Discharges from boiling water reactors

A review of available discharge data

July 2016

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Executive summary

The Environment Agency, together with the Office for Nuclear Regulation, is carrying out a generic design assessment (GDA) of Hitachi-GE's UK advanced boiling water reactor (UK ABWR), which is being considered for nuclear power stations at Wylfa on Anglesey and Oldbury in South Gloucestershire. The advanced boiling water reactor is an update of the boiling water reactor (BWR), which has been used in many nuclear power stations across the world but not in the UK. The Environment Agency's role as regulator is to make sure that discharges and disposals of radioactive waste to the environment are minimised. As part of this process, the Environment Agency requires that best available techniques are used to reduce radiological and chemical discharges to the environment via air and water, and solid waste arisings. As part of its GDA work, the Environment Agency wants to obtain radiological and chemical discharge data from similar operational BWR reactors around the world. This will allow the organisation to validate discharge data submitted as part of the GDA process.

In March 2014, a scoping study to collate these discharges was completed. The scoping study provided useful details on contacts and data sources, but did not provide an analysis of the data, and some of the data sets were incomplete. In particular, there were limited Japanese data, which may have been due to operators and regulators dealing with the impact of the Fukushima incident.

In January 2015, the Environment Agency commissioned Public Health England to carry out the second stage of the project, to identify and fill any gaps in the data, where possible, and provide relevant analysis of the data.

As part of this study, comprehensive data on radioactive discharges to atmosphere and to water bodies from 46 BWRs around the world were collated. Important data sets related to radioactive discharges from Japanese sites and chemical discharges from US power stations were identified and are included in the report. The time period considered was from 2005 to 2013. Discharges per unit of electrical energy generated were calculated using electricity generation data from the International Atomic Energy Agency. Mean and theoretical maximum (based on the mean plus one standard deviation) discharges were derived from all data. The report also contains a comparison of discharges for the different BWR model types. For chemicals, there were few or no data available for atmospheric discharges, but data were available for liquid discharges from most of the US sites and the nuclear power station at Cofrentes in Spain. Some data were available on volumes and activities of operational solid waste and the treatment and conditioning methods, as well as some information on abatement techniques. The tables on the next page summarise the data found and the mean and theoretical maximum of radioactive discharges per unit of electricity generated for all BWRs considered between 2005 and 2013.

Summary of data

Country	Radio-nuclides atmosphere	Radio-nuclides liquid	Chemicals liquid	Solid waste	Abatement techniques
Finland	✓	✓	×	✓	✓
Germany	✓ (no particulates provided)	✓	×	×	×
Japan	✓(H-3, C-14 and particulates not provided)	✓	×	×	×
Spain	✓	✓	✓	✓	×
Sweden	✓	✓	×	✓	✓
Switzerland	✓	✓	×	✓	✓
USA	✓ (C-14 only reported since 2010)	✓	✓ (except Columbia)	×	✓ (for six sites)

Mean and theoretical maximum of radioactive discharges per unit of electricity generated (GBq per GWeh) for all BWRs considered between 2005 and 2013

	Discharges per unit of electricity generated (GBq per GWeh)	
Radionuclide	**Mean**	**Theoretical maximum**
Liquid tritium	1.2E-01	2.3E-01
Other liquid	1.0E-04	3.3E-04
Tritium to air excludes Fermi	1.3E-01	2.7E-01
Fission and activation gases to air	9.4E-01	2.9E+00
Radioiodines to air	4.5E-05	1.6E-04
Particulates to air	6.7E-06	1.8E-05
Carbon-14 to air	5.8E-02	7.8E-02

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1. Introduction

1.1. Project background

The new reactor designs being considered for nuclear power stations at Wylfa on Anglesey and Oldbury in South Gloucestershire are an update to the boiling water reactors (BWRs) known as the advanced boiling water reactors (ABWRs). The Environment Agency, together with the Office for Nuclear Regulation (ONR), is carrying out a generic design assessment (GDA) of Hitachi-GE's UK advanced boiling water reactor (UK ABWR). Details of the GDA process are available on the joint website at http://www.onr.org.uk/new-reactors/index.htm and the Environment Agency pages on GOV.UK at https://www.gov.uk/government/collections/assessing-new-nuclear-power-station-designs. An important part of this assessment is to determine whether the proposed reactor designs represent the best available techniques for reducing radiological and chemical discharges to the environment via air and water, and for reducing solid waste arisings.

In March 2014, the Environment Agency completed a scoping study to obtain radiological and chemical discharge data from similar operational BWR reactors around the world (Environment Agency, 2015). The scoping study provided useful details on contacts and data sources but the data were limited and some of the data sets were incomplete. Phase II of this project is to identify and fill any data gaps, where possible, and provide relevant analysis of the data.

The Environment Agency has analysed chemical and radiological discharge data previously for other reactor designs and the reports (Environment Agency, 2009), (Environment Agency, 2011) are available on the http://www.gov.uk website.

1.2. Objectives

The main objectives of this study are to collate and present baseline data and relevant operational information for radiological and chemical discharges and solid waste arisings from existing BWR reactors around the world. However, this study does not compare proposed discharges from the UK ABWR with discharges from the other BWR reactors.

The data collated includes radiological discharges to air and water as well as non-radiological chemical discharges. Volumes, activity and treatment options for solid radioactive waste were also collected.

The scope of this project was as follows:

- Review the output of Phase I, the scoping study and the available data.
- Conduct a gap analysis on the data already obtained. Obtain further data to address these gaps through further contact with operators/regulators or other data holders.
- Where possible, obtain further contextual data from operators, as the metadata is as important as the actual discharge data. This might include operating regime, number of outages, fuel failure or abnormal operations. The analysis should link discharge data to operating information for the reactors, so that variations in operating regime are accounted for.
- Obtain information on the abatement techniques used at the identified stations, which may have an impact on discharges.
- Carry out further manipulation of the discharge data and in-depth analysis using operational information.
- Identify discharge trends over a 10-year period.

The Environment Agency recognised that achieving these objectives depended on the quality of data available, and this is discussed in the report.

1.3. Evolution in BWR technology

The National Nuclear Laboratory position paper on boiling water reactor technology (National Nuclear Laboratory, 2013) gives a brief summary of the evolution in BWR technology.

According to the paper: 'The first US commercial nuclear power plant, Dresden 1, was a BWR/1. The design then evolved through several variants of reactor and containment up to the General Electric (GE) version BWR/6 as summarised in the table below. The majority of BWRs in operation are GE designed. ABB-Atom (now integrated with Toshiba-Westinghouse) and Siemens-KWU have also successfully built BWRs in Sweden and Germany respectively. In addition, there are four Advanced Boiling Water Reactors (ABWRs) designed by Hitachi-GE and Toshiba in operation in Japan, with a further two under construction'.

Table 1 BWR design evolution (taken from National Nuclear Laboratory, 2013)

Reactor	First commercial operation date	Representative plant/characteristics
BWR/1	1960	Dresden 1 - Initial commercial size BWR
BWR/2	1969	Oyster Creek - Plants purchased solely on economics: large direct cycle
BWR/3	1971	Dresden 2 - First jet pump application; improved emergency core cooling system (ECCS)
BWR/4	1972	Vermont Yankee - Increased power density (20%)
BWR/5	1977	Tokai 2 - Improved ECCS; valve flow control
BWR/6	1978	Cofrentes - Compact control room; solid-state nuclear protection system
ABWR	1996	Kashiwazaki-Kariwa 6 - Reactor internal pumps; fine motion control rod digital and fibre optic technology; improved ECCS; high/low pressure flooders
ESBWR	Not yet applicable	Natural circulation; passive ECCS

A description of the ABWR proposed to be used in the UK is not included in this report, but you can find it on the vendor's website http://www.hitachi-hgne-uk-abwr.co.uk/.

2. Methodology

The first stage of this work was to review the output of the scoping study (Environment Agency, 2015) and the available data. The report provided useful details on contacts for operators and regulators of BWRs, which are included in Appendix A. It identified that the lack of responses from both operators and regulators from Japan was a significant challenge. This may partly be explained as all the Japanese nuclear power stations were shut down following the Fukushima accident in 2011. The study identified 23 candidate BWRs and ABWRs for further study based on certain criteria, including reactor design, operational period, the size of the operating companies and existing relationships between the authors of the report and the operators. The scoping study report also summarised the regulatory regimes and the requirements to demonstrate optimisation in the countries where these reactors are located (Sweden, Spain, Switzerland, Japan, USA and Mexico). This information is not repeated in this report.

The next stage was to use the International Atomic Energy Agency (IAEA) database on Power Reactor Information Systems (PRIS) (IAEA, 2005) to review 80 BWR reactors that were in operation at the start of 2015. The list of reactors considered was expanded from the 23 identified in the scoping study to 46 reactors (see Section 2.1 for more information).

The focus of the data gathering was to collect data from publicly available sources, and significant effort was spent searching the internet. Where data could not be found, contact was made with regulators where appropriate, such as the US and Swedish regulators who provided useful information (see Appendix A for list of contacts). The Electric Power Research Institute (EPRI), which conducts research on issues related to the electric power industry in USA, was identified as having useful reports on topics such as releases related to fuel failures and abatement methodologies. However, EPRI reports are only available to its members and, therefore, could not be included. At the request of the Office for Nuclear Regulation (ONR), all contact with the Japanese Nuclear Regulation Authority was made via ONR. Given the lack of responses from operators in previous studies (Environment Agency, 2009), (Environment Agency, 2015), no further attempt at contacting operators was made. International organisations such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) and IAEA, and the European Commission were approached for information.

2.1. Reactors considered

The IAEA database on Power Reactor Information Systems (PRIS) (IAEA, 2005) records that 80 BWR reactors were in operation at the start of 2015. Reactors that began commercial operation before 1980 were excluded to limit candidate reactors to a more recent design. The exceptions to this are Olkiluoto unit 1 (1979) and Shimane unit 1(1974), since discharge data are aggregated across all reactors at each of these sites, and generation data should, therefore, be aggregated for the same reactors.

Of the remaining 50 reactors, data were unobtainable for the 2 Mexican and 2 Taiwanese reactors, leaving a candidate list of 46 reactors across 24 sites.

Table 2 Reactors considered

Unit name	Country	Model	Nuclear steam supply system supplier	Commercial operation started	Net current capacity (MW)
Olkiluoto-1	Finland	ABB-III, BWR-2500	ASEASTAL	10/10/1979	880
Olkiluoto-2	Finland	ABB-III, BWR-2500	ASEASTAL	10/07/1982	880

Unit name	Country	Model	Nuclear steam supply system supplier	Commercial operation started	Net current capacity (MW)
Gundremmingen-B	Germany	BWR-72	KWU	19/07/1984	1284
Gundremmingen-C	Germany	BWR-72	KWU	18/01/1985	1288
Fukushima-Daini-1	Japan	BWR-5	Toshiba	20/04/1982	1067
Fukushima-Daini-2	Japan	BWR-5	Hitachi	03/02/1984	1067
Fukushima-Daini-3	Japan	BWR-5	Toshiba	21/06/1985	1067
Fukushima-Daini-4	Japan	BWR-5	Hitachi	25/08/1987	1067
Hamaoka-3	Japan	BWR-5	Toshiba	28/08/1987	1056
Hamaoka-4	Japan	BWR-5	Toshiba	03/09/1993	1092
Hamaoka-5	Japan	ABWR	Toshiba	18/01/2005	1325
Higashi Dori-1 (Tohoku)	Japan	BWR-5	Toshiba	08/12/2005	1067
Kashiwazaki Kariwa-1	Japan	BWR-5	Toshiba	18/09/1985	1067
Kashiwazaki Kariwa-2	Japan	BWR-5	Toshiba	28/09/1990	1067
Kashiwazaki Kariwa-3	Japan	BWR-5	Toshiba	11/08/1993	1067
Kashiwazaki Kariwa-4	Japan	BWR-5	Hitachi	11/08/1994	1067
Kashiwazaki Kariwa-5	Japan	BWR-5	Hitachi	10/04/1990	1067
Kashiwazaki Kariwa-6	Japan	ABWR	Toshiba	07/11/1996	1315
Kashiwazaki Kariwa-7	Japan	ABWR	Hitachi	02/07/1997	1315
Onagawa-1	Japan	BWR-4	Toshiba	01/06/1984	498
Onagawa-2	Japan	BWR-5	Toshiba	28/07/1995	796
Onagawa-3	Japan	BWR-5	Toshiba	30/01/2002	796
Shika-1	Japan	BWR-5	Hitachi	30/07/1993	505
Shika-2	Japan	ABWR	Hitachi	15/03/2006	1108
Shimane-1	Japan	BWR-3	Hitachi	29/03/1974	439
Shimane-2	Japan	BWR-5	Hitachi	10/02/1989	789
Cofrentes	Spain	BWR-6	GE	11/03/1985	1064
Forsmark-1	Sweden	ABB-III, BWR-2500	ABB Atom	10/12/1980	984
Forsmark-2	Sweden	ABB-III, BWR-2500	ABB Atom	07/07/1981	1120

Unit name	Country	Model	Nuclear steam supply system supplier	Commercial operation started	Net current capacity (MW)
Forsmark-3	Sweden	ABB-III, BWR-3000	ABB Atom	18/08/1985	1170
Oskarshamn-3	Sweden	ABB-III, BWR-3000	ABB Atom	15/08/1985	1400
Leibstadt	Switzerland	BWR-6	GETSCO	15/12/1984	1220
Clinton-1	USA	BWR-6 (Mark 3)	GE	24/11/1987	1065
Columbia	USA	BWR-5 (Mark 2)	GE	13/12/1984	1107
Fermi-2	USA	BWR-4 (Mark 1)	GE	23/01/1988	1037
Grand Gulf-1	USA	BWR-6 (Mark 3)	GE	01/07/1985	1419
Hope Creek-1	USA	BWR-4 (Mark 1)	GE	20/12/1986	1172
LaSalle-1	USA	BWR-5 (Mark 2)	GE	01/01/1984	1137
LaSalle-2	USA	BWR-5 (Mark 2)	GE	19/10/1984	1140
Limerick-1	USA	BWR-4 (Mark 2)	GE	01/02/1986	1130
Limerick-2	USA	BWR-4 (Mark 2)	GE	08/01/1990	1134
Nine Mile Point-2	USA	BWR-5 (Mark 2)	GE	11/03/1988	1276
Perry-1	USA	BWR-6 (Mark 3)	GE	18/11/1987	1256
River Bend-1	USA	BWR-6 (Mark 3)	GE	16/06/1986	967
Susquehanna-1	USA	BWR-4 (Mark 2)	GE	08/06/1983	1257
Susquehanna-2	USA	BWR-4 (Mark 2)	GE	12/02/1985	1257

2.2. Groups of radionuclides

Regulatory regimes in different countries have different reporting requirements for discharges of radioactive effluents. For example, an operator may be required to report discharges of all detectable particulates or total particulates discharged. In order to compare discharges between countries, radionuclides were grouped as described below.

- Radioactive liquid discharges:
  - tritium
  - all others
- Radioactive airborne discharges:
  - tritium
  - fission/activation gases
  - radioiodines
  - carbon-14
  - particulates

This is consistent with previous work the Environment Agency commissioned looking at historical nuclear reactor discharge data (Environment Agency, 2009).

A number of assumptions were made when grouping radionuclides together:

- Some operators report discharges of noble gases entrained or dissolved into liquid effluents, but many do not. Noble gases in liquid effluents have, therefore, been excluded.
- Fission and activation gases are generally noble gases, but have included nitrogen-13 where reported.
- Some operators simply report an aggregate of radioiodine discharges to air. Where operators report individual radioiodines, these have been aggregated.
- Particulates with half-lives less than 8 days have been excluded. Where an aggregated discharge is reported, the general convention is to include only those radionuclides whose half-lives are greater than 8 days.
- Where measurements of discharged activity for individual radionuclides fall below the limit of detection, operators generally assume that the discharge is zero for calculations of both aggregated total activity and dose. This study adopts the same assumption.

2.3. Electrical normalisation of discharges (GBq per GW_eh)

For each of the candidate reactors identified, the annual electrical output (GW_eh) was taken from the IAEA PRIS database (IAEA, 2005) and collated into a Microsoft Excel spreadsheet. For power stations where multiple reactors were in operation and discharge data was aggregated for all reactors (for example, Olkiluoto), the electrical outputs for all reactors were added to give a total annual electrical output for the site.

The collated data for liquid and airborne discharges were then normalised by dividing the raw discharge data by the annual electrical output (net electrical energy generated) to provide the discharge in becquerels per GW_eh for each of the candidate power stations included in this study.

2.4. Thermal normalisation of discharges (GBq per GW_th)

No data were available for historical annual thermal output. If data are not available, thermal output can be calculated using the following equation:

$$T\square ermal\ output = \frac{T\square ermal\ capacity\ of\ candidate\ reactor}{Net\ electrical\ capacity\ of\ candidate\ reactor}\ x\ Electrical\ output$$

No history of thermal capacity is publicly available and the value in the IAEA PRIS database (IAEA, 2005) is the declared design value. This value is, therefore, constant for all years. In practice, the net electrical capacity of a reactor changes very little over its lifetime (Section 3.1.2). As a result, the thermal output is largely proportional to the electrical output, and thermally normalised discharges show the same general trends as electrically normalised discharges. Thermally normalised data have therefore not been presented in this report.

2.5. Chemical discharges

The total annual chemical discharge was divided by the total annual wastewater flow to give an average annual concentration. In cases where a particular substance was emitted from more than one outfall from the reactor site, the values were added to give an average from the whole site. Where data has been reported as zero in the report, this has been presented in the tables. No information on the limits of detection for the chemicals was provided in the reports.

2.5.1. **Comparison with limits**

The permitted emission limits for chemical parameters have been detailed, where known, in Section 3.4.4. Monitoring and reporting is usually carried out monthly, with limits based on the monthly average values. Table 3 summarises the upper and lower limit values applied in permits at the US sites. Information on limits applied to plants in other countries was unavailable.

The majority of defined regulatory limits state upper concentrations for substances in the final effluent. In the case of mercury, the limit is a daily average based on total weight emitted to control the overall pollutant loading of the receiving environment.

Table 3 Ranges of emission limits for liquid discharges imposed on the US plants

Parameter	Range of emission limits
Total suspended solids (mg/L)	15 - 35 average 30 - 100 max
Oils and grease (mg/L)	15 - 20 max
Total residual chlorine (mg/L)	0.02 average 0.038 - 0. 5 max
Chlorine (free available) (mg/L)	0.2 average 0.5 max
Oxidants (mg/L)	0.1 – 0.2 max
Dissolved oxygen (mg/L)	4 min
BOD (mg/L)	25 - 30 average 45 - 60 max
pH	6 - 6.5 min 9 max
Aluminium (mg/L)	4 max
Carbon - total organic (mg/L)	50 max
Copper (mg/L)	0.053 - 1 max
Chromium (mg/L)	0.2 average 0.2 max
Iron (mg/L)	1-4 max
Mercury	0.000189 lb/day average 0.0000269 - 0.005 mg/L average
Phosphorus (mg/L)	0.5 max
Zinc (mg/L)	1 average 1 max

3. Data sources and data collected

This section discusses the data sources found and what data were obtained and analysed from those sources.

One of the aims of this study was to compare any trends in discharges between reactors, sites and countries over time, so it was important that data were from the same years, where possible. The most widely available data were for 2005 to 2013 inclusive and, where available, these were the data downloaded and analysed.

3.1. Generation data and reactor metadata

3.1.1. **Reactor metadata**

Reactor metadata recorded in PRIS include model, owner, operator and supplier of the nuclear steam supply system (NSSS) (that is, the reactor). Other data includes important dates such as construction start date, first criticality date and start of commercial operations. All these metadata were downloaded for information and for analysing discharge data by reactor model.

3.1.2. **Electrical generation data**

PRIS includes annual values for electricity supplied (GW_eh), reference unit power (MW_e), annual time online (h), operation factor (%), energy availability factor (%) and load factor (%).

The reference unit power is the maximum electrical power that can be maintained under ambient conditions; it can be measured or set by authorisation (IAEA, 2005). The reference unit power is generally constant, although it may change following design or authorisation changes. In practice, the value appears to change very little over the years for a single reactor.

The energy availability factor and load factor were used to assess whether a reactor was performing under normal conditions. For example, in assessing whether certain data should be included in the analysis (see Section 4).

Most discharge data are only available for a reactor type at a site. A site with 2 or more BWRs generally reports discharges aggregated across all BWRS at that site. To normalise the discharge data to electrical generation, electricity supplied and reference unit power have been aggregated for all BWRs on a site. The exception is Oskarshamn (Sweden), where the Swedish regulator supplied data specifically for unit 3 and, therefore, only the electricity supplied and reference unit power for unit 3 have been used.

Unit 1 at Shimane (Japan) ceased operation in 2010. Although it began commercial operation before 1980, it contributed to discharges until operations ceased and, therefore, electricity supplied and reference unit power were aggregated for units 1 and 2 until 2010. After 2010, the reference unit power was assumed to remain the same until permanent shutdown. Units 1 and 2 at Hamaoka (Japan) ceased operating before 2005 (the start of the period of interest) and discharge data for Hamaoka in 2005 to 2013 does not include discharges from these reactors. Therefore, electricity supplied and reference unit power have been aggregated for units 3, 4 and 5.

3.2. Outage data

PRIS data on outages include cause of outage; plant system involved; duration; and (electrical) energy lost during the outage. Outages in the same year with the same cause and same plant system involved are aggregated and it was, therefore, not always possible to identify the duration of or energy lost to a single outage. Furthermore, classification of the system involved in the outage only identifies the group of systems and not the specific system involved, rendering it impossible to infer whether, for example, a fuel pin failure may have been involved. For these reasons, the PRIS outage data were not used.

3.3. Radioactive discharge data

In general, data for radioactive gaseous and liquid discharges are publicly available on the internet, either in databases or summarised in annual reports published by operators or national regulatory bodies. Table 4 presents a summary of the data sources. Discussions of data sources follow the table.

Table 4 Sources of data on radioactive discharges

Country	Site	Data source
Finland	Olkiluoto	(European Commission, 2015)
Germany	Gundremmingen	(European Commission, 2015)
Japan	Fukushima-Daini	(NSRA, 2015)
	Hamaoka	(NSRA, 2015)
	Higashi Dori	(NSRA, 2015)
	Kashiwazaki Kariwa	(NSRA, 2015)
	Onagawa	(NSRA, 2015)
	Shika	(NSRA, 2015)
	Shimane	(NSRA, 2015)
Spain	Cofrentes	(European Commission, 2015)
Sweden	Forsmark	(European Commission, 2015)
	Oskarshamn	(SSM, 2015)
Switzerland	Leibstadt	(ENSI, 2015)
United States of America	Clinton	(US NRC, 2015)
	Columbia	(US NRC, 2015)
	Fermi	(US NRC, 2015)
	Grand Gulf	(US NRC, 2015)
	Hope Creek	(US NRC, 2015)
	LaSalle	(US NRC, 2015)
	Limerick	(US NRC, 2015)
	Nine Mile Point	(US NRC, 2015)
	Perry	(US NRC, 2015)
	River Bend	(US NRC, 2015)
	Susquehanna	(US NRC, 2015)

3.3.1. **European Union**

The European Commission's RAdioactive Discharge Database (RADD) (European Commission, 2015) holds data on radioactive discharge reported by member nations. Data are aggregated by reactor type and site. Data are generally available as gigabecquerels (GBq) discharged by individual radionuclide, but may occasionally be grouped, for example 'Pu-239+Pu-240' for plutonium-239 and plutonium-240 or 'Total A' for all alphas.

3.3.2. **Sweden (Oskarshamn)**

The regulatory body in Sweden provided monthly discharge data for unit 3 at Oskarshamn were provided as an Excel workbook (SSM, 2015). Data were generally given by radionuclide rather than groups. Particulates with half-lives less than 8 days included in the workbook were excluded from analysis for consistency with data for other nuclear power stations.

3.3.3. **Japan**

Limited data on radioactive discharges from Japanese nuclear power stations are available on the Information System on Occupational Exposure (ISOE) Asian Technical Centre's website. ISOE was created by the Organisation for Economic Co-operation and Development (OECD) in 1992 and is now co-sponsored by IAEA. The Asian Technical Centre is hosted by the Nuclear Safety Research Association (NSRA) in Japan.

Data were limited to radioiodines, noble gases, liquid tritium and liquid 'others', all as groups.

3.3.4. **Switzerland**

The Swiss Federal Nuclear Safety Authority (ENSI) publishes an annual radiation protection report, which includes discharge data from all Swiss nuclear facilities. These reports are publicly available on ENSI's website and list atmospheric and liquid discharges by radionuclide.

3.3.5. **USA**

Operators in the United States are required to provide an annual radioactive effluent release report, which includes quarterly release data in curies. Operators differ slightly in the level of detail reported, with some simply summarising groups and others reporting all radionuclides detected. The US Nuclear Regulatory Commission (NRC) has made these reports available publicly on its website. The NRC has also published a report that summarises this information and discusses short-term (3 year) and long-term (34 year) trends (US NRC, 2013).

In the United States, it has only been a requirement to report carbon-14 discharges since 2010. NRC Regulatory Guide 1.21 (US NRC, 2009a) states that quantities discharged can be estimated either by direct sampling, using a normalised carbon-14 source term and scaling factors based on power generation, or using the GALE code from NUREG-0016 (US NRC, 1978). The recommended normalised source term methodology is documented in (NCRP, 1985). However, a more recent methodology is described in (EPRI, 2010) and many operators have adopted this technique.

The estimation methodologies appear to be based on a carbon-14 production rate normalised to the thermal production rating and equivalent full power operation. Therefore, estimates vary with operational hours in the year and thermal output rating, rather than actual generation or measurement.

The table below summarises which method was used to estimate carbon-14 discharges for each plant.

Table 5 Summary of references used to estimate carbon-14 discharges for each plant

Plant	2010	2011	2012	2013
Clinton	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)
Columbia	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)	Effluent report not available
Fermi	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)
Grand Gulf	Taken from Grand Gulf Nuclear Station (GGNS) final safety analysis report (FSAR)	Taken from Grand Gulf Nuclear Station (GGNS) final safety analysis report (FSAR)	(EPRI, 2010)	Taken from Grand Gulf Nuclear Station (GGNS) final safety analysis report (FSAR)
Hope Creek	(NCRP, 1985)	(EPRI, 2010)	Effluent report not available	(EPRI, 2010)
LaSalle	Taken from LaSalle Station final environmental statement	Estimated based on normalised carbon-14 production, unclear whether (NCRP, 1985) or (EPRI, 2010) was used	Estimated based on normalised carbon-14 production, unclear whether (NCRP, 1985) or (EPRI, 2010) was used	Estimated based on normalised carbon-14 production, unclear whether (NCRP, 1985) or (EPRI, 2010) was used
Limerick	Based on Limerick Generating Station final environmental statement (NRC)	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)
Nine Mile Point 2	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)	(EPRI, 2010)
Perry	Estimated by using a carbon-14 source term scaling factor based on power generation; unclear whether (NCRP, 1985) or (EPRI, 2010) was used	Estimated by using a carbon-14 source term scaling factor based on power generation; unclear whether (NCRP, 1985) or (EPRI, 2010) was used	Estimated by using a carbon-14 source term scaling factor based on power generation; unclear whether (NCRP, 1985) or (EPRI, 2010) was used	Estimated by using a carbon-14 source term scaling factor based on power generation; unclear whether (NCRP, 1985) or (EPRI, 2010) was used
River Bend	(US NRC, 1978)	(US NRC, 1978)	(US NRC, 1978)	(US NRC, 1978)
Susquehanna	(EPRI, 2010)	(EPRI, 2010)	Off-gas sampling	Off-gas sampling

3.4. Chemical discharge data

Generally, obtaining information for non-radioactive discharges proves more difficult than for radioactive discharges. Data are not often publicly available; chemical discharges to water and air may be regulated by different authorities and, in some cases, are regulated by a local rather than a national authority. Country-specific issues are discussed below, but no quantitative information on discharges to atmosphere was found for any country, apart from 3 nuclear power stations in the USA. Detailed monthly liquid discharge data were available for the Spanish reactor, Cofrentes for January 2010 to December 2012 for a wide range of chemicals. Data from the US plants were available for liquid chemical discharges between 2007 and 2013 for a more limited range of chemicals.

3.4.1. **European Union**

Discharges to water are regulated in Europe by the Water Framework Directive (2000/60/EC) (European Parliament and Council of the European Union, 2000). This is a general legislative framework designed to protect all surface water bodies and groundwater. Additionally, discharges to water are subject to the Directive 2006/11/EC for discharges of dangerous substances to the aquatic environment (European Parliament and Council of the European Union, 2006). The Directive requires prior authorisation by the member state's competent authority for discharges to water of certain substances considered toxic or damaging to the environment. It requires the competent authority to produce an inventory of toxic discharges. However, for most member states, data are only publicly available at national level, and the only data obtained were for discharges to water from Cofrentes (Spain) (Iberdrola, 2011; Iberdrola, 2012; Iberdrola, 2013).

Legislation covering emissions to air is less straightforward. Directive 2001/81/EC (European Parliament and Council of the European Union, 2001) sets national emission ceilings for specified pollutants; Directives 2004/107/EC and 2008/50/EC set air quality standards for member states. None of these directives require authorisation of emissions or production of an inventory of emissions, and no data on emissions of non-radioactive effluents to air were available.

3.4.2. **Japan**

No data were found on emissions of chemical effluents to air or to water.

3.4.3. **Switzerland**

No data were found on emissions of chemical effluents to air or to water.

3.4.4. **USA**

The US Environmental Protection Agency (EPA) regulates chemical discharges, although managing discharge data is frequently delegated to state level bodies. Effluent standards for point sources are applied via the National Pollutant Discharge Elimination System (NPDES), which establishes national requirements for effluent discharges. Individual states have autonomy to establish limits that are stricter than the national criteria. Monthly discharge monitoring reports (DMR) are submitted to the US EPA, with some reports publicly available via the US EPA website (US EPA, 2015). Each of the sites has a Facility Register Service ID (FRS ID) (see Appendix A), which was used to search for the plants. The DMR website (US EPA, 2015) states that where values are reported below the laboratory analytical method quantitation limit, the annual load calculated by EZ Search (DMR) for that parameter is equal to zero.

Data for liquid chemical discharges from the US plants between 2007 and 2013 were available, although not all parameters have been reported at each plant each year. The most consistently reported parameters were total suspended solids, oil and grease, and total residual chlorine.

Data on chemical discharges to atmosphere were available for only 3 of the plants in the USA and is discussed further in Section 5.2.

4. Analysis of radioactive discharges

This section discusses the results of normalising electrical output data and the reliability and consistency of the results. Charts are presented at the end of the section for discharges by reactor model type.

For sites with more than 1 BWR reactor, discharge data are aggregated across all BWR reactors. The exceptions are Oskarshamn (Sweden), Shimane (Japan) and Hamaoka (Japan), which are discussed in Section 3.1.2. Since the number of reactors varies with site, the raw discharge data are not indicative of anything apart from a general trend for that site, and comparisons between sites cannot be drawn. A possible method for approximating discharges from individual reactors would be to use the fraction of electricity generated by each reactor as a scaling factor. However, this technique would mask any unusual discharges from an individual reactor. Raw data have therefore, not been presented graphically in this report, but are included in Appendix B for completeness.

Electrically normalised data are presented in the following sub-sections and in Appendix B. It was observed that electrically normalised discharge data for each radionuclide group tends to lie within a characteristic range, and data outside this range were judged to be potentially inconsistent. Each potentially inconsistent data point was investigated, and those considered to be unreliable, due to inconsistent groupings of radionuclides or a possible result of non-normal operations, were excluded. The table below discusses each anomaly and indicates whether the data were included in the analysis.

Table 6 Outlying data

Radionuclide group	Site	Anomaly	Discussion and outcome
Liquid tritium	None		
Liquid discharges excluding tritium	Limerick, Hope Creek, Cofrentes, Grand Gulf, Perry, Susquehanna, Nine Mile Point, River Bend	Various high points	The listed plants all include dissolved/entrained noble gases in reporting, whereas other plants do not. For consistency, noble gases in liquid effluents were reclassified as 'Dissolved/entrained gases' and therefore removed from the 'Liquid – others' category.
	Grand Gulf	Values for 2007 and 2008 high after removing noble gases	Effluent reports list some abnormal releases, but all were airborne. Operation factors[1] and load factors[2] slightly lower for these years but not significantly. Data retained for analysis.
Airborne tritium	Fermi	2012 and 2013 high compared to other years/sites	Plant was shut down for just over half of 2012 and did not operate at full capacity for part of 2013. Tritium discharges higher than in other years. No indication of problems or faults. Charts presented with and without 2012 and 2013 discharges of tritium to air.

Radionuclide group	Site	Anomaly	Discussion and outcome
	Hope Creek	2008 and 2011 very low compared to other years/sites	No cause discernible. Data retained.
Fission and activation gases	Fukushima Daini, Onagawa	2010 and 2011	All discharge values from Japanese reactors are for the financial year, which runs from 1 April to 31 March. The accident at Fukushima Daiichi began on 11 March 2011 and is, therefore, included in financial year 2010. Data obtained from ISOE suggests that levels recorded at these plants in 2010 and 2011 include emissions as a result of the accident, and have, therefore, been excluded from analysis.
	LaSalle	All values high, especially 2005	Effluent reports do not list any unusual releases or reportable events. Operation factor[1] and load factor[2] indicate low level of outage in all years. No reports on Nuclear Regulatory Commission (NRC) website to indicate problems at LaSalle. Data retained for analysis.
	River Bend	High value in 2006	Effluent report for River Bend in 2006 does not list any reportable events and states that there were no unusual releases. Operation factor[1] and load factor[2] do not indicate excessive outage. No reports on NRC website to suggest issues or problems at River Bend. Data retained for analysis.
	Grand Gulf	High value in 2013	2014 effluent report describes a higher-than-normal release in 2013 due to refrigeration equipment issues affecting charcoal adsorption efficiency. The relevant vent contributed approximately 90% of the release during the quarter. Data point removed.

Radionuclide group	Site	Anomaly	Discussion and outcome
Airborne radioiodines	Fukushima Daini, Onagawa, Kashiwazaki Kariwa, Hamaoka, Higashi Dori, Shimane	High values 2010 and 2011	All discharge values from Japanese reactors are for the financial year, which runs from 1 April to 31 March. The accident at Fukushima Daiichi began on 11 March 2011 and is, therefore, included in financial year 2010. Data obtained from ISOE suggests that levels recorded at these plants in 2010 and 2011 include emissions as a result of the accident, and have, therefore, been excluded from analysis.
	Cofrentes	Consistently high 2005 to 2011	The annual reports of the Spanish Nuclear Safety Council list discharges from all nuclear power plants in Spain. The values in the reports match the sum of iodine discharges extracted from the EU (RAdioactive Discharges Database) RADD database. The 2012 report (CSN, 2013) suggests that the medium-term trend in collective dose is erratic and that this can be attributed to a lack of regular refuelling. This suggests that the operator was not running the plant as intended, meaning that the plant was not operated normally during most of the years of the period of interest. Although an action was placed on the plant by CSN to remedy this, it is unclear when the operator began operating the plant normally. All radioiodine discharges from Cofrentes have, therefore, been excluded from analysis.
	River Bend	High in 2006 and 2007	Effluent reports for River Bend in these years do not list any reportable events, and state that there were no unusual releases. Operation factor[1] and load factor[2] do not indicate excessive outage. No reports on NRC website to suggest issues or problems at River Bend. Data retained for analysis.
	Nine Mile Point 2	2009 and 2010 values high	Effluent reports do not list any unusual releases or reportable events. Operation factor[1] and load factor[2] indicate no outage for 2009 and a low level of outage in 2010. No reports on NRC website to indicate problems at Nine Mile Point. Data retained for analysis.

Radionuclide group	Site	Anomaly	Discussion and outcome
Airborne particulates	Cofrentes	Value for 2011 extremely high	Comparison of data downloaded from the EU RADD database and the Spanish Nuclear Safety Council annual report for 2011 (CSN, 2012) suggests that the RADD database holds the incorrect value for Lanthanum-140. Total particulate value amended in workbooks to value given in the CSN report.
	Cofrentes	Consistently high 2005 to 2011	Even after excluding short-lived particulates, values are still consistently high. This may be due to the operator not refuelling regularly (CSN, 2013). Since it is unclear when/whether the operator began regular refuelling, all data have been excluded.
	Nine Mile Point 2	Values for 2007 and 2011 very high	Value for 2007 was corrected in the 2008 effluent report. Correct value entered into discharge workbook. Value in 2011 effluent report had been wrongly transcribed. Corrected in the workbook.
	Fermi	Value for 2005 very high	Detailed analysis in 2005 report includes all detected radionuclides, whereas other sites (both within and outside USA) generally report only radionuclides with half-life greater than 8 days. Short-lived radionuclides excluded from total for consistency with other sites, which brings data point into similar range of other sites.
	Clinton, Oskarshamn 3	Various high values	Found to be similar to Fermi above – all radionuclides included. Short-lived radionuclides excluded from analysis for consistency with other sites, which brings data points into similar range of other sites.
	LaSalle	High values in all years but particularly 2005 and 2007	Data does not include short-lived radionuclides. 2007 excess seems to be a higher-than-usual discharge of Strontium-89 in the first quarter; release rates are generally high in the second quarter of 2005. Effluent reports do not list any unusual releases or reportable events. Operation factor[1] and load factor[2] indicate low level of outage in all years. No reports on NRC website to indicate problems at LaSalle. Data retained for analysis.

Radionuclide group	Site	Anomaly	Discussion and outcome
Airborne carbon-14	Forsmark	Generally high compared to other sites, especially 2005 to 2008 and 2010	All 3 Forsmark reactors are designed by Asea-Atom. Unit 3 is the same design as Oskarshamn unit 3, which does not demonstrate a higher carbon-14 discharge. However, it is not possible to disaggregate discharge data for units 1 and 2, an older design and possibly responsible for the higher discharges. Data excluded from model comparison, but included for calculating means and predicted values.

Notes

1	Operation factor: the ratio of the number of hours that the reactor was online to the number of hours available in the year, publicly available from PRIS.
2	Load factor: the ratio of actual unit energy production to reference energy generation, publicly available from PRIS.

4.1. All sites

For all of the figures in the following section the mean is the mean of all normalised discharges over all years. The theoretical maximum is the mean plus one standard deviation (Environment Agency, 2009).

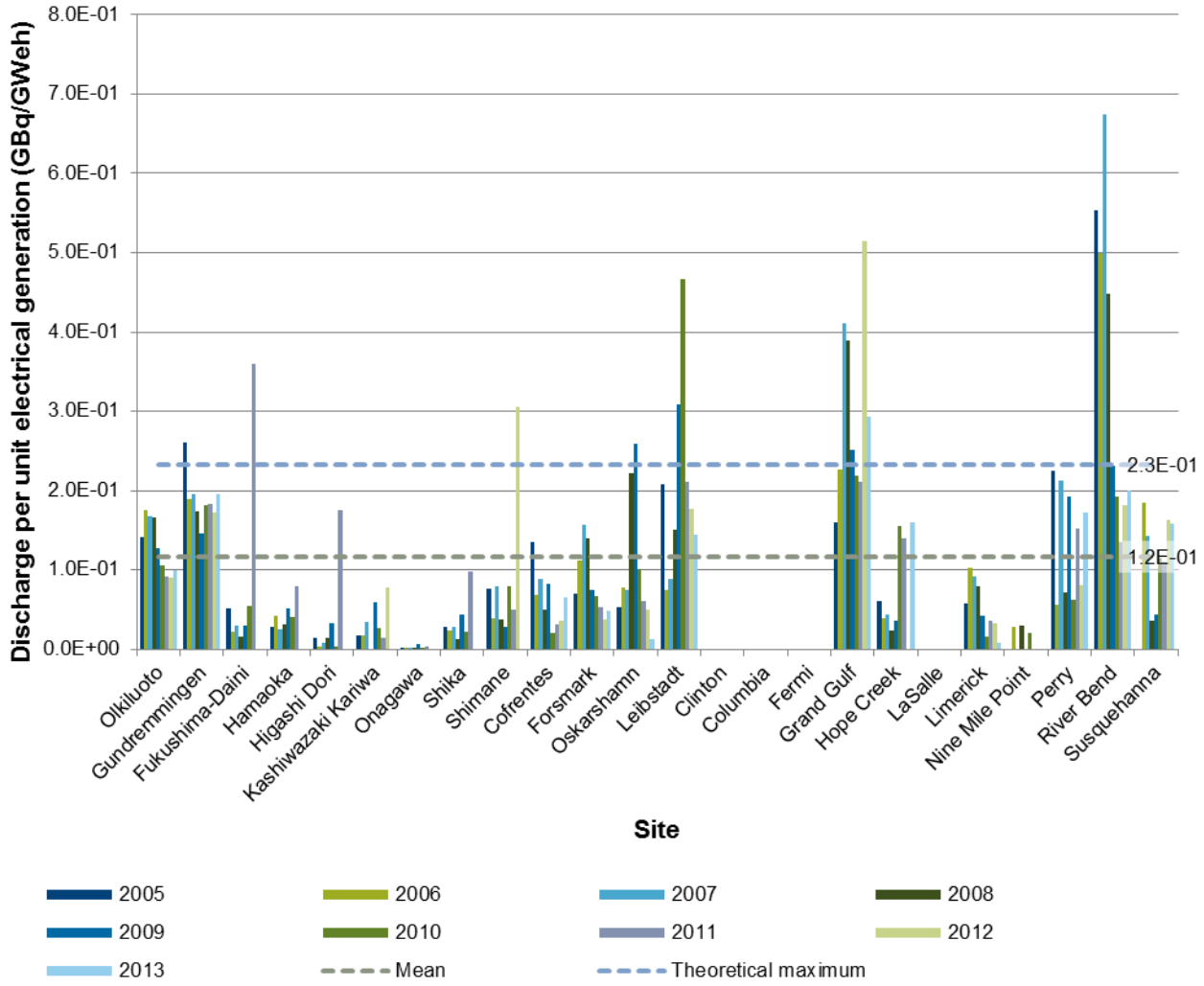

Figure 1 Normalised discharges of liquid tritium for 2005 to 2013 for all sites considered

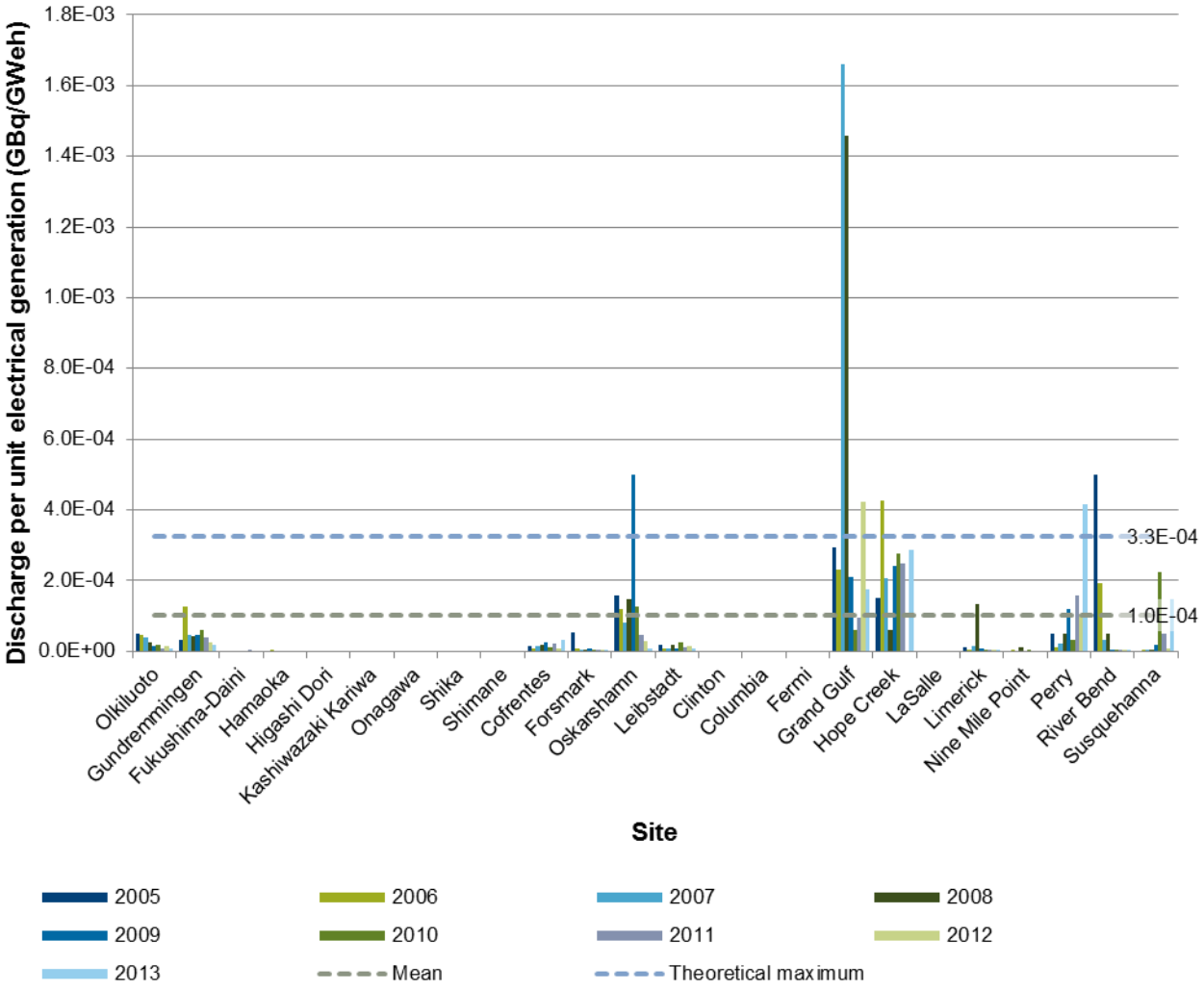

Figure 2 Normalised discharges of other liquids for 2005 to 2013 for all sites considered

Most sites do not report discharges of dissolved or entrained noble gases; therefore, for consistency, dissolved/entrained noble gases have been excluded from liquid discharges for this analysis.

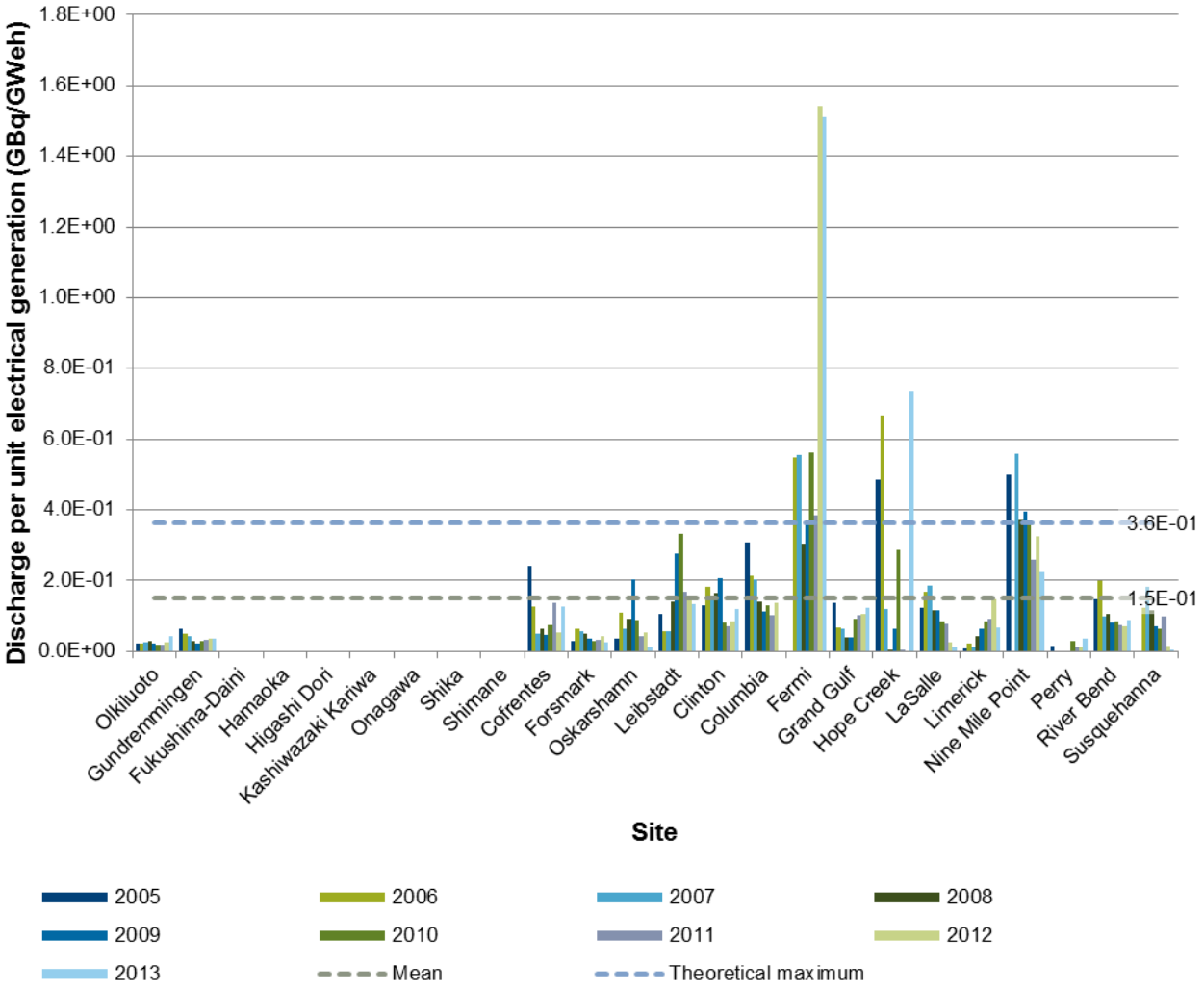

Figure 3 Normalised discharges of tritium to air for 2005 to 2013 for all sites considered

Operation data in the PRIS database indicated that Fermi was not operational for much of 2012 and was not operating at full capacity in 2013 (IAEA, 2005). Combined with the slightly higher than usual discharges of tritium to air, this leads to a normalised discharge value around an order of magnitude greater than the general range. The chart below shows the same data with the 2012 and 2013 Fermi data points removed.

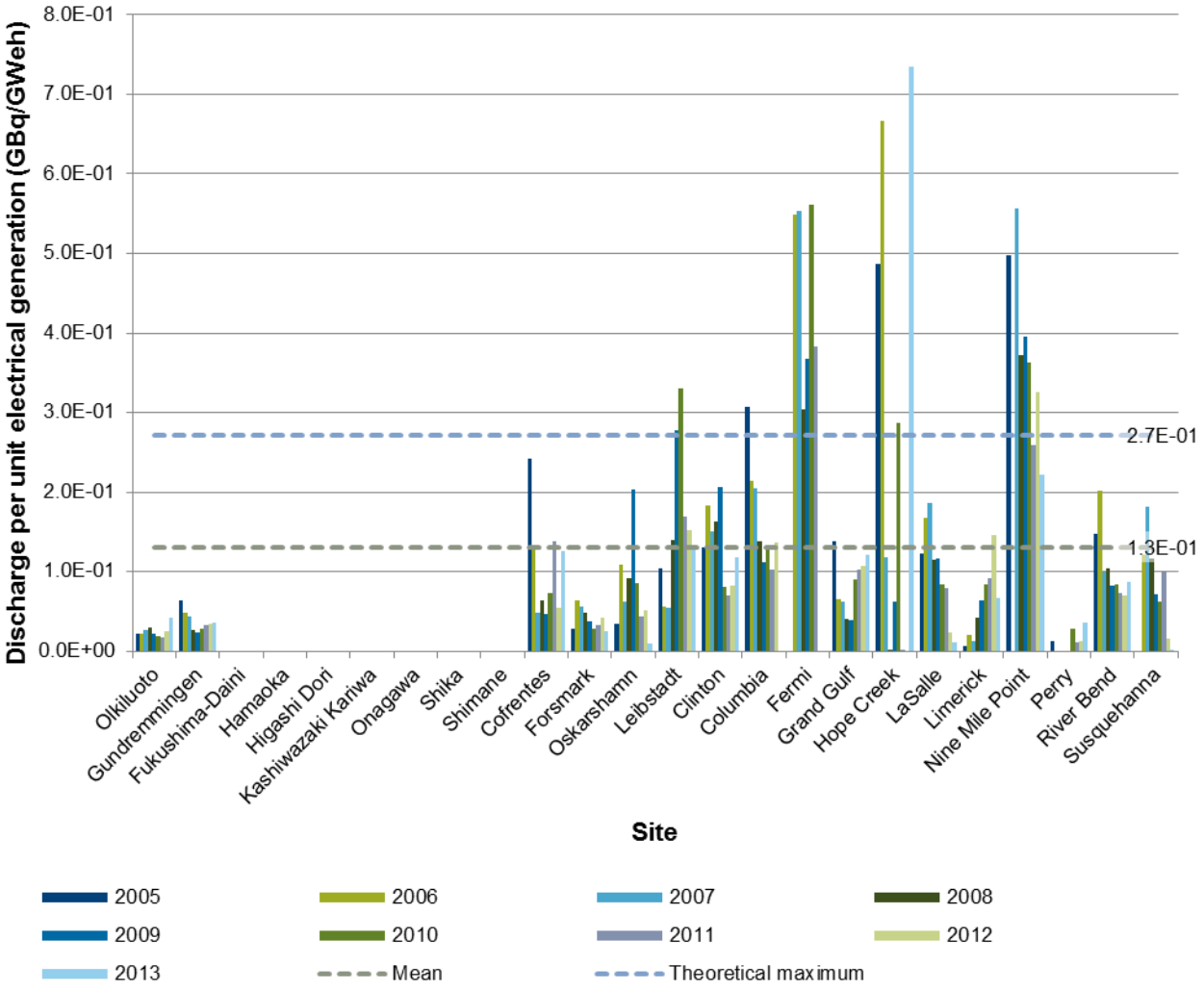

Figure 4 Normalised discharges of tritium to air without Fermi 2012 and 2013

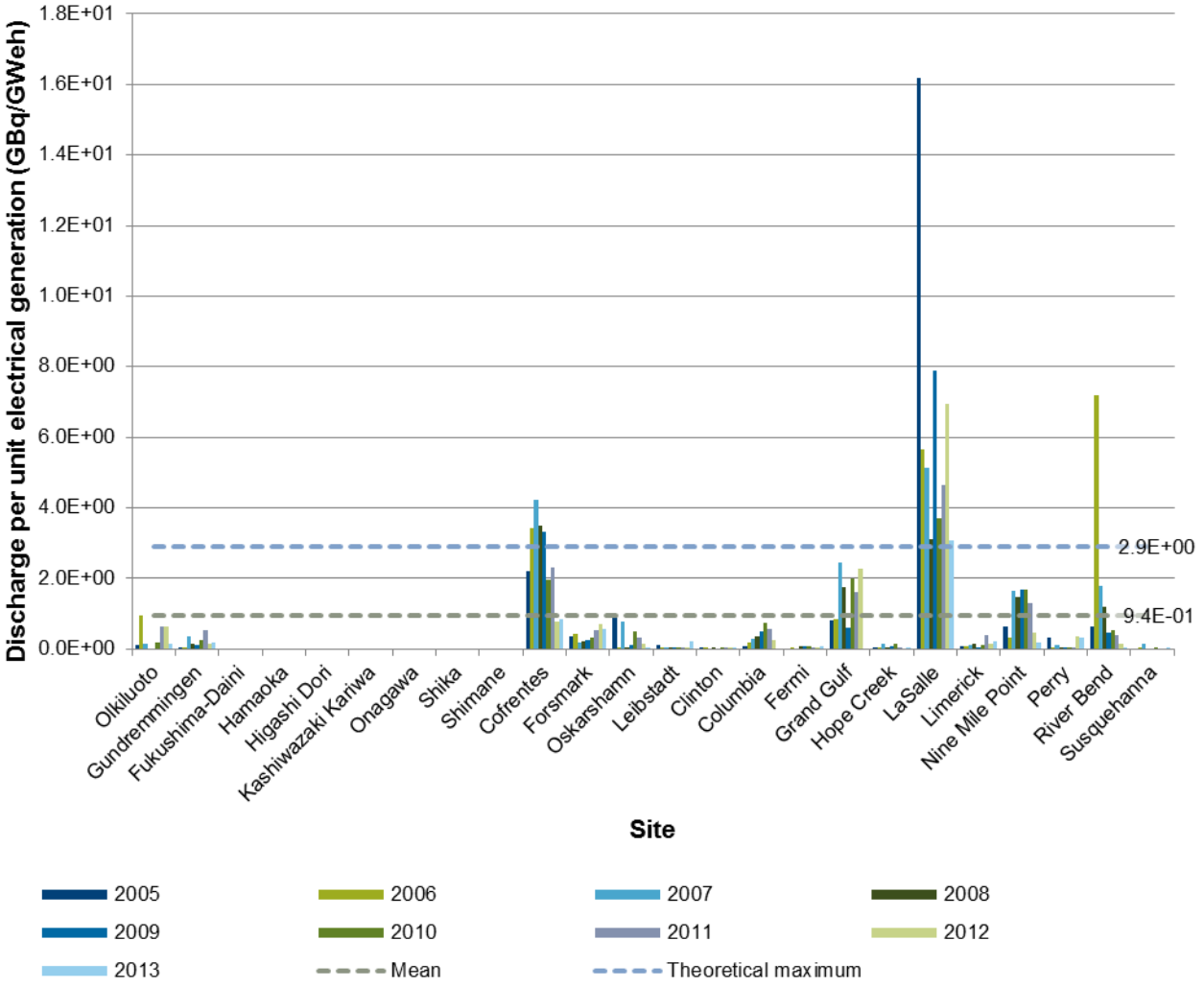

Figure 5 Normalised discharges of fission and activation gases to air for 2005 to 2013 for all sites considered

Japanese discharge data are for the financial year, which runs from 1 April to 31 March and, therefore, the accident at Fukushima Daiichi happened in the financial year 2010. Data obtained from ISOE suggests that levels of fission/activation gases recorded at Fukushima Daini and Onagawa in 2010 and 2011 include contributions from the accident and have, therefore, been excluded from this analysis (NSRA, 2015).

In 2013, refrigeration issues at Grand Gulf affected charcoal adsorption efficiency (Entergy Operation Inc, 2015). As a result, the plant discharged an abnormally high inventory of fission and activation gases. These data have been excluded from this analysis.

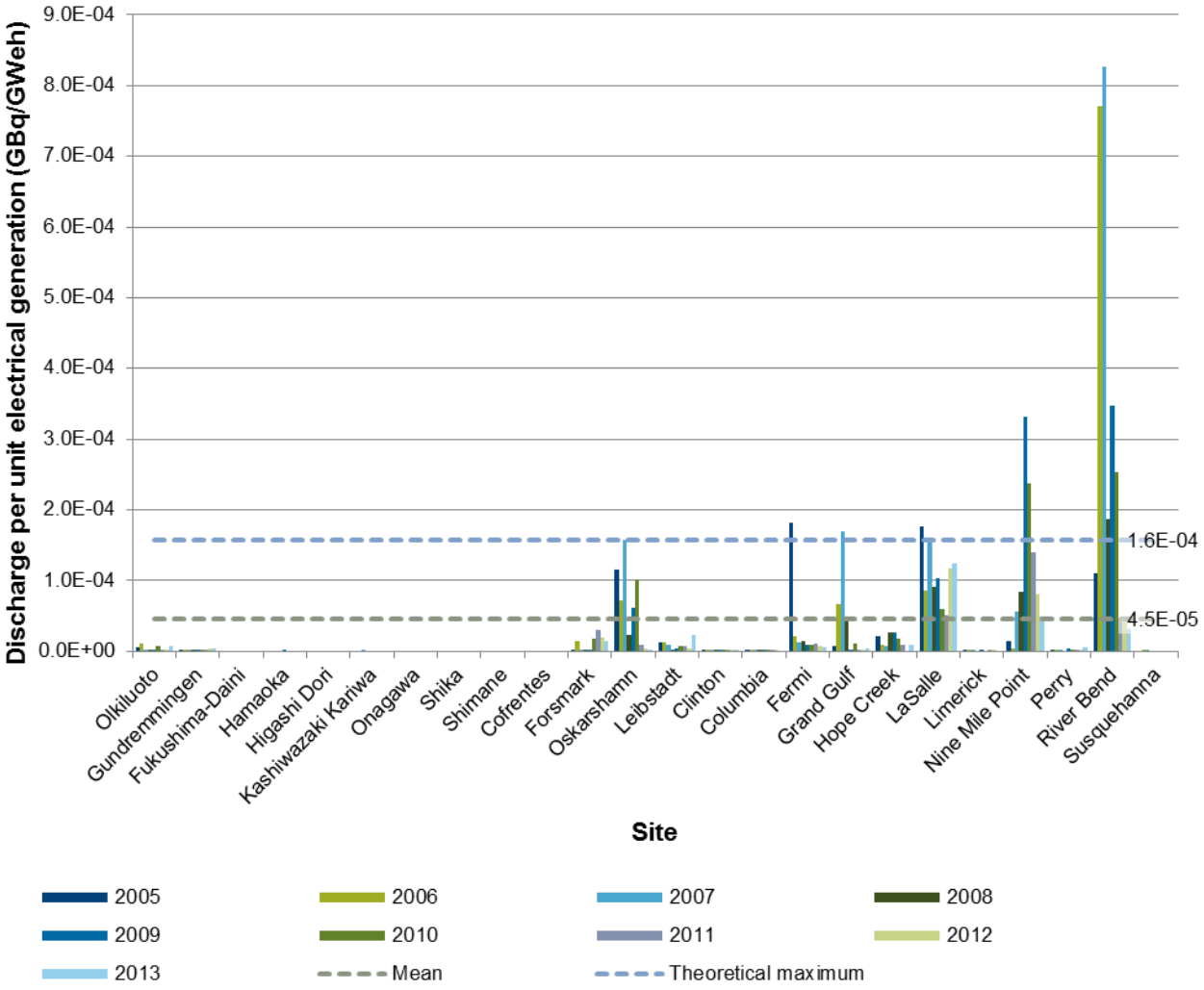

Figure 6 Normalised discharges of radioiodines to air for 2005 to 2013 for all sites considered

Japanese discharge data are for the financial year, which runs from 1 April to 31 March and, therefore, the accident at Fukushima Daiichi happened in the financial year 2010. Data obtained from ISOE suggests that levels of radioiodines recorded at Fukushima Daini, Onagawa, Kashiwazaki Kariwa, Hamaoka, Highasi Dori and Shimane in 2010 and 2011 include contributions from the accident and have, therefore, been excluded from this analysis (NSRA, 2015).

Normalised discharges from Cofrentes for 2005 to 2011 appeared consistently high. The 2012 annual report of the Spanish Nuclear Safety Council (CSN, 2013) observes that the medium-term trend in collective dose is erratic and associates this with a lack of refuelling. CSN has placed an action on Cofrentes' operator to reduce collective dose. It can be inferred that the plant was not operating under normal conditions, and all radioiodine discharges from Cofrentes have, therefore, been excluded from this analysis.

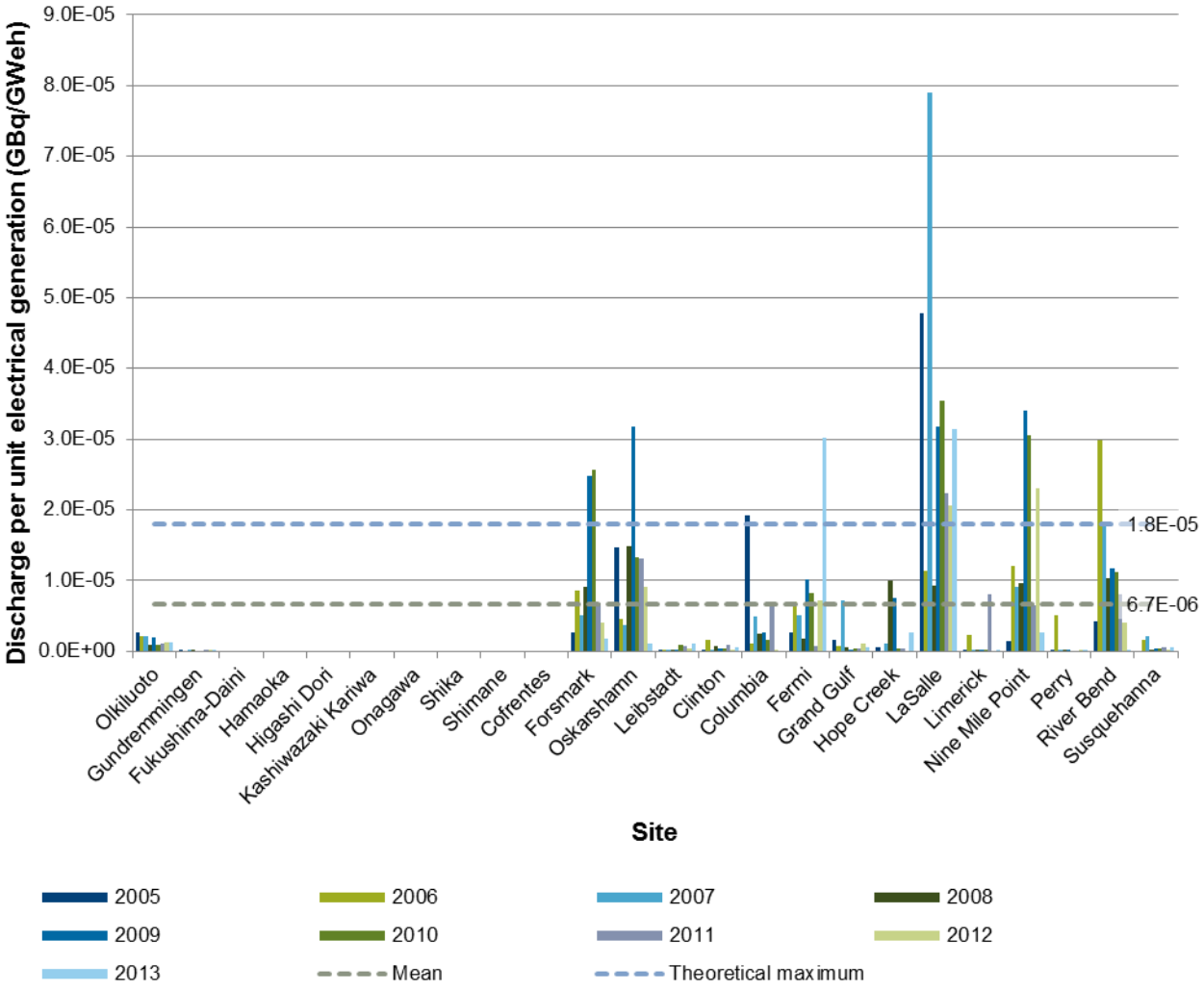

Figure 7 Normalised discharges of particulates to air for 2005 to 2013 for all sites considered

Radionuclides with short half-lives (less than 8 days) have been excluded from this analysis.

Normalised discharges from Cofrentes between 2005 and 2011 appeared consistently high. The 2012 annual report of the CSN (CSN, 2013) observes that the medium-term trend in collective dose is erratic and associates this with a lack of refuelling. CSN has placed an action on Cofrentes' operator to reduce collective dose. It can be inferred that the plant was not operating under normal conditions and all radioiodine discharges from Cofrentes have, therefore, been excluded from this analysis.

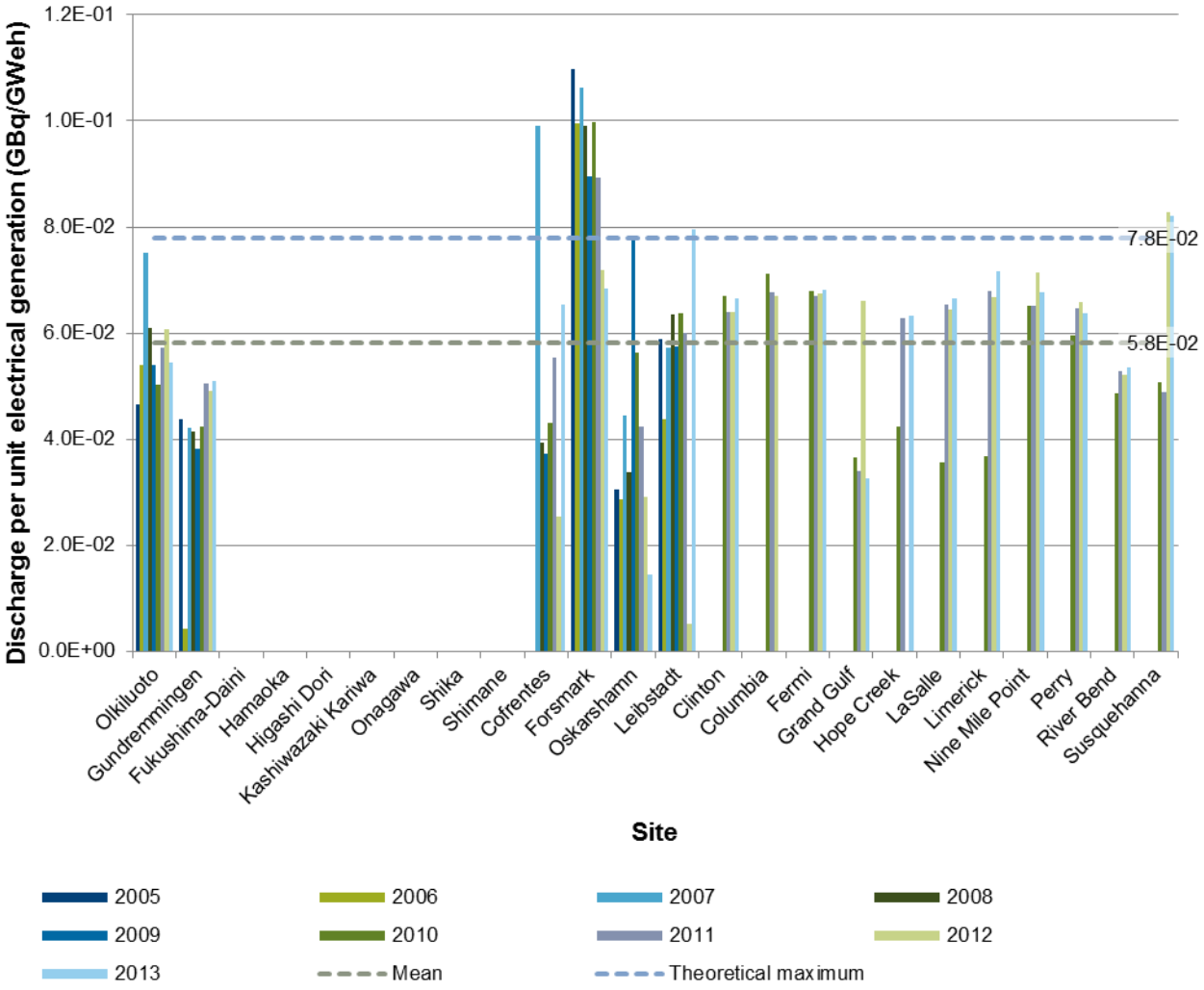

Figure 8 Normalised discharges of carbon-14 to air for 2005 to 2013 for all sites considered

It should be noted that the US Nuclear Regulatory Commission has only required operators to report carbon-14 discharges since 2010.

4.2. Model BWR4

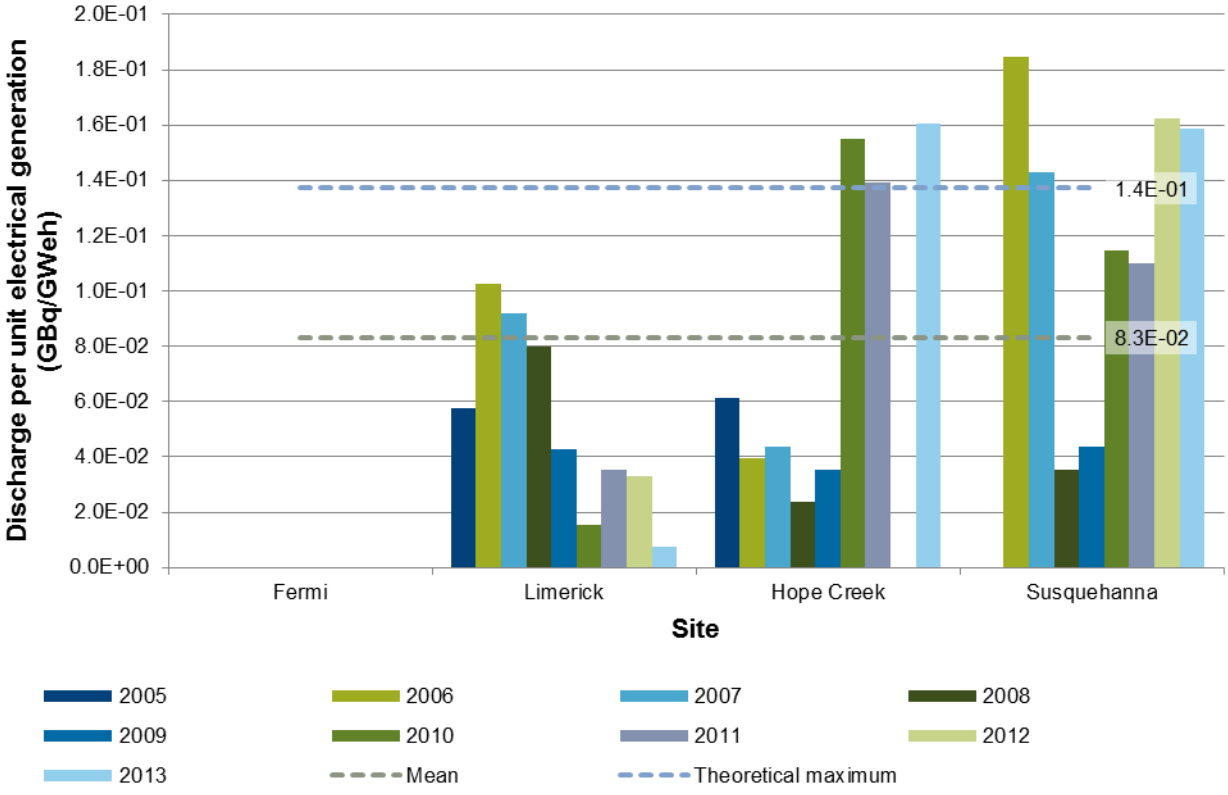

Figure 9 Normalised discharges of liquid tritium for 2005 to 2013 for BWR4 models

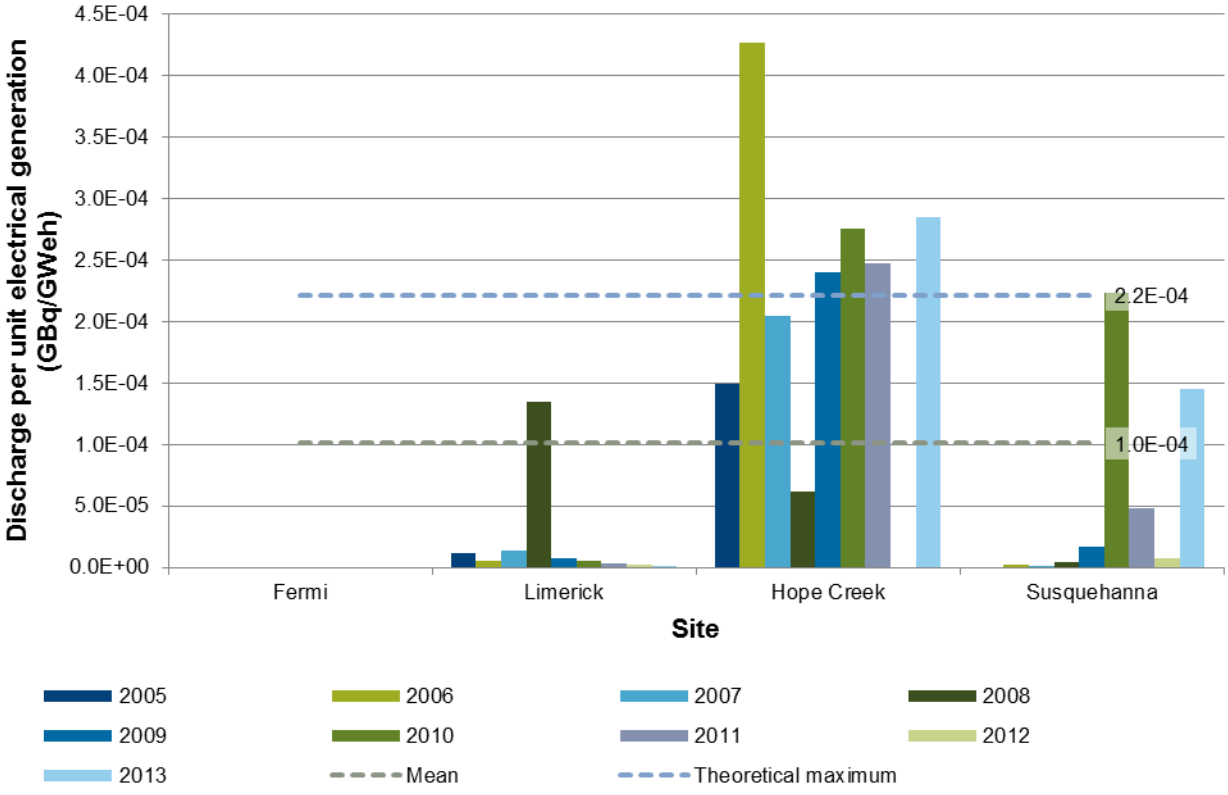

Figure 10 Normalised discharges of other liquids for 2005 to 2013 for BWR4 models

Most sites do not report discharges of dissolved or entrained noble gases; therefore, for consistency, dissolved/entrained noble gases have been excluded from liquid discharges for this analysis.

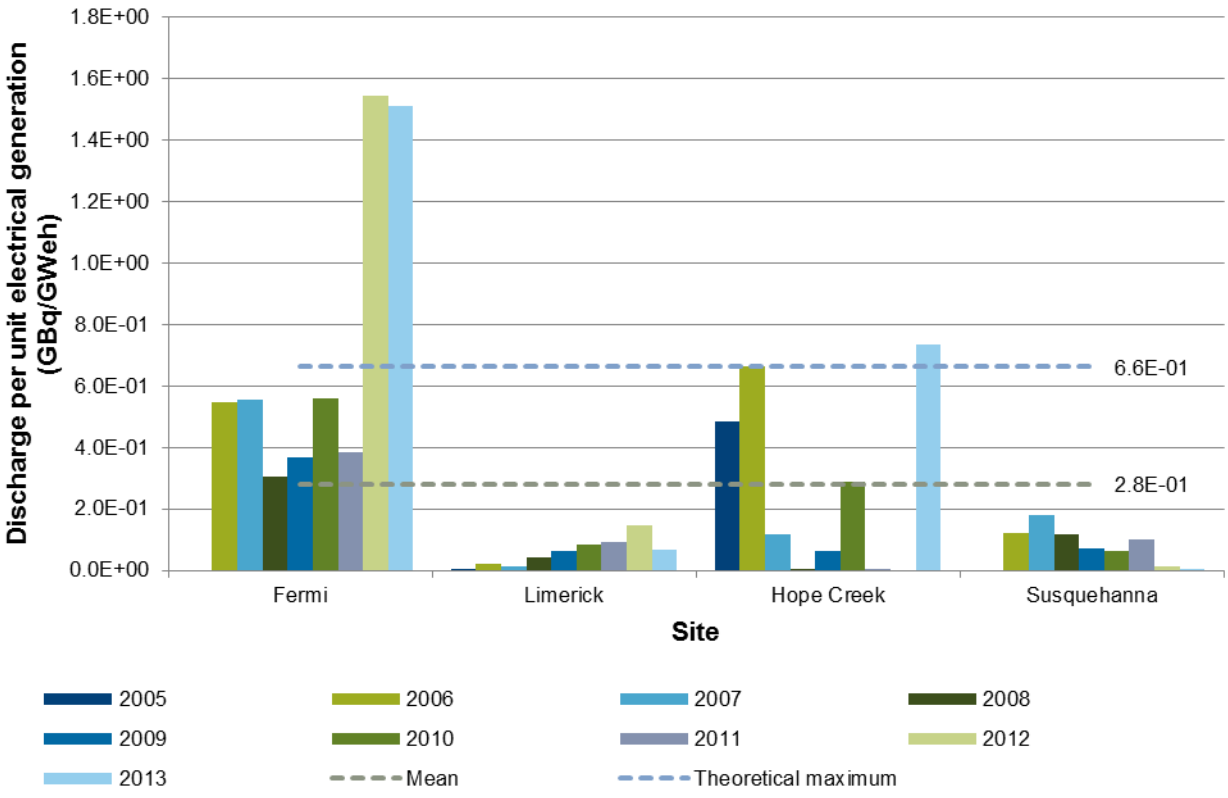

Figure 11 Normalised discharges of tritium to air for 2005 to 2013 for BWR4 models

As discussed previously, normalised discharges from Fermi during 2012 and 2013 are unusually high. The figure below shows the same chart excluding these 2 data points.

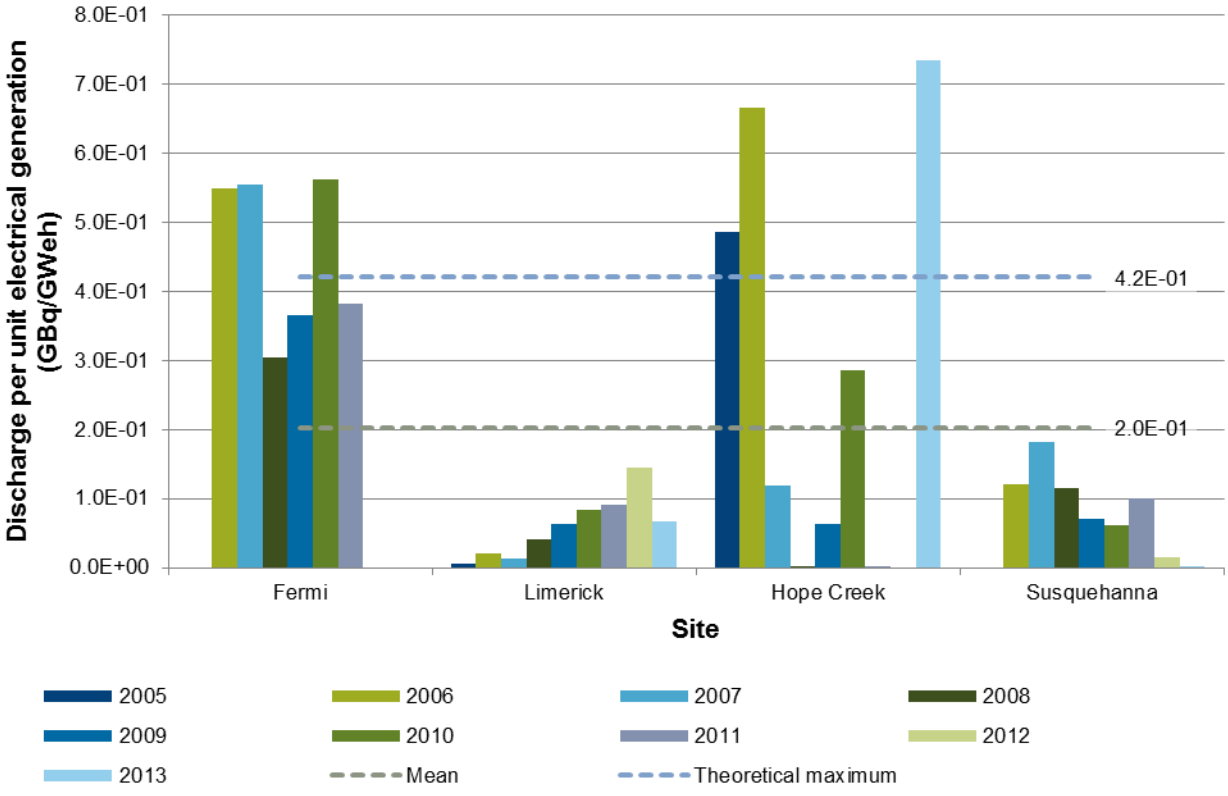

Figure 12 Normalised discharges of tritium to air for 2005 to 2013 for BWR4 models

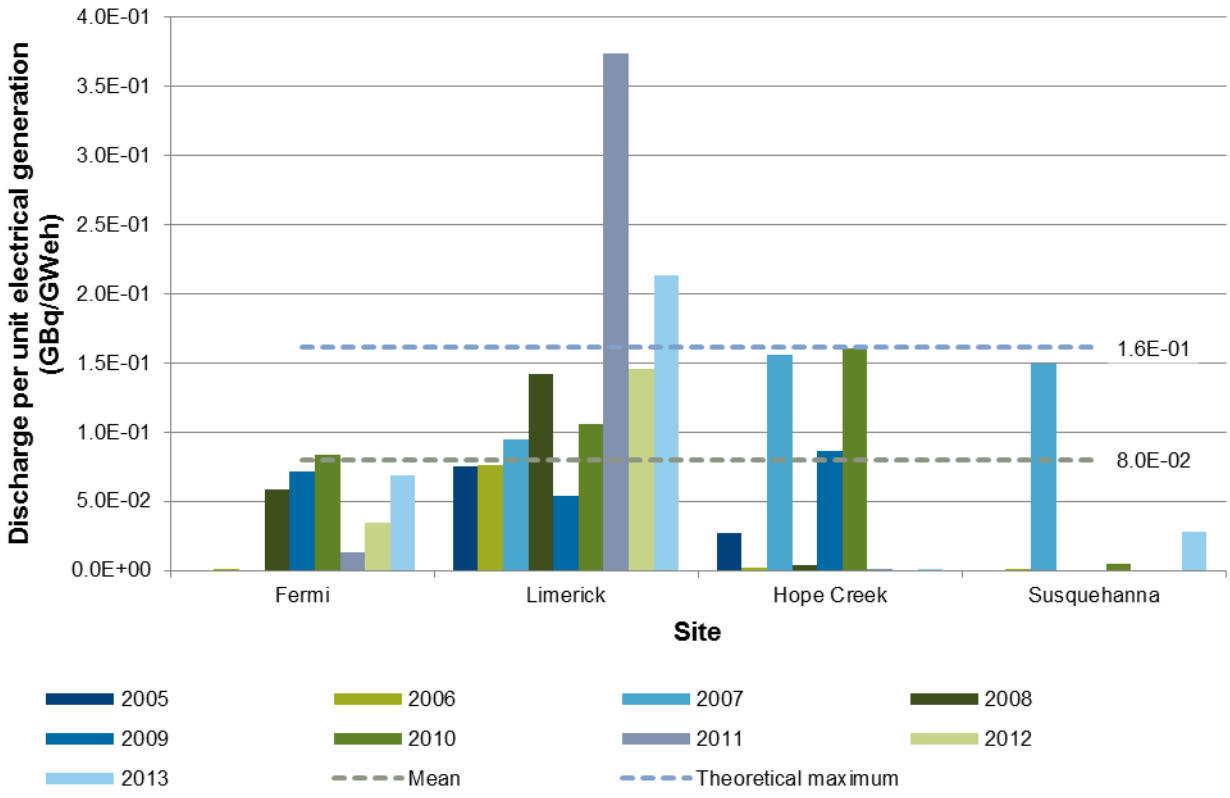

Figure 13 Normalised discharges of fission and activation products to air for 2005 to 2013 for BWR4 models

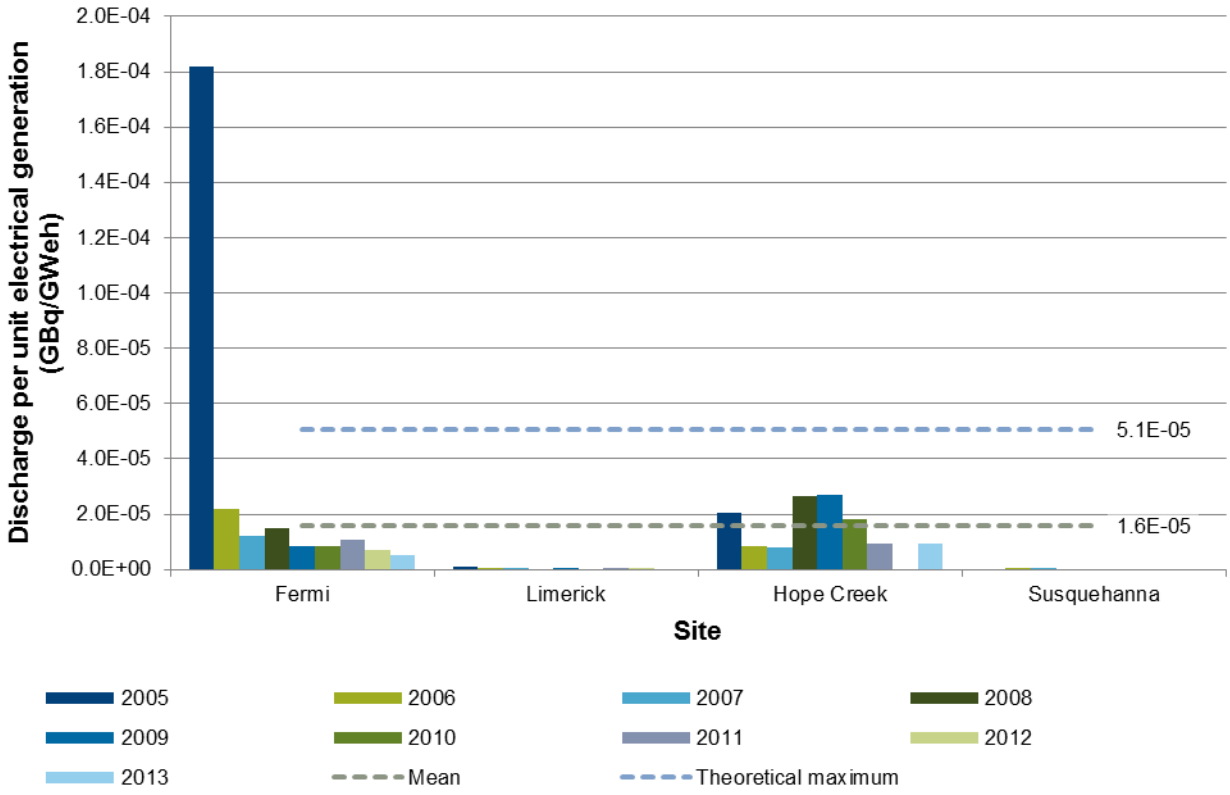

Figure 14 Normalised discharges of radioiodines to air for 2005 to 2013 for BWR4 models

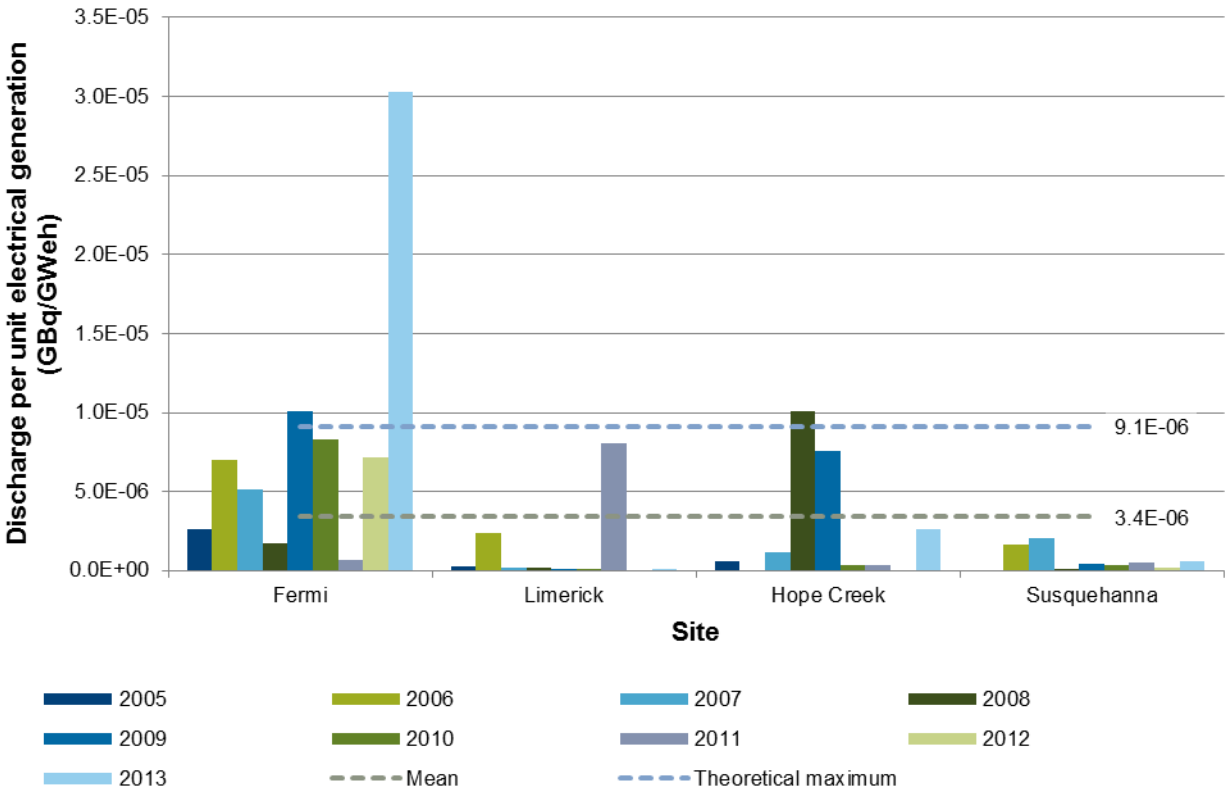

Figure 15 Normalised discharges of particulates to air for 2005 to 2013 for BWR4 models

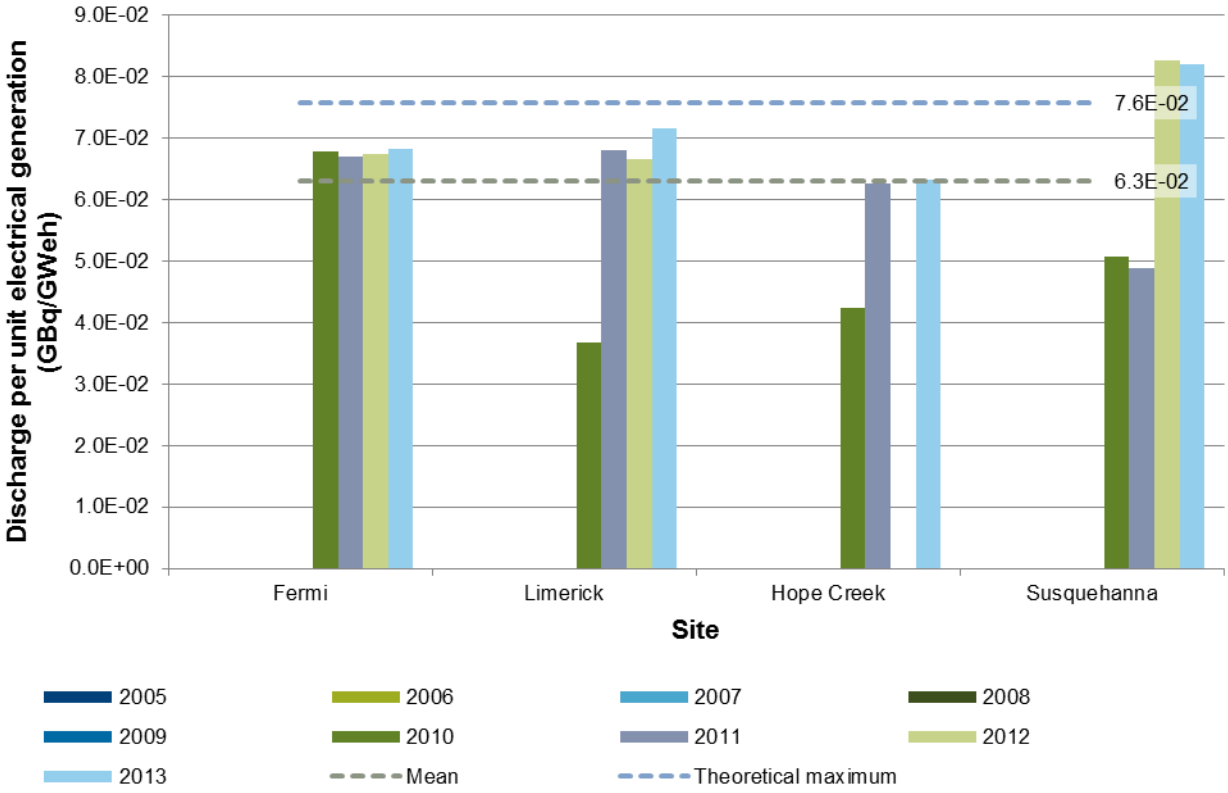

Figure 16 Normalised discharges of carbon-14 to air for 2005 to 2013 for BWR4 models

The US Nuclear Regulation Commission has only required operators to report carbon-14 discharges since 2010. It should be noted that Susquehanna changed its method of estimating carbon-14 discharges from that documented in (EPRI, 2010) to off-gas sampling from 2012 onwards, which may explain the increase in discharges.

4.3. Model BWR5

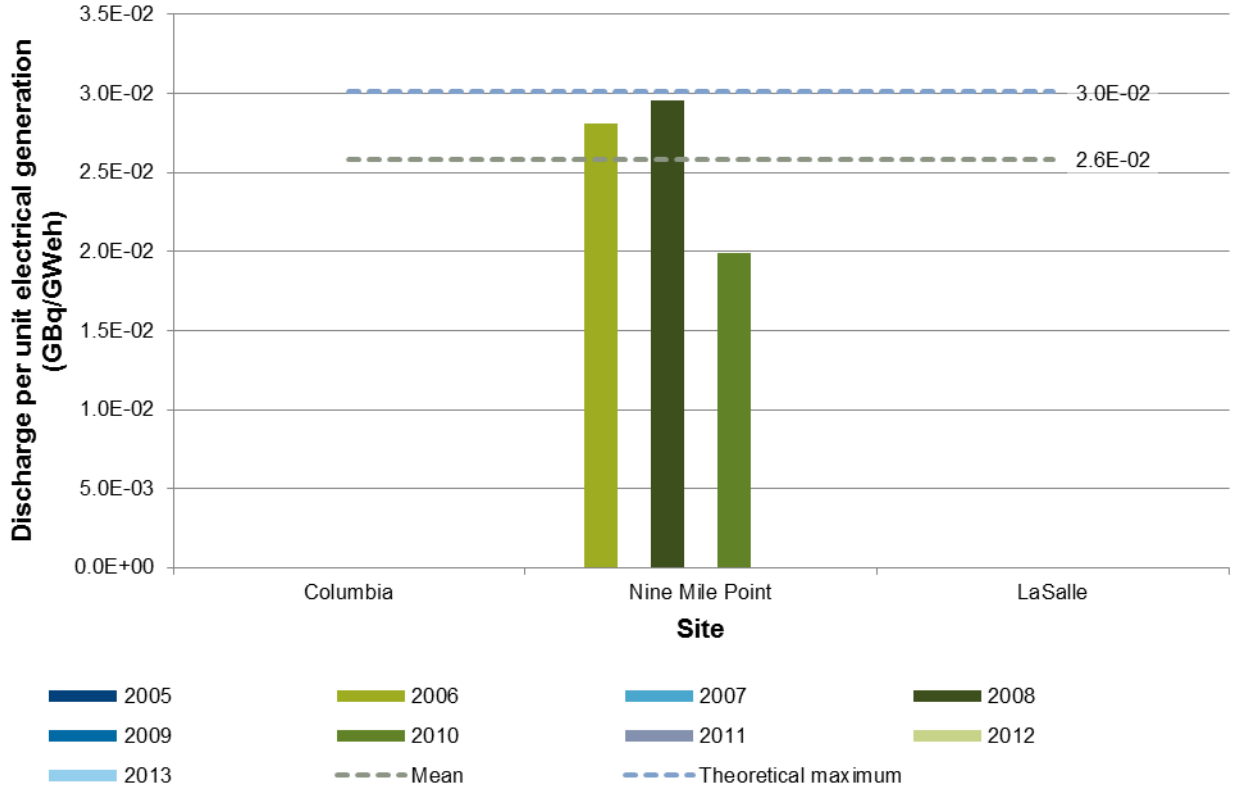

Figure 17 Normalised discharges of liquid tritium for 2005 to 2013 for BWR5 models

Columbia has not released any liquid effluents since 1998.

There were no liquid discharges from Nine Mile Point in 2005, 2007, 2009 and 2011 to 2013.

There were no liquid discharges from LaSalle during the period of interest.

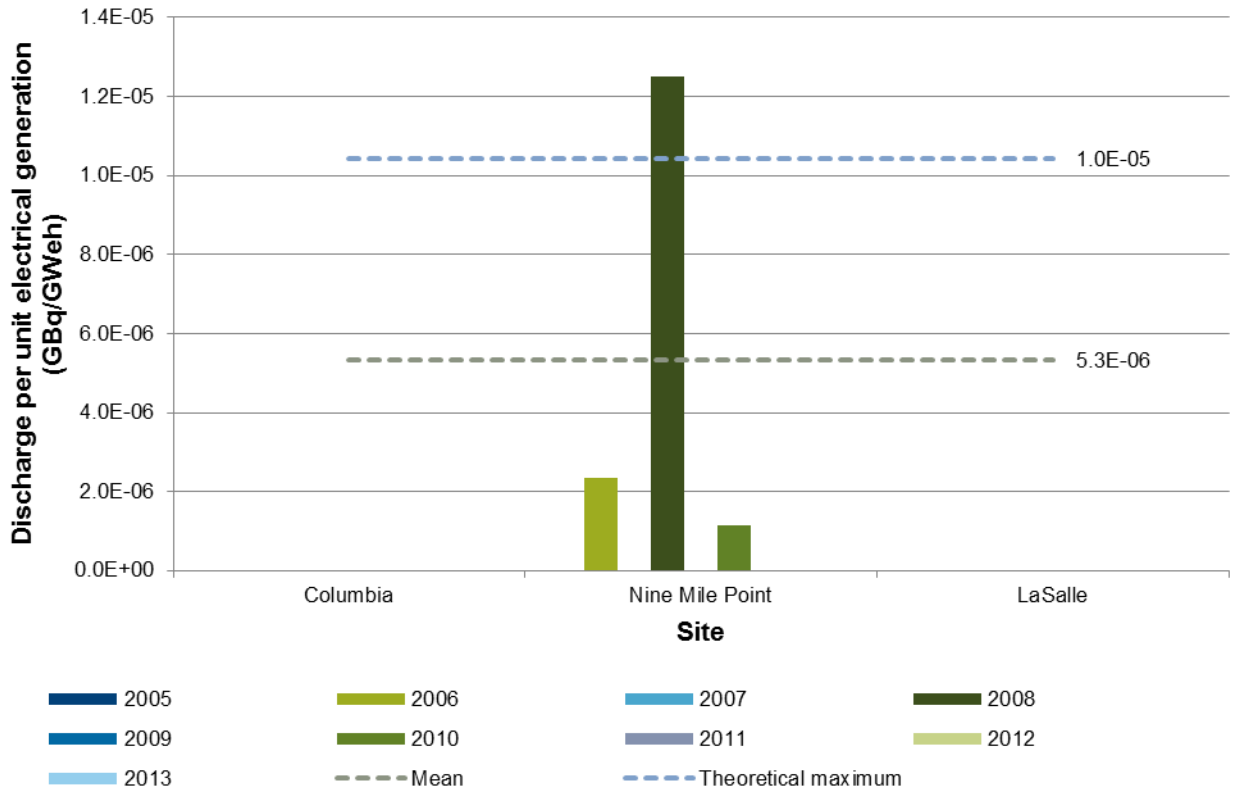

Figure 18 Normalised discharges of other liquids for 2005 to 2013 for BWR5 models

Columbia has not released any liquid effluents since 1998.

There were no liquid discharges from Nine Mile Point in 2005, 2007, 2009 and 2011-2013. Most sites do not report discharges of dissolved or entrained noble gases; therefore, for consistency, dissolved/entrained noble gases included in discharges from Nine Mile Point have been excluded from liquid discharges for this analysis.

There were no liquid discharges from LaSalle during the period of interest.

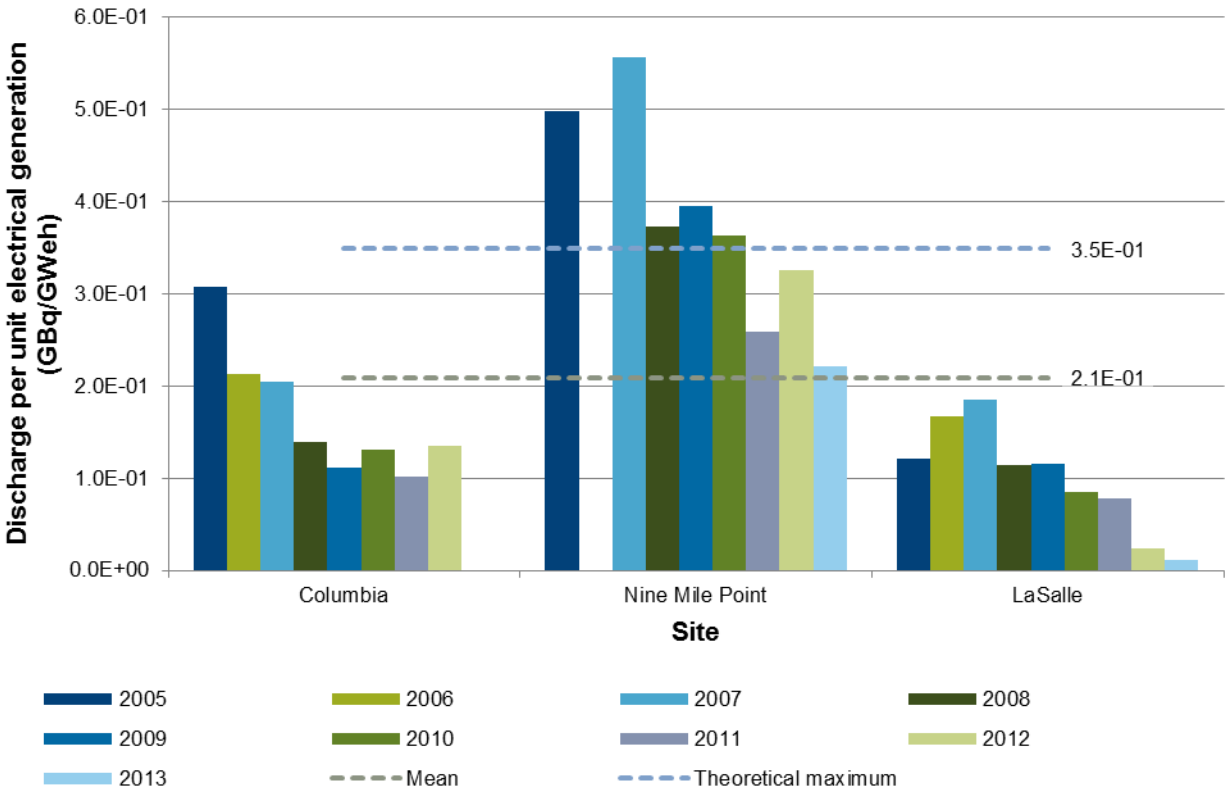

Figure 19 Normalised discharges of tritium to air for 2005 to 2013 for BWR5 models

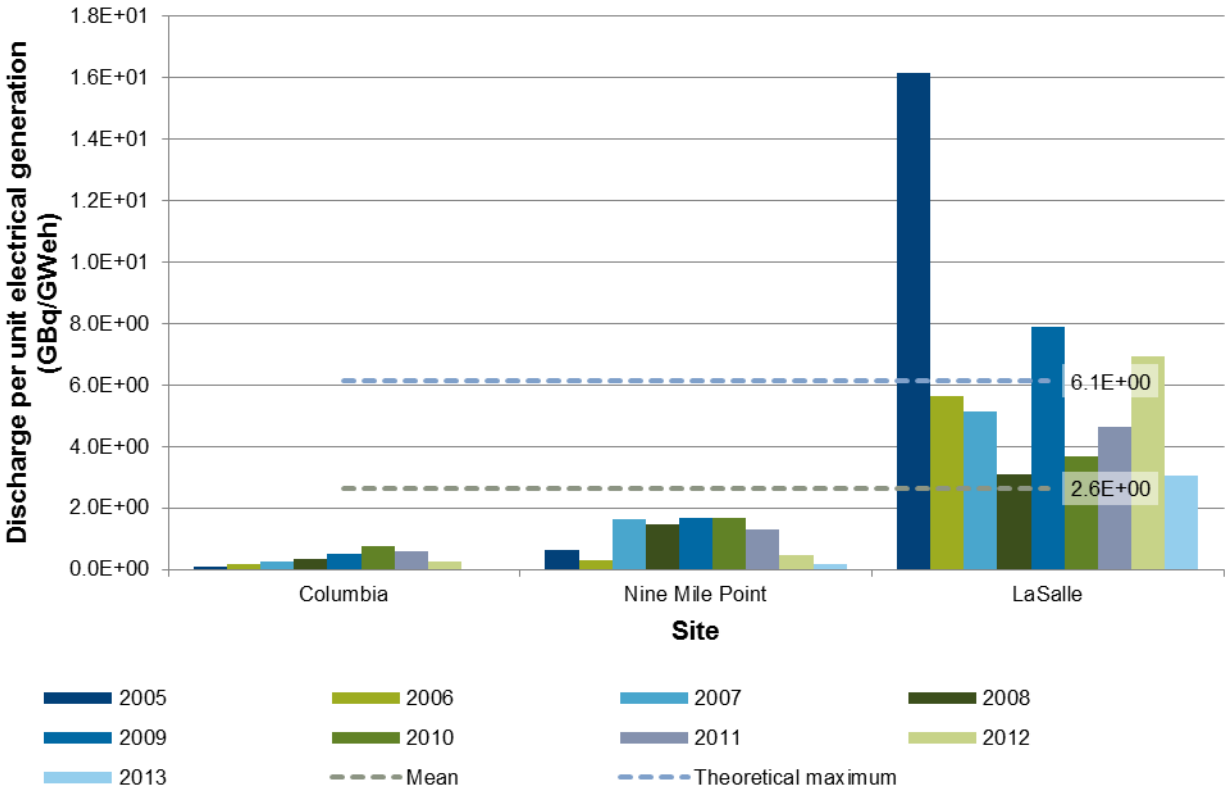

Figure 20 Normalised discharges of fission and activation products to air for 2005 to 2013 for BWR5 models

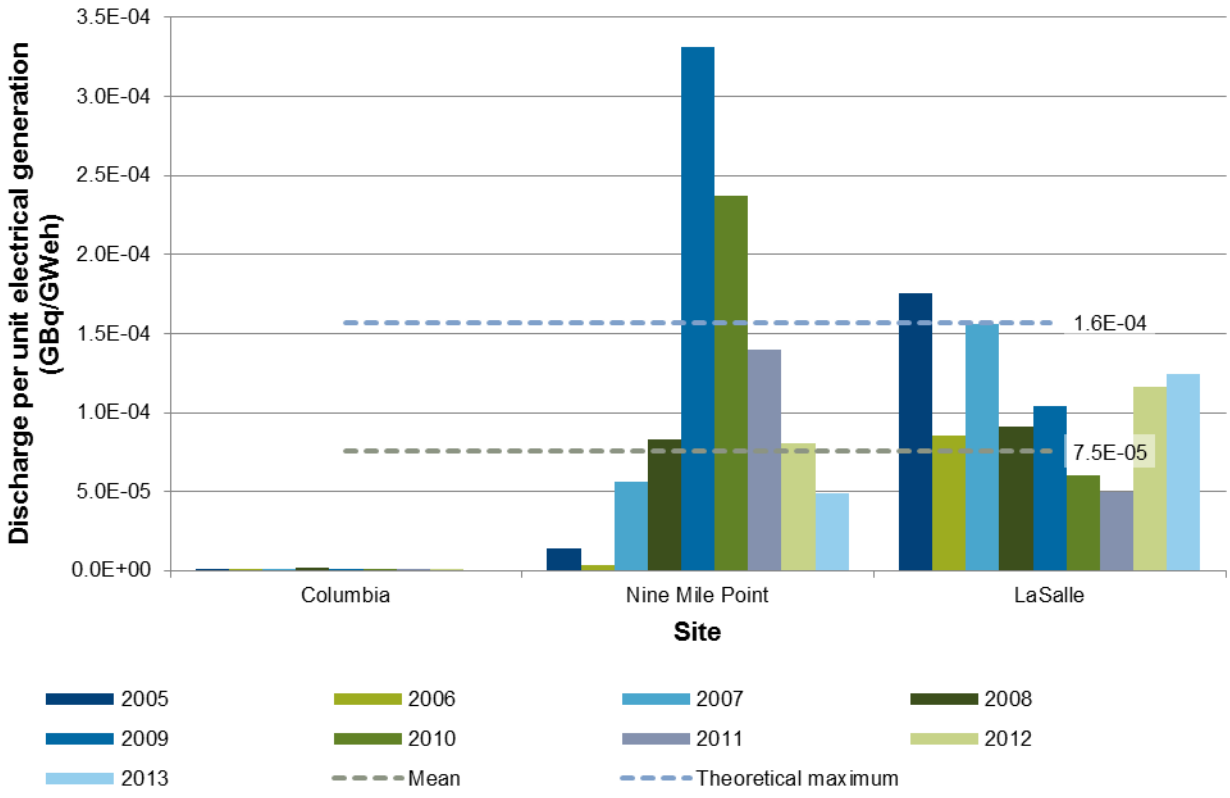

Figure 21 Normalised discharges of radioiodines to air for 2005 to 2013 for BWR5 models

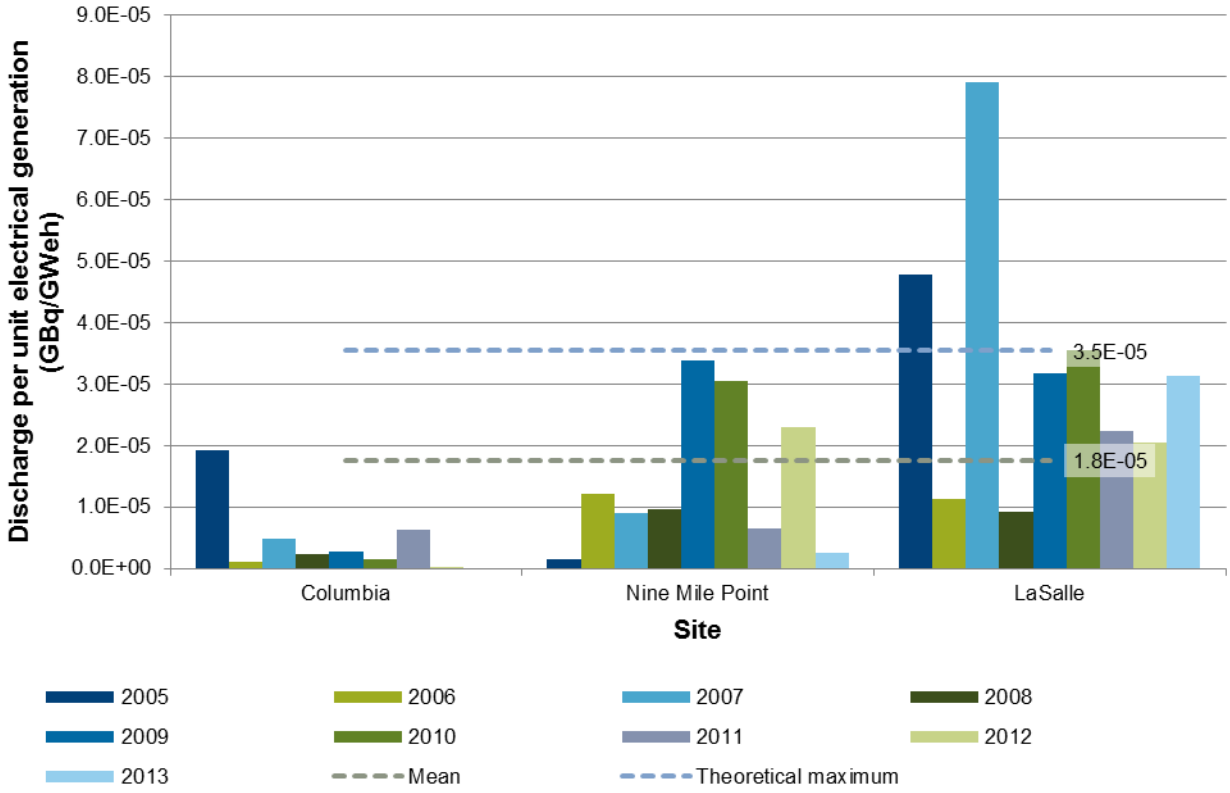

Figure 22 Normalised discharges of particulates to air for 2005 to 2013 for BWR5 models

Radionuclides with short half-lives (less than 8 days) have been excluded from this analysis.

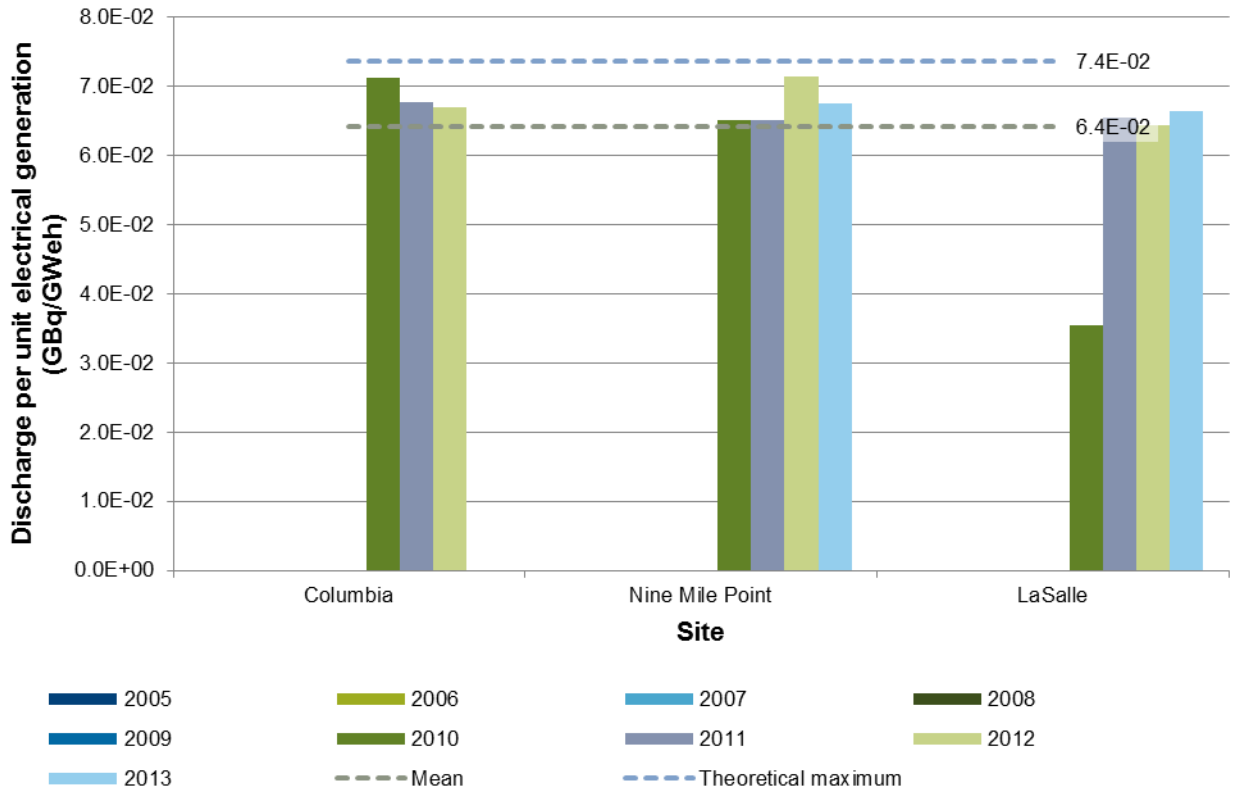

Figure 23 Normalised discharges of carbon-14 to air for 2005 to 2013 for BWR5 models

The US Nuclear Regulatory Commission has only required operators to report carbon-14 discharges since 2010.

4.4. Model BWR6

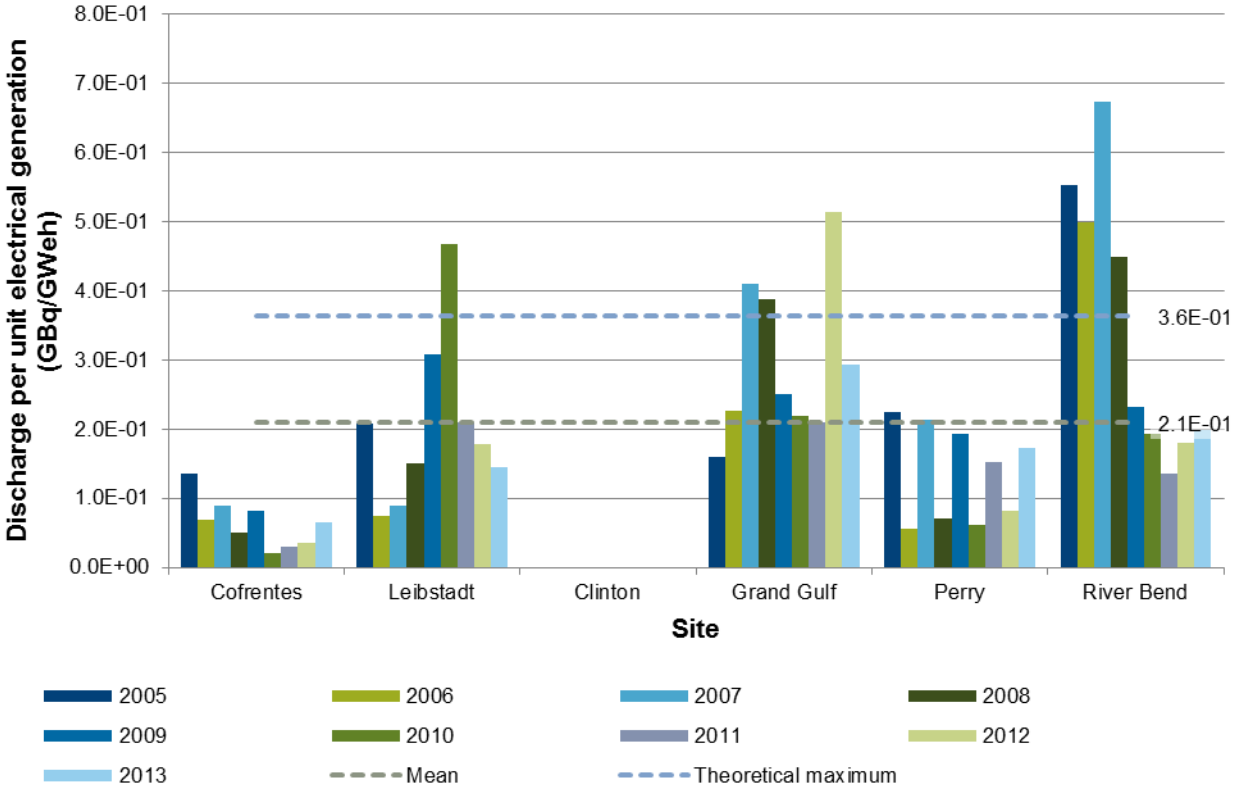

Figure 24 Normalised discharges of liquid tritium for 2005 to 2013 for BWR6 models

Clinton Power Station has not released any liquid effluents since 1992.

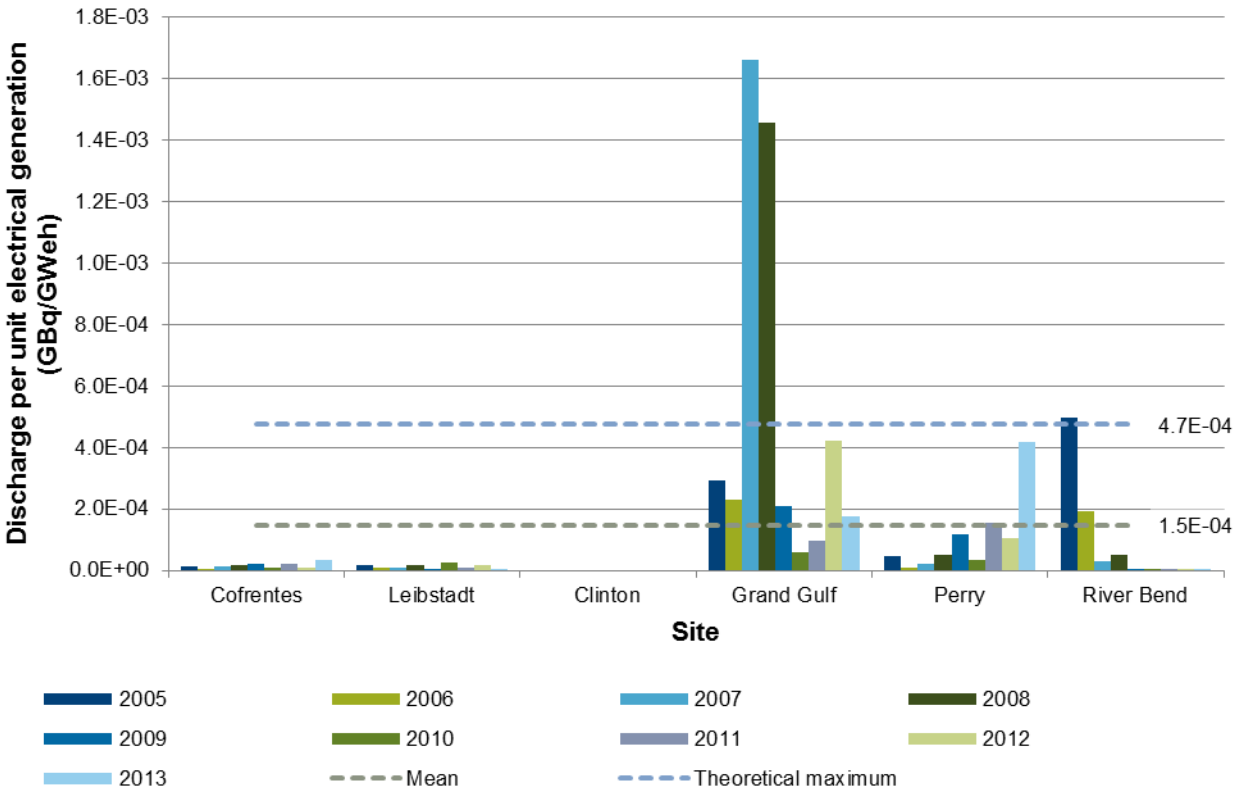

Figure 25 Normalised discharges of other liquids for 2005 to 2013 for BWR6 models

Most sites do not report discharges of dissolved or entrained noble gases; therefore, for consistency, dissolved/entrained noble gases have been excluded from liquid discharges for this analysis.

Clinton Power Station has not released any liquid effluents since 1992.

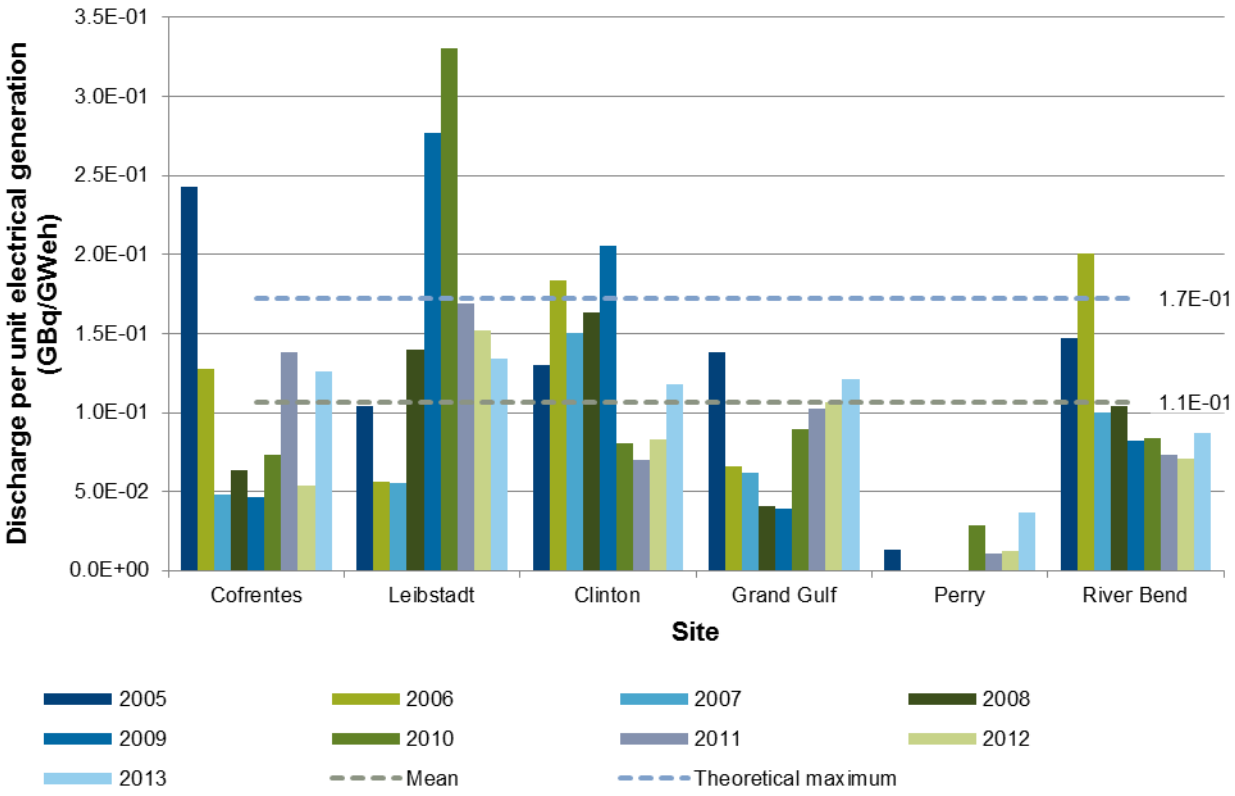

Figure 26 Normalised discharges of tritium to air for 2005 to 2013 for BWR6 models

Airborne tritium releases from Perry in 2006 to 2009 were below the limit of detection.

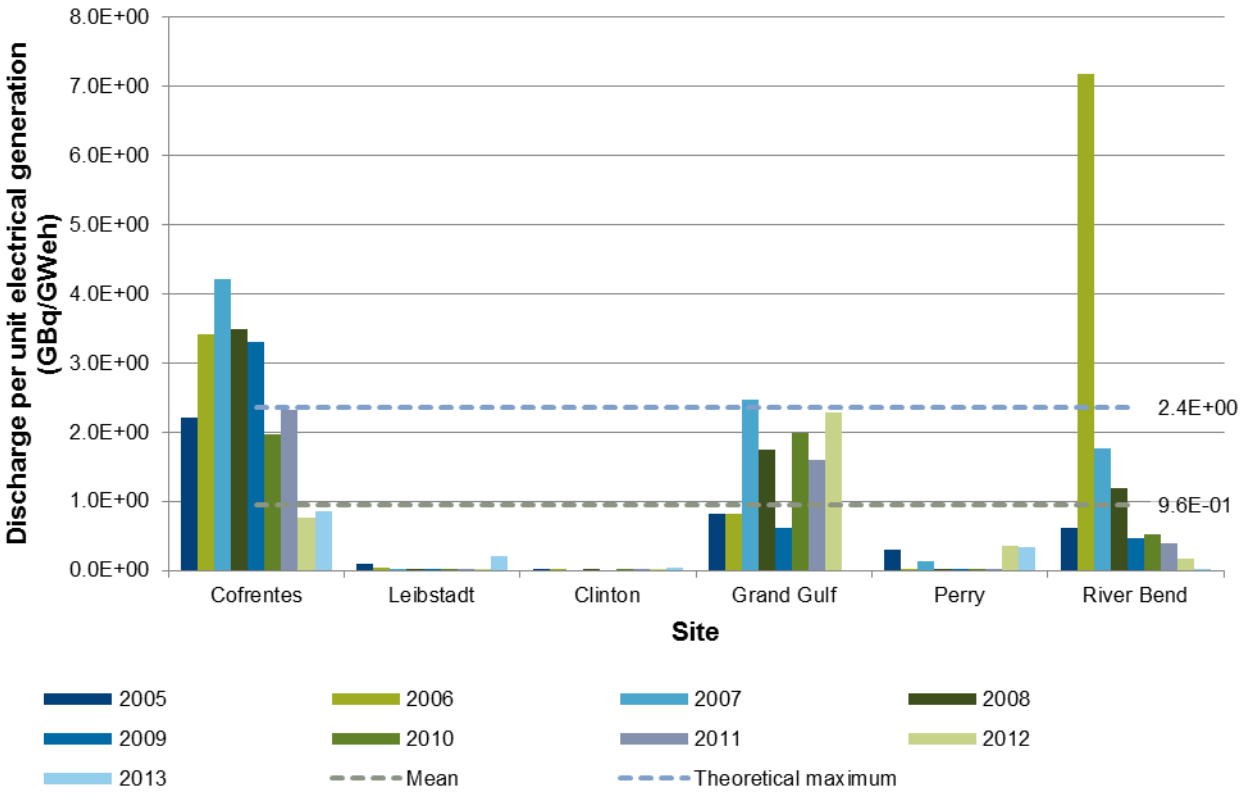

Figure 27 Normalised discharges of fission and activation products to air for 2005 to 2013 for BWR6 models

In 2013, refrigeration issues at Grand Gulf affected charcoal adsorption efficiency (Entergy Operation Inc, 2015). As a result, the plant discharged an abnormally high inventory of fission and activation gases. These data have been excluded from this analysis.

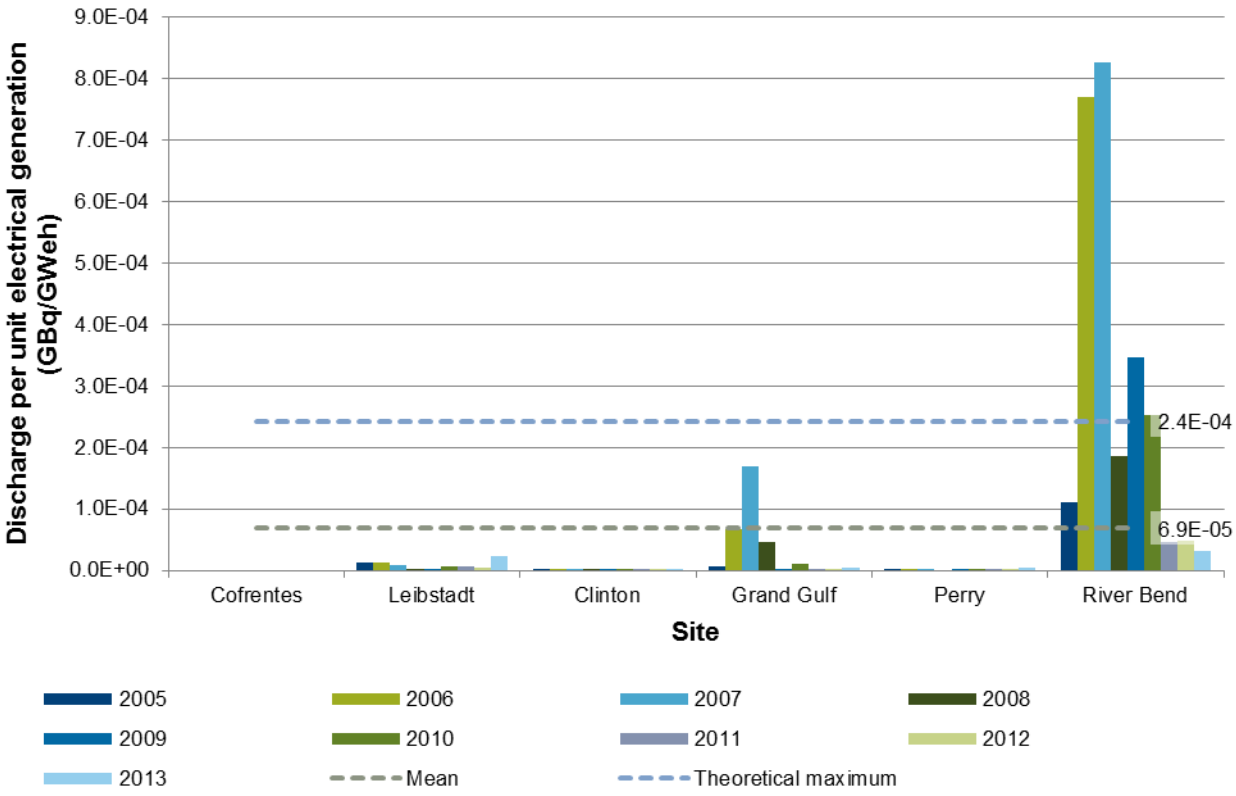

Figure 28 Normalised discharges of radioiodines to air for 2005 to 2013 for BWR6 models

Normalised discharges from Cofrentes from 2005 to 2011 appeared consistently high. The 2012 annual report of the CSN (CSN, 2013) observes that the medium-term trend in collective dose is erratic and associates this with a lack of refuelling. CSN has placed an action on Cofrentes' operator to reduce collective dose. It can be inferred that the plant was not operating under normal conditions and all radioiodine discharges from Cofrentes have, therefore, been excluded from this analysis.

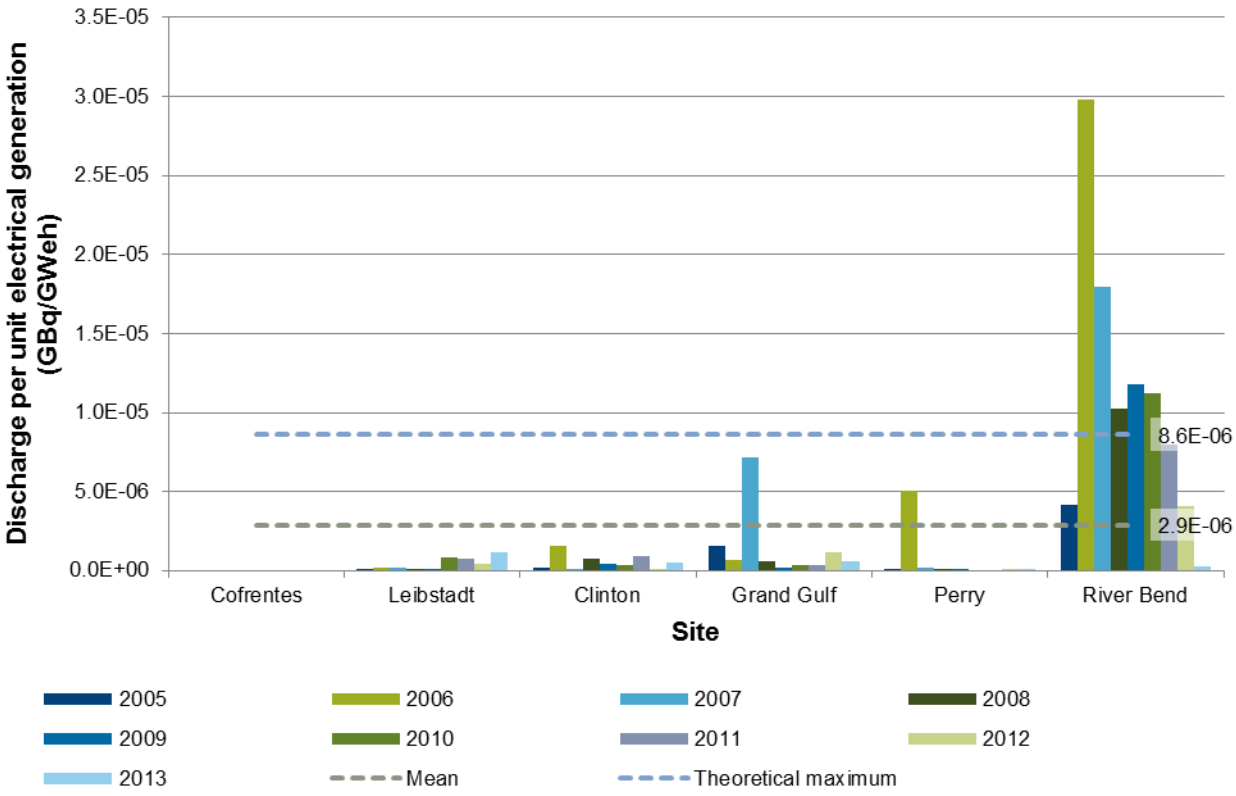

Figure 29 Normalised discharges of particulates to air for 2005 to 2013 for BWR6 models

Normalised discharges from Cofrentes from 2005 to 2011 appeared consistently high. The 2012 annual report of the CSN (CSN, 2013) observes that the medium-term trend in collective dose is erratic and associates this with lack of refuelling. CSN has placed an action on Cofrentes' operator to reduce collective dose. It can be inferred that the plant was not operating under normal conditions and all radioiodine discharges from Cofrentes have, therefore, been excluded from this analysis.

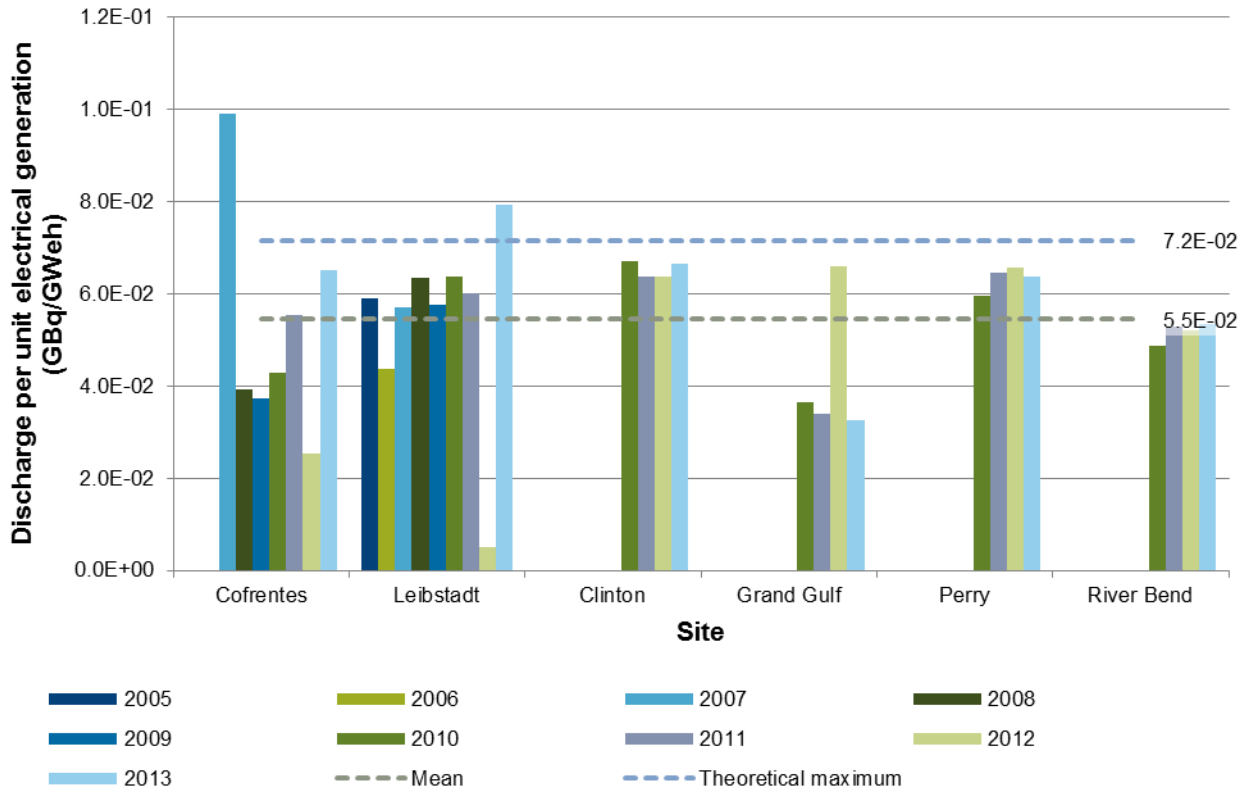

Figure 30 Normalised discharges of carbon-14 to air for 2005 to 2013 for BWR6 models

The US Nuclear Regulatory Commission has only required operators to report carbon-14 discharges since 2010.

4.5. Comparison of model types

In this section, the means for each model are the mean of all data for that model in that year; the overall mean is the mean of data from all sites included in the model analysis for that year.

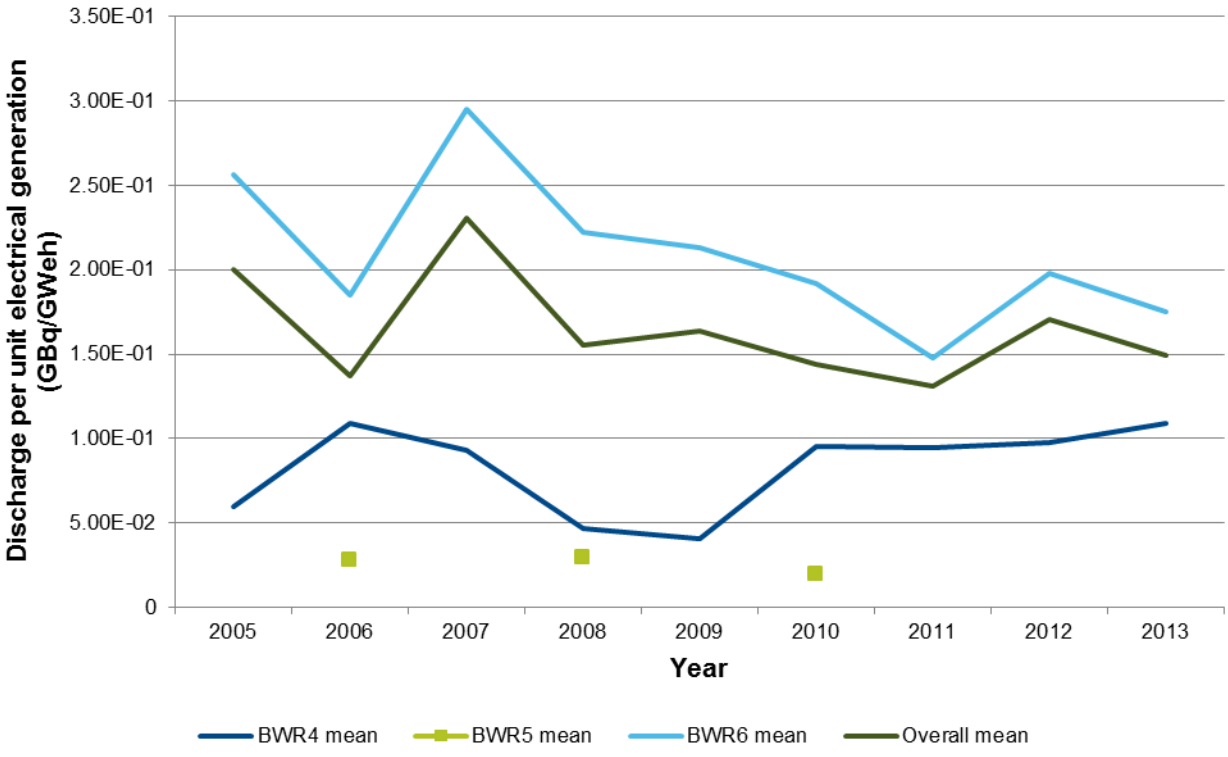

Figure 31 Comparison of model types for discharges of liquid tritium

Of the BWR5 reactors, only one site made any liquid discharges, and only in 2006, 2008 and 2010.

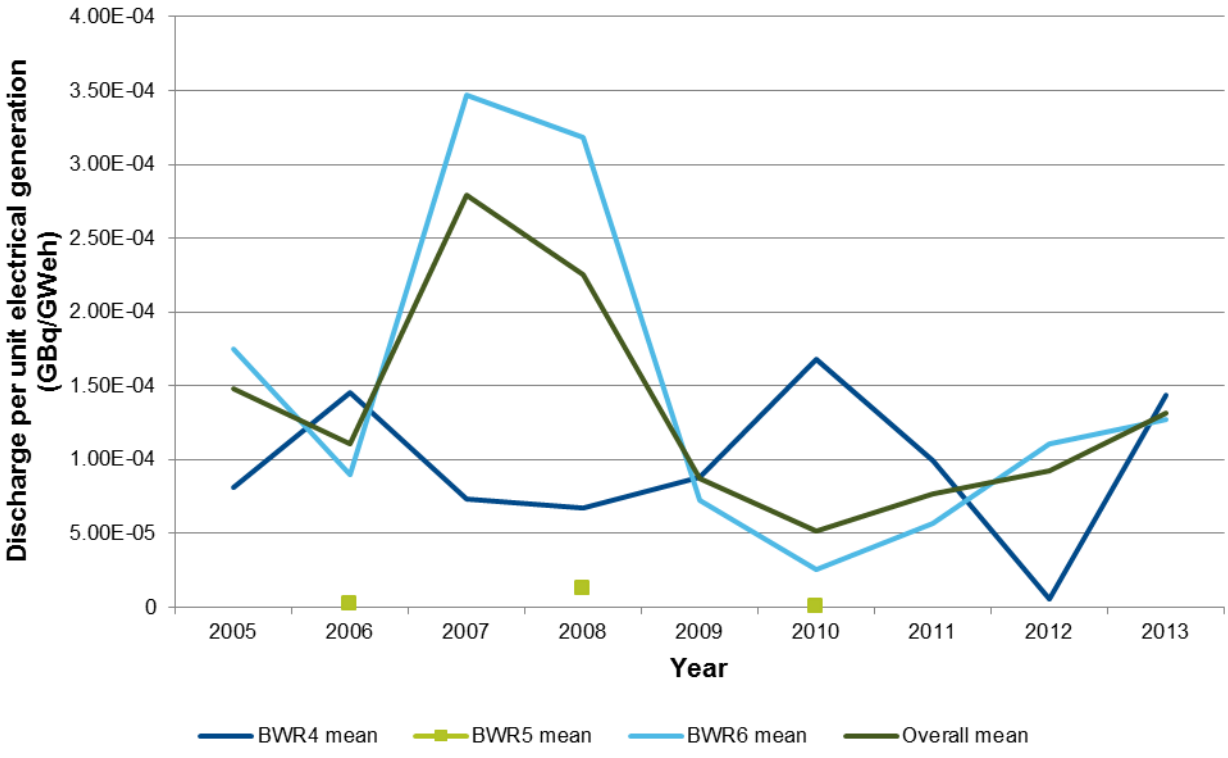

Figure 32 Comparison of model types for discharges of other liquids

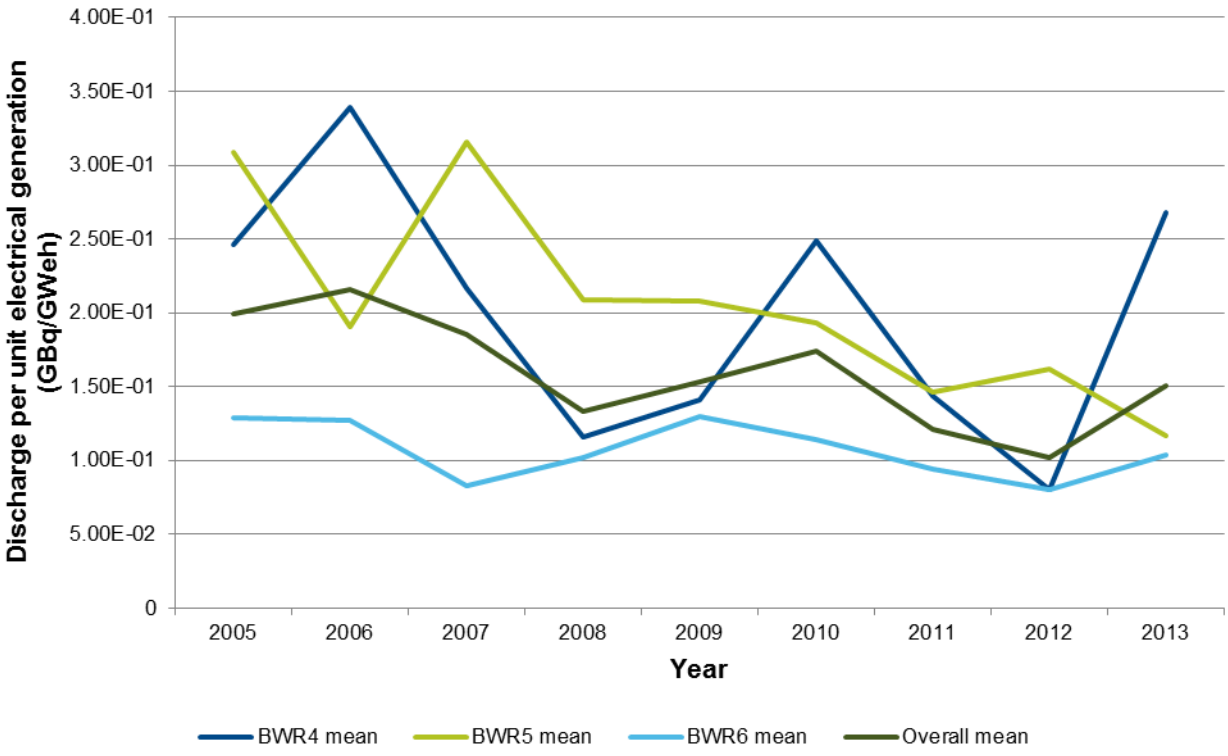

Figure 33 Comparison of model types for discharges of tritium to air

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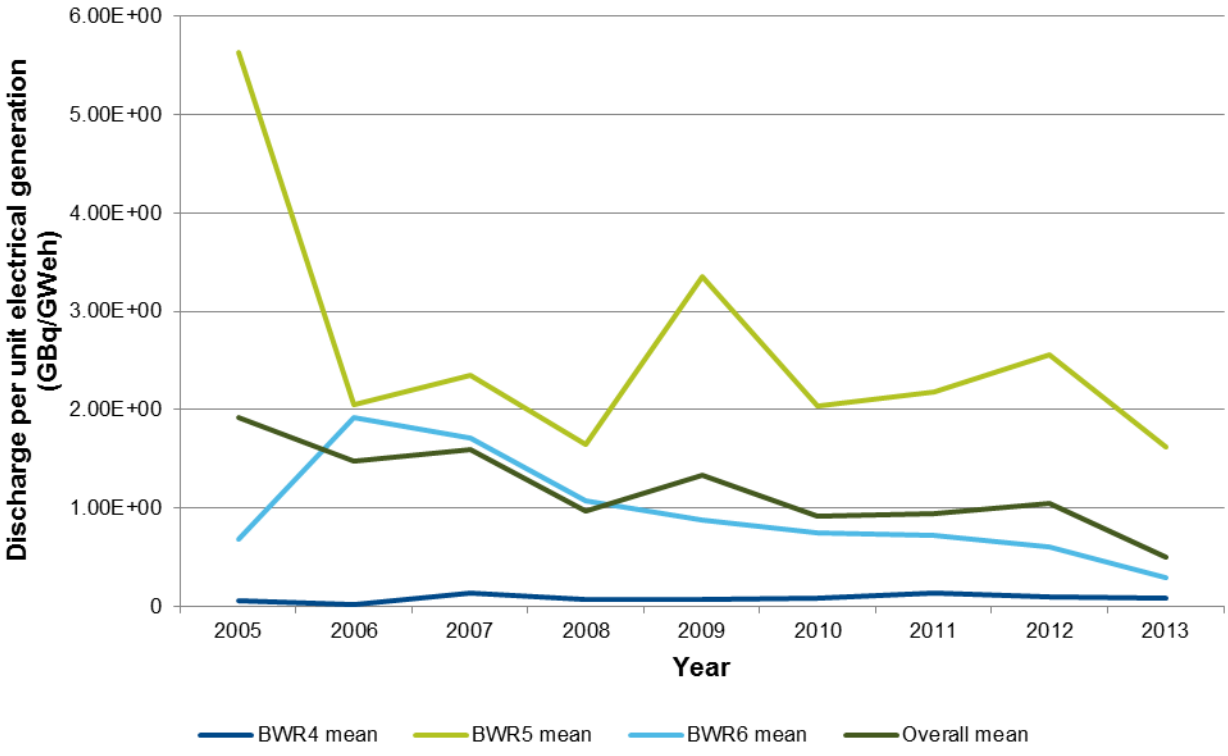


Figure 34 Comparison of model types for discharges of fission and activation gases to air

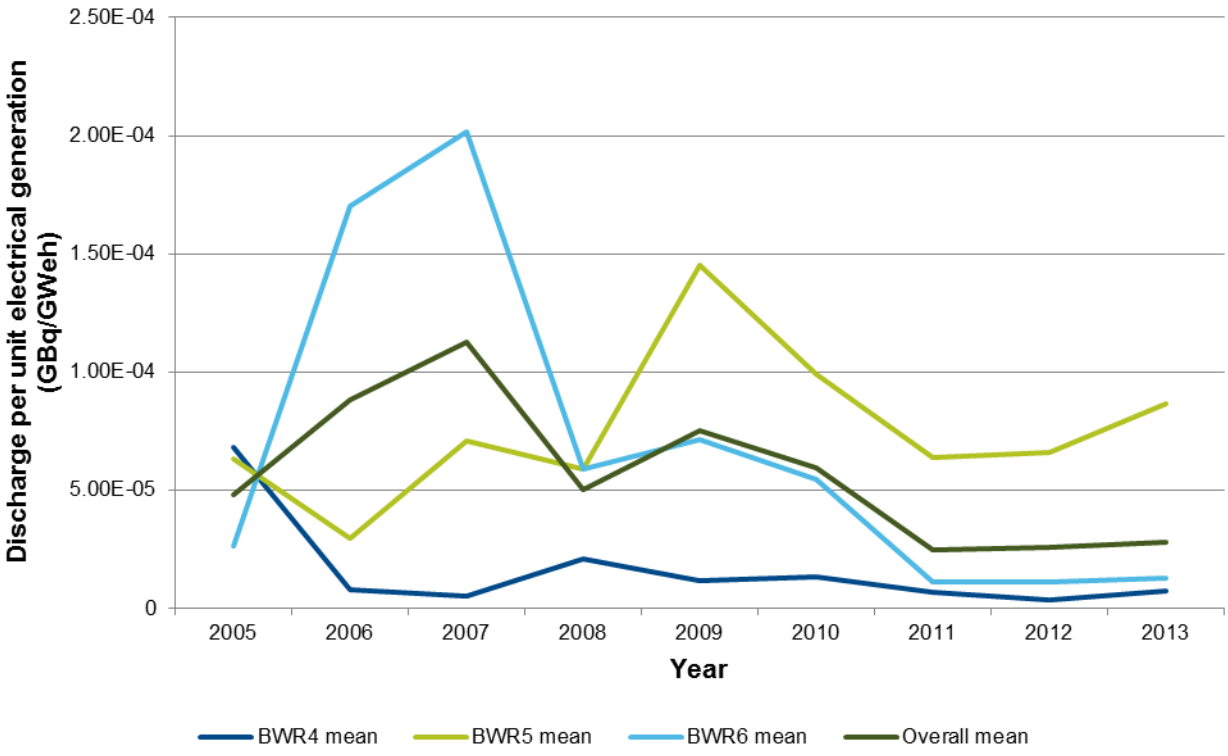


Figure 35 Comparison of model types for discharges of radioiodines to air

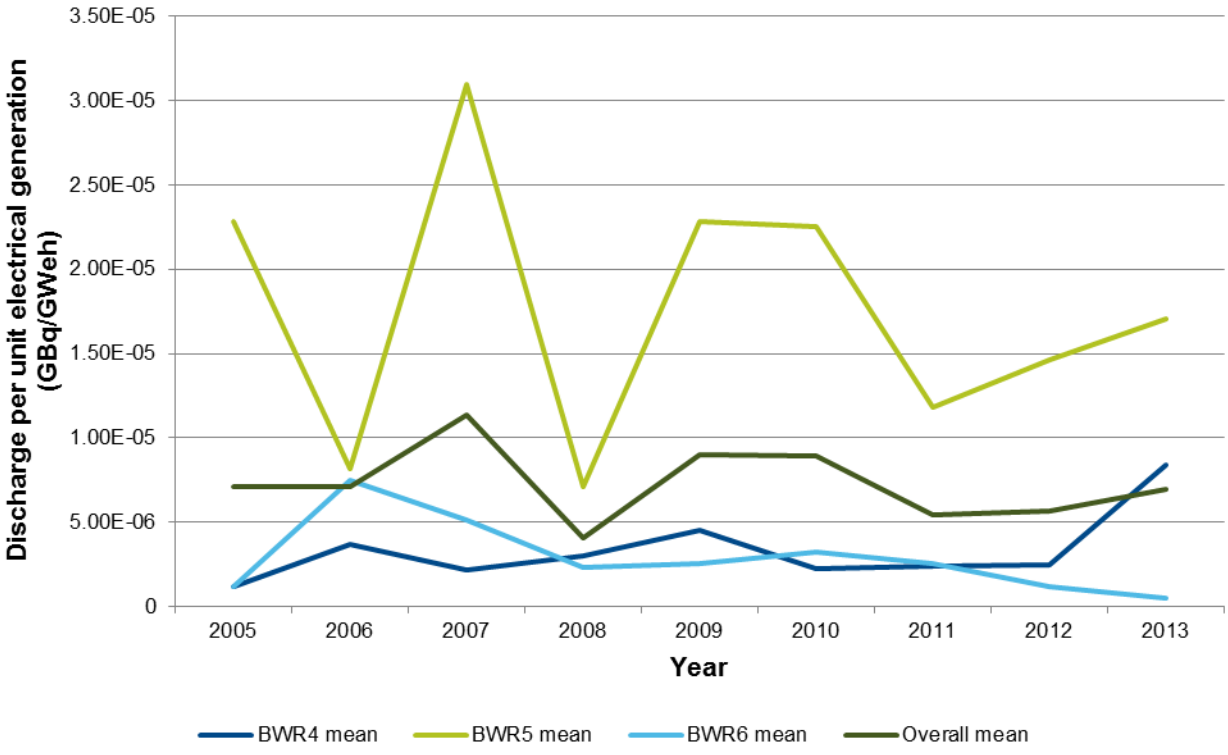


Figure 36 Comparison of model types for discharges of particulates to air

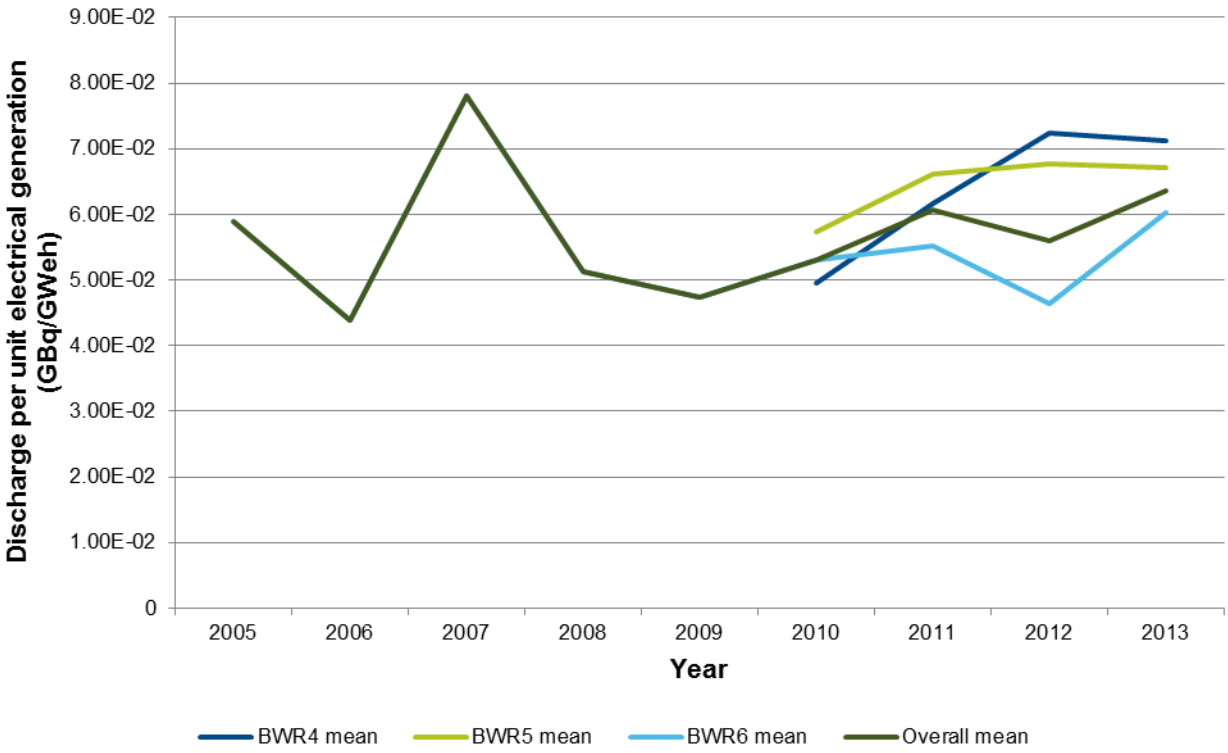


Figure 37 Comparison of model types for discharges of carbon-14 to air

4.6. US NRC report on long-term trends of discharges for US plants

The US Nuclear Regulatory Commission produced a report on Radioactive Effluents from Nuclear Power Plants (US NRC, 2013). It discusses long-term trends in both airborne and liquid effluents from 1975 to 2009 for pressurised water reactors (PWRs) and boiling water reactors (BWRs). Given the importance of long-term trends of discharges to this project, relevant parts of the report are reproduced here. The report includes charts of long-term trends for noble gases and mixed fission and activation products, which are reproduced here; discharged activity is given in curies rather becquerels.

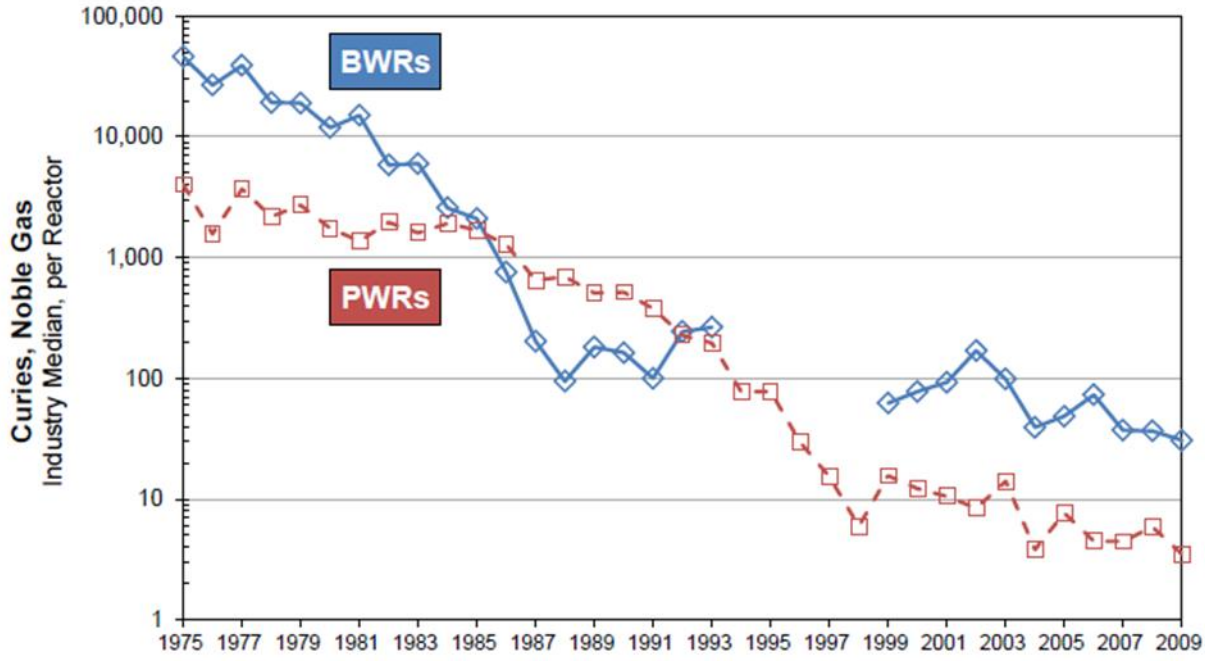


Figure 38 Long-term trend in gaseous effluents - noble gases (taken from US NRC, 2013)

The report states:

'The figure indicates a long-term downward trend in the amounts of noble gases in gaseous effluents from both BWRs and PWRs. The magnitude of the reduction is significant. For example, in 1975, the median release for BWRs was greater than 40,000 curies; however, in 2009, the median was 30.7 curies. That change corresponds to a 99.92% reduction in median noble gas effluents over the last 34 years. One of the primary contributors to the reduction in noble gas effluents is improved fuel integrity in both BWRs and PWRs. The use of advanced off-gas systems in BWRs is also responsible for reductions in the BWR industry averages. Lastly, contributions from the operations, maintenance, chemistry, and health physics departments at the various facilities have improved the handling and processing of gaseous waste to further improve and optimize effluent performance.'

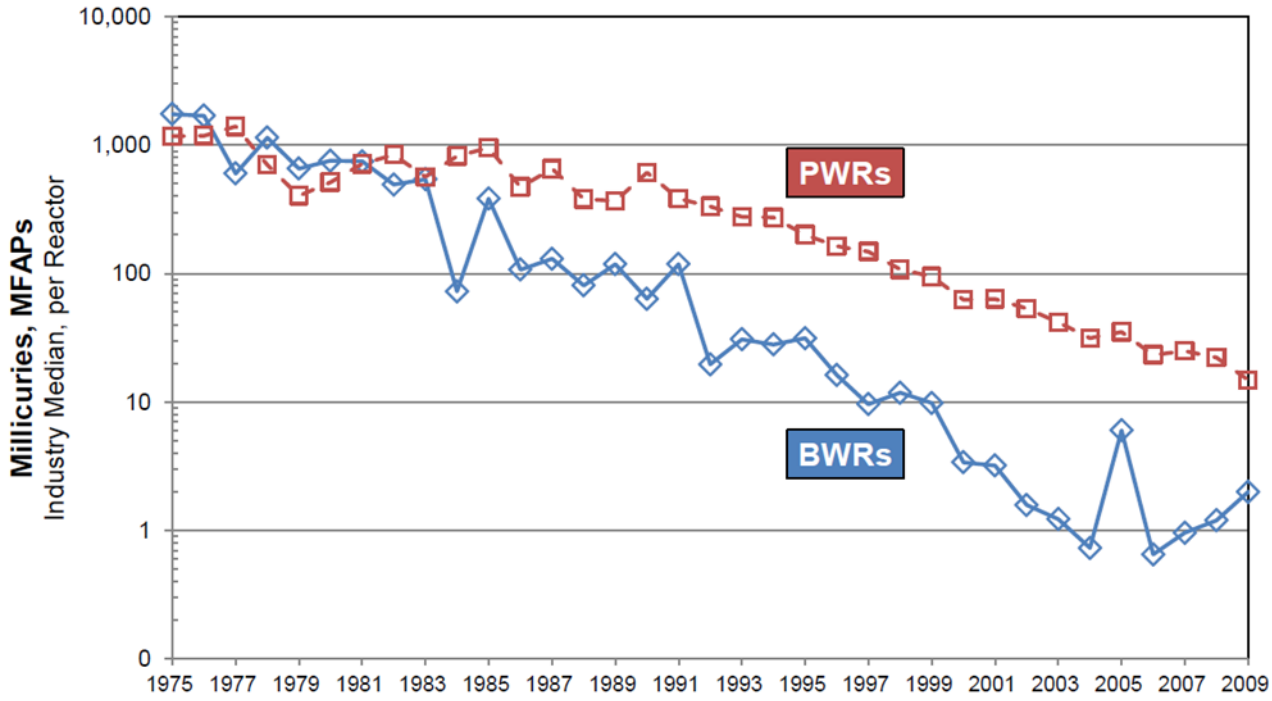


Figure 39 Long-term trend in liquid effluents - mixed fission and activation products (taken from US NRC, 2013)

The report states:

'… [the figure] indicates a long-term downward trend in the amounts of mixed fission and activation products (MFAPs) in liquid effluents from both BWRs and PWRs. The magnitude of the reduction is significant. For example, in 1978, the median activity of liquid effluents from BWRs was greater than 1000 millicuries; however, in 2009, the median was 2.8 millicuries. That corresponds to a 99.7% reduction in MFAPs in liquid effluents over the last 34 years. One of the primary contributors to the reduction in liquid effluents is improved fuel integrity in both BWRs and PWRs. Additionally, many BWRs recycle (or reuse) either some or all of the liquid waste. The recycling of liquid waste at BWRs is one reason why effluents from BWRs are generally lower than from PWRs. Additionally, PWRs use boron in the reactor water, whereas BWRs do not. This also contributes to lower liquid releases in BWRs, particularly for tritium. The use of advanced liquid radioactive waste processing systems has also significantly lowered liquid effluents. Lastly, contributions from the operations, maintenance, chemistry, and health physics departments at the various facilities has improved the handling and processing of liquid waste to further improve and optimize effluent performance. The figure indicates that from 2007 to 2009 median liquid effluents from BWRs increased each year… An analysis of this increase in median MFAP activity of liquid effluents from BWR reveals important information about the control of liquid effluents at BWRs. For many decades, BWRs have embraced a "zero-release" strategy for radioactive liquid effluents. Such a strategy has cost advantages, because it is expensive to discharge very high quality water that could appropriately be reused in designated plant systems. Additionally, a zero-release strategy conserves the natural resources and virtually eliminates radioactive liquid effluents in those BWRs

that adopt this strategy. This combination of factors makes a zero-release strategy very popular among BWRs. The zero-release strategy is partly responsible for the decreases in the median MFAP activity during the 1980s, 1990s, and beyond 2000, which can be seen in the figure. This strategy can be very effective in reducing both the activity and the dose from radioactive effluents. Within the last 10 years, it was recognized that, at some sites, the relative contribution of tritium to personnel exposure was increasing. This increase had the potential to affect plant workers and members of the public. This relative increase can be attributed to 4 factors:

- *As waste water is recycled, the tritium concentration in the water increases over time.*
- *Over the last 20 years, improved fuel integrity, improved fuel loading pattern designs, and improved liquid waste processing capabilities effectively reduced the concentration of mixed fission and activation products in waste water.*
- *When all radioactive liquid releases are eliminated, tritium is released through the gaseous release points.*
- *The dose due to tritium discharged from a gaseous release point can, depending on plant design and site characteristics, be higher than the same amount of tritium discharged from a liquid release point.*

As a result, for some sites, it was a mathematical certainty that doses could be lowered if more tritium was released in liquid effluents. Limited liquid releases containing tritium, along with very low levels of mixed fission and activation products, can shift the release of tritium from a gas release point to a liquid release point, thereby lowering doses due to effluents. This strategy can cause a slight increase in the activity of MFAPs in liquid effluents. This strategy to reduce doses from liquid effluents is partly responsible for the increases in the MFAP activity of liquid effluents at BWRs since about 2005.'

5. Analysis of chemical discharges

5.1. Reported liquid discharges and limits

Table 7 to Table 18 give reported liquid chemical discharges for the Spanish nuclear power plant, Cofrentes, and discharges and permitted limits from some of the US sites. Figures 42 to 52 were produced from the tables. No chart was produced if there were fewer than 8 data points for a particular parameter.

5.1.1. **Cofrentes**

Monitoring results of liquid discharges were available from January 2010 to December 2012 for the Spanish plant and are listed in Appendix C. These results were used to calculate the annual mean concentration for each parameter, which is shown in Table 7. Where data were reported as less than the limit of detection, it was conservatively assumed that the discharge was actually at the limit of detection.

Table 7 Mean annual concentrations of monthly liquid emissions from Cofrentes nuclear power plant from 2010 to 2012

	Mean 2010	Mean 2011	Mean 2012
Coarse solids	Not present	Not present	Not present
Sedimentary solids (mg/L)	0.30	0.33	0.50
Total suspended solids (mg/L)	7.63	8.75	8.75
Biochemical oxygen demand (BOD) (mg/L)	4.67	5.08	3.25
Chemical oxygen demand (COD) (mg/L)	14.92	12.50	13.67
Colour (mg/L Pt/Co)	3.75	8.51	6.59
Conductivity at 20ºC (µS/cm)	2505.83	2038.33	2335.83
pH	8.41	8.43	8.58
Oils and fats (mg/L)	0.29	0.34	0.50
Aldehydes (mg/L)	0.13	0.10	0.10
Hydrocarbons (mg/L)	0.04	0.04	0.03
Total phenols (µg/L)	50.5	42.3	1.00
Anionic surfactants (mg/L)	0.10	0.09	0.05
Copper (µg/L)	3.83	4.64	2.14
Zinc (mg/L)	0.01	0.01	0.02
Nickel (µg/L)	3.22	2.67	1.00
Manganese (µg/L)	3.10	2.89	1.07
Iron (mg/L)	0.03	0.02	0.02
Chromium (µg/L)	3.00	2.67	1.17
Chromium(VI) (µg/L)	5.00	5.00	5.00
Lead (µg/L)	3.00	2.67	1.00
Mercury (µg/L)	8.88	0.45	0.10

	Mean 2010	Mean 2011	Mean 2012
Aluminium (mg/L)	0.11	0.10	0.12
Ammonium (mg/L)	0.07	0.13	0.08
Nonionisable ammonia (mg/L)	0.02	0.02	0.01
Antimony (µg/L)	1.57	1.36	0.22
Arsenic (µg/L)	3.32	3.05	1.74
Barium (mg/L)	0.08	0.07	0.09
Boron (mg/L)	0.14	0.12	0.13
Cadmium (µg/L)	nr	nr	0.09
Calcium (mg/L)	331.07	307.90	351.25
Chlorides (mg/L)	250.85	188.98	211.00
Residual free chlorine (mg/L)	0.053	0.045	0.005
Total residual chlorine	nr	nr	nr
Cobalt (µg/L)	5.50	4.75	1.00
Cyanide (mg/L)	0.01	0.01	0.01
Fluorides (mg/L)	0.66	0.56	0.58
Magnesium (mg/L)	99.94	97.52	110.78
Nitric nitrogen (mg/L)	3.32	3.02	3.34
Nitrites (mg/L)	0.05	0.05	0.06
Total Kjeldahl nitrogen (mg/L)	1.02	1.41	1.26
Selenium (µg/L)	1.98	1.99	2.87
Silver (µg/L)	3.00	2.67	1.00
Sodium (mg/L)	151.79	119.40	130.33
Sulphates (mg/L)	973.53	783.78	895.08
Sulfites (mg/L)	0.46	0.46	0.50
Sulfides (mg/L)	0.14	0.14	0.10
Tin (mg/L)	0.501	0.417	0.001
Total phosphorus (mg/L)	0.23	0.25	0.19
Total phenols (mg/L)	0.051	0.042	0.001
Hydrocarbons (mg/L)	0.04	0.04	0.03
Pesticides: total (µg/L)	0.06	0.06	0.10

Note: nr = not reported

5.1.2. US plants

Data for liquid chemical discharges from US plants were available for the years 2007 to 2013, which allows some trend analysis. Discharge levels do not appear to have any obvious year-on-year trends over the time period studied. The exception to this is the clear downward trend in biogeochemical oxygen demand of the effluent from La Salle (see Figure 42). At each plant there appears to be variation in the average annual concentrations of chemical discharges. Detail on the operating techniques and activities at each of the sites studied may provide further insight into the causes of inter-annual variations in average discharge levels for specific years, but this information was not available. Each site has several points from which liquid discharges are emitted. Different discharge limits may be in places for different discharge points. Where there is more than 1 entry for a particular parameter in Tables 8 and 9, this indicates that there is more than one limit applied at the same site.

5.1.2.1. Permitted discharge limits

Table 8 Permitted liquid discharge limits at US plants - water quality parameters

All values are in mg/L (except for pH).

Site	Solids, TS	Oil & grease	pH	BOD	DO	Oxidants (total residual)	TOC
Clinton	15 ave 30 max; 30 average 60 max	15 ave 20 max	6 min 9 max	30 ave 60 max	-	-	-
Fermi	35-70 max; 30-100 max	15-20 max	6.5 min 9 max	-	-	-	-
Grand Gulf	30 max; 30 ave 45 max; 30 ave 100 max	-	-	30 ave 45 max	-	-	-
La Salle	15 ave 30 max; 30 ave 60 max	15 ave 20 max	-	25 ave 50 max	-	-	-
Limerick	100 max	-	-	-	-	0.2 max	-
Nine Mile	25 ave 45 max; 30 ave 50 max; 50 max	15 max	-	25 ave 45 max	4 min	0.1 max; 0.2 max	-
River Bend	100 max	15 max	-	-	-	-	50 max
Susquehanna	30 ave	15 ave	-	25 ave	-	-	-

Site	Solids, TS	Oil & grease	pH	BOD	DO	Oxidants (total residual)	TOC
	100 max	20 max					

Table 9 Permitted liquid discharge limits at US plants - elemental chemical parameters

All values are in mg/L (except where noted for Hg).

Site	Al	Cl, total residual	Cl, free available	Cr	Cu	Fe	Hg	P	Zn
Clinton	-	0.05 max	-	-		-	-	-	-
Fermi	-	0.038 max	-	-	1 max	-	0.000189 lb/day monthly ave 0.0000269 mg/L monthly ave	-	-
Grand Gulf	-	0. 5 max; 0.2 ave 0.5 max	-	-	-	-	-	-	1 ave 1 max
La Salle	-	0. 2 max	-	-	-	-	-	-	-
Limerick	-	-	-	-	-	-	-	-	-
Nine Mile	4 max	0. 1 max; 0.2 ave 0.27 max	-	-	0.053 max; 0.25 max	4 max	0.005 max	0.5 max	-
River Bend	-	-	0.2 ave 0.5 ave	0.2 ave 0.2 max	-	-	-	-	1 ave 1 max
Susquehanna	-	1 ave	0.2 max	0.2 max	-	-	-	-	1 max

Abbreviations:
Ave - Monthly average
Max - Monthly maximum
Min - Monthly minimum
BOD - Biogeochemical oxygen demand
DO - Dissolved oxygen
TOC - Total organic carbon
Solids, TS - Solids, total suspended

5.1.2.2. Clinton

Table 10 Reported liquid discharges between 2007 and 2013 at Clinton

Reported results	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	3.1	7.5	4.9	28.4	5.3	5.1	3.6
Solids total dissolved (mg/L)	386.5	325.6	339.7	337.3	361.5	nr	nr
Oils and fats (mg/L)	0.5	6.5	3.1	0.2	0.2	5.1	5.5
Zinc (mg/L)	nr	nr	nr	nr	nr	0.02	0.01
Chlorides (mg/L)	nr	nr	nr	nr	nr	45.9	57.5
Total residual chlorine (µg/L)	0	1.79	1.19	0.71	0.53	6.09E-04	0
Sulphate (mg/L)	nr	nr	nr	nr	nr	49.6	59.1
Total phosphorus (mg/L)	nr	nr	nr	nr	nr	0.19	0.09

Note: nr = not reported

5.1.2.3. Fermi

Monitoring is carried out monthly and the permit includes limits for the parameters specified in Tables 8 and 9. There is also a requirement to monitor for temperature, flow and selenium (daily maximum concentration) with no limits applied.

Table 11 Reported liquid discharges between 2007 and 2013 at Fermi

Reported results	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	16.4	55.5	8.7	11.3	4.9	7.6	21.7
Oils and fats (mg/L)	0	0	0	0	0	0	5.4
Copper (µg/L)	6.8	3.3	5.1	9.5	nr	nr	nr
Boron (mg/L)	0.4	0.3	0.2	0.4	nr	nr	nr
Total residual chlorine (mg/L)	0	0	0	0	0	0	0

Note: nr = not reported

5.1.2.4. Grand Gulf

Table 12 Reported liquid discharges between 2007 and 2013 at Grand Gulf

	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	8.7	12.2	45.9	10.5	23.1	7.7	20.1
Biogeochemical oxygen demand (BOD) (mg/L)	4.3	3.9	6.9	11.6	5.3	8.9	1.8
Oils and fats (mg/L)	nr	nr	0.46	0.31	0.09	nr	nr
Zinc (mg/L)	0.38	0.42	0.37	0.33	0.29	0.40	0.31
Residual free chlorine (µg/L)	4.32	1.58	0.30	nr	0.37	nr	0.44
Total residual chlorine (µg/L)	117	62	47	180	17	381	60

Note: nr = not reported

5.1.2.5. La Salle

Table 13 Reported liquid discharges between 2007 and 2013 at La Salle

	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	1.8	3.1	2.1	1.6	1.2	0.5	0.8
Biogeochemical oxygen demand (BOD) (mg/L)	11.4	8.9	5.7	3.7	4.4	3.4	1.3
Oils and fats (mg/L)	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Zinc (mg/L)	nr	nr	nr	nr	nr	nr	0.0
Total residual chlorine (µg/L)	nr	3.0	5.1	6.2	7.2	3.8	2.9

Note: nr = not reported

5.1.2.6. Hope Creek

Hope Creek is a boiling water reactor, but is co-located with 2 other nuclear generation plants at Salem. The 2 other plants are pressurised water reactors. Hope Creek chemical discharge data is combined with Salem chemical discharge data available from the US Environmental Protection Agency (EPA). It is not possible to determine what proportions of the reported discharges are generated by each of the different reactors. As this data cannot be disaggregated, it has been left out of this study.

5.1.2.7. Limerick

Data for liquid discharges from this plant was available for only 3 years; 2011 to 2013.

Table 14 Reported liquid discharges between 2011 and 2013 at Limerick

	2011	2012	2013
Total suspended solids (mg/L)	18.89	7.07	21.69
Biogeochemical oxygen demand (BOD) (mg/L)	0	0	0
Chemical oxygen demand (COD) (mg/L)	0	0	0
Oils and fats (mg/L)	0	0	0
Iron, dissolved as Fe (mg/L)	0	0	0
Oxidants, total residual (mg/L)	0.09	0.05	0.05
Cadmium, total as Cd (mg/L)	0	0	0
Nitrogen, Kjeldahl, total as N (mg/L)	0	0	0
Phosphorus, total as P (mg/L)	0	0	0

Note: nr = not reported; Kjeldahl refers to the method of ammonium ion analysis.

5.1.2.8. Nine Mile

Table 15 Reported liquid discharges between 2007 and 2013 at Nine Mile

	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	5.4	4.6	4.5	0.02	0.2	2.8	1.9
Biogeochemical oxygen demand (BOD) (mg/L)	1.2	1.1	1.2	3.4	2.5	1.5	0.04
Oils and fats (mg/L)	0.00	0.00	0.03	0.04	0.01	0.00	0.00
Copper (µg/L)	11.5	11.4	7.3	4.6	6.8	6.4	6.0
Iron (mg/L)	0.49	0.56	0.16	0.12	0.10	0.19	0.14
Mercury (µg/L)	nr	nr	0.003	0.008	0.004	0.001	0.0003
Aluminium (mg/L)	0.25	0.10	0.05	0.12	0.02	0.13	0.08
Residual free chlorine (µg/L)	8.6	4.3	1.6	2.2	6.0	4.9	2.5
Total residual chlorine (µg/L)	23.8	22.4	8.4	2.2	1.5	1.0	0
Total phosphorus (µg/L)	nr	nr	5.2	25.6	90.7	36.8	597.7

Note: nr = not reported

5.1.2.9. Perry

Monitoring is required for average and maximum concentrations of copper, mercury and selenium, however no limits are set. Measurement of the maximum concentrations of chlorine (total residual) and oxidants (total residual) is required, again with no limit enforced. There is also a requirement to monitor flow and temperature, and pH is required to be between a minimum of pH6.5 and a maximum of pH9.0

Table 16 Reported liquid discharges between 2007 and 2013 at Perry

Reported results	2007	2008	2009	2010	2011	2012	2013
Copper (µg/L)	8.0	6.2	3.1	7.7	3.2	5.5	4.0
Zinc (µg/L)	4.1	3.4	2.3	6.7	6.6	7.9	nr
Mercury (mg/L)	nr	nr	nr	nr	nr	1.8E-12	2.4E-12
Total residual chlorine (µg/L)	12.4	37.9	63.2	34.1	50.8	49.4	55.0
Selenium (mg/L)	nr	nr	nr	nr	nr	0.01	0.01

Note: nr = not reported

5.1.2.10. River Bend

Toxicity testing of the final effluent is a requirement of the permit at this facility, although no limits are applied. Tests are carried out over 48 hours on species such as *Daphnia pulex* and *Pimephales promela* to determine lethality and no observable effect levels (NOEL). Whole ecosystem effects are further considered by including pollutant load limit for free available chlorine of 0.285 lb/day (average) and 0.743 lb/day (maximum). There are also requirements to monitor maximum flow rates and to ensure that the temperature of the final effluent is between 105 and 110 F, with pH between pH6 and pH9.

Table 17 Reported liquid discharges between 2007 and 2013 at River Bend

Reported results	2007	2008	2009	2010	2011	2012	2013
Total suspended solids (mg/L)	3.3	8.0	3.0	2.8	3.9	4.2	nr
Oils and fats (mg/L)	0.23	0.14	1.66	3.66	1.59	0.00	0.00
Total organic carbon (mg/L)	11.4	23.9	17.7	8.0	14.5	14.0	58.3
Zinc (mg/L)	0.19	0.21	0.11	0.13	0.09	0.10	nr
Residual free chlorine (mg/L)	0	0	0	0	0	0	nr

Note: nr = not reported

5.1.2.11. Susquehanna

Table 18 Reported liquid discharges between 2007 and 2013 at Susquehanna

	2007	2008	2009	2010	2011	2012	2013
BOD, carbonaceous, 05 day, 20 C (mg/L)	12.49	8.45	8.88	8.69	9.11	7.60	9.10
Chlorine, free available (µg/L)	0.00	0.45	0.00	1.38	0.00	0.00	0.00
Chlorine, total residual (µg/L)	0.00	0.00	0.35	0.30	0.00	0.30	0.00
Chromium, total (as Cr) (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrite plus nitrate total (mg/L)*	25.91	38.70	35.96	53.64	22.98	nr	nr
Nitrite plus nitrate total 1 det. (as N) (mg/L)*	27.68	34.89	40.11	39.90	22.61	nr	nr
Nitrogen, ammonia total (mg/L)*	40.30	24.08	23.10	53.20	74.69	nr	nr
Nitrogen, ammonia total (as N) (mg/L)*	36.43	21.34	24.28	48.94	69.09	nr	nr
Nitrogen, Kjeldahl total (mg/L)*	42.24	22.96	22.51	56.27	76.49	nr	nr
Nitrogen, Kjeldahl, total (as N) (mg/L)*	38.23	20.59	23.46	50.97	70.53	nr	nr
Nitrogen, total (mg/L)*	70.46	60.60	57.98	109.90	99.22	nr	nr
Nitrogen, total (as N) (mg/L)*	66.01	54.54	63.22	90.86	92.92	nr	nr
Oil and grease (mg/L)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphorus, total (mg/L)	8.24	9.52	8.38	12.24	11.72	nr	nr
Phosphorus, total (as P) (mg/L)	7.78	8.46	9.05	10.08	10.98	nr	nr
Solids, total suspended (mg/L)	6.52	5.94	4.83	2.52	6.50	8.03	7.29
Zinc, total (as Zn) (mg/L)	0.04	0.04	0.00	0.00	0.00	0.00	0.00

Note: nr = not reported

*All results from the same outfall location.

Zero values have been presented, as this is how the site reported the liquid discharges data. There was no information on the limits of detection for the various measures.

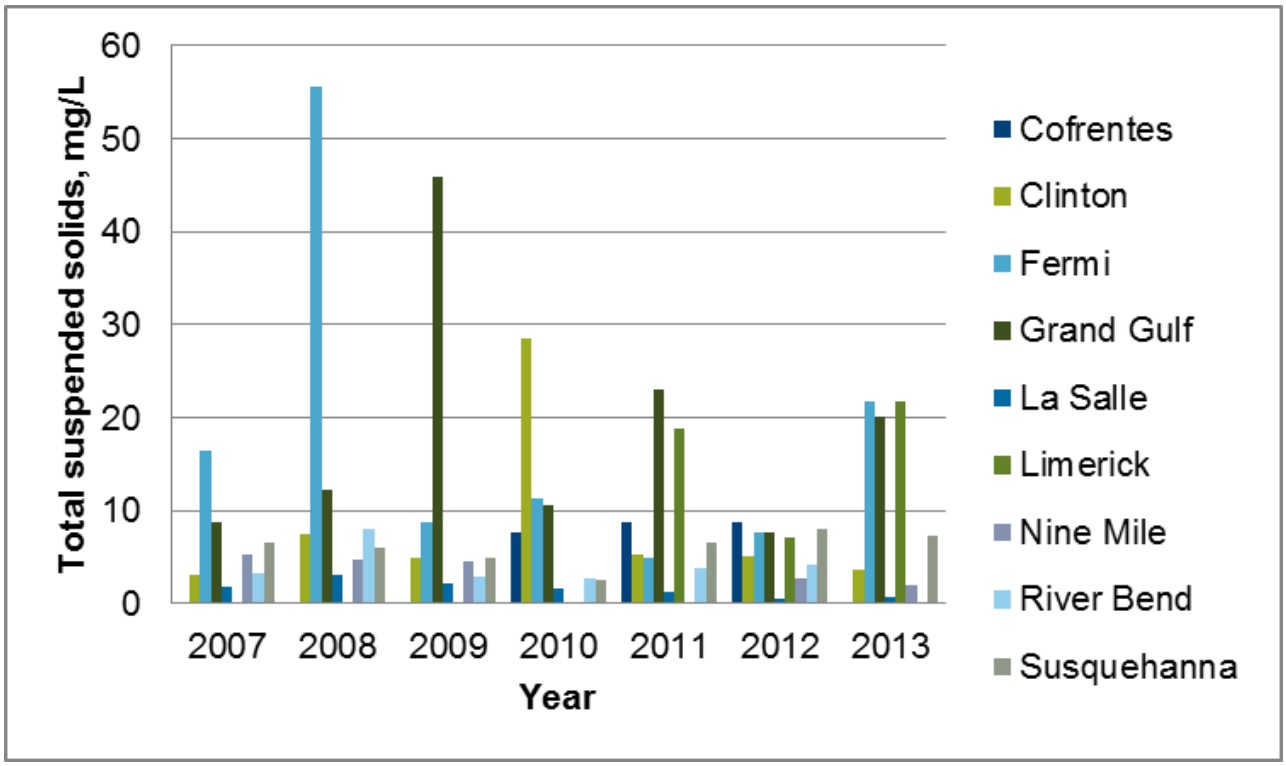


Figure 40 Concentration of total suspended solids in liquid discharges for 2007 to 2013

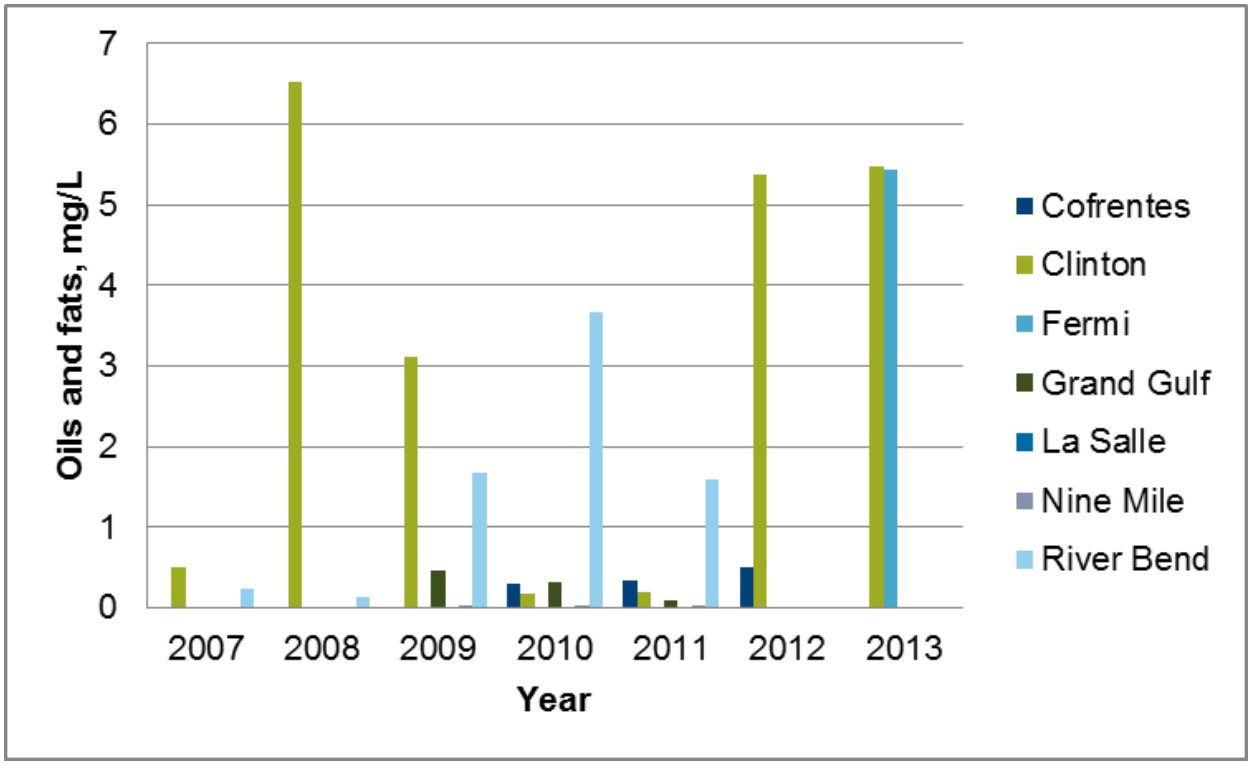


Figure 41 Concentration of oils and fats in liquid discharges for 2007 to 2013

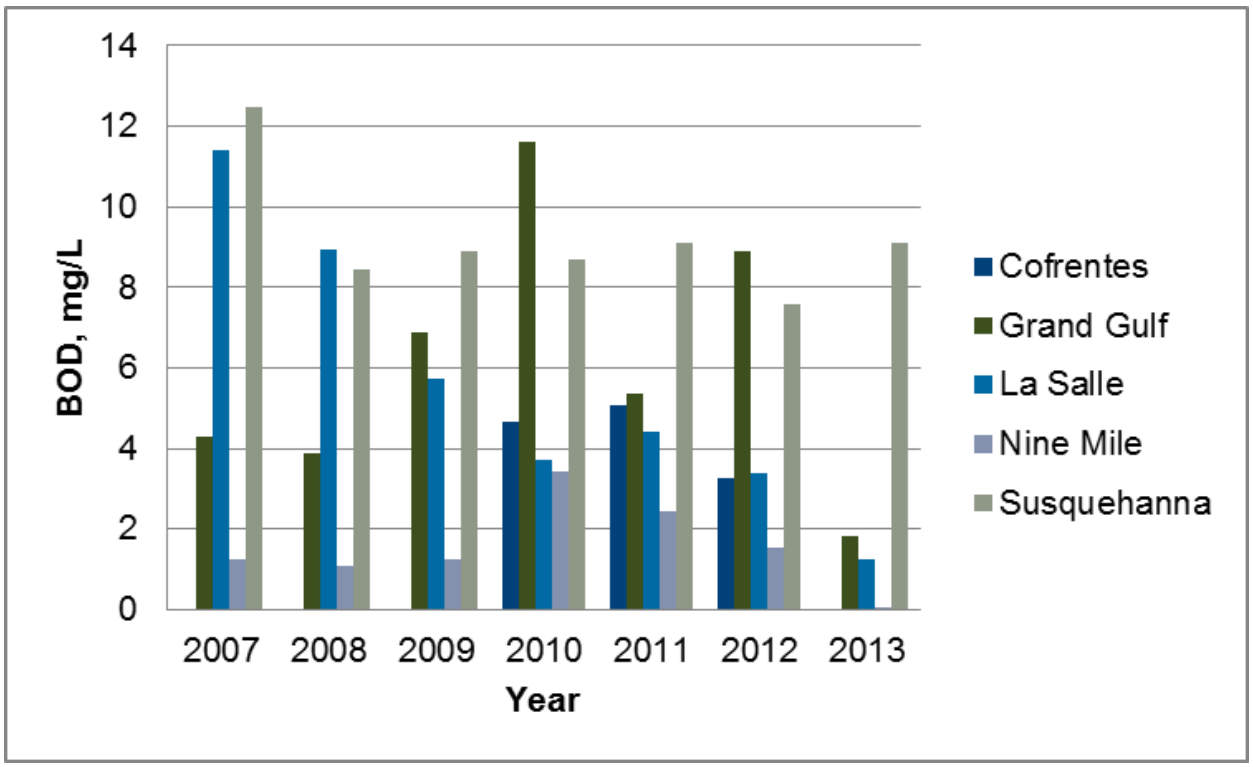


Figure 42 Biogeochemical oxygen demand of liquid discharges for 2007 to 2013

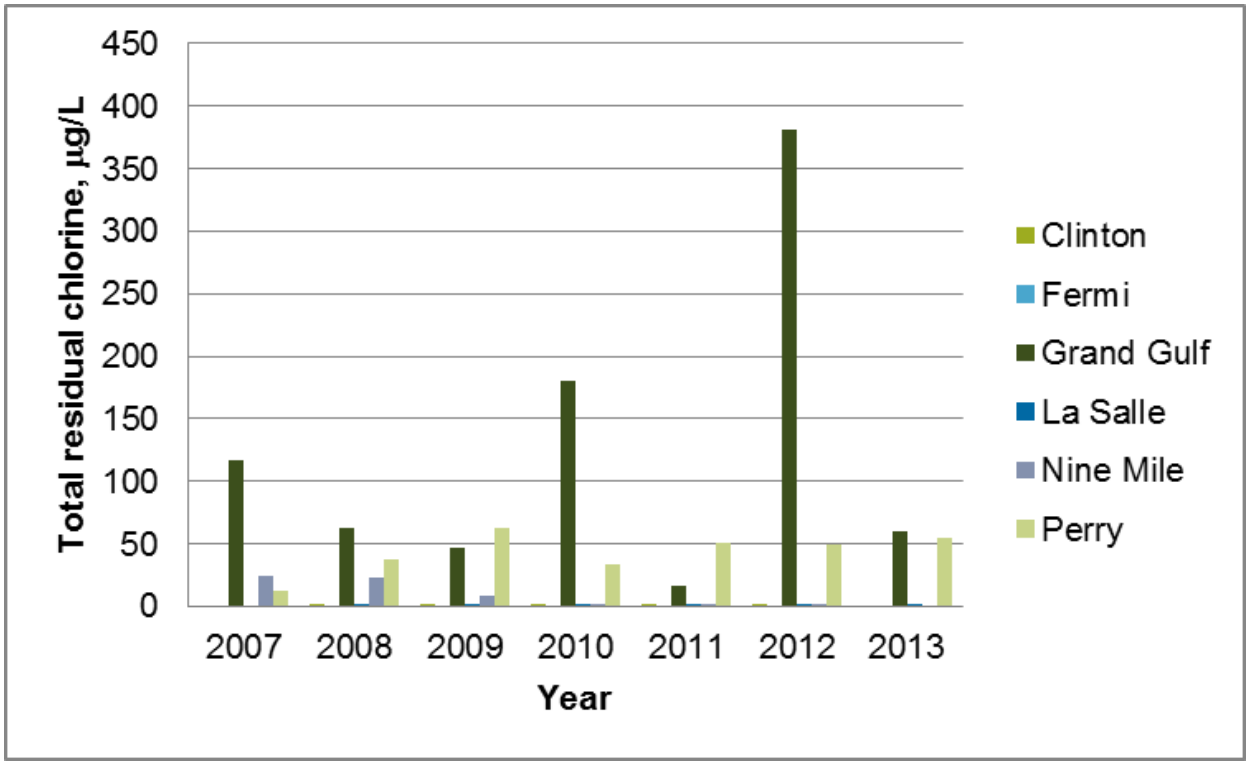


Figure 43 Concentration of total residual chlorine in liquid discharges for 2007 to 2013

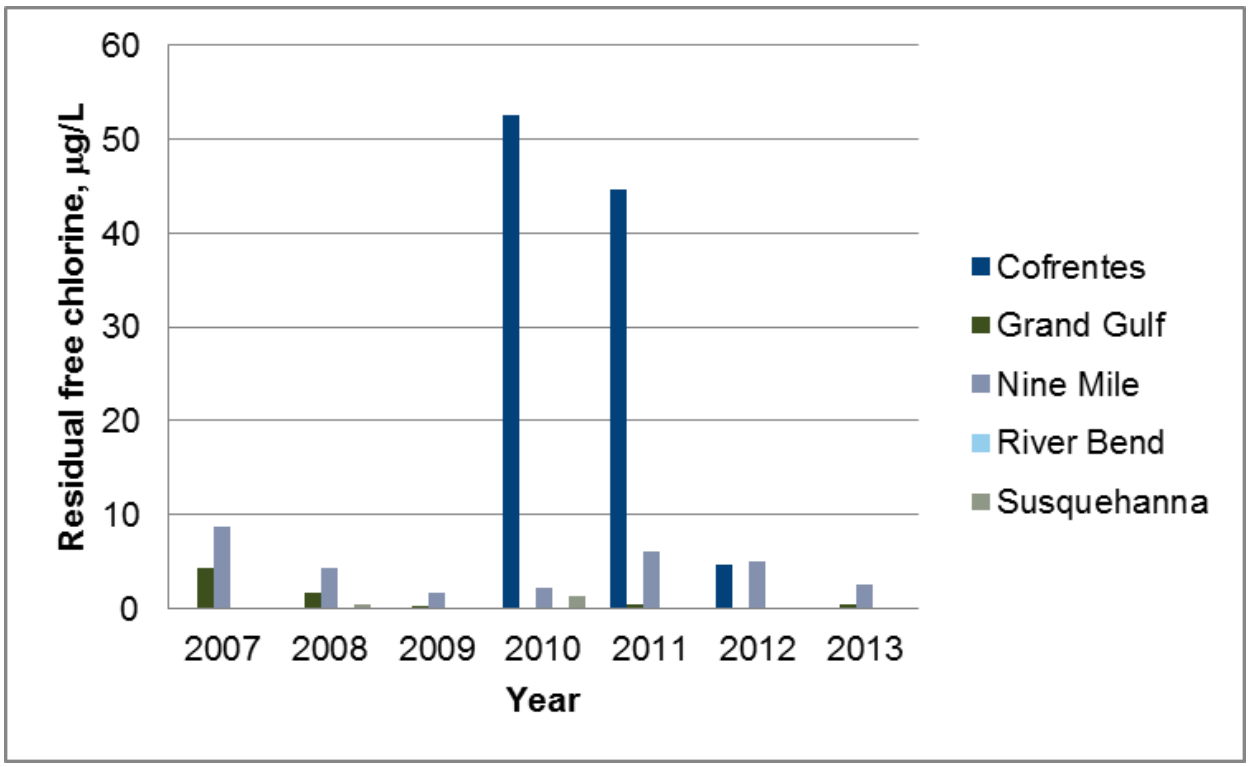


Figure 44 Concentration of free residual chlorine in liquid discharges for 2007 to 2013

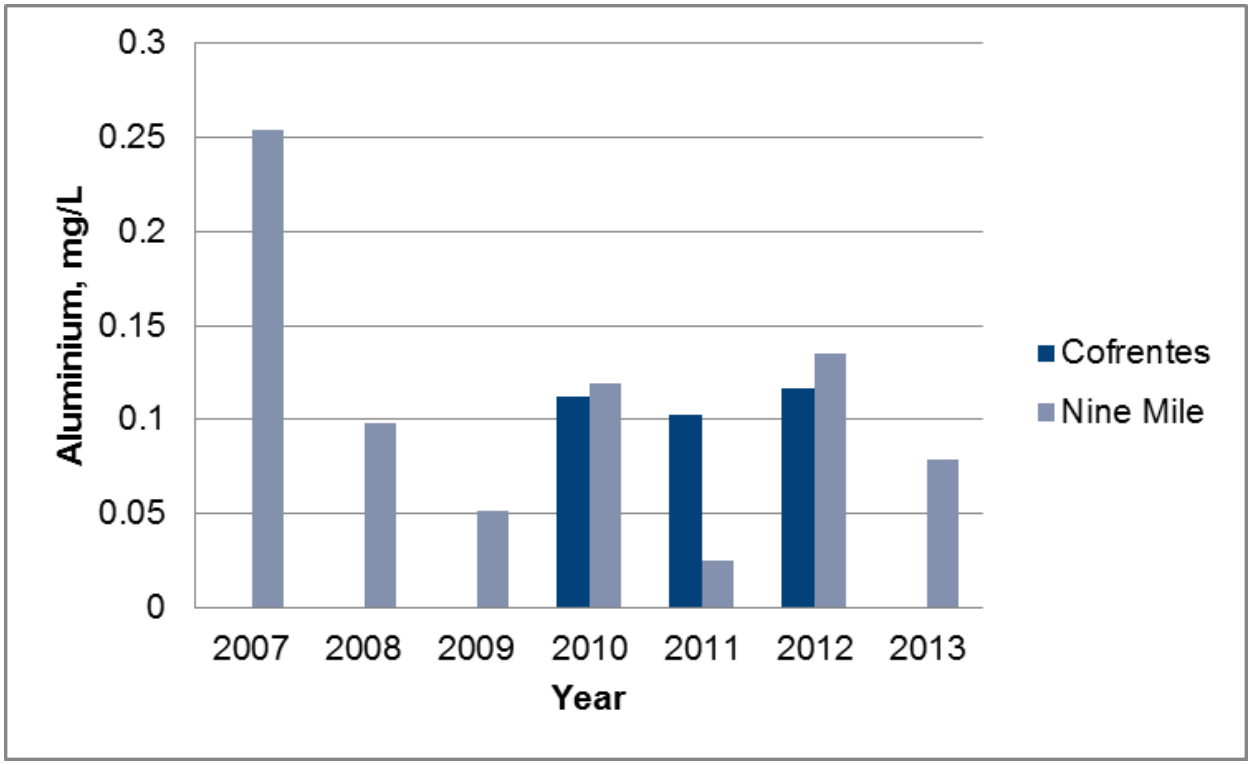


Figure 45 Concentration of aluminium in liquid discharges for 2007 to 2013

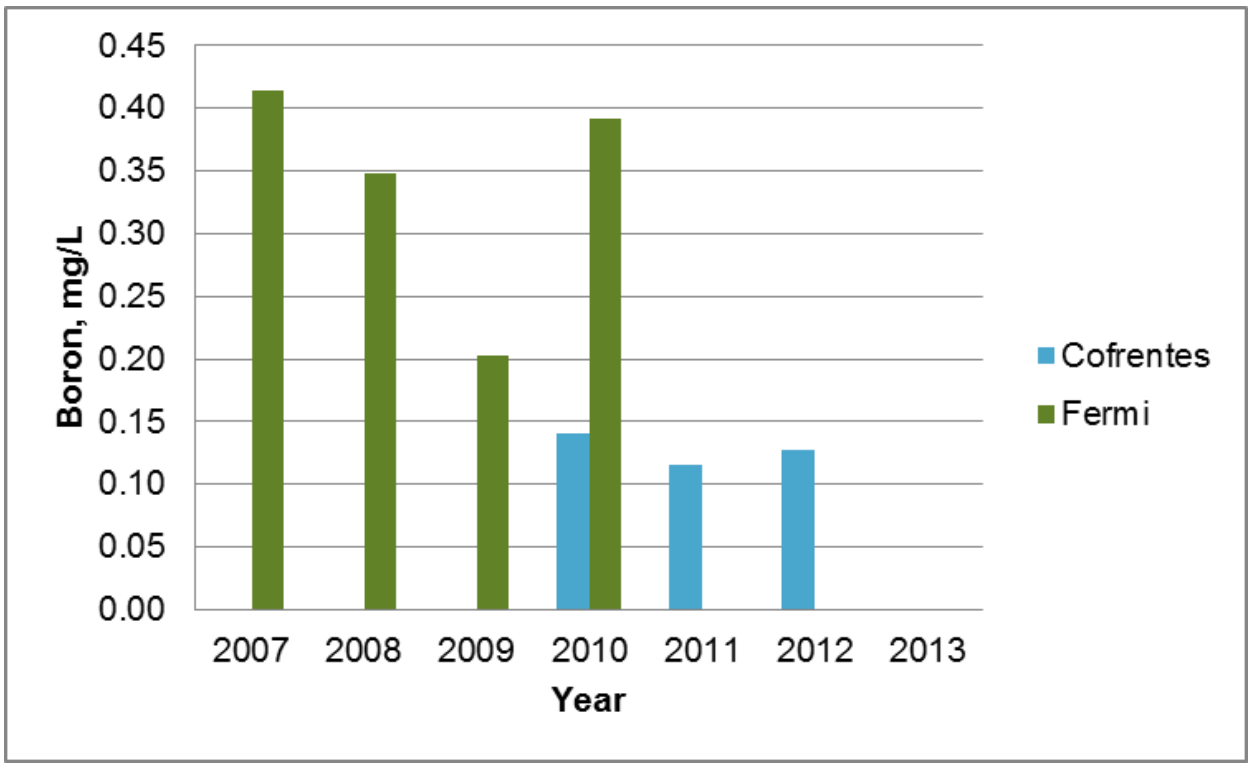


Figure 46 Concentration of boron in liquid discharges for 2007 to 2013

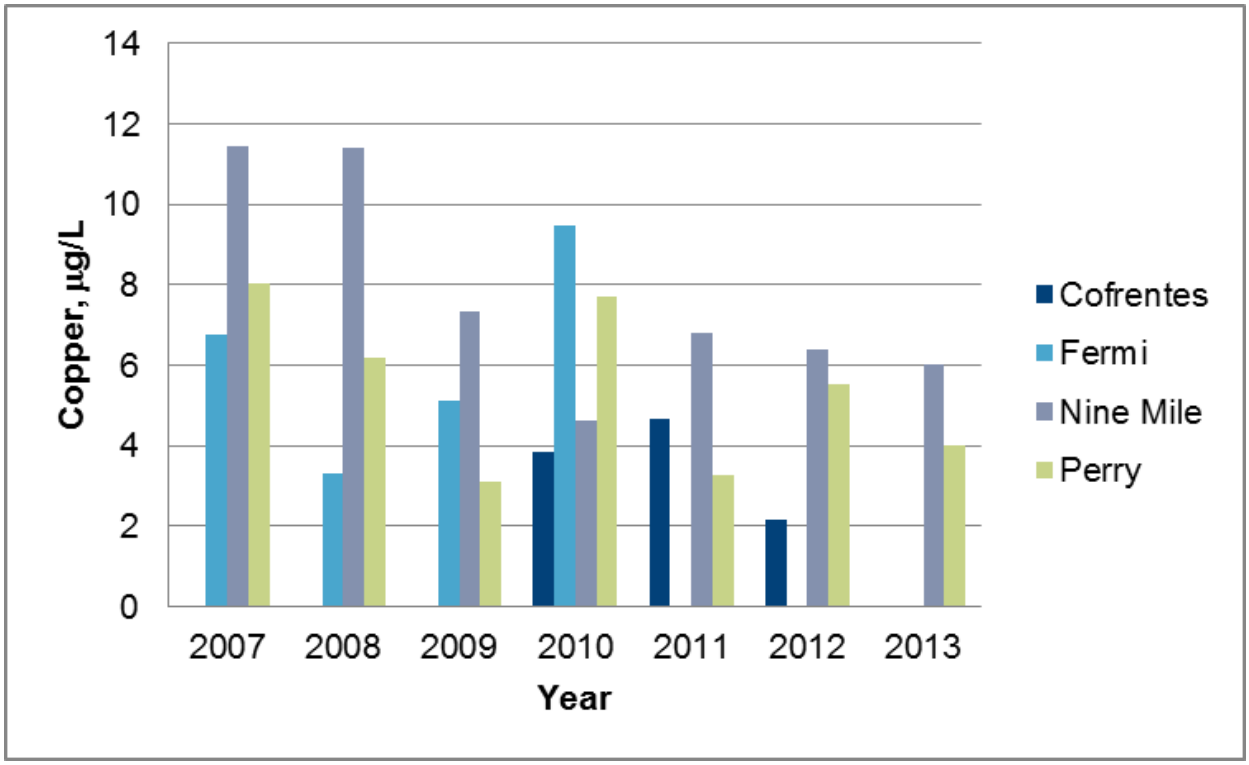


Figure 47 Concentration of copper in liquid discharges for 2007 to 2013

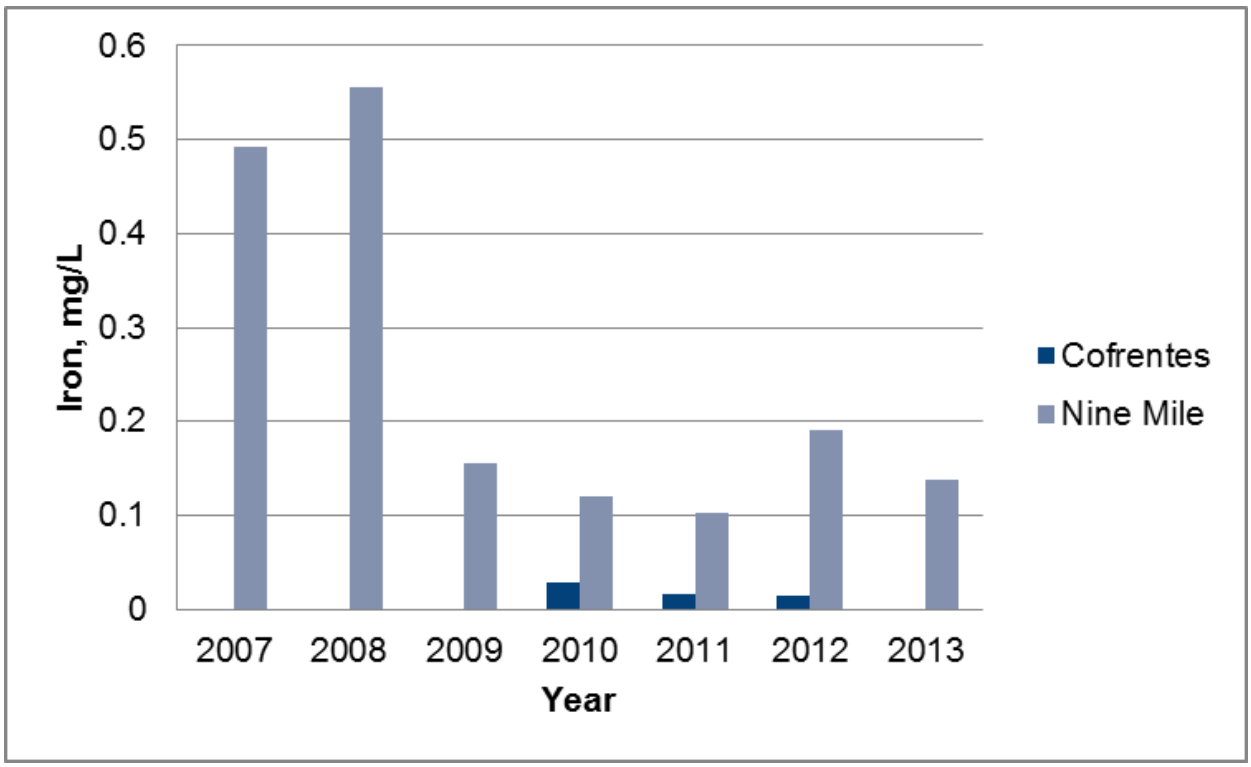


Figure 48 Concentration of iron in liquid discharges for 2007 to 2013

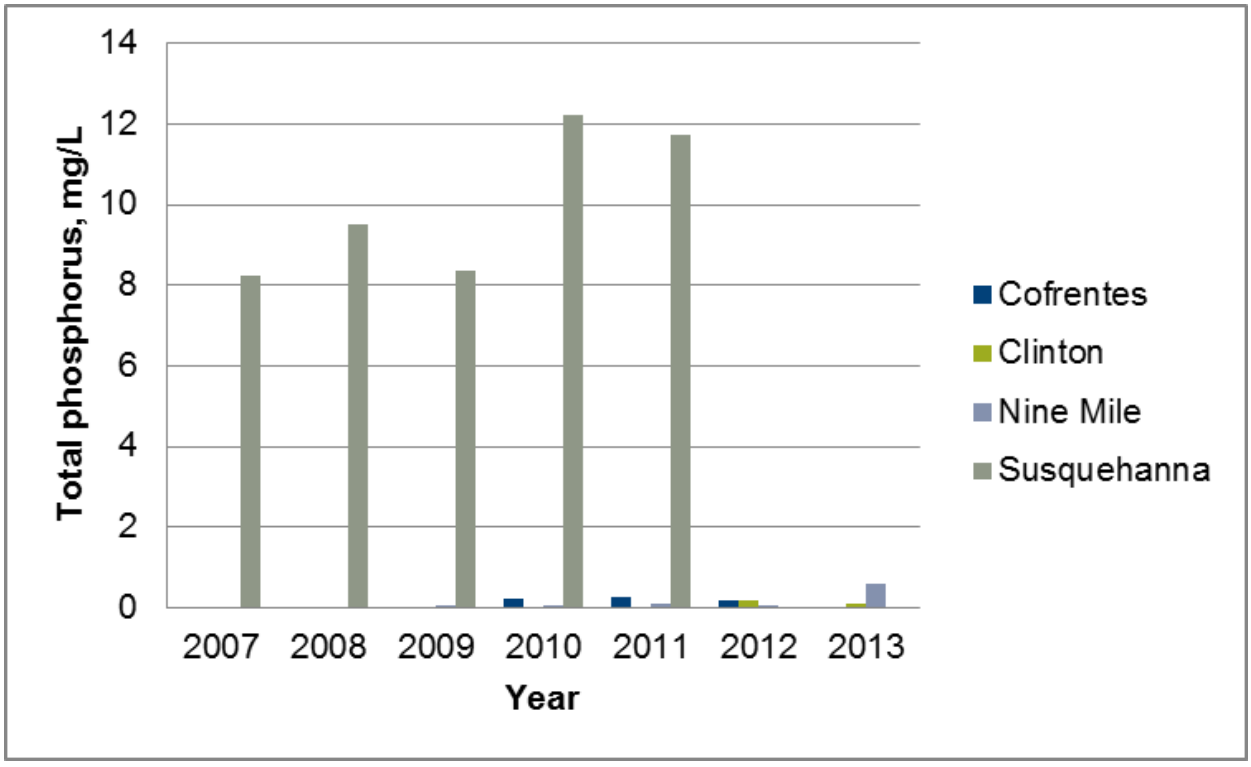


Figure 49 Concentration of total phosphorus in liquid discharges for 2007 to 2013

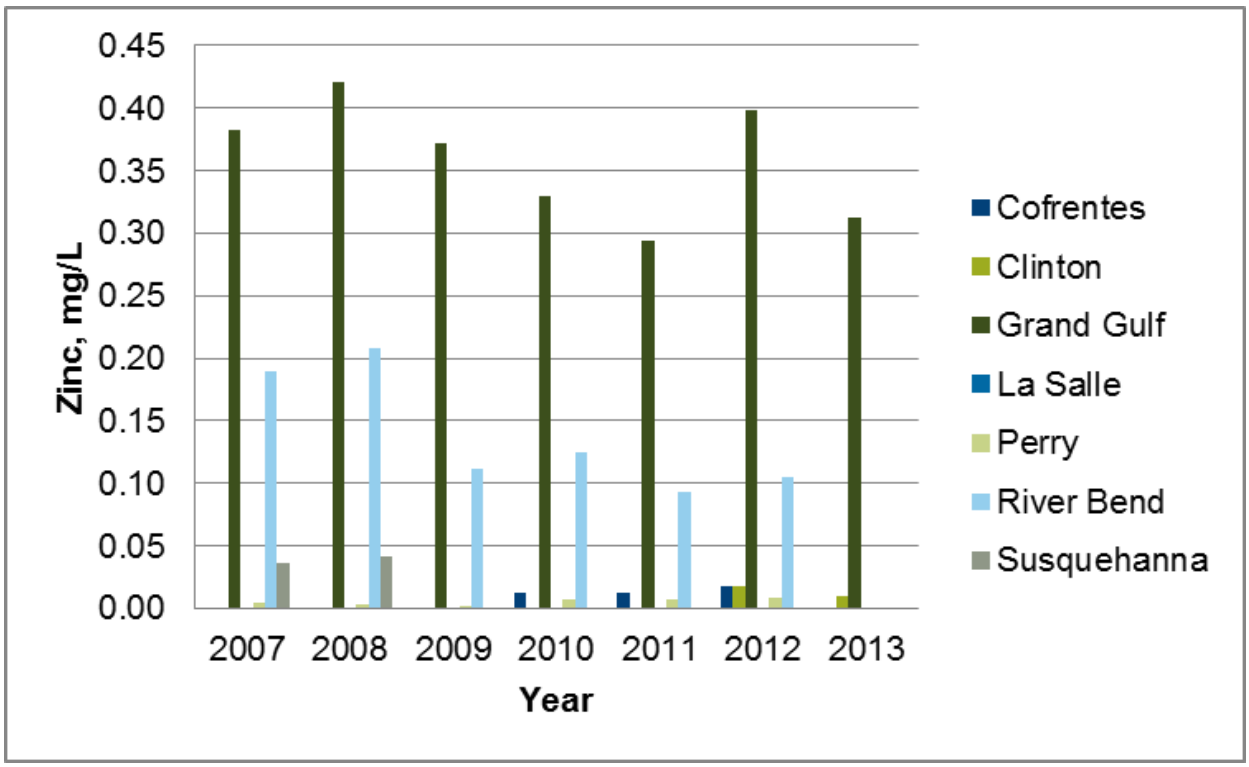


Figure 50 Concentration of zinc in liquid discharges for 2007 to 2013

5.2. Reported atmospheric discharges

There were limited data available on discharges to atmosphere from the BWR plants within the scope of this report. No data were available for Sweden or Switzerland. For the Spanish Cofrentes plant, annual reports do discuss discharges, but only qualitatively. The only country where detailed information was available was the USA, but only for 3 plants, namely Fermi, Limerick and Susquehanna. These data, given in tons per year, are presented in Appendix C.

6. Solid radioactive waste data

This project is interested in the volume and activity of waste generated during the operational phase of the plant as well as any information available on treatment options.

The International Atomic Energy Agency (IAEA) has an online information resource for radioactive waste management, The Net-Enabled Radioactive Waste Management Database (NEWMDB) (IAEA, 2015), which contains information on radioactive waste inventories as well as some information on treatment options. Since the information in NEWMDB is based on voluntary contributions from IAEA member states, not all of the information is complete or provided annually. For Germany, Japan and the USA the aggregation of data across many sites means that no specific data related to BWRs can be given.

Countries may define their waste in different ways to the IAEA waste classification (IAEA, 2009). Very low level waste (VLLW), low level waste (LLW) and intermediate level waste (ILW) is the waste relevant to this work and the relationship between the IAEA classification and the individual countries' classification is given in the database. Many countries also use the low and intermediate level waste (LILW) category, which is subdivided into long-lived waste (LILW-LL) and short-lived waste (LILW-SW). Long-lived waste is defined in the IAEA waste glossary (IAEA, 2003) as being radioactive waste that contains significant levels of radionuclides with half-lives greater than 30 years.

6.1. Finland

Table 19 gives the information for the most recent year reported in NEWMDB (2010) for the Olkiluoto nuclear power plant. It is estimated that approximately 1% of the waste volume is ILW (intermediate level waste), with this waste mainly being activated metal. The waste treatment methods given are compaction, decontamination, evaporation, filtration, ion exchange, segregation/sorting, size reduction and wastewater treatment. The conditioning methods given are bituminization and solidification.

Table 19 Selected extract of NEWMDB entry for Olkiluoto nuclear power plant

Facility	Description	Processed (Y/N)	Est	Volume (m3)
NPP-Area	Power plant storage area	N	Y	1052
OL1	Processing and storage of reactor waste	N	Y	27
OL1	Processing and storage of reactor waste	Y	Y	2
OL2	Processing and storage of reactor waste	N	Y	26
VLJ-KAJ	KAJ silo in the VLJ-Cave repository. The KAJ silo is used to dispose of mainly the intermediate level waste (ILW) component of low and intermediate level (LILW) reactor waste	Y	N	1777
VLJ-MAJ	MAJ silo in the VLJ-Cave repository. The MAJ silo is used to dispose of mainly LLW component of LILW reactor waste	Y	N	3538

Est=distribution is an estimate

6.2. Germany

For the most recent year reported in NEWMDB (2007) it was not possible to extract data related to specific BWR nuclear power plants.

6.3. Spain

For the most recent year reported in NEWMDB (2010) for the Cofrentes nuclear power plant the information is given in Table 20. The treatment methods are carbon adsorption, compaction, decontamination, evaporation, filtration, ion exchange and size reduction. The waste conditioning method is cementation.

Table 20 Selected extract of NEWMDB entry for Spain

Facility	Description	Processed (Y/N)	Est	Volume (m3)
Storage	RBMA	Y	N	772
Storage	RBBA	Y	N	1094

Est=distribution is an estimate

RBBA (residuos de muy baja actividad) is defined as as 100% VLLW.

RBMA (residuos de baja y media actividad) is defined 95% LLW and 5% ILW.

The operator of Cofrentes nuclear power plant, Iberdrola, provides the following information in its annual environmental report 2013 (Iberdrola, 2014).

Table 21 Quantity of LLW and ILW related to electrical output (Iberdrola, 2014)

Year	Quantity of RBMA (m3)	Gross electrical output (MWh)	RBMA normalised to electrical output (m3 per MWh)
2010	174.9	9549319	1.83E-05
2011	212.3	7900455	2.69E-05
2012	161.9	9376203	1.73E-05

6.4. Sweden

Table 22 gives the information for the most recent year reported in NEWMDB (2008) for the Forsmark nuclear power plant. The waste treatment method is compaction. The waste conditioning methods are cementation and bituminization.

Table 22 Selected extract of NEWMDB entry for Forsmark nuclear power plant

Facility	Description	Processed (Y/N)	Est	Volume (m3)
Disposal	LILW-SL	Y	N	3900

Est=distribution is an estimate

For the most recent year reported in NEWMDB (2008) for the Oskarshamn nuclear power plant the information is given in Table 23. The waste treatment method is compaction and the waste conditioning methods are cementation and solidification.

Table 23 Selected extract of NEWMDB entry for Oskarshamn nuclear power plant

Facility	Description	Processed (Y/N)	Est	Volume (m3)
Disposal	LILW-SL	Y	N	7500
Storage	LILW-LL	Y	N	913

Est=distribution is an estimate

The Swedish Nuclear Fuel and Waste Management Company produced a report (SKB, 2007) to describe all the waste and the waste package that is expected to be disposed of in the repository for short-lived, low and intermediate level radioactive waste. The report gives the number of waste packages, which have been disposed of in the repository up until 31 December 2006. It also presents estimated future annual production rates for the different nuclear facilities and wastes. The appendices to the SKB report give a description of the waste package in terms of packaging, treatment and conditioning, chemical composition and the radionuclide composition of a reference package.

6.5. Switzerland

Table 24 gives the information for the most recent year reported in NEWMDB (2012) for the Leibstadt nuclear power plant. The radionuclide inventory in storage is 68 GBq of total alpha activity and 320000 GBq of total beta/gamma activity. The treatment methods are decontamination, evaporation, size reduction and super compaction. The conditioning method is cementation.

Table 24 Selected extract of NEWMDB entry for Leibstadt nuclear power plant

Facility	Description	Processed (Y/N)	Est	Volume (m3)
Storage	SMA	Y	N	1288.1
Storage	SMA (ybc)	N	N	7.9

SMA ('schwach- und mittelaktive Abfälle') is defined as 15.9% VLLW, 83.8% LLW and 0.3% ILW

SMA ybc (yet to be conditioned) is defined as 0.8% VLLW, 98.4% LLW and 0.8% ILW

6.6. Japan

For the most recent year reported in NEWMDB (2009) the data are aggregated across 18 nuclear power stations and, therefore, it was not possible to determine the data related to BWRs. The website of Information System on Occupational Exposure (ISOE) Asian Technical Centre gives the equivalent number of drums generated and stored in different financial years. The meaning of the term equivalent drum is not clear, but comments in the NEWMDB for the Japanese entry would indicate that a drum is likely to be 200 l of LLW. However, this was not possible to confirm.

6.7. United States of America

For the most recent year reported in NEWMDB (2008) it was not possible to extract data related to specific BWR NPPs. The effluent reports detailed in Section 3.3.5 give quantity and activity of waste shipped off site every year. However, this information only relates to disposals and does not detail arisings.

7. Abatement techniques

The methods available for the abatement of waste streams at nuclear power plants depend on the nature and content of the radionuclides present. Other factors to be taken into account in selecting the appropriate abatement technique include the presence in the waste streams of other components such as dissolved salts, suspended solids and materials that may be troublesome in abatement plant, such as certain organics (for example, detergents) and oil (Environment Agency, 1999).

The following section highlights the current abatement techniques used in operating BWR plants in different parts of the world.

7.1. European nuclear power plants

You can find a summary of the abatement techniques used within European countries in the scoping study on the discharges from boiling water reactor plants carried out by the Environment Agency (Environment Agency, 2015). The following section gives a more detailed description of the plant specific abatement techniques.

7.1.1. **Olkiluoto units 1 and 2, Finland**

Limited information is available about the abatement techniques used at nuclear power plants in Finland. However, Teollisuuden Voima Oy, the operator of the Olkiluoto units 1 and 2 BWR plants, includes a brief description of the techniques used in an overview of the two power plants (Teollisuuden Voima Oy, 2008).

The primary circuit water is treated by 2 independent, coordinated clean-up systems: the reactor water clean-up system and the condensate clean-up system. The reactor water clean-up system consists of 2 ion exchanger units of radial flow and bed-filtration system. The condensate clean-up system is 7 parallel-coupled trains with rod-type pre-coat filters. These filters clean the feed-water returning from the condenser to the reactor both mechanically and with a thin ion-exchange resin layer on the surface of the filter rods.

Process waste treatment systems include equipment for handling both liquid and solid process waste. Liquid process waste is collected in a number of systems at the power plant and pumped into dedicated reception tanks in the waste treatment plant. Chemically pure water is filtered and passed through ion exchangers and then reintroduced into the power plant processes. Water from floor drainage and the ‘active laundry’, and other water with particle impurities are cleaned by spinning, filtering, ion exchange or evaporation and then pumped into the sea.

The off-gas system limits the emission of radioactive noble gases from the power plant units. The system includes a decay phase and an adsorption phase.

1. Decay phase one – Consisting of a sand tank which slows down the progress of off-gas, allowing short-lived nuclides time to decay.
2. Adsorption phase – 3 active charcoal filters are situated between the sand tanks as well as 2 parallel coolers to reduce humidity in the off-gas. The active charcoal absorbs radioactive substances, which are periodically flushed back into the condenser. 2 of the 3 filters are in use at any given time, one being connected to the off-gas flow and the other being used for flushing back to the condenser.
3. Decay phase two – After passing through the active charcoal filters, the gas is conveyed through the second sand tank and then through the off-gas filter to the stack. The off-gas filter removes 99.9 % of any iodine content in the off-gas.

7.1.2. **Forsmark unit 3 and Oskarshamn unit 3, Sweden**

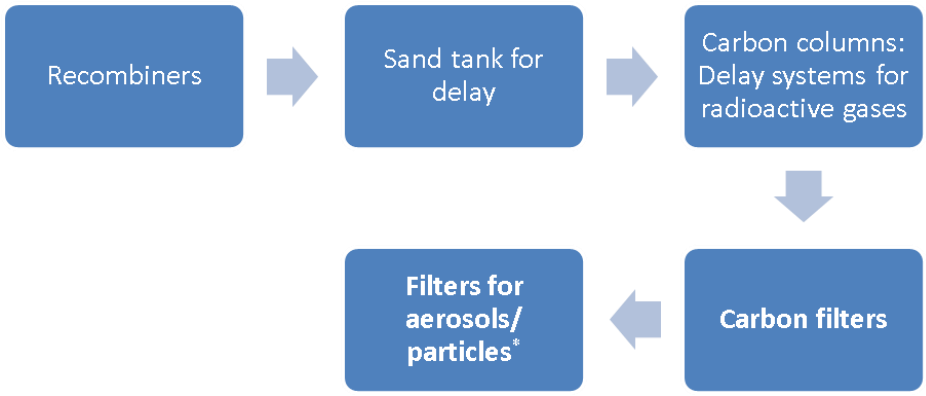
In Sweden, the following abatement techniques for gaseous discharges are used at both Forsmark unit 3 and Oskarshamn unit 3. Information was not available for the techniques used in Forsmark 1 and 2.

Table 25 shows the current use of abatement techniques for liquid waste streams in the Swedish nuclear power plant (SSM, 2015).

Table 25 Liquid waste stream abatement techniques used in Swedish BWR

	Evaporator	Ion exchangers	Extra tank for emptying and filling of the reactor pool
Forsmark unit 3	X	X	X
Oskarshamn unit 3		X	

Figure 51 Gaseous abatement techniques in Swedish nuclear power plant



* Limited use in some operating modes and some rooms

7.1.3. Leibstadt and Mühleberg, Switzerland

In Switzerland, batch abatement techniques are used for waste water at all nuclear power plants. However, each plant uses a different technique for the treatment of waste water as shown in Table 26 (Federal Department for the Environment, 2010).

Table 26 Abatement techniques used in Swiss BWRs

Nuclear power plant	Liquid abatement techniques	Gaseous abatement techniques
Leibstadt	centrifugation and evaporation	catalytic recombiners, off-gas-condensers, hold-up-lines, activated carbon filter columns, HEPA-filters and off-gas pumps
Mühleberg	centrifugation and ion exchange techniques	

The nuclear power plants have site-specific target values for liquid and gaseous discharges, designed to keep doses to the general public low in a reasonable way and reflecting the principle of optimisation. To reduce iodine gaseous discharges, the Leibstadt nuclear power plant has added a filter to the gland seal system in the turbine building. The filter cleans the feed water used for producing the gland seal steam.

Every 10 years, the licensee of each Swiss nuclear power plant is required to carry out a periodic safety review. As part of the review, the licensee must assess the liquid and atmospheric discharges from the plant and benchmark them against the corresponding discharges from similar European reactors.

The Mühleberg nuclear power plant carried out a periodic safety review in 2005. The Inspectorate assessed this review in depth and required the licensee to reduce the total activity, excluding tritium in the liquid discharges, to less than 1 GBq per year until 2010. To achieve this target, the licensee studied ways of reducing the quantity of waste water as well as separating different qualities of waste water for specific treatment. This work has resulted in a decrease in the activity released from 7 GBq in 2007 to less than 3 GBq in 2009.

7.2. US plants

The following sections briefly summarise the abatement techniques used by the different BWR plants in the USA as described in various United States Nuclear Regulatory Commission reports.

7.2.1. **Columbia nuclear power plant**

The US NRC NUREG-1437 Supplement 47 report (US NRC, 2012) states:

'…liquid wastes that accumulate in tanks or in sumps are transferred to collection tanks in the "radwaste building" and segregated into three categories: high purity waste, low purity waste, and chemical waste. Radioactive material is removed from high purity liquid wastes using filtration and ion exchange. Chemical wastes may be treated using a neutralizing agent, and they are processed by routing to a backwash tank or phase separator and then to the floor drain subsystem for further processing.

All liquid radioactive waste process streams end in either a sample or distillate tank. Liquid wastes are processed on a batch basis so that each treated batch can be sampled. Depending on sample results, the waste is either reprocessed or returned to the condensate storage tanks for reuse.

Before radioactive gaseous wastes are released into the environment through the reactor building elevated release duct, treatment of the gases includes the following:

Volume reduction through a catalytic recombiner to recombine hydrogen and oxygen

Water vapour removal through a condenser

Decay of short-lived radioisotopes through a holdup line

HEPA filtration

Adsorption of isotopes on activated charcoal beds.'

7.2.2. **Grand Gulf nuclear power plant**

The US NRC NUREG-1437 Supplement 50 report (US NRC, 2014a) states:

'…the liquid radwaste system collects, processes, recycles, and disposes of potentially radioactive wastes produced during operation of the plant. Comprising of a group of subsystems designed to collect and treat different types of liquid waste, designated as the equipment drain processing subsystem (clean radwaste), floor drain processing subsystem (dirty radwaste), chemical waste subsystem, and miscellaneous supporting subsystems. Liquid wastes that accumulate in radwaste drain tanks or in sumps are transferred to collection and sample tanks in the radwaste building. The liquid wastes are processed through filters and demineralizers and returned to the condensate system or released from the plant.

The gaseous radwaste system processes and controls the release of gaseous radioactive effluents to the atmosphere. Gaseous effluents are released via several different vents. Radioactive gas is continuously removed from the main condenser by the air ejector during plant operation. It is then filtered, cooled, and discharged to the environment.'

7.2.3. **Hope Creek nuclear power plant**

The US NRC NUREG-1437 Supplement 45 report (US NRC, 2011) states:

'potentially radioactive liquid waste streams (RLWS) are managed under the liquid waste management system (LWMS). Liquid radioactive waste entering the RLWS is released in

accordance with NRC regulations. Prior to release, liquids are collected in tanks, sampled, and analysed.

Potentially radioactive liquid wastes entering the LWMS are collected in tanks in the auxiliary building. Radioactive contaminants are removed from the wastewater either by demineralization or filtration. This ensures that the water quality is restored before being returned to the condensate storage tank or discharged via the cooling tower blowdown line. Radioactivity removed from the liquid wastes is concentrated in the filter media and ion exchange resins, which are managed as solid radioactive wastes.

Radioactive gases are collected so that the short-lived gaseous isotopes (principally air with traces of krypton and xenon) are allowed to decay in holdup pipes prior to entering a treatment section where adsorption of gases on charcoal provides additional time for decay. Gases are then filtered using HEPA filters before being released to the atmosphere from the north plant vent.'

7.2.4. **Limerick nuclear power plant**

The US NRC NUREG-1437 Supplement 49 report (US NRC, 2014b) states:

'..liquid wastes are processed for packaging and off-site shipment, returned to the condensate system, or mixed with cooling-tower blowdown and released from the plant. Wastes from the equipment drains and floor drains are processed through separate precoat filters and mixed resin bed demineralizers. The processed waste is collected in one of two sample tanks. Usually, the water from these tanks is sent to the condensate tank for reuse, but if necessary, it will be treated or discharged.

Laboratory wastes, decontamination solutions, and other wastes that may be corrosive are collected and, if necessary, chemically neutralized before being sent to the floor drain system for processing. Waste from decontamination laundry facilities is processed through the laundry filter and then collected in a sample tank. The contamination in the liquid wastes is concentrated in filters and ion exchange resins and then sent to solid waste management for processing. The waste is stored and eventually shipped to a licensed waste disposal facility. The processed liquids are either recycled or discharged from the plant.

The condenser off-gases are the largest source of radioactive gaseous waste. The off-gas system collects the non-condensable radioactive gases. The release of the off-gas is delayed to allow for radioactive decay. The stream is released to the turbine enclosure vent stack and diluted with air and monitored upon release through the north stack. Secondary systems called the standby gas treatment system and the reactor enclosure recirculation system are used to reduce radioactivity levels in gases from the reactor enclosures before they are discharged into the environment.'

7.2.5. **Nine Mile Point nuclear power plant**

The US NRC NUREG-1437 Supplement 24 report (US NRC, 2006) states:

'..the abatement processes used for the liquid waste systems at Nine Mile Point BWR is not well described however; it is known that the liquid waste system is divided into the following four subsystems: the waste collector subsystem, the floor drain collector subsystem, the regenerant waste subsystem, and the phase separator subsystem. These subsystems permit wastes from various sources to be combined according to similarity of conductivity and isotopic concentration for appropriate processing. For example, the waste collector subsystem collects, monitors, and processes for reuse or disposal of relatively low-conductivity waste from various equipment drains and removes radioactivity from these liquids via filtration and ion exchange. Similarly, the floor drain collector subsystem collects, monitors, and processes potentially high-conductivity waste from various building drains.

The gaseous waste management system includes the off-gas system, the standby gas treatment system, various building ventilation systems, and two monitored release points, namely the main stack and the combined radioactive waste/reactor building vent. The off-gas system in each unit collects, contains, and processes the radioactive gases extracted from the steam condenser. The gases are exhausted by the steam jet air ejectors and flow through a preheater to a catalytic recombiner, where the hydrogen is recombined with oxygen to form steam. All steam from the off-gas stream is condensed for return as condensate, and the noncondensible gases flow to a holdup

pipe. The holdup pipe allows the short-lived radioisotopes such as nitrogen-16, nitrogen-17, and oxygen-19 to decay. The gas flow continues through a cooler condenser, a moisture separator, electric reheaters, a prefilter, activated charcoal adsorber vessels, and HEPA filters. Then, along with dilution make-up air, it continues to each unit's respective stack for discharge to the environment. Xenon and krypton isotopes are adsorbed on the charcoal, allowing them to decay, thereby significantly reducing the offsite doses.'

7.2.6. **Susquehanna nuclear power plant**

The US NRC NUREG-1437 Supplement 35 report (US NRC, 2009b) states:

'…liquid waste is processed by a series of components employing various processes specifically designed to provide maximum decontamination factors. The processing methods used include filtration and/or demineralization. Following treatment, the processed wastes in the waste evaporator condensate tank, waste monitor tanks, or secondary liquid waste monitor tanks are analysed for chemical and radioactive content prior to being discharged. The effluent is discharged into the cooling tower blowdown line for dilution prior to release to the Susquehanna River.

At Susquehanna, the gaseous waste management system includes subsystems that process gases from the off-gas system and various ventilation systems. This system reduces radioactive gaseous releases from the plant by filtration or delay, which allows decay of radioactive materials prior to release to the atmosphere from one of the five rooftop vents.

The off-gas system removes the non-condensable gases from the main condenser for each unit by the mechanical vacuum pump or by steam air ejectors. After leaving the condenser, the off-gas is passed through a hydrogen dilution and recombination system where hydrogen and oxygen are catalytically recombined into water. After recombination, the off-gas is routed to a chiller to remove moisture, and then is sent through the activated carbon adsorber train. The activated carbon selectively adsorbs and delays the noble fission product gases, which have short half-lives, for decay. The gases then pass through a HEPA filter where any entrained particulates or any activated carbon dust are collected. The off-gas stream exiting the HEPA filter is directed to the vent on top of the reactor building for that unit. Prior to release through the ventilation systems, the gases are monitored and passed through a prefilter, high-efficiency particulate filter, charcoal filter, and another high-efficiency particulate filter in series, which reduce any airborne particulate radioactive material to very low levels. The effluents are continuously monitored, and an alarm is activated in the control room if the monitor set points are exceeded.'

8. Fuel failures

A fuel failure is any defect in a fuel rod that allows water or steam inside the rod. For BWRs, the main cause of failure is debris fretting, which occurs when a foreign material, such as a small piece of wire or scrap metal, becomes trapped - typically between the grid and the fuel rod - and vibrates in the coolant flow against the fuel rod surface until it wears a hole in the rod. The article *EPRI and the zero fuel failures program* (Edsinger, 2010) reports that 'preventing debris fretting is pursued from two directions. First, it's important to prevent foreign material from entering the coolant, either from maintenance or other plant activities. Second, debris filters, which are traps installed where the coolant enters the fuel assembly, are now standard and continue to be improved. Roughly speaking, in any given year, there may be 15 to 20 fuel rods that fail out of something like 5 million fuel rods in U.S. reactors. (A reactor has in the order of 50000 fuel rods, and there are 104 operating reactors in the United States). Current statistics suggest that 90 percent of U.S. reactors won't report a single failure in 2010, and that percentage is expected to continue to increase with continued efforts on fuel reliability.'

A review of fuel failures in light water reactors (that is, PWRs and BWRs) by the International Atomic Agency in 2010 (IAEA, 2010) revealed that the fuel rod failure rate in light water reactors has been significantly reduced since 1987, on average to levels of 1 in 100,000 fuel rods during the period 2003 to 2006. The review discusses how the monitoring of the activity of 3 chemical families: noble gases (xenon-133, xenon-133m, xenon-135, xenon-138, krypton-85m, krypton-87, krypton-88); iodine: (iodine-131, iodine-132, iodine-133, iodine-134, iodine-135) and caesium (caesium-134, caesium-136, caesium-137) means that it is possible to identify the time during an operating cycle when fuel failures occurred, to estimate the approximate number and type of failures, and to predict the approximate exposure of failed fuel. The best early failure indication is an increase in xenon-133 activity. Some Swedish BWRs have installed centrifugal filter devices on feedwater lines to collect and trap debris.

The figure below is taken from the International Atomic Energy Agency (IAEA) report (IAEA, 2010) and shows the BWR fuel assembly (FA) failure rates given as a ratio of the number of leaking FAs per 1000 discharged FAs.

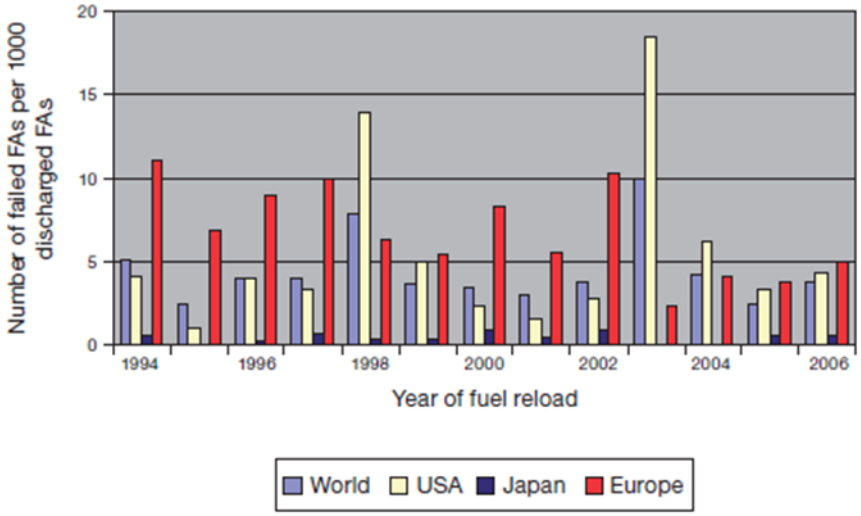


Figure 52 BWR fuel assembly failure rates calculated as the ratio of leaking FAs per 1000 discharged FAs

The Swedish regulatory authority (SSM, 2015) provided information on fuel damage for the years 2004 to 2013 for Forsmark unit 3 and Oskarshamn unit 3, which is given in Table 27. It also

provided monthly discharges for Oskarshamn unit 3. It was hoped that some correlation between the monthly discharges and fuel failure could be seen, but unfortunately this was not the case due to the aggregation of data over the month. Table 27 shows that the fuel assemblies can remain within the reactor for several months before removal depending on the severity of the leak.

Table 27 Fuel failures reported for Forsmark unit 3 and Oskarshamn unit 3 for years 2004 to 2013

Forsmark unit 3			Oskarshamn unit 3		
Detected	Removed	Number of fuel assemblies damaged	Detected	Removed	Number of fuel assemblies damaged
January 2005	08/06/2005	1	04/11/2004	03/06/2005	1
June 2006	December 2006	3	22/06/2005	22/10/2005	1
08/01/2007	30/06/2007	1	30/10/2005	31/12/2005	1
30/07/2007	10/06/2008	2	11/03/2006	07/07/2006	1
09/09/2008	03/11/2009	1	28/10/2006	09/04/2007	2
10/10/2009	15/04/2010	1	19/08/2007	29/09/2007	1
10/05/2010	06/07/2010	6	29/10/2007	20/02/2008	1
26/11/2010	April 2011	1	30/06/2008	Not sure	1
01/12/2012	May 2013	3	16/03/2010	31/5/2010-	1
01/09/2013	Not reported	1	06/06/2010	02/12/2010	1
			12/03/2011	03/04/2011	1
			10/02/2012	04/06/2012	1
			20/06/2012	23/08/2012	1
			15/11/2013	Not reported	1

9. Summary

The objective of this study was to collate and present data on radioactive and chemical discharges and operational solid waste arisings from existing BWRs around the world. The purpose of this project was to identify and fill any data gaps where possible, and provide relevant analysis of the data. The project considered data from 46 BWRs operating at 24 sites between 2005 and 2013.

Comprehensive data on radioactive discharges to atmosphere and to water bodies were collated from 3 main sources; the European Commission's Radioactive Discharge Database, the US Nuclear Regulatory Commission's (NRC) Radioactive Effluent and Environmental Reports and the Information System on Occupational Exposure (ISOE) Asian Technical Centre's website. Discharges per unit of electricity generated were calculated using electricity generation data from the International Atomic Energy Agency. Mean and theoretical maximum (based on the mean plus one standard deviation) discharges per unit of electricity output were derived from all data. A comparison of discharges for different BWR model types (BWR4, 5 and 6) over time was made, but no discernible trends could be identified. Information from a US NRC report on long-term trends (1975 to 2009) in discharges from US BWRs has been included in this report for comparison.

For chemicals, there were little data available for atmospheric discharges, but there were data available for liquid discharges from most of the US sites from the US Environmental Protection Agency's (EPA) website and the Spanish operator of the Cofrentes nuclear power plant. The discharge levels did not appear to have any obvious year-on-year trends over the time period studied apart from biogeochemical demand of the effluent of the LaSalle nuclear power plant. There were limited data available on volumes and activities of operational solid waste and the treatment and conditioning methods from the International Atomic Energy Agency (IAEA) Net Enabled Waste Management Database (NEWMDB) database and some other country-specific reports. The main difficulty was separating information on operational waste from that on waste from defuelling and decommissioning. Some information on abatement techniques was found for most sites. The Electric Power Research Institute (EPRI), which conducts research on issues related to the electric power industry in USA, was identified as having useful reports on topics such as releases related to fuel failures and abatement methodologies. However, EPRI reports are only available to its members and, therefore, could not be included. The Swedish regulatory authority provided useful information on fuel failures at Swedish BWRs and monthly discharge data for the Oskarshamn-3 nuclear power plant. The data showed no correlation between monthly discharges and fuel failure, because any spikes in discharges were masked by the aggregation of data over the reporting period.

The table below provides a summary of the discharge data that was collated for the study.

Table 28 Summary of data

Country	Radio-nuclides atmosphere	Radio-nuclides liquid	Chemicals liquid	Solid waste	Abatement techniques
Finland	✓	✓	×	✓	✓
Germany	✓ (no particulates provided)	✓	×	×	×
Japan	✓(H-3, C-14 and particulates not provided)	✓	×	×	×
Spain	✓	✓	✓	✓	×
Sweden	✓	✓	×	✓	✓
Switzerland	✓	✓	×	✓	✓

Country	Radio-nuclides atmosphere	Radio-nuclides liquid	Chemicals liquid	Solid waste	Abatement techniques
USA	✓ (C-14 only reported since 2010)	✓	✓ (except Columbia)	✗	✓ (for six sites)

The table below gives the mean and theoretical maximum of radioactive discharges per unit of electricity generated for all BWRs considered for the years 2005 to 2013. Section 4 of the report details how these values were derived.

Table 29 Mean and theoretical maximum of radioactive discharges per unit of electricity generated (GBq per GWeh) for all BWRs considered for the years 2005 to 2013

Radionuclide	Discharges per unit of electricity generated (GBq per GWeh)	
	Mean	Theoretical maximum
Liquid tritium	1.2E-01	2.3E-01
Other liquid	1.0E-04	3.3E-04
Tritium to air excludes Fermi	1.3E-01	2.7E-01
Fission and activation gases to air	9.4E-01	2.9E+00
Radioiodines to air	4.5E-05	1.6E-04
Particulates to air	6.7E-06	1.8E-05
Carbon-14 to air	5.8E-02	7.8E-02

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List of abbreviations

ABWR	Advanced boiling water reactor
BAT	Best available technique
BWR	Boiling water reactor
CSN	Consejo de Seguridad Nuclear (Nuclear Safety Council, Spain)
DMR	Discharge monthly reports
ENSI	Swiss Federal Nuclear Safety Inspectorate
EPA	Environmental Protection Agency (USA)
FA	Fuel assembly
FSAR	Final safety analysis report
GDA	Generic design assessment
GGNS	Grand Gulf Nuclear Station
HCW	High conductivity liquid waste
HEPA	High-efficiency particulate air
HLW	High level waste
IAEA	International Atomic Energy Agency
ILW	Intermediate level waste
ISOE	Information System on Occupational Exposure
LD	Laundry drain
LCW	Low conductivity liquid waste
LILW	Low and intermediate waste
LILW-SL	Low and intermediate waste – short-lived
LILW-LL	Low and intermediate waste – long-lived
LLW	Low level waste
LWTS	Liquid waste treatment system
MFAP	Mixed fission and activation products
NSSS	Nuclear steam supply system
NPDES	National Pollutant Discharge Elimination System (USA)
NOEL	No observable effect levels
NPP	Nuclear power plant
NSRA	Nuclear Safety Research Association (Japan)
NRC	Nuclear Regulatory Commission (USA)
ONR	Office for Nuclear Regulation
PRIS	Power Reactor Information Systems (IAEA)

PWR	Pressurised water reactor
RADD	Radioactive Discharge Database (EU)
SSM	Swedish Radiation Safety Authority
SWTS	Solid waste treatment system
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
VLLW	Very low level waste

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