net environmental impact.
USEPA	**US Environmental Protection Agency.** The EPA implements laws passed by the Congress by formulating regulations or setting national standards. For more information, see: http://www.epa.gov/aboutepa/whatwedo.html
US toxic and priority pollutants	The USEPA developed a generic list of toxic pollutants covering a wide range of industrial chemicals that are of concern. The list provides a starting point for developing national discharge standards (such as effluent guidelines) or in national permitting programmes (such as NPDES). The Priority Pollutant list makes the list of toxic pollutants more usable and practical for the purposes of the Clean Water Act. In particular it lists 126 individual chemicals for testing rather than open-ended groups.
WQBEL	**Water quality-based effluent limitations.** A term used in the US Clean Water Act. Limits apply to discharges of aqueous effluents to ensure they do not impact on the water quality standards that may apply to the receiving water. Water quality standards include water quality criteria, use designations (for example, fish and aquatic life uses, public water supplies, recreational uses, outstanding or exceptional resource waters) and anti-degradation provisions. Water quality standards under the US Clean Water Act are equivalent to the EQS that apply in the UK and Europe under the Water Framework Directive.

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