GE Hitachi Nuclear Energy

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BWRX-300 UK Generic Design Assessment (GDA) Chapter E9 - Prospective Radiological Assessment

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EXECUTIVE SUMMARY

The GEH BWRX-300 is a Boiling Water Reactor (BWR) that is designed as a Small Modular Reactor (SMR).

This chapter is part of the Preliminary Environmental Report (PER) and is one of the documents that makes up the Environmental Case. It presents the results of the initial prospective radiological dose assessment of the predicted radiation doses to the public and to non-human species arising from exposure to ionising radiation due to planned discharges from the BWRX-300 to the atmosphere and to the aquatic environment. The contribution of direct dose has also been considered.

The dose assessment has been performed using the Environment Agency's (EA) Initial Radiological Assessment Tool (IRAT) (Reference 9-1, Reference 9-2). The discharge data used to perform the assessment were based on the annual average aqueous liquid and gaseous effluent activity releases derived by GEH for a BWRX-300 standard plant rather than the proposed discharge limits. These source terms are conservative and include contributions from Anticipated Operational Occurrences (AOO). Environmental information has been taken from NEDC-34219P, "BWRX-300 UK GDA Ch. E2: Generic Site Description," (Reference 9-3). Where information or data are not yet available, a reasoned assumption has been made.

The initial prospective radiological dose assessment yields the following estimate:

1. An annual dose to the most exposed member of the public of 12.1 μSv/y, which is well below the source dose constraint of 300 μSv/y and below the Environment Agency's screening dose of 20 μSv/y.
2. A dose rate to the most exposed non-human species of 1.7E-02 μGy/h, which is well below the Environment Agency's screening dose rate of 1 μGy/h and the combined dose rate to habitats of 40 μGy/h.

These doses are the initial cautious screening outputs from Step 1 and Step 2 of the Generic Design Assessment (GDA). It is expected that there will be a reduction in the gaseous and aqueous liquid discharge activities once refined End User Source Terms and the aqueous liquid discharge volumes are confirmed.

GEH (General Electric-Hitachi) considers that the radioactive discharge dose assessment presented fundamentally satisfies Step 2 of the GDA.

GEH has entered into the GDA process up to Step 2. Following GDA there will be a more realistic assessment of radiation doses associated with gaseous and aqueous liquid discharges using more sophisticated dose assessment tools and applying generic habit data. A proposed outline methodology for this Stage 3 dose assessment is provided within this chapter and a Forward Action Plan is provided in Appendix B.

ACRONYMS AND ABBREVIATIONS

Acronym	Explanation
ABWR	Advanced Boiling Water Reactor
ADMS	Atmospheric Dispersion Modeling Software
ALARA	As Low As Reasonably Achievable
AOO	Anticipated Occupational Occurrence
BAT	Best Available Techniques
BSSD	Euratom Basic Safety Standards Directive
BWR	Boiling Water Reactor
CEFAS	Centre for Environment, Fisheries and Aquaculture Science
CERC	Cambridge Environmental Research Consultants
CRP	Candidate for the Representative Person
DPUR	Dose Per Unit Release
EA	Environment Agency
EMCL	Environmental Media Concentration Limits
EPR16	Environmental Permitting Regulations 2016
ERICA	Environmental Risks from Ionising Contaminants: assessment and management
ESBWR	Economic Simplified Boiling Water Reactor
EUST	End User Source Terms
FSA	Food Standards Agency
GALE	Gaseous and Liquid Effluents
GDA	Generic Design Assessment
GEH	GE-Hitachi Nuclear Energy Americas, LLC
HPA	Health Protection Agency
HSE	Health and Safety Executive
ICRP	International Commission on Radiological Protection
IRAT2	Initial Radiological Assessment Tool 2
NDAWG	National Dose Assessment Working Group
NHS	Non-Human Species
NPP	Nuclear Power Plant
OPEX	Operational Experience
PER	Preliminary Environmental Report
PSR	Preliminary Safety Report
RP	Requesting Party
RSR	Radioactive Substances Regulation
SMR	Small Modular Reactor
TLD	Thermoluminescent Detectors
UK	United Kingdom

Acronym	Explanation
UKHSA	UK Health Security Agency
U.S.	United States
USNRC	U.S. Nuclear Regulatory Commission

DEFINITIONS AND SYMBOLS

Term	Definition
Collective dose	The collective dose is the summated individual exposures to a population group from a specified source within a specified time period. The unit of collective dose is joule per kilogram and is referred to as man Sievert (Man Sv).
Direct radiation	Ionising radiation emitted directly by processes or operations on premises and not as a result of discharges of radioactive substances to the environment. Mostly consisting of gamma photons that are attenuated to varying degrees by distance or structures such as walls and other barriers.
Representative Person	An individual receiving a dose that is representative of the more highly exposed individuals in the population.

Symbol	Definition
Bq	Becquerel (SI) unit of activity, defined as one decay per second.
MBq	1.0E+06 Bq.
Gy	Gray (SI) unit of radiation dose, expressed as absorbed energy per unit mass of tissue. Does not describe the biological effects of different radiations. 1 Gy = 1 Joule/kilogram.
µGy	1.0E-06 Gy.
mGy	1.0E-03 Gy.
m^3/s	Cubic metres per second.
m^3/y	Cubic metres per year.
R	Roentgen (legacy) unit of measurement for the exposure of X-rays and gamma rays, where 1 R = 0.000258 coulombs per kilogram (C/kilogram) of air.
mR	1.0E-03 R.
rem	Roentgen equivalent man (centimetre-gram-second) unit of radiation dose which represents the stochastic health risks of radiation, by applying radiation weighting factors and tissue weighting factors. 1 rem is equivalent to 0.01 Sv.
mrem	1.0E-03 rem.
Std. qtr	Standard quarter year, ~ 90 days.
Sv	Sievert, (SI) unit of radiation dose which represents the stochastic health risks of radiation, by applying radiation weighting factors and tissue weighting factors. 1 Sv = 1 joule/kilogram (biological effect).
µSv	1.0E-06 Sv.
µSv/h	Rate at which the radiation dose is delivered per hour.
mSv	1.0E-03 Sv.

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Revision #	Section Modified	Revision Summary
A	All	Initial Issuance

9 PROSPECTIVE RADIOLOGICAL ASSESSMENT

Purpose

The BWRX-300 SMR is the tenth iteration of the BWR design, as denoted by the letter X. The BWRX-300 is a 300 MW(e) reactor design based on, and very similar to, predecessor BWRs including the Advanced Boiling Water Reactor (ABWR) and the Economic Simplified Boiling Water Reactor (ESBWR). The ABWR successfully completed GDA in the United Kingdom (UK) in 2017 and received regulatory approval in the form of a Design Acceptance Confirmation from the Office for Nuclear Regulation and a Statement of Design Acceptability from the Environment Agency (EA).

Routine operation of the BWRX-300 has the potential to affect the surrounding environment due to the emission of radionuclides generated in the reactor, either as aqueous liquid (henceforth referred to as liquid) or gaseous effluents.

This chapter forms part of the PER for the BWRX-300. It presents the methodology, parameters, and results of calculations undertaken to determine the effect that routine radioactive liquid and gaseous discharges may have on the surrounding human population and Non-Human Species (NHS) during normal operation of the BWRX-300 SMR at a generic coastal site.

The overall objective of the PER is to demonstrate that the design of the BWRX-300 has been optimised to reduce environmental impacts to As Low As Reasonably Achievable (ALARA) throughout the whole lifecycle (construction, commissioning, operation, and decommissioning), where ALARA is a radiation protection principle that everything reasonably possible should be done to reduce radiation exposure.

This chapter supports the overall environmental claim that:

- The BWRX-300 is capable of being constructed, operated, and decommissioned in accordance with the standards of environmental, safety, security, and safeguard protection required in the UK.

The environmental Level 1 claim is:

- The design of the BWRX-300 SMR has been optimised to reduce environmental impacts via application of ALARA principles throughout the whole lifecycle (construction, commissioning, operation, and decommissioning).

The environmental Level 2 claim applicable to this report is:

- Minimisation of the impact of radioactive discharges on members of the public and the environment.

The environmental claims for the BWRX-300 are discussed in more detail in NEDC-34223P, "BWRX-300 UK GDA Ch. E6: Demonstration of Best Available Techniques (BAT) Approach," (Reference 9-4).

Scope

The GEH BWRX-300 Nuclear Power Plant (NPP) design has entered into GDA with the objective to gain regulatory confidence on the acceptability of a conceptual full plant design through Steps 1 and 2 of GDA (Reference 9-5). This approach is used when the design and substantiation are not yet mature enough to complete a detailed assessment. This document is one part of the suite of documents required for GDA and is part of the environmental case submission.

This chapter provides a radiological impact assessment of the radiation dose due to offsite liquid and gaseous effluent discharges from a BWRX-300 SMR to members of the public and NHS during normal operations.

The assessment also includes consideration of the contribution from direct dose which is based upon a review of Operational Experience (OPEX) for BWR NPP's in the United States (U.S). This direct dose is added to the doses calculated for liquid and gaseous discharges to estimate the total dose from the BWRX-300.

It is noted that the BWRX-300 is designed such that it can be operated with a zero liquid discharge, 007N1460, "BWRX-300 Annual Average Liquid Effluent Activity Releases," (Reference 9-6), with liquid wastes being managed by the Liquid Waste Management System; however, in the event that a liquid discharge is required then this will be made from the Circulating Water System.

The BWRX-300 gaseous discharges are associated with the Off-Gas System and the Heating, Ventilation, and Cooling System discharge into the Continuous Exhaust Air Plenum and then the Plant Vent Stack, NEDC-34224P, "BWRX-300 UK GDA, Ch. E7: Radioactive Discharges," (Reference 9-7).

The items listed below have been excluded from the Step 1 and Step 2 GDA radiological impact assessment. However, the proposed methodology for assessing the dose contributions at a later stage in the GDA process for collective dose, build-up and short-term dose is provided within this chapter.

- Collective dose truncated at 500 years to the UK, European, and world populations.
- An assessment of whether the build-up of radionuclides in the local environment of the facility, based on the anticipated lifetime discharges, might have the potential to prejudice the activities of other legitimate users or uses of the land or sea.
- Potential short-term doses, including via the food chain, based on the maximum anticipated short-term discharges from the facility in normal operation.
- Doses due to discharges associated with accidents or fault conditions (noting that contributions from AOO are included in the annual average gaseous and liquid discharge source terms that have been assessed).
- Doses due to discharges arising from the construction phase or the decommissioning phase.
- Doses due to disposal of radioactive waste to offsite waste facilities in accordance with the Environmental Permitting Regulations 2016 (EPR16) (Reference 9-8) site permit.

Occupational doses to workers will be considered in NEDC-34175P, "BWRX-300 UK GDA, Ch. 12: Radiation Protection," (Reference 9-9).

Document Structure

This PER chapter is divided into the following sections:

- Section 9.1 – Regulatory context: discusses the legislative framework, dose limits and constraints, and radioactive substances guidance within the UK.
- Section 9.2 – Dose assessment: discusses the regulatory requirements for dose assessment, the three-stage process, and suitability of the proposed assessment tool.
- Section 9.3 – Radiological assessment data inputs provides the assumptions for the generic site, the liquid discharge and gaseous discharge source terms, the approach taken for direct radiation, and outlines the Stage 1 and Stage 2 dose assessment methodology.
- Section 9.4 – Dose assessment results and discussion presents the results for the Stage 1 and Stage 2 dose assessments for liquid and gaseous discharges, and the Stage 1 and Stage 2 dose assessment to the representative person and wildlife.

- Section 9.5 – Stage 3 dose assessment methodology: presents the proposed methodology for the Stage 3 dose assessment, considering the source term, dispersion modeling to the marine and terrestrial environments, exposure pathways, habit data, candidates for the representative person, individual and collective dose assessment, build up dose assessment, short-term release dose assessment, and consideration of dose assessment uncertainties.
- Section 9.6 – Conclusion: summary of the Stage 1 and Stage 2 dose assessment.
- Section 9.7 – References: a list of the supporting references used in this chapter.

Further information of relevance to this chapter is provided in the Appendices:

- Appendix A: Initial Radiological Assessment Tool (IRAT2) outputs
- Appendix B: Forward Action Plan

Chapter Interfaces

This chapter interfaces with, and references data and information from, the following:

- NEDC-34219P, “BWRX-300 UK GDA Ch. E2: Generic Site Description,” (Reference 9-3)
- NEDC-34223P, “BWRX-300 UK GDA Ch. E6: Demonstration of Best Available Techniques (BAT) Approach,” (Reference 9-4)
- NEDC-34224P, “BWRX-300 UK GDA, Ch. E7: Radioactive Discharges,” (Reference 9-7)

Volumes Interfaces

This chapter also interfaces with the BWRX-300 PSR, especially:

- NEDC-34175P, “BWRX-300 UK GDA, Ch. 12, Radiation Protection,” (Reference 9-9)

9.1 Regulatory Context

9.1.1 Legislative Framework

The legislative framework for radiological protection in the UK is derived from the International Commission on Radiological Protection's (ICRP) recommendations, first in the implementation of the 1990 recommendations (Reference 9-10) as part of the 1996 Euratom Basic Safety Standards Directive (BSSD) (Reference 9-11) within the European Union, and later revised in 2013 to address the 2007 Recommendations of the ICRP (Reference 9-12). This new BSSD (Council Directive 2013/59/Euratom of 5 December 2013) (Reference 9-13) was adopted in 2014 and had to be enacted into national legislation of EU member states by February 2018.

In the UK, BSSD has been incorporated into legislation through several regulations to ensure the UK's regulations align with European standards for radiological protection, including the 2017 Ionising Radiations Regulations (Reference 9-14) and, with respect to the control of radioactive waste, through EPR16 (Reference 9-8) for England and Wales, The Environmental Authorisations (Scotland) Regulations 2018 (EA(S)R) in Scotland (Reference 9-15), and The Radioactive Substances (Modification of Enactments) Regulations (Northern Ireland) (Reference 9-16).

9.1.2 United Kingdom Legislative Requirements

9.1.2.1 Basic Safety Standards Directive

Article 12 of the BSSD (Reference 9-13) sets a limit on the effective dose for public exposure at 1 mSv/y, and Article 66 of the BSSD (Reference 9-13) requires that Member States ensure that arrangements are made for the estimation of doses to members of the public from authorised practices, and requires that this dose assessment must be carried out in a realistic way.

9.1.2.2 Environmental Permitting Regulations

Schedule 23 part 4 of EPR16 (Reference 9-8) confirms the requirements for exposures and doses relating to radioactive waste discharges to the environment.

Optimisation and dose limits:

- In respect of a radioactive substances activity that relates to radioactive waste, the regulator must exercise its relevant functions to ensure that:
    - All exposures to ionising radiation of any member of the public and of the population as a whole resulting from the disposal of radioactive waste are kept ALARA, taking into account economic and social factors, and
    - The sum of the doses resulting from the exposure of any member of the public to ionising radiation does not exceed the dose limits set out in Article 13 of the Basic Safety Standards Directive subject to the exclusions set out in Article 6(4) of that Directive.

Specific dose limits and calculation:

- In exercising those relevant functions in relation to the planning stage of radiation protection, the regulator must have regard to the following maximum doses to individuals which may result from a defined source:
    - 0.3 millisieverts per year from any source from which radioactive discharges are first made on or after 13th May 2000, or
    - 0.5 millisieverts per year from the discharges from any single site.

9.1.2.3 Application of the 2007 Recommendations of the ICRP to the United Kingdom

For planned exposure situations relating to new NPPs and new waste disposal facilities, the Health Protection Agency (HPA) (now known as the UK Health Security Agency (UKHSA)) advised the UK Government to adopt a lower dose constraint of 0.15 mSv per year to take into account uncertainties in the understanding of some health effects and the possibility that judgements on radiation risks might change within the timescale of planning and constructing a new NPP (Reference 9-17). However, this advice has not become formal guidance.

9.1.2.4 Other Guidance

In 1995, a review of the UK radioactive waste policy (Reference 9-18) set a threshold of 0.02 mSv/y as being broadly and cautiously equivalent to an annual risk of death of 1 in 1.0E+06, considering this to be a lower-bound optimisation consistent with the general practices of the Health and Safety Executive (HSE).

The UK Environment Agencies (EA, Scottish Environment Protection Agency, Northern Ireland Environment Agency) have worked with UKHSA and the Food Standards Agency (FSA) to produce guidance on the “Principles for Assessment of Prospective Public Doses from Discharges of Radioactive Waste to the Environment,” (Reference 9-19). This is a key reference document which recommends taking a staged approach to prospective dose assessments, also referencing a screening dose limit of 0.02 mSv.

A lower threshold for the most exposed members of the public of 10 µSv/y was advised under EPR, “Criteria for Setting Limits on the Discharge of Radioactive Waste from Nuclear Sites,” (Reference 9-20) below which the EA should not seek to further reduce the discharge limits that are in place, provided that the holder of the permit continues to apply BAT.

9.1.2.5 Non-Human Species

For non-human species, ICRP recommendations (Reference 9-12) detail that during planned, existing, and emergency situations, all of the environment needs to be considered, including areas where humans are absent. The aims of environmental radiation protection are focused on preventing or reducing the frequency of radiation effects to a level where they would have a negligible impact on the maintenance of biological diversity, the conservation of species, or the health and status of natural habitats, communities, and ecosystems.

The EA, Natural England, and the Countryside Council for Wales have agreed a dose rate threshold of 40 µGy/h (Reference 9-21), below which it has been concluded that there will be no adverse effect on the integrity of a Natura 2000 site (a European protected area covering valuable and threatened species and habitats). It is also a requirement of the environmental permit application for a nuclear site that there is an assessment of the impact of radioactive discharges on non-human species (Reference 9-22), with this assessment being applicable to the setting of site limits for specific radionuclides (Reference 9-20). For the purpose of the prospective dose assessment, a more restrictive dose rate to wildlife of 1 µGy/h is applied (Reference 9-1, Reference 9-2).

9.1.3 Radioactive Substances Guidance

The EA has published a suite of guidance documentation relating to regulation of activities involving radioactive substances, and the principles that are applied. The EA Radioactive Substances Regulation (RSR) objective and principles (Reference 9-23) states an objective to protect people and the environment from the harmful effects of ionising radiation by applying relevant legislation, government policy, and international standards.

The EA RSR Generic Developed Principles (Reference 9-24) detail the generic developed principles on regulatory assessment for radioactive substances activities, divided into eight sections. The principles considered to be most relevant to a prospective dose assessment for members of the public and wildlife are:

- RSMDP12 – Limits and levels should be established on the quantities of radioactivity that can be discharged into the environment where these are necessary to secure proper protection of human health and the environment.
- RPDP1 – All exposures to ionising radiation of any member of the public and of the population as a whole shall be kept ALARA, economic and social factors being taken into account.
- RPDP2 – Radiation doses to individual people shall be below the relevant dose limits and in general should be below the relevant constraints.
- RPDP3 – Non-human species should be adequately protected from exposure to ionising radiation.
- RPDP4 – Assessments of potential doses to people and to non-human species should be made prior to granting any new or revised permit for the discharge of radioactive wastes into the environment.
- SEDP1 – When evaluating sites for a new facility, account should be taken of the factors that might affect the protection of people and the environment from radiological hazards and the generation of radioactive waste.
- SEDP2 – Data should be provided to allow the assessment of rates and patterns of migration of radioactive materials in the air and the aquatic and terrestrial environments around sites.
- ENDP1 – The underpinning environmental aim for any facility should be that the design inherently protects people and the environment, consistent with the operational purpose of the facility.

9.2 Dose Assessment

9.2.1 Regulatory Requirements

The GDA guidance for Requesting Parties, "New Nuclear Power Plants: Generic Design Assessment Guidance for Requesting Parties, (Reference 9-5) outlines a three-step process:

- Step 1: Initiation
- Step 2: Fundamental Assessment
- Step 3: Detailed Assessment

The guidance also specifies the requirements for a prospective dose assessment, stating that the Requesting Party (RP) must provide a radiological assessment of proposed limits for:

- Annual dose to most exposed members of the public for liquid discharges*
- Annual dose to most exposed members of the public for gaseous discharges (separately identify the dose associated with on-site incineration where applicable)*
- Annual dose to the most exposed members of the public for all discharges from the facility*
- Annual dose from direct radiation to the most exposed members of the public

The RP must also provide:

- Annual dose to the representative person for the facility
- Potential short-term doses, including via the food chain, based on the maximum anticipated short-term discharges from the facility in normal operation
- A comparison of the calculated doses with the relevant dose constraints
- An assessment of whether the build-up of radionuclides in the local environment of the facility, based on the anticipated lifetime discharges, might have the potential to prejudice the activities of other legitimate users or uses of the land or sea
- Collective dose truncated at 500 years to the UK, European and world populations
- Dose-rate to NHS*.

The RP must state which models they have used to calculate these doses and why the models are appropriate. They must set out all the data and assumptions they have used as input to the models, together with reasoning as to why these assumptions are appropriate.

For items marked with an asterisk (*), the guidance recommends that the RP uses the EA's IRAT2 (Reference 9-1, Reference 9-2), refining the default data to reflect the characteristics of the facility and generic site.

The BWRX-300 dose assessment presented in this chapter is for Step 1 and Step 2 only and does not include more realistic dose assessment which would be undertaken at Step 3. GDA guidance to the requesting parties (Reference 9-5) does not specify as to which of the above listed dose estimations must be included in the Step 2 assessment, but EA guidance (Reference 9-19) lists evaluation of short-term release and collective dose under the detailed source and site assessment (Step 3), along with comparison of doses to the source and site limits and dose constraints.

9.2.2 Dose Assessment Approach

Guidance on the principles for assessment of prospective public doses from radioactive waste discharges to the environment (Reference 9-19) recommends taking a staged approach to dose assessments, comprising an initial cautious assessment of dose using a screening value of 0.02 mSv followed by a more detailed and realistic assessment using site specific information (when available). This staged approach is also advised by the National Dose Assessment Working Group (NDAWG) in their guidance note (Reference 9-25), which also identifies a number of simple radiological assessment tools suitable for the initial radiological assessment, including the EA's IRAT2 methodology (Reference 9-1, Reference 9-2).

The staged approach can be broken down as follows:

- Stage 1: an initial cautious assessment for routine discharges using conservative default data and generic assumptions about the site and the representative person, multiplying Dose Per Unit Release (DPUR) values by the radioactive discharge activities. This can be achieved using the EA's IRAT2 (Reference 9-1, Reference 9-2) spreadsheets which are available by request (Reference 9-26, and Reference 9-27). The IRAT2 spreadsheets can also be used to calculate the dose rate to the worst-affected wildlife group using the same inputs.
- Stage 2: the Stage 1 screening dose assessment is refined by adjusting some of the default parameters to more realistic ones. This is largely achieved by scaling the dose to take account of the dispersion conditions, for example, modifying the volumetric exchange rate for liquid effluent discharges and using a more realistic release height for gaseous discharges.
- Stage 3: the dose assessment is now refined to reflect more realistic parameters, such as the volumetric exchange rate, the release height, meteorological conditions and receptor points, and generic habit data. At this more detailed stage, in addition to routine discharges, there is also consideration of contribution to dose from a short-term discharge, from build-up of radionuclides in the environment, and of both individual and collective doses to members of the public.

The Stage 1 screening dose assessment aligns with GDA Step 1, and the Stage 2 refined screening dose assessment aligns with GDA Step 2. The Stage 3 more realistic dose assessment aligns with GDA Step 3, noting that GEH has entered into the GDA process up to Step 2 only.

EA guidance (Reference 9-19) states that a Stage 3 assessment is not usually required for most non-nuclear premises if the Stage 1 and Stage 2 doses are below the threshold of 0.02 mSv/y, however a Stage 3 assessment will be required at a later date in support of environmental permitting applications.

9.2.3 Selection and Suitability of the IRAT2 Dose Assessment Tool

The IRAT2 methodology has been selected as the radiological assessment tool in-line with recommended UK guidance from the EA and NDAWG (Reference 9-5, Reference 9-25). The IRAT2 is considered to be suitable as it allows a cautious assessment for the release of over 100 radionuclides to air and coastal/estuary waters. The tool is supported by four spreadsheets (Reference 9-26, Reference 9-27, Reference 9-28, Reference 9-29) which calculate doses for different release routes, exposure groups, and different age groups (offspring, infant, child, adult), and the dose rates to wildlife. Each spreadsheet provides the total dose to the worst affected population exposure group, the contribution to the dose from food pathways, and the dose rate to the worst affected reference organism. The most recent IRAT2 version of the spreadsheets have been used, as provided by the EA (References 9-26, Reference 9-27).

Comparison to other dose assessment tools (Reference 9-25) confirms that they are broadly equivalent for a ground-level release to air provided the same assumptions are used, and IRAT2 also offers the flexibility to vary release height. For release to estuary/coastal waters, the IRAT2 tool accounts for radioactive decay and thus does not over-estimate doses in this respect.

9.3 Radiological Assessment Data Inputs

9.3.1 Generic Site Description

The generic site for the BWRX-300 does not represent any particular location in the UK but represents the envelope of the potential UK site conditions potentially suitable for the deployment of new nuclear power stations by the end of 2025. It is described in NEDC-34219P (Reference 9-3).

The main assumptions about the Generic Site relevant to the radiological dose assessment are:

- The BWRX-300 is a single unit of 300 MW(e) capacity
- The site is coastal; radioactive liquid discharges will be made to the marine or estuarine environments
- There are no radioactive liquid discharges to river
- There are no radioactive liquid discharges to groundwater
- There are no radioactive liquid discharges to the sewage network
- Gaseous discharges are made through the main stack
- There is no radioactive gaseous discharge via incineration
- The site and its surrounding area are assumed to lie on a flat plain with no large buildings in the immediate vicinity. The effects of neighboring buildings and local terrain on the gaseous discharge will not be considered at the site-specific permitting stage.

9.3.2 Liquid and Gaseous Discharge Source Terms

The Stage 1 and Stage 2 dose assessments have been performed using the BWRX-300 annual average liquid, 007N1460 (Reference 9-6) and 007N1078 "Annual Average Gaseous Effluent Releases for the BWRX-300 Standard Plant," (Reference 9-30), which includes AOOs. How the liquid and gaseous effluent activities have been calculated is described in detail in the corresponding references.

NEDC-34224P (Reference 9-7) Section 7.2 discusses how the annual average discharge source terms have been developed using the Gaseous and Liquid Effluents (GALE), GALE-BWR, methodology (Reference 9-31). As described in PER Ch. E7, these discharge activities are considered to be conservative and bounding and are comparable to those for other relevant international plants. For this reason, a headroom factor has not been included at Step 2 of the GDA to avoid adding further conservatism.

The annual average liquid effluent discharge is presented in Table 9-1 and the annual average gaseous effluent release is presented in Table 9-2. The liquid release activities in Table 9-1 are assumed to correspond to a maximum release volume of 5,968 m^3/y based on the low purity waste input stated in Table 4-1 of Reference 9-6.

9.3.3 Direct Radiation

At this point in the GDA, there has not been any assessment of potential dose-rates at the site perimeter due to direct radiation from the various BWRX-300 facilities. This will be modelled and estimated at a later stage in the process.

To allow a consideration of the contribution from direct dose for a member of the public during the Step 1 and Step 2 dose assessment, OPEX from operational BWRs in the U.S. has been used based on environmental monitoring using Thermoluminescent Detectors (TLD), as reported in the U.S. Nuclear Regulatory Commission (USNRC) environmental reports (Reference 9-32). Looking at the data reported for the 20 sites with operational BWRs listed in Table 9-3, the average dose rate at the site boundary (based on an engineering judgement regarding the range of doses reported for each site) was 0.084 μSv/h.

An occupancy of two hours per week was assumed (considered to be a reasonable assumption for an expected activity such as a regular dog walk), which would result in an annual dose of 8.6 μSv/y. This is the value for direct dose-rate that will used for the Stage 1 and Stage 2 BWRX-300 dose assessment.

9.3.4 Stage 1 Assessment Methodology

9.3.4.1 Stage 1 Liquid Effluent Discharge

For releases to an estuary or coastal water, the exposure group considered is a coastal fishing family who are exposed to the radioactive discharge via:

- External radiation from radionuclides deposited in shore sediments
- Consumption of seafood incorporating radionuclides

Dose to marine reference organisms inhabiting the coastal environment is also considered.

The DPUR values in IRAT2 have been calculated for a release into a local marine compartment with a volumetric exchange rate of 100 m^3/s. Assumptions include:

- Radionuclides with a half-life less than three hours are not considered
- All shellfish and 50% of fish are assumed to be from the local compartment
- Coastal wildlife is assumed to dwell in the sea immediately offshore from the point of release

DPUR values are presented in Table 4 of the Initial Radiological Assessment Tool 2: Part 1 User Guide, Chief Scientist's Group Report, (Reference 9-1) for a fishing family coastal release scenario.

The Stage 1 dose to the representative person is calculated as the BWRX-300 SMR annual average liquid release rate multiplied by the relevant DPUR value, scaled by the default IRAT2 average coastal exchange rate of 30 m^3/s to provide a conservative dilution.

It is noted that the BWRX-300 has been designed such that it can be operated under normal conditions with a zero-liquid discharge to the environment. However, as it cannot be guaranteed that a liquid discharge will never be made, three scenarios have been modelled for the purpose of the prospective dose assessment:

- Scenario 1: No liquid effluent discharge
- Scenario 2: Maximum liquid effluent release volume of 5,968 m^3/y
- Scenario 3: Liquid effluent release volume of 600 m^3/y. This is comparable to that used for the UK ABWR (560 m^3/y at the outlet of the High Chemical Impurity Waste System (Reference 9-33) and is about 10% of the maximum release volume of liquid effluent (scaling factor of 0.101 used) 007N1460 (Reference 9-6)).

In the case of Scenario 3, this would effectively constitute a short-term discharge. However, NDAWG guidance (Reference 9-34) considered that the total dose assessed for the 12 monthly limits released in short releases will not differ significantly from the dose assessed assuming a continuous release.

During zero discharge, tritium releases are assumed to be included in the gaseous discharge. In the event that there is a liquid discharge, then an assumption is made as to the tritium component. For the prospective dose assessment, it has been assumed that the concentration of tritium is the same as in the reactor coolant (water phase), 005N4258, "BWRX-300 Coolant Radiation Concentrations," (Reference 9-35) which would be equivalent to an activity of

3.10E+12 Bq/y for a maximum discharge volume of 5,968 m^3/y (Scenario 2) or 3.12E+11 Bq/y (Scenario 3).

Despite IRAT2 providing DPUR values for over 100 radionuclides, there are 23 radionuclides[1] in the BWRX-300 liquid discharge source term that are not listed in IRAT2 and so do not have a DPUR. In this instance, the IRAT2 methodology directs the use of the default ‘other alpha’ and ‘other beta/gamma’ categories. It is noted that the other beta/gamma category is modelled as Cs-137. For the Stage 1 assessment, the other beta/gamma activity is the sum of the activities of radionuclides without a DPUR as below:

- Scenario 1 – no liquid discharge
- Scenario 2 – 5.81E+08 Bq/y
- Scenario 3 – 5.84E+07 Bq/y

9.3.4.2 Stage 1 Gaseous Effluent Discharge

For releases to air, the human exposure group considered is a local resident family who are exposed to the radioactive discharge via:

- Inhalation of radionuclides in the effluent plume
- External radiation from radionuclides in the effluent plume and deposited to the ground
- Consumption of terrestrial food incorporating radionuclides deposited to the ground

Terrestrial wildlife reference organisms inhabiting areas exposed to the effluent plume and deposition on the ground are also considered.

The DPUR values in the IRAT2 tool have been determined for a release at ground level under 50% category D conditions (neutral stability, typically overcast). The local resident and terrestrial wildlife are located at 100 m from the release point for 100% of the time, food is produced at 500 m from the release point, and radionuclides with a half-life of less than three hours are not being considered for consumption of food as the radionuclides will have decayed prior to consumption. DPUR values are presented in Table 2 of the Initial Radiological Assessment Tool 2: Part 2 Methods and Input Data, Chief Scientist’s Group Report, (Reference 9-2) for a local resident family atmospheric release scenario.

The Stage 1 dose to the representative person is calculated as the BWRX-300 SMR annual average gaseous release rate multiplied by the relevant DPUR value. The discharge is made at ground level.

IRAT2 provides DPUR values for over 100 radionuclides, but there are 26 radionuclides[2] in the BWRX-300 gaseous annual average discharge source term that are not listed in IRAT2 and so do not have a DPUR. In this instance, the IRAT2 methodology directs the use of the default ‘other alpha’ and ‘other beta/gamma’ categories. It is noted that the ‘other beta/gamma’ category is modelled as Cs-137.

However, for noble gases[3] it is considered that the use of the default radionuclide DPUR values are not appropriate as this will lead to overestimation of inhalation and ingestion doses

[1] For a liquid discharge, the following radionuclides do not have a DPUR in IRAT2 and have been modelled as ‘other beta/gamma’: Ba-139, Br-83, Ce-143, I-132, La-142, Mn-56, Nb-98, Nd-147, Ni-65, Np-239, Pr-143, Ru-105, Sr-91, Sr-92, Te-129m, Te-131m, Te-132, W-187, Y-91, Y-92, Y-93, Zn-69m, Zr-97

[2] For a gaseous discharge, the following radionuclides do not have a DPUR in IRAT2 and have been modelled as ‘other beta/gamma’: Cs-138, Np-239, Pr-144, Rb-89, Rh-103m, Rh-106, Sb-124, Sr-91, Sr-92, Te-129m, Te-131m, Te-132, W-187, Y-91, Y-92, Y-93

[3] For a gaseous discharge, the following radionuclides do not have a DPUR in IRAT2 and have been modelled separately as both Xe-133 and as Kr-88: Kr-83m, Kr-87, Kr-88, Kr-89, Xe-131m, Xe-133m, Xe-135, Xe-135m, Xe-137, Xe-138

which are not viable exposure pathways for noble gases. Two approaches to modeling the impact of noble gases that do not have a DPUR have been taken and compared, which are:

- Modeling noble gases as Xe-133[4].
- Modeling noble gases as Kr-88 using a derived DPUR[5] of 5.10E-12 µSv/y per Bq/y (more cautious approach, noting that the DPUR for Kr-88 is a factor of 70 higher than the DPUR for Xe-133).
- When assessing the dose due to gaseous discharges, no reduction has been made to the tritium component to account for liquid discharge Scenarios 2 or 3, effectively double accounting for the tritium in the bounding case.

9.3.5 Stage 2 Assessment Methodology

9.3.5.1 Stage 2 Liquid Effluent Discharge

The Stage 2 assessment for liquid discharges refines the Stage 1 assessment by selecting a more representative (less conservative) coastal exchange rate.

Although there is not yet a selected site location for the BWRX-300, NEDC-34219P (Reference 9-3) Table 2-2 identifies a number of sites potentially suitable for the deployment of new nuclear power stations in England and Wales before the end of 2025. These are listed in Table 9-4 along with the IRAT2 coastal exchange rate for each location. A higher coastal exchange rate will reduce the calculated dose due to increased dispersion. For the Stage 2 dose assessment, a coastal exchange rate of 634 m^3/s has been selected as a suitable mid-range value.

Another key refinement for the Stage 2 assessment is to review how realistic any use of the default 'other alpha' and 'other beta/gamma' categories has been. These can be substituted with specific radionuclides if the typical composition of the discharge is known. Table 16 of IRAT2 (Reference 9-1) provides guidance as to the suggested radionuclides which result in the highest doses in each category.

Considering the 23 radionuclides in the BWRX-300 liquid discharge source term which do not have a DPUR, it can be seen in Table 9-5 that the majority are fission products, for which Cs-137 would remain the most appropriate surrogate radionuclide. For those few radionuclides that are not fission products, the IRAT2 guidance (Reference 9-1) has been followed, noting that both Mn-52 and Pb-212 have a slightly lower total DPUR than Cs-137.

For the Stage 2 assessment, the radionuclides in Table 9-5 will be modelled in IRAT2 as per the categories shown in Table 9-6, where the Bq/y activities presented are the sum of the activities of the individual radionuclides being modelled in each category.

It is noted that the 'other beta/gamma' category used in the Stage 1 assessment is also modelled as Cs-137. For the human dose assessment, the DPURs for Pb-212 and Mn-54 are smaller than the DPUR for Cs-137. However, for the wildlife dose assessment, Pb-212 has a significantly higher dose rate per unit release than Cs-137 and so results in a much more cautious dose to wildlife.

9.3.5.2 Stage 2 Gaseous Effluent Discharge

The Stage 1 dose to the representative person was calculated for a gaseous discharge at ground level. For the Stage 2 refined assessment, a stack height of 35 m, 005N9751, "BWRX-300 General Description," (Reference 9-38) has been assumed. The higher discharge elevation results in increased dispersion, which in turn reduces the radiation dose received from food and (more significantly) from inhalation and external exposure.

[4] This is the approach taken in the Rolls Royce Step 1 and Step 2 prospective radiological assessment (Reference 9-36)
[5] This is the approach taken in the UK HPR1000 GDA (Reference 9-37)

As for the Stage 2 liquid discharge assessment, a review was performed of the radionuclides modelled as ‘other beta/gamma’ during the Stage 1 assessment.

Considering the 26 radionuclides in the BWRX-300 gaseous discharge source term which do not have a DPUR, it can be seen in Table 9-7 that, again, the majority are fission products, for which Cs-137 would remain the most appropriate surrogate radionuclide. For those few radionuclides that are not fission products, the IRAT2 (Reference 9-1) guidance has been followed, noting that both Mn-52 and Pb-210 have a slightly lower total DPUR than Cs-137.

For the Stage 2 assessment, the radionuclides in Table 9-7 will be modelled in IRAT2 as per the categories shown in Table 9-8.

It is noted that the ‘other beta/gamma’ category used in the Stage 1 assessment is also modelled as Cs-137. For both the human dose assessment and the wildlife dose assessment, Cs-137 provides a more cautious dose estimate than the Mn-52 and Pb-212 surrogates.

9.4 Dose Assessment Results and Discussion

9.4.1 Stage 1 Assessment

9.4.1.1 Stage 1 Dose to the Representative Person – Liquid Discharge

Table 9-9 presents the IRAT2 Stage 1 estimated doses to the representative person for each liquid discharge scenario. Table 9-10 and Table 9-11 present a breakdown of the dose by radionuclide and pathway for those radionuclides contributing more than 1% to the total dose, plus tritium.

The full IRAT2 Stage 1 dose to the representative person for the Scenario 2 bounding case is provided in Appendix A Table A-1 and the Stage 1 dose to wildlife in Appendix A Table A-2.

9.4.1.2 Stage 1 Dose to the Representative Person – Gaseous Discharge

Table 9-12 presents the IRAT2 Stage 1 estimated doses to the representative person when the noble gases are modelled as Xe-133 and as Kr-88. Table 9-13 and Table 9-14 present a breakdown of the dose by radionuclide and pathway for those radionuclides contributing more than 1% to the total dose.

The full IRAT2 Stage 1 dose to the representative person with Xe-133 as surrogate is provided in Appendix A Table A-3, equivalent calculations with Kr-88 as surrogate in Appendix A Table A-4, and the Stage 1 dose to wildlife in Appendix A Table A-5.

9.4.1.3 Stage 1 Dose to the Representative Person and Wildlife – Discussion

For liquid discharges, the total dose to the worst affected member of the fishing family was estimated to be 5.5 μSv/y for the bounding Scenario 2 case.

The dose due to the liquid discharge was dominated by Co-60 (54.0%), Zn-65 (17.0%), and P-32 (12.2%).

The dose rate to the worst affected organism (polychaete worm) was 3.1E-02 μGy/h and was dominated by Co-60 (33.7%), Ba-140 (27.6%), and Mn-54 (10.9%).

For gaseous discharges, the total dose to the worst affected member of the local resident family depended upon how the noble gases were modelled. Using Xe-133 as a surrogate resulted in a dose of 34.0 μSv/y which was dominated by C-14 (83.2%), I-131 (6.9%), and Xe-133 (4.4%). Using Kr-88 as the surrogate resulted in a much higher dose of 128 μSv/y due to the external irradiation DPUR for Kr-88 being much higher than the DPUR for Xe-133 (5.0E-12 compared to 7.12E-14 μSv/y per Bq/y), which was dominated by Kr-89 (46.8%), C-14 (21.8%), and Xe-138 (9.4%).

With Xe-133 as a surrogate, the dose rate to the worst affected organism (bird, large mammal, small-burrowing mammal, reptile) was 5.0E-02 μGy/h and was dominated by C-14 (90.1%). A dose rate was not calculated with Kr-88 as a surrogate as this radionuclide is not available within the IRAT2 tool.

The IRAT2 Stage 1 dose assessment for liquid and gaseous discharges plus direct radiation dose is summarized in Table 9-15. The total dose is estimated to be 48.1 μSv/y if noble gases are modelled as Xe-133 and 142.3 μSv/y if noble gases are modelled as Kr-88, reflecting the much higher DPUR value for Kr-88 compared to Xe-133. Both total dose values exceed the 20 μSv/y threshold and are dominated by the gaseous discharge.

9.4.2 Stage 2 Assessment

9.4.2.1 Stage 2 Dose to the Representative Person – Liquid Discharge

Table 9-16 presents the IRAT2 Stage 2 estimated doses to the representative person for each liquid discharge scenario. Table 9-17 and Table 9-18 present a breakdown of the dose by radionuclide and pathway for those radionuclides contributing more than 1% to the total dose, plus tritium. The reduction in the Stage 2 marine doses compared to the Stage 1 marine doses are a consequence of the increased dispersion of the liquid discharge due to the much higher coastal exchange rate.

The full IRAT2 Stage 2 dose to the representative person for the Scenario 2 bounding case is provided in Appendix A Table A-6 and the Stage 2 dose to wildlife in Appendix A Table A-7.

9.4.2.2 Stage 2 Dose to the Representative Person – Gaseous Discharge

Table 9-19 presents the IRAT2 Stage 2 estimated doses to the representative person when the noble gases are modelled as Xe-133 and as Kr-88. Table 9-20 and Table 9-21 present a breakdown of the dose by radionuclide and pathway for those radionuclides contributing more than 1% to the total dose. The reduction in the Stage 2 terrestrial doses compared to the Stage 1 terrestrial doses are a consequence of the increased dispersion of the gaseous discharge due to the much higher release height.

The full IRAT2 Stage 2 dose to the representative person with Xe-133 as surrogate is provided in Appendix A Table A-8, equivalent calculations with Kr-88 as surrogate in Appendix A Table A-9, and the Stage 2 dose to wildlife in Appendix A Table A-10.

9.4.2.3 Stage 2 Dose to the Representative Person and Wildlife – Summary and Discussion

For liquid discharges, the total dose to the worst affected member of the fishing family was estimated to be 0.26 μSv/y for the bounding Scenario 2 case.

The dose due to the liquid discharge was dominated by Co-60 (54.8%), Zn-65 (17.3%), and P-32 (12.4%).

The dose rate to the worst affected organism (phytoplankton) was 1.7E-02 μGy/h and was dominated by Pb-212 (90.7%), however this is a feature of the high dose rate per unit release value for Pb-212. For comparison, if all of the radionuclides without a DPUR had been modelled as Cs-137 (i.e., only the coastal exchange rate had been changed between Stage 1 and Stage 2) then the dose rate to the worst affected organism would have been 1.5E- 03 μGy/h (polychaete worm) and be dominated by Co-60 (33.7%). However, even with the more cautious approach of using Pb-212 as the surrogate, the dose to wildlife is well below the statutory dose rate threshold of 40 μGy/h and the EA screening threshold of 1 μGy/h.

For gaseous discharges, the total dose to the worst affected member of the local resident family depended upon how the noble gases were modelled. Using Xe-133 as a surrogate resulted in a dose of 2.7 μSv/y which was dominated by C-14 (84.1%) and I-131 (12.7%). Using Kr-88 as the surrogate resulted in a slightly higher dose of 3.2 μSv/y which was dominated by C-14 (70.7%), I-131 (10.7%), and Kr-89 (10.1%).

With Xe-133 as a surrogate, the dose rate to the worst affected organism (bird, large mammal, small-burrowing mammal, reptile) was 7.9E-03 μGy/h and was dominated by C-14 (90.1%). A dose rate was not calculated with Kr-88 as a surrogate as this radionuclide is not available within the IRAT2 tool.

The IRAT2 Stage 2 dose assessment for liquid and gaseous discharges plus direct radiation dose is summarised in Table 9-22, using the bounding Scenario 2 case for the liquid discharge. The total dose is estimated to be 11.6 μSv/y if noble gases are modelled as Xe-133 and 12.1 μSv/y if noble gases are modelled as Kr-88, with the increased dispersion due to the increase in release height resulting in more comparable doses, even where Kr-88 is the surrogate. Both total dose values are below the 20 μSv/y threshold and are dominated by the assumed contribution from direct radiation.

9.4.3 Conclusion

Results for the Stage 1 dose assessment estimated a worst-case total dose of 143 μSv/y to the representative person for members of the public for liquid and gaseous discharges and direct radiation. This dose is:

- Well below the single site dose constraint of 500 μSv/y (Reference 9-8, Reference 9-24)
- Below the source constraint of 300 μSv/y (Reference 9-8, Reference 9-24)
- Just below the advisory lower dose constraint of 150 μSv/y (Reference 9-17)
- Greater than the Stage 1 screening threshold of 20 μSv/y (Reference 9-1, Reference 9-19)

For NHS, the Stage 1 estimated dose rate to the worst affected organism was well below the statutory guidance level of 40 μGy/h and the EA screening level of 1 μGy/h (Reference 9-1, Reference 9-24) for both liquid and gaseous discharges.

Results for the Stage 2 dose assessment estimated a worst-case total dose of 12 μSv/y to the representative person for members of the public for liquid and gaseous discharges and direct radiation. This dose is:

- Well below the single site dose constraint of 500 μSv/y (Reference 9-8, Reference 9-24)
- Well below the source constraint of 300 μSv/y (Reference 9-8, Reference 9-24)
- Well below the advisory lower dose constraint of 150 μSv/y (Reference 9-17)
- Below the Stage 2 screening threshold of 20 μSv/y (Reference 9-1, Reference 9-19)

For NHS, the Stage 2 estimated dose rate to the worst affected organism was well below the statutory guidance level of 40 μGy/h and the EA screening level of 1 μGy/h (Reference 9-1, Reference 9-24) for both liquid and gaseous discharges.

The Stage 2 dose assessment is below the IRAT2 20 μSv/y screening limit (Reference 9-1), but this will be refined in a more realistic detailed radiological impact assessment in support of environmental permitting applications.

These results demonstrate that, even for the conservative bounding scenarios, at a fundamental level the design is capable of meeting UK dose constraints, noting that the future owner/operator is not committed to the chosen modelled scenarios.

9.5 Proposed Methodology for Stage 3 Assessment of Radiation Doses due to Continuous Liquid and Gaseous Discharge

9.5.1 Introduction

GEH has entered into the GDA process up to Step 2. The refined radiological assessment (Stage 3) which would ordinarily be undertaken in GDA Step 3 is still required to support environmental permitting applications for the BWRX-300. An outline of the proposed methodology is provided below.

Step 3 of the GDA process for the BWRX-300 requires a more realistic assessment of the radiological impacts of routine liquid and gaseous discharges to the environment. The steps for this more realistic assessment are as summarised below (Reference 9-19).

- Identify/quantify the source term
- Model radionuclide transfer in the environment
- Determine exposure pathways
- Identify habits and data for the exposure pathways
- Determine the candidates for the representative person from a realistic combination of habits
- Estimate doses to the candidates for the representative person
- Determine the representative person
- Calculate the total dose (including historical and future discharges and direct radiation)

The following sections outline the proposed approach for performing the more realistic detailed assessment.

9.5.2 BWRX-300 Source Term

The Stage 1 and Stage 2 dose assessment was performed using the annual average liquid and gaseous discharge source terms, which included AOOs. These source terms are recognised to be very conservative, as discussed in NEDC-34224P (Reference 9-7) Section 7.2.4.3, and it was considered that current inclusion of addition headroom factors would have added in further conservatism and resulted in an overly pessimistic dose assessment.

However, the BWRX-300 source term will be developed and refined as the GDA process progresses. GEH expect the gaseous and liquid discharge activities to reduce once refined End User Source Terms (EUST) and the liquid discharge volume are confirmed. Source term work will look at AOOs, reviewing the EUST against 2004/2 Euratom recommendations, consideration of sources of liquid or gaseous radioactive discharge introduced from outside of the nuclear island, headroom factors, and the proposed discharge limits.

The Stage 3 dose assessment will be performed using the BWRX-300 refined source term.

9.5.3 Dose Assessment Modeling

The Environment Agencies make no specific recommendation as to the specific environmental dispersion and dose assessment model to be used for the detailed assessment (Reference 9-19) but note that the PC-CREAM (Consequences of Releases to the Environment Assessment Methodology) Radiological Impact Assessment Software (Reference 9-39) is a suitable model for many applications. It is proposed that PC-CREAM 08 is used for the Stage 3 BWRX-300 dose assessment.

PC-CREAM 08 comprises a suite of models and databases which can be used to perform prospective radiological impact assessment of both individual and collective doses for routine, continuous liquid and gaseous discharges.

PC-CREAM 08 includes a dose assessment program called ASSESSOR which uses mathematical models to predict the transfer of radionuclides through the environment (which includes the food chain) and provide estimates of activity concentrations in various environmental media following a continuous release. PLUME, RESUS, GRANIS, and FARMLAND consider dispersion following a gaseous release, and DORIS looks at marine dispersion.

The PC-CREAM 08 models have been verified and validated (Reference 9-40) and are widely used within the nuclear industry for dose assessment modeling.

9.5.4 Dispersion Modeling

9.5.4.1 Modeling of Liquid Discharges to the Marine Environment

A more detailed description of DORIS can be found in the UKHSA verification report for PC-CREAM 08 (Reference 9-40).

The PC-CREAM 08 DORIS module estimates activity concentrations in sea water, marine sediments, and marine biota.

DORIS allows specification of the site location; radionuclides and discharge rates; element dependent parameters (sediment distribution coefficients and concentration ratios for marine biota); local marine compartment characteristics; regional compartment characteristics; volumetric exchange rates; output materials (filtered and unfiltered seawater, suspended solids, seabed sediments, fish, crustaceans, seaweed, and molluscs); and the output time(s) in years.

As highlighted in Section 9.3.4.1, the BWRX-300 has been designed such that it can be operated under normal conditions with a zero liquid discharge to the environment. This mode of operation is supported by a review (Reference 9-41) of publicly available data for U.S. NPPs which showed that several U.S. BWR plants operate on a zero liquid effluent discharge basis and have done so for many years. Other U.S. BWRs generally operate on a zero liquid effluent basis with occasional liquid discharges. It will be for the BWRX-300 plant owner / operator to determine the operational requirements for liquid discharges at the site-specific stage.

An occasional liquid discharge would effectively constitute a short-term discharge to the environment, something which PC-CREAM 08 is not suitable to assess. NDAWG explicitly considers and provides guidance regarding a short-term discharge to coast/estuary (Reference 9-34). NDAWG concludes that as there is little annual variation in dispersion (which is largely driven by tidal currents) or in habits (fish consumption and occupancy on sediments), and fish are a mobile population within coastal and estuarine waters (so unlikely to be constantly exposed to a short-term plume) the total dose assessed for the 12 monthly limits released in short releases will not differ significantly from the dose assessed assuming a continuous release. For this reason, NDAWG conclude that there is unlikely to be a need for a short-term release assessment for discharges of radioactive substances to estuaries or coastal environments.

It is considered that for Stage 3, the DORIS module in PC-CREAM 08 is a suitable software tool to assess the radiological impact of a liquid discharge from the BWRX-300 which will be modelled as a continuous release. Data reflecting the generic site would be used for the Stage 3 assessment, and data for the specific site for the detailed assessment.

9.5.4.2 Modeling of Gaseous Discharges to the Terrestrial Environment

PC-CREAM 08 uses the PLUME module which calculates activity concentrations in air, deposition rates, and external gamma dose rates from radionuclides in the cloud (cloud gamma) at various distances downwind of the release point. The GRANIS module estimates the external exposure to gamma radiation from radionuclides deposited on the ground. The FARMLAND module predicts the transfer of radionuclides into terrestrial foods following deposition onto the ground. The RESUS module estimates the activity concentrations in air arising from the resuspension of previously deposited radionuclides. Each of these four modules is discussed in more detail below.

PC-CREAM 08 is not suitable for assessment of radiological impacts due to short-term gaseous discharges to the environment, which must be considered separately via a different methodology, as discussed in Section 9.5.14.

PLUME

A more detailed description of PLUME can be found in the UKHSA verification report for PC- CREAM 08 (Reference 9-40).

PLUME is based on a Gaussian plume model (Reference 9-39) and considers the meteorological conditions during the release, the roughness of the land surface and the physical characteristics of the radionuclides being released to calculate the atmospheric dispersion at specified distances downwind of the release point.

The latest available BWRX-300 refined source term will be used to specify the radionuclides and discharges rates, alongside user defined distances that will represent the locations of interest (e.g., location of food production, location of habitations).

The release height used for the Stage 2 dose assessment was 35 m, but this will need to be modified to account for entrainment of the plume by nearby buildings as PC- CREAM 08 does not account for this effect and could otherwise potentially underestimate concentrations close to the release point. An effective stack height will be defined using the one-third reduction rule (Reference 9-42) which will result in a proposed effective discharge height of 12 m for the Stage 3 assessment. For the detailed dose assessment, a stack height study based on dispersion modeling is recommended to determine the optimum stack height above which the benefits of increasing height will have limited impact on further reducing ground level activity concentrations.

A surface roughness of 0.3 m is proposed for near-field modeling, which is typical for agricultural areas, and the lowest PC-CREAM 08 surface roughness option of 0.01 m is proposed for long-range dispersion modeling which is typical of the sea or very short grass.

PC-CREAM 08 offers three meteorological sampling schemes (Doury, Hosker-Smith or Pasquill), each with six stability categories ranging from A (most turbulent) to F (most stable). It is proposed to use the default PC-CREAM 08 scheme (Hosker-Smith) for the Stage 3 dose assessment.

GRANIS

A more detailed description of GRANIS can be found in Reference 9-40.

GRANIS estimates both the activity concentration of radionuclides in the soil and the corresponding external ground gamma dose, considering the shielding properties of the soil when estimating doses 1 m above the soil surface.

The latest available BWRX-300 refined source term will be used to specify the radionuclides and a deposition rate of 1 $Bq/m^2/s$ is proposed for the assessment to allow scaling.

GRANIS offers two soil models, undisturbed and well mixed, each having a depth profile that can be defined as generic wet or generic dry soil. It is proposed that the Stage 3 dose assessment uses the undisturbed soil model with a generic wet soil profile, which is broadly representative of the conditions expected for a generic coastal site.

FARMLAND

A more detailed description of FARMLAND can be found in Reference 9-40.

FARMLAND comprises a suite of models (cows, sheep, fruit, grain, green vegetables, and root vegetables) that can be used to predict the transfer of radionuclides into terrestrial foods following deposition onto the ground. It is not proposed to include grain in the Stage 3 assessment as grain is usually farmed, processed, and consumed at a national rather than local level, nor is it proposed to include food products from poultry and pigs, as these are often reared indoors and fed from nationally produced foodstuffs.

The latest available BWRX-300 refined source term will be used to specify the radionuclides and a deposition rate of 1 Bq/m^2/s is proposed for the Stage 3 assessment to allow scaling. PC-CREAM 08 defaults are proposed to be used for plant and animal dependent model parameters, concentration ratios, animal equilibrium transfer factors, and other element dependent parameters.

RESUS

More information on RESUS can be found in (Reference 9-39 and Reference 9-40).

Resuspension can occur due to either man-made or wind-initiated disturbance. RESUS models, wind-driven resuspension, and estimates activity concentrations in air arising from the resuspension of previously deposited radionuclides using a formula which is independent of the radionuclide considered aside from accounting for radioactive decay. A time-dependent resuspension factor is used to reflect that material becomes less available for resuspension over time.

9.5.5 Exposure Pathways

The following exposure pathways to people from the activity concentrations and dose-rates in environmental media are proposed.

9.5.5.1 Pathways for Marine Discharges

The marine pathways considered to be relevant for the Stage 3 assessment are:

- Ingestion: internal exposure from ingestion of locally caught seafood (fish, crustaceans, mollusks, seaweed).
- Inhalation: internal exposure from inhalation of sea-spray.
- External irradiation: external exposure from beta/gamma radionuclides in beach sediment and from handling contaminated fishing equipment.

9.5.5.2 Pathways for Gaseous Discharges

The terrestrial pathways considered to be relevant for the Stage 3 assessment are:

- Ingestion: internal exposure from ingestion of locally produced foodstuffs.
- Inhalation: internal exposure from inhalation of radionuclides in the gaseous plume and of deposited radionuclides that have been resuspended.
- External irradiation: external exposure from radionuclides in the gaseous plume and from deposited radionuclides.
- Skin absorption of tritium.

9.5.5.3 Other Pathways

The following additional pathways are proposed:

- Direct radiation: exposure of members of the public at the site boundary to external radiation associated with BWRX-300 facilities. The assumption for the Stage 1 and Stage 2 assessment was 8.6 μSv/y based on OPEX from U.S. BWRs, but it is proposed that this should be refined based on mathematical modeling of key buildings (e.g., turbine hall, reactor building, waste storage facilities) for receptors at defined distances combined with occupancy data.

It is proposed that the following pathways will be excluded from the Stage 3 assessment:

- Inadvertent ingestion of seawater and beach sediment, both considered to be minor exposure pathways.
- Consumption of honey, as the point of origin is likely to be outside of that impacted by the gaseous plume, and consumption rates of this foodstuff are comparatively low.
- Consumption of wild game, as the point of origin is likely to be outside of that impacted by the gaseous plume, and consumption rates of this foodstuff are comparatively low.

9.5.6 Habit Data

The radiation doses received by the public due to the operation of the BWRX-300 SMR are a combination of radionuclides and activities discharges, the exposure pathways, and individual habits (occupancy at key locations and for key activities and consumption rates of locally produced foodstuffs).

Habit data are available as generic (general use), such as in NRPB-W41 (Reference 9-43), or site-specific, such as that collected in site-specific habit surveys published by the Centre for Environment, Fisheries and Aquaculture Science (CEFAS) (Reference 9-44).

It is proposed that the Stage 3 dose assessment will be based on generic habits data as presented in NRPB-W41 (Reference 9-43) for the identified exposure pathways.

NDAWG provides guidance on the use of habits data for prospective dose assessments (Reference 9-45) and recommends use of the 'top two' method using generic UK habit data when site-specific data is unavailable. This approach is judged by NDAWG to result in a reasonably realistic assessment of doses for the next 5-10 years, which will be more conservative and give higher doses than using habits profiles.

A top two assessment is made with all terrestrial food intakes initially set to critical levels to identify the two terrestrial food types that give rise to the highest doses. These two foods are then retained with a critical intake and the remaining foods are ingested at 50th percentile levels. It is proposed that the BWRX-300 Stage 3 dose assessment uses the top two approach. It will be assumed that all shellfish and 50% of the fish are caught from a local compartment adjacent to the generic site, with the other 50% of the fish assumed to be caught in a larger surrounding region, termed the 'regional compartment' (Reference 9-1). Terrestrial foods will be assumed to be 100% locally sourced, with milk, cow, and sheep meat being produced at a local farm, and vegetables and fruit being grown at the local habitation.

9.5.7 Candidates for the Representative Person

The representative person is defined as the individual receiving a dose that is representative of the more highly exposed individuals in the population (Reference 9-17). To identify the representative person, an assessment is made looking at different groups of individuals who have different exposure profiles, the Candidates for the Representative Person (CRP). The representative person will be the CRP who has the highest estimated dose.

The CRP should reflect a realistic combination of habits based on local knowledge or plausible assumptions (Reference 9-19). A full range of exposure pathways should be considered for each of the CRP as it is likely that these individuals receive contributions to dose from more than one pathway. It is considered reasonable to assume a combination of average and higher than average habits, for example the CRP for the marine pathway is likely to consume higher than average amounts of seafood but average amounts of terrestrial foods whereas the CRP for the terrestrial pathway is likely to eat higher than average terrestrial foods and average marine foods.

The CRPs proposed for the BWRX-300 SMR are:

1. Liquid discharges: A fishing family (adult, child, and infant) who spend their time on the coast close to the liquid discharge point. The family consume 100% locally caught

seafood, inhale sea-spray, are exposed to external radiation due to handling contaminated fishing equipment and are also exposed to contaminated beach sediment. The adults will go fishing near the coast and the child and infant will spend time playing on the beach.

2. Gaseous discharges: A local resident family (adult, child, and infant) living at a dwelling that is close to and downwind of the gaseous discharge, being located at the area of highest deposition rate. The family consume 100% locally produced terrestrial foods, inhale the plume, inhale resuspended material, and are exposed to external radiation both from being immersed in the plume and from deposited activity on the ground. The family are afforded some protection from the plume and from deposited material due to shielding offered by their dwelling but also spend time outdoors.
3. Direct Radiation: Local dog walkers who take the same daily route close to the site perimeter and local residents who live close to the site and access the local beach for recreational activities, which include the fishing family and the local resident family.

The CRP with the highest combined dose from all pathways including direct radiation will be considered the representative person for the BWRX-300 SMR. This total dose will be assessed against the dose limits referenced in Section 9.1.1, namely:

- 0.5 millisieverts per year from the discharges from any single site
- 0.3 millisieverts per year from any source
- 0.15 millisieverts per year for new NPPs and new waste disposal facilities

9.5.8 Individual Dose Assessment for the CRPs

The ASSESSOR module in PC-CREAM 08 will be used to calculate individual doses to adult, child, and infant from gaseous discharges to the atmosphere based on the PLUME, GRANIS, FARMLAND, and RESUS outputs, and individual doses to adult, child, and infant due to liquid discharges based on the DORIS output. ASSESSOR combines the results of the models with actual discharge rates, generic site data, generic habit data, and ICRP60 dose coefficients to calculate effective doses for the identified exposure pathways for different age groups (Reference 9-40, Reference 9-46).

For gaseous releases, the outputs from PLUME, GRANIS, FARMLAND, and RESUS are picked up by ASSESSOR where they are used alongside receptor points and habit data (e.g., ingestion data, occupancy times and inhalation rates) to calculate the individual dose to the CRPs.

For marine discharges, the outputs from DORIS are picked up by ASSESSOR where they are used alongside habit data (ingestion data for adult, child, and infant, occupancy in the local and regional compartment, occupancy and inhalation rate for sea-spray and exposure to fishing equipment) to calculate the individual radiation dose to the CRPs.

Consideration will be made regarding the potential dose to embryo and foetus and to the newborn child, where the dose to the offspring could exceed that of the mother. ICRP have published dose coefficients for assessing these doses (Reference 9-47) and UKHSA (as HPA) have provided guidance on their applications (Reference 9-48), identifying the radionuclides that should be assessed (for example P-32, Ph-33, Ca-45, Sr-89) where they form a significant part of a release to the environment. A review of the updated BWRX-300 source term will be performed to identify if an assessment of the dose to embryo and foetus is required.

The annual effective dose will be calculated assuming that the discharge continues for the expected operating life of the plant (60 years), with the dose assessed for the final year of discharge in accordance with regulatory guidance (Reference 9-19). The total dose due to a combined exposure to both liquid and gaseous discharges and direct radiation (currently assumed to be 8.6 μSv/y but which will be refined at Stage 3) will be estimated by considering:

- The fishing family, who also consume terrestrial foods at average rates and reside at a habitation close to the site where they will be exposed to radionuclides in the plume and deposited by the plume.
- A local resident family, who also consume seafoods at average rates and spend leisure time at the local beach where they will be exposed to radionuclides in the beach sediment and where they will inhale sea spray.

The CRP with the highest total dose will be identified as the representative person for the BWRX-300. The estimated doses will be compared to the relevant dose constraints (0.3 mSv and 0.15 mSv).

9.5.9 Collective Dose Assessment

The ASSESSOR module in PC-CREAM 08 will be used to perform an assessment of the collective dose to defined population groups (e.g., United Kingdom, EU12, World) using the in-built databases combined with the outputs of the PLUME, GRANIS, FARMLAND, and RESUS models for gaseous discharges and the output of the DORIS model for liquid discharges.

The collective effective dose is the time integrated dose from a single year of discharge, which includes external exposures and the committed effective dose received from intakes of radionuclides. The collective dose assessment considers both "first pass" (the contribution to collective dose that arises as the dispersing plume initially passes over the target population) and “global circulation” components (important for long-lived radionuclides, such as C-14, which are globally dispersed and continue to contribute to the collective dose after long periods of time). The collective dose will be truncated at 500 years.

PC-CREAM 08 divides the area around the discharge point into annular segments, within which the population and agricultural production distributions are assumed to be uniform. The distributions of individual dose and radionuclide concentrations in the environment are also assumed to be uniform. Individual external and inhalation doses in each annular segment of the polar grid are scaled by the population in that segment to calculate the collective dose.

For liquid discharges, collective doses are calculated using the radionuclide concentrations in each compartment and then summing to obtain the total collective dose. Liquid discharge doses to individuals will usually be highest close to the discharge point because of dispersion in the water. Sediment movement between compartments is not considered important within marine environments and as a result is not modelled.

For this assessment, it will be assumed that the population is made up of adults only and that they do not move from one place to another. Default values will be used for the average fraction of time spent indoors and the location factors for exposure to cloud gamma, deposited gamma, cloud beta, deposited beta, and inhalation, where locations factors are a measure of the reduction in dose that is likely to arise as a result of being indoors.

The per-caput dose will be calculated from the collective dose for each population group by dividing by the number of individuals in each group.

9.5.10 Build-Up Dose Assessment

A build-up of radionuclides in the local environment may impact upon and prejudice the potential future uses (or users of) the land and the sea at the end-of-life of the power station.

The build-up of radionuclides in the terrestrial and marine environment will be calculated at the end of 60 years of continuous operations using PC-CREAM 08.

The DORIS module will be used to determine the activity concentration in filtered and unfiltered seawater and in seabed sediment.

The PLUME and FARMLAND modules will be used to determine the activity concentration in soil, except for carbon-14 and tritium which will be assessed using a specific activity model

(Reference 9-49). PLUME will model air concentrations for carbon-14 and tritium. The assessment location will correspond to the area with the highest deposition rates.

The activity concentrations will be compared to the out-of-scope values (Reference 9-8, Reference 9-50) for each radionuclide assessed.

9.5.11 Short-Term Dose Assessment

9.5.11.1 Outline

An assessment will be performed to estimate the expected annual dose to a member of the public due to a short-term gaseous discharge during normal operations

A short-term discharge is defined as a release which is larger than a normal release (≥ 2% of 12-monthly actual or expected discharges) and which occurs over a relatively short period of time (≤1 day). For a normally uniform discharge profile, this equates to about 1 week's discharge being released in 1 day or less (Reference 9-34).

NDAWG provide guidance on short-term release assessments (Reference 9-34) and methodology and examples (Reference 9-51). Additional methodology is provided in NRPB-W54 (Reference 9-52). This is the methodology proposed to be followed for the BWRX-300 Stage 3 short-term dose assessment.

9.5.11.2 Short-Term Discharge Source Term

As stated in Section 9.5.7.1 and in NDAWG guidance (Reference 9-34), a short-term assessment is not proposed for a liquid discharge due to the expectation that doses caused by a short-term liquid release will not differ significantly from the dose assessed assuming a continuous liquid release. For this reason, only the impact of a short-term gaseous discharge with a proposed effective release height of 35 m will be assessed.

The short-term discharge source term will be based upon an expected event for the BWRX- 300 which is a fuel pin failure. In a fuel pin failure, gaseous fission products (e.g., noble gases and iodine) may be released into the reactor coolant along with other particulate and soluble fission products (e.g., caesium). Soluble and particulate species remain in solution and are removed by the reactor water treatment system; however, volatile fission products could be carried over with the steam and are potentially discharged into the environment via the gaseous system. Radioiodine is removed via charcoal beds prior to release, meaning that the short-term discharge is expected to comprise only of noble gas fission products.

9.5.11.3 Modeling Dispersion and Deposition

The Atmospheric Dispersion Modeling Software (ADMS) code (Reference 9-52 and 9-53) produced by Cambridge Environmental Research Consultants (CERC) is used to calculate the activity concentrations in the plume and the deposition rate for a unit discharge, as well as plume gamma doses.

ADMS6 is a new generation Gaussian plume air dispersion model, characterising the atmospheric boundary layer properties via the boundary layer depth and the Monin-Obukhov length as opposed to the single parameter Pasquill-Gifford class. The software allows flexible input of meteorological data and has options to model aspects such as dry and wet deposition, impacts of hills, variable roughness, buildings and coastlines, short-term releases, and radioactivity decay including gamma dose.

ADMS6 is a well-established dispersion modeling code which has been widely used within the UK for applications such as new NPP planning/permitting, stack height studies, and environmental impact assessments. The code has a broad range of users including the UK Environment Agencies, the HSE, and the FSA. In addition, CERC evaluate their codes against available measured data obtained from real world situations, field campaigns, and wind tunnel experiments and publish this data on their website (References 9-52 and 9-53).

The BWRX-300 short-term dose assessment will be performed for the local resident dwelling and food production locations using general meteorological conditions suitable for a generic site.

9.5.11.4 Exposure Pathways and Habit Data

The short-term discharge is expected to be comprised only of noble gas fission products, which means that the only relevant exposure pathway is submersion in the plume (cloud dose). This is because these radionuclides do not deposit and so do not accumulate in the environment or food-chain. Neither are they absorbed through inhalation into the body resulting in an internal exposure.

Individuals will be assumed to be at the residential location for the duration of the short-term release (24 hours). The indoor and outdoor occupancy will be as defined in the IRAT2 methodology (Reference 9-2) meaning that the adult, child, and infant will be indoors 50%, 80%, and 90% of the time, respectively.

Other assumptions will be made in line with Table 1 of the NDAWG guidance for short-term releases to air (Reference 9-34).

9.5.11.5 Short Term Dose Assessment

Doses will be calculated for the period of the passage of the plume using standard methods. The external dose from immersion in air containing radioactive noble gases will be based on cloud gamma and cloud beta skin dose coefficients which will be taken from DCFPAK (Reference 9-54) and Appendix E of PC-Cream 08 (Reference 9-39), respectively.

The estimated short-term doses will be compared to the relevant dose constraints (0.3 mSv and 0.15 mSv), with consideration of the dose also received from a continuous release.

9.5.12 Dose Assessment for Non-Human Species

9.5.12.1 Outline

The Stage 3 assessment will include a more realistic assessment of the radiological impact on NHS, considering species expected to be present in the marine and terrestrial environments local to the BWRX-300.

9.5.12.2 Dose Assessment Methodology for NHS

PC-CREAM 08 (Reference 9-39) will be used to model environmental dispersion of radioactive releases and calculate activity concentrations in the assessed habitats based on the latest source term.

It is proposed to use the Environmental Risks from Ionising Contaminants: Assessment and Management (ERICA) 2.0 tool (Reference 9-55) which calculates dose rates to organisms by applying dose conversion coefficients to the concentrations of radionuclides in environmental media or in biota. ERICA contains reference organisms that complement the reference animals and plants proposed by ICRP (Reference 9-56).

ERICA 2.0 includes a new dosimetric methodology, to reflect changes presented in ICRP Publication 136 (Reference 9-57), and revised wildlife concentration factors and associated updated Environmental Media Concentration Limit (EMCL) values.

The ERICA assessment tool consists of three tiers (Reference 9-58): an initial screening assessment where, should the pass criteria (dose rate screening value) be met, the user can exit the assessment process; a second tier, where more site specific parameters can be used; and finally a third tier, which consists of a probabilistic risk assessment used when the screening dose criteria are exceeded at Tier 1 and Tier 2.

- Tier 1: a simple and conservative assessment based upon the site description, the radionuclides present, the ecosystem being assessed (e.g., marine, terrestrial), input media concentrations, and time dependent and spatial data. Input media activity concentrations are compared against EMCLs which have been calculated for the most limiting organism for each radionuclide. A risk quotient is produced for each specific radionuclide selected for inclusion in the assessment. If the sum of the risk quotients is < 1 then it can be assured that there is a very low probability that the assessment dose rate to any organism exceeds the incremental screening dose rate and therefore the risk to non-human biota can be considered negligible. If the sum of risk quotients is >1 then the assessment progresses to Tier 2.

- Tier 2: a more detailed assessment where the user is able to exert more choice in terms of parameter selection. In addition to selecting the radionuclides and reference organisms, the user can also specify their own user-defined geometries and modify default parameters (e.g., concentration ratios, distribution coefficients etc.), to produce a more tailored assessment.
- Tier 3: a probabilistic risk assessment in which uncertainties associated with the results may be determined using sensitivity analysis, and that allows the assessor to access a compilation of up-to-date available scientific literature on the biological effects of exposure to ionising radiation in a number of different species.

9.5.13 Uncertainty Assessment

The radiological dose assessment process requires a series of assumptions regarding the discharge, the exposure pathways, and expected human habits, as well as the various parameters specified in the modeling software.

Guidance on how to consider the uncertainty and variability in radiological assessments is provided by NDAWG (Reference 9-59). If the annual dose to the representative person exceeds 20 μSv per year, then it is required that the uncertainty and variability in the key assumptions used for the dose assessment are reviewed (Reference 9-19). However, a semi-quantitative review and analysis of identified dose assessment uncertainties will be performed for the BWRX-300 at Stage 3 regardless of the magnitude of the estimated dose.

The uncertainty review will include consideration of the following aspects. This list will be reviewed and extended as new sources of uncertainty are identified or introduced.

- Discharges: comparison of expected discharges and the proposed discharge limits. Consideration of headroom factors, when applied. Consideration of the expected discharge variation for the most radiologically significant radionuclides.
- Marine modeling: choice of PC-CREAM 08 model parameters, particularly those relating to dispersion in the local marine compartment such as the volumetric exchange rate, sediment load, sedimentation rate etc.
- Terrestrial modeling: the impact of release height, use of a Gaussian plume model, impact of buildings, impact of meteorological conditions, agricultural practices.
- Exposure pathways: selection of exposure locations for the local resident, for food production and for assessment of direct dose.
- Habits: use of generic habit data (Reference 9-43) versus site specific habit data (Reference 9-44).
- Dosimetric data: reliability of dose coefficients, including the chemical form of the discharged radionuclides that these correspond to.
- Other: impact of extended plant operational life, impact of climate change.

9.6 Conclusion

This chapter presents the results of the BWRX-300 Stage 1 and Stage 2 radiological impact assessment to human and NHS due to liquid and gaseous discharges and direct radiation.

The dose assessment has used the EA IRAT2 tool (Reference 9-1, Reference 9-2) which provides a simple and cautious initial assessment of dose using a screening value of 0.02 mSv.

The results from the dose assessment indicate that the total dose to a representative member of the public from the pathways considered is well below both the source dose constraint of 0.3 mSv/y (Reference 9-8, Reference 9-18, Reference 9-19) and the lower dose constraint of 0.15 mSv recommended for new NPPs (Reference 9-17, Reference 9-19).

The total dose rate to NHS, as represented by the worst affected organisms, is also below the recommended screening value of 40 μGy/h (Reference 9-21) and the investigation level of 1 μGy/h (Reference 9-1, Reference 9-2).

A proposed methodology for a more realistic detailed Stage 3 radiological impacts dose assessment has been proposed, using generic habit data (Reference 9-43) and more complex modeling tools (Reference 9-39).

Table 9-1: BWRX-300 Annual Average Liquid Effluent Activity Releases

Nuclide	Annual Release (Bq/y*)	Nuclide	Annual Release (Bq/y*)	Nuclide	Annual Release (Bq/y*)
Ag-110m	2.59E+06	I-133	7.03E+07	Sr-89	1.85E+06
Ba-139	8.14E+06	I-135	3.18E+07	Sr-91	7.40E+07
Ba-140	1.81E+08	La-142	6.66E+06	Sr-92	1.78E+07
Br-83	2.48E+07	Mn-54	2.41E+08	Tc-99m	1.04E+08
Ce-141	1.22E+07	Mn-56	7.40E+06	Te-129m	1.85E+07
Ce-143	5.92E+06	Mo-99	1.04E+08	Te-131m	7.77E+06
Ce-144	8.51E+06	Na-24	7.03E+07	Te-132	2.59E+06
Co-58	1.26E+08	Nb-95	4.44E+07	W-187	2.74E+07
Co-60	2.44E+08	Nb-98	3.70E+05	Y-91	2.48E+07
Cr-51	4.44E+08	Nd-147	1.48E+06	Y-92	5.55E+07
Cs-134	8.51E+07	Ni-63	3.70E+06	Y-93	5.92E+06
Cs-136	4.81E+07	Ni-65	1.48E+06	Zn-65	9.99E+07
Cs-137	1.30E+08	Np-239	7.77E+07	Zn-69m	1.55E+08
Cu-64	2.74E+08	P-32	1.74E+07	Zr-95	4.07E+07
Fe-55	5.18E+08	Pr-143	2.18E+07	Zr-97	7.40E+05
Fe-59	1.30E+08	Ru-103	9.99E+06		
I-131	4.07E+07	Ru-105	2.92E+07	**Total****	**3.68E+09**
I-132	5.55E+06	Ru-106	1.78E+07		

Notes:

* In converting the Reference 9-6 Curie activities to Becquerels, it is assumed that 1.0 Ci = 3.7E+10 Bq

**This total activity corresponds to the sum of the annual average liquid effluent release activities by radionuclide as listed in this table, noting that radionuclides with effluent release activities less than 370 kBq/year have not been included in the table or in the total activity calculated.

007N1460 (Reference 9-6)

Table 9-2: BWRX-300 Annual Average Gaseous Effluent Activity Releases

Nuclide	Annual Release (Bq/y*)	Nuclide	Annual Release (Bq/y)	Nuclide	Annual Release (Bq/y)
Ag-110m	2.40E+04	Kr-85	2.20E+12	Sr-91	1.70E+06
Ar-41	3.20E+08	Kr-85m	3.40E+10	Sr-92	1.00E+06
Ba-140	7.10E+06	Kr-87	1.20E+11	Tc-99m	2.20E+05
C-14	4.00E+11	Kr-88	1.20E+11	Te-129m	8.40E+05
Ce-141	4.50E+05	Kr-89	1.20E+13	Te-131m	1.50E+05
Ce-144	7.20E+04	La-140	1.60E+06	Te-132	6.80E+04
Co-58	5.20E+06	Mn-54	1.20E+07	W-187	5.30E+05
Co-60	1.10E+07	Mn-56	4.50E+05	Xe-131m	3.80E+10
Cr-51	2.00E+07	Mo-99	2.60E+06	Xe-133	1.60E+12
Cs-134	6.60E+05	Na-24	1.40E+06	Xe-133m	1.10E+09
Cs-136	3.70E+05	Nb-95	1.80E+06	Xe-135	1.30E+12
Cs-137	1.00E+06	Ni-63	2.50E+04	Xe-135m	1.20E+12
Cs-138	1.10E+05	Np-239	1.80E+06	Xe-137	1.70E+12
Cu-64	5.80E+06	P-32	6.90E+05	Xe-138	2.40E+12
Fe-55	2.40E+07	Pr-144	8.40E+01	Y-90	8.80E+02
Fe-59	5.80E+06	Rb-89	4.40E+04	Y-91	8.90E+05
H-3	9.70E+11	Rh-103m	1.90E+03	Y-92	4.10E+05
I-131	5.20E+08	Rh-106	1.00E+04	Y-93	1.30E+05
I-132	3.10E+09	Ru-103	4.50E+05	Zn-65	4.90E+06
I-133	2.40E+09	Ru-106	7.30E+04	Zr-95	1.90E+06
I-134	8.70E+09	Sb-124	4.90E+02		
I-135	4.60E+09	Sr-89	8.00E+04	**Total**	**2.44E+13**
Kr-83m	3.30E+11	Sr-90	3.60E+03		

Notes:

* In converting the Reference 9-30 Curies activities to Becquerels, a conversion of 1.0 Ci = 3.7E+10 Bq has been applied

007N1078 (Reference 9-30)

Table 9-3: Summary of Operational BWR Reported TLD Data from the 2023 USNRC Environmental Reports

Station	2023 Dose (engineering judgement* of reported dose or dose range)	Annual Dose (based on maximum)	Annual Dose μSv**	Dose rate μSv/h	Annual Dose μSv (occupancy of 104 h/y)
Browns Ferry 1, 2 & 3	15-22 mrem/std. qtr	88 mrem	880	0.10	10.4
Brunswick 1 & 2	10 mR/std. qtr	40 mR	400	0.05	4.7
Clinton	19-21 mrem/std. qtr	84 mrem	840	0.10	10.0
Colombia	0.28-0.34 mR/day	124 mR	1240	0.14	14.7
Cooper	20 mR/qtr	80 mR	800	0.09	9.5
Dresden 2&3	7.6-24.0 mrem/qtr	96 mrem	960	0.11	11.4
Edwin Hatch 1 & 2	10-13 mR/qtr	52 mrem	520	0.06	6.2
Fermi 2	11-19 mR/std. qtr	76 mR	760	0.09	9.0
Grand Gulf 1	10 mR/qtr	40 mR	400	0.05	4.7
Hope Creek 1	15 mR/qtr	60 mR	600	0.07	7.1
James A Fitzpatrick	4-5.7 mrem/std month	68 mrem	680	0.08	8.1
La Salle County 1 & 2	75 mrem/year	75 mrem	750	0.09	8.9
Limerick 1 & 2	12-28 mrem/qtr	112 mrem	1120	0.13	13.3
Monticello	10-16 mrem/std. qtr	64 mrem	640	0.07	7.6
Nine Mile Point 1 & 2	5 mrem / std. month	60 mrem	600	0.07	7.1
Peach Bottom 2 & 3	100 mrem/year	100 mrem	1000	0.11	11.9
Perry 1	14 mrem/qtr	56 mrem	560	0.06	6.6
Quad Cities 1 & 2	30 mrem/year	30 mrem	300	0.03	3.6
River Bend 1	11-17 mrem/std. qtr	68 mrem	680	0.08	8.1
Susquehanna 1& 2	15-17 mrem/std. qtr	68 mrem	680	0.08	8.1
			Average	**0.08**	**8.6**

Notes:

* Engineering judgement of the typical range of reported values, excluding outliers
** a conversion of 1 mR = 1 mrem = 0.01 mSv = 10 μSv has been applied, noting that this is rounded up for mR

"Radioactive Effluent and Environmental Reports," (Reference 9-32)

Table 9-4: Sites Potentially Suitable for Deployment of a New Nuclear Power Station and Their Coastal Exchange Rate

Site Location	Coastal Exchange Rate m^3/s
Bradwell	231.32
Hartlepool	634
Heysham	634
Hinkley Point	634
Oldbury	570
Sizewell	444
Sellafield	3170
Wylfa	1010

Note:

LIT 15793 (Reference 9-26)

Table 9-5: Liquid Discharge: Radionuclides Without a DPUR, Origin and Proposed Surrogate

Nuclide	Fission product?	Surrogate	Nuclide	Fission product?	Surrogate
Ba-139	Yes	Cs-137	Sr-91	Yes	Cs-137
Br-83	Yes	Cs-137	Sr-92	Yes	Cs-137
Ce-143	Yes	Cs-137	Te-129m	Yes	Cs-137
I-132	Yes	Cs-137	Te-131m	Yes	Cs-137
La-142	Yes	Cs-137	Te-132	Yes	Cs-137
Mn-56	No	Pb-212	W-187	No	Pb-212
Nb-98	Yes	Cs-137	Y-91	Yes	Cs-137
Nd-147	Yes	Cs-137	Y-92	Yes	Cs-137
Ni-65	No	Pb-212	Y-93	Yes	Cs-137
Np-239	No	Mn-52	Zn-69m	No	Pb-212
Pr-143	Yes	Cs-137	Zr-97	Yes	Cs-137
Ru-105	Yes	Cs-137			

Table 9-6: Liquid Discharge: Radionuclides Without a DPUR, Categories for Stage 2 IRAT2 Modeling

Category	Scenario 1 Bq/y	Scenario 2 Bq/y	Scenario 3 Bq/y
Mn-52	0	7.77E+07	7.81E+06
Cs-137	0	4.42E+08	4.44E+07
(true Cs-137 only*)	0	1.30E+08	1.31E+07
Pb-212	0	1.91E+08	1.92E+07

Note:

* For comparison, this is the activity of true Cs-137 as declared in the BWRX-300 liquid discharge source term, see Table 9-1

Table 9-7: Gaseous Discharge: Radionuclides Without a DPUR, Origin and Proposed Surrogate

Nuclide	Fission product?	Surrogate	Nuclide	Fission product?	Surrogate
Cs-138	Yes	Cs-137	Te-129m	Yes	Cs-137
Kr-83m	Noble gas	See 9.3.4.2	Te-131m	Yes	Cs-137
Kr-87	Noble gas	See 9.3.4.2	Te-132	Yes	Cs-137
Kr-88	Noble gas	See 9.3.4.2	W-187	No	Pb-212
Kr-89	Noble gas	See 9.3.4.2	Xe-131m	Noble gas	See 9.3.4.2
Np-239	No	Mn-52	Xe-133m	Noble gas	See 9.3.4.2
Pr-144	Yes	Cs-137	Xe-135	Noble gas	See 9.3.4.2
Rb-89	Yes	Cs-137	Xe-135m	Noble gas	See 9.3.4.2
Rh-103m	Yes	Cs-137	Xe-137	Noble gas	See 9.3.4.2
Rh-106	Yes	Cs-137	Xe-138	Noble gas	See 9.3.4.2
Sb-124	Yes	Cs-137	Y-91	Yes	Cs-137
Sr-91	Yes	Cs-137	Y-92	Yes	Cs-137
Sr-92	Yes	Cs-137	Y-93	Yes	Cs-137

Table 9-8: Gaseous Discharge: Radionuclides Without a DPUR, Categories for Stage 2 IRAT2 Modeling

Category	Noble Gases modelled as Xe-133 Bq/y	Noble Gases modelled as Kr-88 Bq/y
Mn-52	1.80E+06	1.80E+06
Kr-88	-	1.92E+13
(true Kr-88 only*)	-	1.20E+11
Xe-133 (including Xe-133)	2.08E+13	-
(true Xe-133 only*)	1.60E+12	-
Cs-137 (including Cs-137)	6.35E+06	6.35E+06
(true Cs-137 only*)	1.00E+06	1.00E+06
Pb-212	5.30E+05	5.30E+05

Note:

* For comparison, this is the activity of true Cs-137, true Kr-88 and true Xe-133 as declared in the BWRX-300 gaseous discharge source term, see Table 9-2.

Table 9-9: Estimated Stage 1 Dose to the Representative Person (Liquid Discharge)

Scenario	Description	External Dose µSv/y	Food Dose µSv/y	Total Dose µSv/y
1	Zero annual liquid discharge	0.0	0.0	0.0
2	Full annual liquid discharge plus tritium at reactor coolant concentrations (H-3 = 3.10E+12 Bq/y).	3.8	1.8	5.5
3	Nominal annual liquid discharge, proposed as a discharge volume of 600 m^3/y. Scenario 2 activities scaled by a factor of 0.101.	0.38	0.18	0.55

Table 9-10: Breakdown of Stage 1 Scenario 2 Dose to the Representative Person by Radionuclide (Liquid Discharge)

Radionuclide	External dose μSv/y	Fish / shellfish dose μSv/y	Total dose μSv/y	% Contribution
Co-60	2.9E+00	4.9E-02	3.0E+00	54.0%
Zn-65	4.2E-02	9.0E-01	9.4E-01	17.0%
P-32	1.5E-08	6.7E-01	6.7E-01	12.2%
Other beta/gamma	3.3E-01	5.2E-02	3.8E-01	6.9%
Mn-54	2.5E-01	2.9E-03	2.5E-01	4.6%
Cs-137	7.3E-02	1.2E-02	8.5E-02	1.5%
Tritium	0.0E+00	9.3E-03	9.3E-03	0.2%

Table 9-11: Breakdown of Stage 1 Scenario 3 Dose to the Representative Person by Radionuclide (Liquid Discharge)

Radionuclide	External dose μSv/y	Fish / shellfish dose μSv/y	Total dose μSv/y	% Contribution
Co-60	2.9E-01	4.9E-03	3.0E-01	54.0%
Zn-65	4.2E-03	9.0E-02	9.5E-02	17.0%
P-32	1.5E-09	6.8E-02	6.8E-02	12.2%
Other beta/gamma	3.3E-02	5.3E-03	3.8E-02	6.9%
Mn-54	2.5E-02	3.0E-04	2.5E-02	4.6%
Cs-137	7.4E-03	1.2E-03	8.6E-03	1.5%
Tritium	0.0E+00	9.4E-04	9.4E-04	0.2%

Table 9-12: Estimated Stage 1 Dose to the Representative Person (Gaseous Discharge)

Scenario	Description	Inhalation Dose μSv/y	External Dose μSv/y	Food Dose μSv/y	Total Dose μSv/y
1	Noble gases modelled as Xe-133	16.0	2.0	16.0	34.0
2	Noble gases modelled as Kr-88	15.5	96.7	16.1	128.2

Table 9-13: Breakdown of Stage 1 Dose to the Representative Person by Radionuclide (Gaseous Discharge – Noble Gases as Xe-133)

Radionuclide	Inhalation dose µSv/y	External dose µSv/y	Fish / shellfish dose µSv/y	Total dose µSv/y	% Contribution
C-14	1.4E+01	2.6E-05	1.4E+01	2.8E+01	83.2%
I-131	1.8E-01	2.0E-02	2.1E+00	2.3E+00	6.9%
Xe-133	0.0E+00	1.5E+00	0.0E+00	1.5E+00	4.4%
Tritium	6.9E-01	0.0E+00	2.7E-01	9.5E-01	2.8%
I-133	2.1E-01	1.8E-02	1.5E-01	3.8E-01	1.1%

Table 9-14: Breakdown of Stage 1 Dose to the Representative Person by Radionuclide (Gaseous Discharge – Noble Gases as Kr-88)

Radionuclide	Inhalation dose μSv/y	External dose μSv/y	Terrestrial food dose μSv/y	Total dose μSv/y	% Contribution
Kr-89	0.0E+00	6.0E+01	0.0E+00	6.0E+01	46.8%
C-14	1.4E+01	2.6E-05	1.4E+01	2.8E+01	21.8%
Xe-138	0.0E+00	1.2E+01	0.0E+00	1.2E+01	9.4%
Xe-137	0.0E+00	8.5E+00	0.0E+00	8.5E+00	6.6%
Xe-135	0.0E+00	6.5E+00	0.0E+00	6.5E+00	5.1%
Xe-135m	0.0E+00	6.0E+00	0.0E+00	6.0E+00	4.7%
I-131	1.8E-01	2.0E-02	2.1E+00	2.3E+00	1.8%
Kr-83m	0.0E+00	1.7E+00	0.0E+00	1.7E+00	1.3%

Table 9-15: Stage 1 Assessment – Total Dose to the Representative Person

Discharge route	Estimated dose (as Xe-133) µSv/y	Estimated dose (as Kr-88) µSv/y
Liquid discharge (Scenario 2)	5.5	5.5
Gaseous Discharge (noble gases modelled as Xe-133)	34.0	-
Gaseous Discharge (noble gases modelled as Kr-88)	-	128.2
Direct Radiation	8.6	8.6
Total	**48.1**	**142.3**

Table 9-16: Estimated Stage 2 Dose to the Representative Person (Liquid Discharge)

Scenario	Description	External Dose µSv/y	Food Dose µSv/y	Total Dose µSv/y
1	Zero annual liquid discharge	0.0	0.0	0.0
2	Full annual liquid discharge plus tritium at reactor coolant concentrations (H-3 = 3.10E+12 Bq/y).	0.17	0.09	0.26
3	Nominal annual liquid discharge, proposed as a discharge volume of 600 m^3/y. Scenario 2 activities scaled by a factor of 0.101.	0.02	0.01	0.03

Table 9-17: Breakdown of Stage 2 Scenario 2 Dose to the Representative Person by Radionuclide (Liquid Discharge)

Radionuclide	External dose µSv/y	Fish / shellfish dose µSv/y	Total dose µSv/y	% Contribution
Co-60	1.4E-01	2.3E-03	1.4E-01	54.8%
Zn-65	2.0E-03	4.2E-02	4.4E-02	17.3%
P-32	7.0E-10	3.2E-02	3.2E-02	12.4%
Cs-137*	1.2E-02	1.9E-03	1.4E-02	5.3%
Mn-54	1.2E-02	1.4E-04	1.2E-02	4.7%
Pb-212**	5.0E-07	4.3E-03	4.3E-03	1.7%
Tritium	0.0E+00	4.4E-04	4.4E-04	0.2%

Notes:

* Cs-137 now also includes other fission products

** Pb-212 is a surrogate radionuclide

Table 9-18: Breakdown of Stage 2 Scenario 3 Dose to the Representative Person by Radionuclide (Liquid Discharge)

Radionuclide	External dose µSv/y	Fish / shellfish dose µSv/y	Total dose µSv/y	% Contribution
Co-60	1.4E-02	2.3E-04	1.4E-02	54.8%
Zn-65	2.0E-04	4.3E-03	4.5E-03	17.2%
P-32	7.0E-11	3.2E-03	3.2E-03	12.4%
Cs-137*	1.2E-03	1.9E-04	1.4E-03	5.3%
Mn-54	1.2E-03	1.4E-05	1.2E-03	4.7%
Pb-212**	5.0E-08	4.3E-04	4.3E-04	1.7%
Tritium	0.0E+00	4.4E-05	4.4E-05	0.2%

Notes:

* Cs-137 now also includes other fission products

** Pb-212 is a surrogate radionuclide

Table 9-19: Estimated Stage 2 Dose to the Representative Person (Gaseous Discharge)

Scenario	Description	Inhalation Dose µSv/y	External Dose µSv/y	Food Dose µSv/y	Total Dose µSv/y
1	Noble gases modelled as Xe-133	0.1	0.0	2.6	2.7
2	Noble gases modelled as Kr-88	0.1	0.5	2.6	3.2

Table 9-20: Breakdown of Stage 2 Dose to the Representative Person by Radionuclide (Gaseous Discharge – Noble Gases as Xe-133)

Radionuclide	Inhalation dose µSv/y	External dose µSv/y	Terrestrial food dose µSv/y	Total dose µSv/y	% Contribution
C-14	7.7E-02	1.4E-07	2.2E+00	2.2E+00	84.1%
I-131	9.8E-04	1.1E-04	3.4E-01	3.4E-01	12.7%
Tritium	3.6E-03	0.0E+00	4.3E-02	4.6E-02	1.7%

Table 9-21: Breakdown of Stage 2 Dose to the Representative Person by Radionuclide (Gaseous Discharge – Noble Gases as Kr-88)

Radionuclide	Inhalation dose µSv/y	External dose µSv/y	Terrestrial food dose µSv/y	Total dose µSv/y	% Contribution
C-14	7.7E-02	1.4E-07	2.2E+00	2.2E+00	70.7%
I-131	9.8E-04	1.1E-04	3.4E-01	3.4E-01	10.7%
Kr-89	0.0E+00	3.2E-01	0.0E+00	3.2E-01	10.1%
Xe-138	0.0E+00	6.4E-02	0.0E+00	6.4E-02	2.0%
H-3	3.7E-03	0.0E+00	4.3E-02	4.6E-02	1.5%
Xe-137	0.0E+00	4.5E-02	0.0E+00	4.5E-02	1.4%
Xe-135	0.0E+00	3.5E-02	0.0E+00	3.5E-02	1.1%
Xe-135m	0.0E+00	3.2E-02	0.0E+00	3.2E-02	1.0%

Table 9-22: Stage 2 Assessment – Total Dose to the Representative Person

Discharge route	Estimated dose (as Xe-133) μSv/y	Estimated dose (as Kr-88) μSv/y
Liquid discharge (Scenario 2)	0.26	0.26
Gaseous Discharge (noble gases modelled as Xe-133)	2.7	-
Gaseous Discharge (noble gases modelled as Kr-88)	-	3.2
Direct Radiation	8.6	8.6
Total	**11.6**	**12.1**

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APPENDIX A IRAT2 Outputs

Table A-1: Estimated Stage 1 Dose to the Representative Person (Liquid Discharge, Bounding Case Scenario 2)

Radionuclide	External dose µSv/y	Fish / shellfish dose µSv/y	Total dose µSv/y	% Contribution
Tritium	0.0E+00	9.3E-03	9.3E-03	0.17%
Sodium-24	1.0E-07	1.3E-07	2.4E-07	0.00%
Phosphorus-32	**1.5E-08**	**6.7E-01**	**6.7E-01**	**12.19%**
Chromium-51	9.2E-04	2.9E-04	1.2E-03	0.02%
Manganese-54	2.5E-01	2.9E-03	2.5E-01	4.60%
Iron-55	0.0E+00	4.0E-04	4.0E-04	0.01%
Iron-59	3.0E-02	4.7E-04	3.0E-02	0.55%
Cobalt-58	3.3E-02	4.7E-03	3.8E-02	0.69%
Cobalt-60	**2.9E+00**	**4.9E-02**	**3.0E+00**	**53.97%**
Nickel-63	0.0E+00	4.2E-05	4.2E-05	0.00%
Copper-64	1.1E-05	9.1E-03	9.1E-03	0.16%
Zinc-65	**4.2E-02**	**9.0E-01**	**9.4E-01**	**17.04%**
Strontium-89	1.7E-09	9.1E-06	9.1E-06	0.00%
Zirconium-95	1.7E-02	6.3E-05	1.7E-02	0.31%
Niobium-95	4.9E-03	2.2E-05	4.9E-03	0.09%
Molybdenum-99	6.6E-06	7.5E-05	8.2E-05	0.00%
Technetium-99m	1.8E-09	2.5E-06	2.5E-06	0.00%
Ruthenium-103	4.3E-04	3.4E-05	4.6E-04	0.01%
Ruthenium-106	3.3E-03	6.6E-04	3.9E-03	0.07%
Silver-110m	1.9E-03	3.1E-02	3.3E-02	0.60%
Iodine-131	1.1E-06	3.5E-04	3.5E-04	0.01%
Iodine-133	7.3E-08	2.2E-05	2.2E-05	0.00%
Iodine-135	1.1E-08	7.3E-07	7.5E-07	0.00%
Caesium-134	4.1E-02	1.1E-02	5.2E-02	0.94%
Caesium-136	5.0E-04	6.1E-04	1.1E-03	0.02%
Caesium-137	7.3E-02	1.2E-02	8.5E-02	1.54%
Barium-140	4.9E-03	2.1E-04	5.1E-03	0.09%
Cerium-141	9.3E-05	4.9E-06	9.8E-05	0.00%
Cerium-144	5.6E-04	2.8E-05	5.9E-04	0.01%
Other beta/gamma-emitting nuclides	3.3E-01	5.2E-02	3.8E-01	6.89%
Total µSv/y	**3.8E+00**	**1.8E+00**	**5.5E+00**	

Table A-2: Estimated Stage 1 Dose to Wildlife (Liquid Discharge, Bounding Case Scenario 2)

Radionuclide	Dose rate μGy/h	% Contribution
Tritium	2.7E-05	0.09%
Sodium-24	3.5E-06	0.01%
Phosphorus-32	4.5E-04	1.44%
Chromium-51	1.3E-04	0.42%
Manganese-54	**3.4E-03**	**10.86%**
Iron-55	1.2E-06	0.00%
Iron-59	2.5E-03	7.88%
Cobalt-58	1.8E-03	5.82%
Cobalt-60	**1.1E-02**	**33.72%**
Nickel-63	2.0E-07	0.00%
Copper-64	2.9E-04	0.93%
Zinc-65	7.5E-04	2.40%
Strontium-89	9.1E-08	0.00%
Zirconium-95	5.2E-04	1.66%
Niobium-95	5.1E-04	1.63%
Molybdenum-99	8.9E-05	0.29%
Technetium-99m	3.4E-06	0.01%
Ruthenium-103	4.1E-05	0.13%
Ruthenium-106	1.1E-04	0.36%
Silver-110m	3.9E-05	0.12%
Iodine-131	2.3E-05	0.07%
Iodine-133	1.5E-05	0.05%
Iodine-135	2.4E-06	0.01%
Caesium-134	2.8E-04	0.89%
Caesium-136	1.4E-04	0.44%
Caesium-137	1.7E-04	0.54%
Barium-140	**8.6E-03**	**27.61%**
Cerium-141	1.5E-05	0.05%
Cerium-144	5.1E-05	0.16%
Other beta/gamma-emitting nuclides	7.5E-04	2.39%
Total dose rate μGy/h	**3.1E-02**	

Table A-3: Estimated Stage 1 Dose to the Representative Person (Gaseous Discharge, Noble Gases Modeled as Xe-133)

Radionuclide	Inhalation Dose µSv/y	External dose (cloud and deposited) µSv/y	Food dose µSv/y	Total dose µSv/y	% Contribution
Tritium	6.9E-01	0.0E+00	2.7E-01	9.5E-01	2.84%
Carbon-14	**1.4E+01**	**2.6E-05**	**1.4E+01**	**2.8E+01**	**83.17%**
Sodium-24	8.5E-06	2.8E-05	6.8E-08	3.7E-05	0.00%
Phosphorus-32	1.0E-04	2.0E-08	1.5E-04	2.5E-04	0.00%
Argon-41	0.0E+00	1.0E-03	0.0E+00	1.0E-03	0.00%
Chromium-51	1.7E-05	7.1E-05	1.6E-06	8.9E-05	0.00%
Manganese-54	4.1E-04	1.1E-02	3.4E-04	1.2E-02	0.04%
Manganese-56	1.2E-06	2.2E-06	0.0E+00	3.5E-06	0.00%
Iron-55	1.8E-04	6.5E-08	7.4E-04	9.2E-04	0.00%
Iron-59	4.8E-04	1.2E-03	4.8E-05	1.7E-03	0.01%
Cobalt-58	1.9E-04	1.4E-03	1.6E-05	1.6E-03	0.00%
Cobalt-60	2.5E-03	1.3E-01	5.5E-04	1.3E-01	0.38%
Nickel-63	2.6E-07	0.0E+00	1.1E-07	3.7E-07	0.00%
Copper-64	1.8E-05	2.8E-06	1.8E-07	2.1E-05	0.00%
Zinc-65	1.8E-04	2.5E-03	6.9E-04	3.3E-03	0.01%
Krypton-85	0.0E+00	2.8E-02	0.0E+00	2.8E-02	0.08%
Krypton-85m	0.0E+00	1.2E-02	0.0E+00	1.2E-02	0.04%
Strontium-89	1.0E-05	1.3E-09	1.8E-06	1.2E-05	0.00%
Strontium-90	2.1E-06	8.9E-12	4.9E-06	7.0E-06	0.00%
Yttrium-90	4.2E-08	1.7E-11	8.8E-10	4.3E-08	0.00%
Zirconium-95	2.1E-04	9.3E-04	2.2E-06	1.1E-03	0.00%
Niobium-95	6.1E-05	1.9E-04	1.1E-06	2.6E-04	0.00%
Molybdenum-99	6.2E-05	3.2E-06	4.0E-06	6.9E-05	0.00%
Technetium-99m	9.4E-08	8.7E-08	2.6E-09	1.8E-07	0.00%
Ruthenium-103	2.4E-05	3.4E-05	3.5E-07	5.8E-05	0.00%
Ruthenium-106	4.6E-05	1.9E-05	8.9E-07	6.6E-05	0.00%
Silver-110m	4.1E-06	6.0E-05	7.4E-06	7.1E-05	0.00%
Iodine-131	1.8E-01	2.0E-02	2.1E+00	2.3E+00	6.89%
Iodine-132	6.0E-03	4.0E-02	0.0E+00	4.6E-02	0.14%
Iodine-133	2.1E-01	1.8E-02	1.5E-01	3.8E-01	1.14%
Iodine-134	8.0E-03	8.0E-02	0.0E+00	8.8E-02	0.26%
Iodine-135	3.0E-02	9.6E-02	1.2E-03	1.3E-01	0.38%
Xenon-133	0.0E+00	1.5E+00	0.0E+00	1.5E+00	4.41%

Radionuclide	Inhalation Dose µSv/y	External dose (cloud and deposited) µSv/y	Food dose µSv/y	Total dose µSv/y	% Contribution
Caesium-134	9.8E-05	2.4E-03	3.8E-04	2.9E-03	0.01%
Caesium-136	1.0E-05	4.3E-05	7.4E-06	6.1E-05	0.00%
Caesium-137	1.0E-04	6.6E-03	4.7E-04	7.1E-03	0.02%
Barium-140	8.2E-04	9.7E-04	1.5E-05	1.8E-03	0.01%
Lanthanum-140	4.0E-05	3.3E-05	4.7E-07	7.3E-05	0.00%
Cerium-141	3.2E-05	4.0E-06	3.6E-07	3.7E-05	0.00%
Cerium-144	6.2E-05	1.2E-06	2.1E-06	6.5E-05	0.00%
Other beta/gamma-emitting nuclides	8.0E-04	5.0E-02	3.6E-03	5.5E-02	0.16%
Total dose µSv/y	**1.6E+01**	**2.0E+00**	**1.6E+01**	**3.4E+01**	

Table A-4: Estimated Stage 1 Dose to the Representative Person (Gaseous Discharge, Noble Gases Modeled as Kr-88)

Radionuclide	Inhalation Dose μSv/y	External dose (cloud and deposited) μSv/y	Food dose μSv/y	Total dose μSv/y	% Contribution
Tritium	6.9E-01	0.0E+00	2.7E-01	9.5E-01	0.74%
Carbon-14	**1.4E+01**	**2.6E-05**	**1.4E+01**	**2.8E+01**	**21.77%**
Sodium-24	8.5E-06	2.8E-05	6.8E-08	3.7E-05	0.00%
Phosphorus-32	1.0E-04	2.0E-08	1.5E-04	2.5E-04	0.00%
Argon-41	0.0E+00	1.0E-03	0.0E+00	1.0E-03	0.00%
Chromium-51	1.7E-05	7.1E-05	1.6E-06	8.9E-05	0.00%
Manganese-54	4.1E-04	1.1E-02	3.4E-04	1.2E-02	0.01%
Manganese-56	1.2E-06	2.2E-06	0.0E+00	3.5E-06	0.00%
Iron-55	1.8E-04	6.5E-08	7.4E-04	9.2E-04	0.00%
Iron-59	4.8E-04	1.2E-03	4.8E-05	1.7E-03	0.00%
Cobalt-58	1.9E-04	1.4E-03	1.6E-05	1.6E-03	0.00%
Cobalt-60	2.5E-03	1.3E-01	5.5E-04	1.3E-01	0.10%
Nickel-63	2.6E-07	0.0E+00	1.1E-07	3.7E-07	0.00%
Copper-64	1.8E-05	2.8E-06	1.8E-07	2.1E-05	0.00%
Zinc-65	1.8E-04	2.5E-03	6.9E-04	3.3E-03	0.00%
Krypton-85	0.0E+00	2.8E-02	0.0E+00	2.8E-02	0.02%
Krypton-85m	0.00E+00	1.25E-02	0.00E+00	1.25E-02	0.01%
Krypton-88	**0.00E+00**	**9.60E+01**	**0.00E+00**	**9.60E+01**	**74.89%**
Strontium-89	1.0E-05	1.3E-09	1.8E-06	1.2E-05	0.00%
Strontium-90	2.1E-06	8.9E-12	4.9E-06	7.0E-06	0.00%
Yttrium-90	4.2E-08	1.7E-11	8.8E-10	4.3E-08	0.00%
Zirconium-95	2.1E-04	9.3E-04	2.2E-06	1.1E-03	0.00%
Niobium-95	6.1E-05	1.9E-04	1.1E-06	2.6E-04	0.00%
Molybdenum-99	6.2E-05	3.2E-06	4.0E-06	6.9E-05	0.00%
Technetium-99m	9.4E-08	8.7E-08	2.6E-09	1.8E-07	0.00%
Ruthenium-103	2.4E-05	3.4E-05	3.5E-07	5.8E-05	0.00%
Ruthenium-106	4.6E-05	1.9E-05	8.9E-07	6.6E-05	0.00%
Silver-110m	4.1E-06	6.0E-05	7.4E-06	7.1E-05	0.00%
Iodine-131	1.8E-01	2.0E-02	2.1E+00	2.3E+00	1.80%
Iodine-132	6.0E-03	4.0E-02	0.0E+00	4.6E-02	0.04%
Iodine-133	2.1E-01	1.8E-02	1.5E-01	3.8E-01	0.30%
Iodine-134	8.0E-03	8.0E-02	0.0E+00	8.8E-02	0.07%
Iodine-135	3.0E-02	9.6E-02	1.2E-03	1.3E-01	0.10%

Radionuclide	Inhalation Dose µSv/y	External dose (cloud and deposited) µSv/y	Food dose µSv/y	Total dose µSv/y	% Contribution
Xenon-133	0.00E+00	1.14E-01	0.00E+00	1.14E-01	0.09%
Caesium-134	9.8E-05	2.4E-03	3.8E-04	2.9E-03	0.00%
Caesium-136	1.0E-05	4.3E-05	7.4E-06	6.1E-05	0.00%
Caesium-137	1.0E-04	6.6E-03	4.7E-04	7.1E-03	0.01%
Barium-140	8.2E-04	9.7E-04	1.5E-05	1.8E-03	0.00%
Lanthanum-140	4.0E-05	3.3E-05	4.7E-07	7.3E-05	0.00%
Cerium-141	3.2E-05	4.0E-06	3.6E-07	3.7E-05	0.00%
Cerium-144	6.2E-05	1.2E-06	2.1E-06	6.5E-05	0.00%
Other beta/gamma-emitting nuclides	7.98E-04	5.04E-02	3.59E-03	5.48E-02	0.04%
Total dose µSv/y	**15.5**	**96.7**	**16.1**	**128.2**	

Table A-5: Estimated Stage 1 Dose to Wildlife (Gaseous Discharge, Noble Gases Modeled as Xe-133)

Radionuclide	Dose rate μGy/h	% Contribution
Tritium	3.4E-03	6.82%
Carbon-14	**4.5E-02**	**90.11%**
Sodium-24	3.8E-09	0.00%
Phosphorus-32	1.0E-06	0.00%
Argon-41	5.8E-07	0.00%
Chromium-51	7.6E-09	0.00%
Manganese-54	1.6E-06	0.00%
Manganese-56	7.2E-11	0.00%
Iron-55	7.3E-07	0.00%
Iron-59	1.5E-07	0.00%
Cobalt-58	1.9E-07	0.00%
Cobalt-60	2.2E-05	0.04%
Nickel-63	6.7E-10	0.00%
Coppr-64	1.1E-09	0.00%
Zinc-65	7.9E-07	0.00%
Krypton-85	1.2E-04	0.24%
Krypton-85m	1.9E-06	0.00%
Strontium-89	3.5E-09	0.00%
Strontium-90	2.7E-08	0.00%
Yttrium-90	1.3E-13	0.00%
Zirconium-95	4.7E-08	0.00%
Niobium-95	2.4E-08	0.00%
Molybdenum-99	8.9E-10	0.00%
Technetium-99m	9.2E-12	0.00%
Ruthenium-103	8.6E-09	0.00%
Ruthenium-106	4.0E-08	0.00%
Silver-110m	9.2E-09	0.00%
Iodine-131	7.3E-06	0.01%
Iodine-132	2.8E-06	0.01%
Iodine-133	6.2E-06	0.01%
Iodine-134	3.4E-06	0.01%
Iodine-135	8.4E-06	0.02%
Xenon-133	1.3E-03	2.60%
Caesium-134	1.0E-06	0.00%
Caesium-136	1.2E-08	0.00%

Radionuclide	Dose rate µGy/h	% Contribution
Caesium-137	6.4E-06	0.01%
Barium-140	7.3E-07	0.00%
Lanthanum-140	2.9E-09	0.00%
Cerium-141	3.6E-10	0.00%
Cerium-144	1.2E-09	0.00%
Other beta/gamma-emitting nuclides	4.9E-05	0.10%
Total dose rate µGy/h	**5.0E-02**	

Table A-6: Estimated Stage 2 Dose to the Representative Person (Liquid Discharge, Bounding Case Scenario 2)

Radionuclide	External dose µSv/y	Fish / shellfish dose µSv/y	Total dose µSv/y	% Contribution
Tritium	0.0E+00	4.4E-04	4.4E-04	0.17%
Sodium-24	4.9E-09	6.3E-09	1.1E-08	0.00%
Phosphorus-32	**7.0E-10**	**3.2E-02**	**3.2E-02**	**12.37%**
Chromium-51	4.4E-05	1.4E-05	5.7E-05	0.02%
Manganese-52	2.3E-04	7.8E-05	3.1E-04	0.12%
Manganese-54	1.2E-02	1.4E-04	1.2E-02	4.66%
Iron-55	0.0E+00	1.9E-05	1.9E-05	0.01%
Iron-59	1.4E-03	2.2E-05	1.4E-03	0.56%
Cobalt-58	1.6E-03	2.2E-04	1.8E-03	0.70%
Cobalt-60	**1.4E-01**	**2.3E-03**	**1.4E-01**	**54.76%**
Nickel-63	0.0E+00	2.0E-06	2.0E-06	0.00%
Copper-64	5.0E-07	4.3E-04	4.3E-04	0.17%
Zinc-65	**2.0E-03**	**4.2E-02**	**4.4E-02**	**17.29%**
Strontium-89	8.1E-11	4.3E-07	4.3E-07	0.00%
Zirconium-95	8.1E-04	3.0E-06	8.1E-04	0.32%
Niobium-95	2.3E-04	1.0E-06	2.3E-04	0.09%
Molybdenum-99	3.1E-07	3.6E-06	3.9E-06	0.00%
Technetium-99m	8.7E-11	1.2E-07	1.2E-07	0.00%
Ruthenium-103	2.0E-05	1.6E-06	2.2E-05	0.01%
Ruthenium-106	1.5E-04	3.1E-05	1.9E-04	0.07%
Silver-110m	8.9E-05	1.5E-03	1.6E-03	0.61%
Iodine-131	5.4E-08	1.6E-05	1.7E-05	0.01%
Iodine-133	3.4E-09	1.0E-06	1.0E-06	0.00%
Iodine-135	5.2E-10	3.5E-08	3.5E-08	0.00%
Caesium-134	2.0E-03	5.1E-04	2.5E-03	0.96%
Caesium-136	2.4E-05	2.9E-05	5.3E-05	0.02%
Caesium-137	1.2E-02	1.9E-03	1.4E-02	5.31%
Barium-140	2.3E-04	1.0E-05	2.4E-04	0.09%
Cerium-141	4.4E-06	2.3E-07	4.6E-06	0.00%
Cerium-144	2.7E-05	1.3E-06	2.8E-05	0.01%
Lead-212	5.0E-07	4.3E-03	4.3E-03	1.67%
Total µSv/y	**1.7E-01**	**8.6E-02**	**2.6E-01**	

Table A-7: Estimated Stage 2 Dose to Wildlife (Liquid Discharge, Bounding Case Scenario 2)

Radionuclide	Dose rate μGy/h	% Contribution
Tritium	1.3E-06	0.01%
Sodium-24	1.6E-07	0.00%
Phosphorus-32	2.1E-05	0.12%
Chromium-51	6.2E-06	0.04%
Manganese-52	1.5E-04	0.86%
Manganese-54	1.6E-04	0.93%
Iron-55	5.9E-08	0.00%
Iron-59	1.2E-04	0.68%
Cobalt-58	8.6E-05	0.50%
Cobalt-60	5.0E-04	2.89%
Nickel-63	9.5E-09	0.00%
Copper-64	1.4E-05	0.08%
Zinc-65	3.5E-05	0.21%
Strontium-89	4.3E-09	0.00%
Niobium-95	2.4E-05	0.14%
Molybdenum-99	4.2E-06	0.02%
Technetium-99m	1.6E-07	0.00%
Ruthenium-103	1.9E-06	0.01%
Ruthenium-106	5.4E-06	0.03%
Silver-110m	1.8E-06	0.01%
Iodine-131	1.1E-06	0.01%
Iodine-133	7.3E-07	0.00%
Iodine-135	1.1E-07	0.00%
Caesium-134	1.3E-05	0.08%
Caesium-136	6.5E-06	0.04%
Caesium-137	2.7E-05	0.16%
Barium-140	4.1E-04	2.37%
Cerium-141	7.1E-07	0.00%
Cerium-144	2.4E-06	0.01%
Lead-212	**1.6E-02**	**90.66%**
Total dose rate μGy/h	**1.7E-02**	

Table A-8: Estimated Stage 2 Dose to the Representative Person (Gaseous Discharge, Noble Gases Modeled as Xe-133)

Radionuclide	Inhalation Dose µSv/y	External dose (cloud and deposited) µSv/y	Food dose µSv/y	Total dose µSv/y	% Contribution
Tritium	3.6E-03	0.0E+00	4.3E-02	4.6E-02	1.74%
Carbon-14	**7.7E-02**	**1.4E-07**	**2.2E+00**	**2.2E+00**	**84.14%**
Sodium-24	4.5E-08	1.5E-07	1.1E-08	2.1E-07	0.00%
Phosphorus-32	5.4E-07	1.0E-10	2.4E-05	2.5E-05	0.00%
Argon-41	0.0E+00	5.6E-06	0.0E+00	5.6E-06	0.00%
Chromium-51	8.9E-08	3.8E-07	2.5E-07	7.2E-07	0.00%
Manganese-52	3.0E-07	8.1E-07	1.0E-06	2.1E-06	0.00%
Manganese-54	2.2E-06	5.9E-05	5.5E-05	1.2E-04	0.00%
Manganese-56	6.5E-09	1.2E-08	0.0E+00	1.8E-08	0.00%
Iron-55	9.6E-07	3.4E-10	1.2E-04	1.2E-04	0.00%
Iron-59	2.6E-06	6.3E-06	7.6E-06	1.7E-05	0.00%
Cobalt-58	1.0E-06	7.4E-06	2.6E-06	1.1E-05	0.00%
Cobalt-60	1.3E-05	6.7E-04	8.7E-05	7.7E-04	0.03%
Nickel-63	1.4E-09	0.0E+00	1.8E-08	1.9E-08	0.00%
Copper-64	9.7E-08	1.5E-08	2.8E-08	1.4E-07	0.00%
Zinc-65	9.4E-07	1.3E-05	1.1E-04	1.2E-04	0.00%
Krypton-85	0.0E+00	1.5E-04	0.0E+00	1.5E-04	0.01%
Krypton-85m	0.0E+00	6.6E-05	0.0E+00	6.6E-05	0.00%
Strontium-89	5.5E-08	7.0E-12	2.8E-07	3.4E-07	0.00%
Strontium-90	1.1E-08	4.7E-14	7.8E-07	7.9E-07	0.00%
Yttrium-90	2.2E-10	9.2E-14	1.4E-10	3.6E-10	0.00%
Zirconium-95	1.1E-06	5.0E-06	3.6E-07	6.4E-06	0.00%
Niobium-95	3.2E-07	1.0E-06	1.7E-07	1.5E-06	0.00%
Molybdenum-99	3.3E-07	1.7E-08	6.4E-07	9.8E-07	0.00%
Technetium-99m	5.0E-10	4.6E-10	4.1E-10	1.4E-09	0.00%
Ruthenium-103	1.3E-07	1.8E-07	5.7E-08	3.7E-07	0.00%
Ruthenium-106	2.5E-07	1.0E-07	1.4E-07	4.9E-07	0.00%
Silver-110m	2.2E-08	3.2E-07	1.2E-06	1.5E-06	0.00%
Iodine-131	**9.8E-04**	**1.1E-04**	**3.4E-01**	**3.4E-01**	**12.71%**
Iodine-132	3.2E-05	2.1E-04	0.0E+00	2.4E-04	0.01%
Iodine-133	1.1E-03	9.5E-05	2.4E-02	2.5E-02	0.96%
Iodine-134	4.2E-05	4.3E-04	0.0E+00	4.7E-04	0.02%
Iodine-135	1.6E-04	5.1E-04	1.8E-04	8.6E-04	0.03%
Xenon-133	0.0E+00	7.9E-03	0.0E+00	7.9E-03	0.30%

Radionuclide	Inhalation Dose μSv/y	External dose (cloud and deposited) μSv/y	Food dose μSv/y	Total dose μSv/y	% Contribution
Caesium-134	5.2E-07	1.3E-05	6.1E-05	7.4E-05	0.00%
Caesium-136	5.3E-08	2.3E-07	1.2E-06	1.5E-06	0.00%
Caesium-137	3.5E-06	2.2E-04	4.7E-04	7.0E-04	0.03%
Barium-140	4.3E-06	5.2E-06	2.3E-06	1.2E-05	0.00%
Lanthanum-140	2.1E-07	1.8E-07	7.5E-08	4.6E-07	0.00%
Cerium-141	1.7E-07	2.1E-08	5.7E-08	2.5E-07	0.00%
Cerium-144	3.3E-07	6.2E-09	3.3E-07	6.7E-07	0.00%
Lead-212	1.1E-05	2.6E-09	2.3E-08	1.1E-05	0.00%
Total dose μSv/y	**8.3E-02**	**1.0E-02**	**2.6E+00**	**2.7E+00**	

Table A-9: Estimated Stage 2 Dose to the Representative Person (Gaseous Discharge, Noble Gases Modeled as Kr-88)

Radionuclide	Inhalation Dose μSv/y	External dose (cloud and deposited) μSv/y	Food dose μSv/y	Total dose μSv/y	% Contribution
Tritium	3.65E-03	0.00E+00	4.26E-02	4.62E-02	1.47%
Carbon-14	7.66E-02	1.38E-07	2.15E+00	2.23E+00	70.71%
Sodium-24	4.54E-08	1.50E-07	1.09E-08	2.07E-07	0.00%
Phosphorus-32	5.39E-07	1.04E-10	2.40E-05	2.45E-05	0.00%
Argon-41	0.00E+00	5.58E-06	0.00E+00	5.58E-06	0.00%
Chromium-51	8.89E-08	3.77E-07	2.52E-07	7.18E-07	0.00%
Manganese-52	3.03E-07	8.09E-07	1.00E-06	2.12E-06	0.00%
Manganese-54	2.16E-06	5.86E-05	5.48E-05	1.16E-04	0.00%
Manganese-56	6.46E-09	1.20E-08	0.00E+00	1.84E-08	0.00%
Iron-55	9.65E-07	3.44E-10	1.18E-04	1.19E-04	0.00%
Iron-59	2.58E-06	6.32E-06	7.61E-06	1.65E-05	0.00%
Cobalt-58	9.99E-07	7.44E-06	2.61E-06	1.11E-05	0.00%
Cobalt-60	1.32E-05	6.71E-04	8.75E-05	7.71E-04	0.02%
Nickel-63	1.36E-09	0.00E+00	1.78E-08	1.92E-08	0.00%
Copper-64	9.69E-08	1.48E-08	2.79E-08	1.40E-07	0.00%
Zinc-65	9.41E-07	1.31E-05	1.10E-04	1.24E-04	0.00%
Krypton-85	0.00E+00	1.50E-04	0.00E+00	1.50E-04	0.00%
Krypton-85m	0.00E+00	6.63E-05	0.00E+00	6.63E-05	0.00%
Krypton-88	0.00E+00	5.11E-01	0.00E+00	5.11E-01	**16.20%**
Strontium-89	5.51E-08	6.99E-12	2.83E-07	3.38E-07	0.00%
Strontium-90	1.14E-08	4.74E-14	7.79E-07	7.90E-07	0.00%
Yttrium-90	2.22E-10	9.17E-14	1.41E-10	3.63E-10	0.00%
Zirconium-95	1.10E-06	4.95E-06	3.57E-07	6.41E-06	0.00%
Niobium-95	3.24E-07	1.03E-06	1.75E-07	1.53E-06	0.00%
Molybdenum-99	3.28E-07	1.70E-08	6.39E-07	9.85E-07	0.00%
Technetium-99m	5.02E-10	4.64E-10	4.12E-10	1.38E-09	0.00%
Ruthenium-103	1.30E-07	1.79E-07	5.66E-08	3.66E-07	0.00%
Ruthenium-106	2.45E-07	1.02E-07	1.43E-07	4.90E-07	0.00%
Silver-110m	2.19E-08	3.17E-07	1.17E-06	1.51E-06	0.00%
Iodine-131	9.79E-04	1.08E-04	3.36E-01	3.37E-01	10.68%
Iodine-132	3.17E-05	2.11E-04	0.00E+00	2.42E-04	0.01%
Iodine-133	1.13E-03	9.55E-05	2.42E-02	2.54E-02	0.81%
Iodine-134	4.25E-05	4.25E-04	0.00E+00	4.68E-04	0.01%
Iodine-135	1.61E-04	5.11E-04	1.85E-04	8.57E-04	0.03%

Radionuclide	Inhalation Dose µSv/y	External dose (cloud and deposited) µSv/y	Food dose µSv/y	Total dose µSv/y	% Contribution
Xenon-133	0.00E+00	6.06E-04	0.00E+00	6.06E-04	0.02%
Caesium-134	5.23E-07	1.26E-05	6.10E-05	7.42E-05	0.00%
Caesium-136	5.33E-08	2.30E-07	1.18E-06	1.46E-06	0.00%
Caesium-137	5.52E-07	3.49E-05	7.44E-05	1.10E-04	0.00%
Barium-140	4.35E-06	5.17E-06	2.33E-06	1.19E-05	0.00%
Lanthanum-140	2.11E-07	1.77E-07	7.52E-08	4.63E-07	0.00%
Cerium-141	1.73E-07	2.15E-08	5.70E-08	2.51E-07	0.00%
Cerium-144	3.31E-07	6.23E-09	3.31E-07	6.68E-07	0.00%
Pb-212	1.08E-05	2.63E-09	2.33E-08	1.08E-05	0.00%
Total dose µSv/y	**0.08**	**0.51**	**2.56**	**3.15**	

Table A-10: Estimated Stage 2 Dose to Wildlife (Gaseous Discharge, Noble Gases Modeled as Xe-133)

Radionuclide	Dose rate µGy/h	% Contribution
Tritium	5.4E-04	6.82%
Carbon-14	7.1E-03	90.13%
Sodium-24	6.1E-10	0.00%
Phosphorus-32	1.6E-07	0.00%
Argon-41	9.2E-08	0.00%
Chromium-51	1.2E-09	0.00%
Manganese-52	2.4E-09	0.00%
Manganese-54	2.6E-07	0.00%
Manganese-56	1.1E-11	0.00%
Iron-55	1.2E-07	0.00%
Iron-59	2.4E-08	0.00%
Cobalt-58	3.0E-08	0.00%
Cobalt-60	3.6E-06	0.04%
Nickel-63	1.1E-10	0.00%
Coppr-64	1.7E-10	0.00%
Zinc-65	1.3E-07	0.00%
Krypton-85	1.9E-05	0.24%
Krypton-85m	3.0E-07	0.00%
Strontium-89	5.5E-10	0.00%
Strontium-90	4.4E-09	0.00%
Yttrium-90	2.1E-14	0.00%
Zirconium-95	7.6E-09	0.00%
Niobium-95	3.8E-09	0.00%
Molybdenum-99	1.4E-10	0.00%
Technetium-99m	1.5E-12	0.00%
Ruthenium-103	1.4E-09	0.00%
Ruthenium-106	6.4E-09	0.00%
Silver-110m	1.5E-09	0.00%
Iodine-131	1.2E-06	0.01%
Iodine-132	4.4E-07	0.01%
Iodine-133	9.8E-07	0.01%
Iodine-134	5.4E-07	0.01%
Iodine-135	1.3E-06	0.02%
Xenon-133	2.1E-04	2.60%
Caesium-134	1.6E-07	0.00%

Radionuclide	Dose rate μGy/h	% Contribution
Caesium-136	1.9E-09	0.00%
Caesium-137	6.4E-06	0.08%
Barium-140	1.2E-07	0.00%
Lanthanum-140	4.7E-10	0.00%
Cerium-141	5.7E-11	0.00%
Cerium-144	1.9E-10	0.00%
Lead-212	3.9E-09	0.00%
Total dose rate μGy/h	**7.9E-03**	

APPENDIX B Forward Action Plan

The following actions have been identified for incorporation into the Forward Action Plan for development of a UK version of the BWRX-300 SMR:

Table B-1: Forward Action Plan

Action ID	Source	Finding	Forward Action	Lead Discipline	Delivery Phase
PER9-116	PER Chapter E9	A considerable expansion in the detail of source terms will be needed for later stages of regulator assessment.	The current annual average liquid/airborne discharge source terms are overly conservative and need to be re-evaluated.	GEH	For PCSR/PCER
PER9-117	PER Chapter E9	Regulator expectation is for the radiological assessment to be performed at the proposed discharge limits.	Discharge limits for liquid and gaseous discharges to be confirmed.	GEH	For PCSR/PCER
PER9-118	PER Chapter E9	A more detailed dose assessment is required.	PC-CREAM 08 offers more comprehensive assessment of prospective individual and collective doses for routine continuous discharges of liquid and gaseous radioactive effluents. This can be performed using generic data. The dose assessment can be further refined using site-specific data when a site has been identified.	Environmental – Radiological Assessment	For PCSR/PCER

Action ID	Source	Finding	Forward Action	Lead Discipline	Delivery Phase
PER9-119	PER Chapter E9	The IRAT2 tool used for Step 1 and Step 2 considers the following exposure pathways: Liquid discharges: external radiation from radionuclides deposited in shore sediments & consumption of seafood incorporating radionuclides. Gaseous discharges: Inhalation of radionuclides in the effluent plume, external radiation from radionuclides in the effluent plume and deposited to the ground, consumption of terrestrial food incorporating radionuclides deposited to the ground.	Review and expansion of potential exposure pathways.	Environmental – Radiological Assessment	For PCSR/PCER
PER9-120	PER Chapter E9	Direct radiation dose has been based on a review of OPEX from U.S. operational BWR plants.	The direct dose rates should be assessed for the BWRX-300 based on mathematical modeling of buildings containing a source term.	Physics – Radiation Protection	For PCSR/PCER
PER9-121	PER Chapter E9	The dose due to a short-term release has not been assessed during Step 1 or Step 2.	Develop a scenario for a short-term release over a 24-hour period, identify exposure pathways and habits data, model dispersion and assess the dose associated using methodology detailed in NDAWG Guidance Note 6B.	Environmental – Radiological Assessment	For PCSR/PCER

Action ID	Source	Finding	Forward Action	Lead Discipline	Delivery Phase
PER9-122	PER Chapter E9	The dose due to a build-up of radionuclides in the environment has not been assessed during Step 1 or Step 2.	Use PC-CREAM 08 to make an assessment of whether the build-up of radionuclides in the local environment of the facility, based on the anticipated lifetime discharges, have the potential to prejudice legitimate users or uses of the land or sea.	Environmental – Radiological Assessment	For Site License Application
PER9-123	PER Chapter E9	The contribution to dose due to historical or future discharges from other nearby facilities has not been considered during Step 1 or Step 2.	Consideration of historical and future discharges from other facilities in the locality.	Environmental – Radiological Assessment	For Site License Application
PER9-124	PER Chapter E9	The IRAT2 tool used for Step 1 and Step 2 assesses dose for a coastal fishing family (liquid discharges) and a local resident family (gaseous discharges).	Review and confirm the candidates for the representative person, including for direct radiation.	Environmental – Radiological Assessment	For PCSR/PCER
PER9-125	PER Chapter E9	Habit data has not been considered during the Step 1 and Step 2 prospective dose assessment.	Use NRPB-W41 (Generalised habits data for radiological assessments) to identify realistic habit data for the detailed dose assessment. Use CEFAS radiological habits survey data for the site-specific dose assessment.	Environmental – Radiological Assessment	For PCSR/PCER

Action ID	Source	Finding	Forward Action	Lead Discipline	Delivery Phase
PER9-126	PER Chapter E9	Food ingestion habits have not been considered during the Step 1 and Step 2 prospective dose assessment.	Use NRPB-W41 (Generalised habits data for radiological assessments) and the 'top two' approach to generate realistic consumption data for the detailed dose assessment. Use CEFAS radiological habits survey data for the site-specific dose assessment.	Environmental – Radiological Assessment	For PCSR/PCER
PER9-127	PER Chapter E9	IRAT2 assumes Category D conditions (neutral stability, typically overcast) persist for 50 % of the time. This is a conservative approach for most locations in the UK, since the assumed meteorological conditions over-represents those conditions that lead to the highest surface air concentrations when the source is at ground level.	Site-specific meteorological data will be required for the site-specific dose assessment.	Environmental – Radiological Assessment	For Site License Application
PER9-128	PER Chapter E9	The Step 1 and 2 dose assessment assumes a uniform windrose and that the local resident and terrestrial wildlife being located at 100 m from the release point for 100% of the time, and food produced at 500 m from the release point.	Perform gaseous dispersion modeling using site-specific meteorological data to assess ground-level activity concentrations (Bq/m^3) and identify receptor locations.	Environmental – Radiological Assessment	For Site License Application
PER9-129	PER Chapter E9	Step 2 assumed a stack height of 35 m, noting that the turbine building roof is at an elevation of approximately 31.5 m, which may not be the optimum stack height to ensure that public exposures to gaseous discharges are ALARA.	Perform a stack height study using ADMS (or equivalent) to identify the stack height above which benefits of improved dispersion from greater release height start to diminish.	Environmental – Radiological Assessment	For Site License Application

Action ID	Source	Finding	Forward Action	Lead Discipline	Delivery Phase
PER9-130	PER Chapter E9	A simple and cautious assessment of exposure for NHS has been made using IRAT2.	A more complex assessment of the dose to NHS should be performed using the ERICA tool.	Environmental – Radiological Assessment	For PCSR/PCER
PER9-131	PER Chapter E9	The uncertainty in the Step 1 and Step 2 prospective dose assessment has not been considered.	An assessment should be made of the uncertainty and variability associated with key assumptions for the detailed and site-specific dose assessments.	Environmental – Radiological Assessment	For PCSR/PCER