Assessing new nuclear power station designs

Generic design assessment of Hitachi-GE's Advanced Boiling Water Reactor

Assessment report - AR09 Public Dose

12 December 2016

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- Adviser: principal adviser to Welsh Government, and adviser to industry and the wider public and voluntary sector, and communicator about issues relating to the environment and its natural resources
- Regulator: protecting people and the environment including marine, forest and waste industries, and prosecuting those who breach the regulations that we are responsible for
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- Employer: of almost 1,900 staff, as well as supporting other employment through contract work.

Published by:

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Executive summary

Protective status	This document contains no sensitive nuclear information or commercially confidential information.

Process and Information Document[1]	The following Sections of Table 1 in our process and information document (P&ID) are relevant to this assessment: Item 7: a prospective radiological assessment at the proposed limits for discharges and for any on-site incineration. This lays down the main areas to be covered in the dose assessment.

Radioactive Substances Regulation Environmental Principles[2]	The following Regulation Environmental Principles (REPs) are relevant to this assessment:
	Fundamental Principle E – Protecting Human Health and the Environment Specifically the following REPs are partly or completely relevant: SEDP1 - General RSR Principle for siting new facilities SEDP2 - Movement of radioactive material in the environment RPDP1 - Optimisation of protection RPDP2 - Dose limits and constraints RPDP4 - Prospective dose assessments for radioactive discharges to the environment

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In order to demonstrate that radioactive discharges resulting from the operation of a reactor design would not challenge the UK's dose constraints and limit for the radiation exposure of the public, we require a radiological impact assessment to be carried out by reactor vendors, in this case Hitachi-GE.

We have carried out an assessment of Hitachi-GE's radiological assessment that it provided under generic design assessment (GDA) for the UK Advanced Boiling Water Reactor (UK ABWR). This assessment report addresses important parts of the process and information document (P&ID)

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[1] Process and Information Document for Generic Assessment of Candidate Nuclear Power Plant Designs, Version 2, Environment Agency, Mar 2013. http://webarchive.nationalarchives.gov.uk/20151009003754/https://www.gov.uk/government/publications/assessment-of-candidate-nuclear-power-plant-designs

[2] Regulatory Guidance Series, No RSR 1: Radioactive Substances Regulation – Environmental Principles, Version 2), Environment Agency, April 2010. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/296388/geho0709bqsb-e-e.pdf

(Environment Agency, 2013) and relevant parts of the Radioactive Substances Regulation Environmental Principles (REPs) (Environment Agency, 2010).

We have assessed information in the GDA submission Hitachi-GE made for the UK ABWR (Hitachi-GE, 2016a), with respect to prospective (future) doses to members of the public as a result of the disposal of liquid and gaseous radioactive waste from the UK ABWR to the environment.

We appointed contactors to verify and validate the radiological impact assessment Hitachi-GE made for the UK ABWR at the generic site, and to make an independent assessment of doses to members of the public from the UK ABWR at the generic site (Environment Agency, 2016a).

A number of the sites listed in the Nuclear National Policy Statement as potentially suitable for a new nuclear power station are adjacent to existing nuclear power stations, including Oldbury in Gloucestershire and Wylfa on Anglesey. The first site at which the UK ABWR might be constructed is Wylfa, Oldbury may also be a site for the UK ABWR in the future. These locations have been taken into account in the generic site description (Hitachi-GE, 2016b; Environment Agency, 2016b) that was used in the dose assessment Hitachi-GE carried out (Hitachi-GE, 2016a) and in our independent dose assessment (Environment Agency, 2016a).

Hitachi-GE's dose assessment indicates that, potentially, the highest total doses will be between 14-24 micro-Sieverts per year (μSv/y). This will be from a single UK ABWR reactor. The highest dose of 24 μSv/y would be to an infant assumed to be consuming milk produced around the site. Most of the dose is predicted from the intake of carbon-14, released in gaseous effluent, in local foodstuffs.

Our independent assessment indicates the highest total dose is more or less the same ranging from 14-24 μSv/y. Most of the dose is from carbon-14 in gaseous discharges. The highest dose is to an infant consuming local milk and milk products. This is the same outcome as Hitachi-GE's assessment.

We conclude that doses from a single UK ABWR will be well below the dose constraint for members of the public of 300 μSv/y, (Stationary Office 2010) and the dose constraint recommended by Public Health England for new reactors of 150 μSv/y (Health Protection Agency, 2009). The assessed doses are also well below the public dose limit of 1,000 uSv/y (Stationary Office, 2010; EC, 1996).

Contents

1. Introduction

In order to assess the potential radiological impact of a particular reactor design we need to assess the potential radiation exposure of members of the public. These may result from discharges of radionuclides and from any exposure off-site from direct radiation from radioactive sources within the reactor structures. Prospective dose assessments are required to determine the potential radiological impact of a reactor design and to inform optimisation decisions at the design stage.

At the generic design assessment stage (GDA) we need to satisfy ourselves that:

- the reactor design is such that any radiological impacts would be acceptable to the UK
- any particular features of the reactor design that may lead to impacts of a type or size that could constrain the locations at which such a plant could be located are identified
- any radiological impacts of new build reactors in the UK are as low as reasonable achievable (ALARA), in line with the policy set out in the Energy white paper (BERR, 2008) and in the Environmental Protection Regulations 2010 (Schedule 23) (Stationary Office, 2010)

The assessment Hitachi-GE provided is of the predicted radiological impact of the UK ABWR on people and wildlife from discharges into the environment (at requested permit limits) and from direct radiation (Hitachi-GE, 2016a). Our assessment of the Hitachi-GE submission is to make sure that it is comprehensive, is based on a valid approach and is technically correct. We have also commissioned an independent assessment, taking into account the information Hitachi-GE provided. The report of this assessment will be reported separately as an independent dose assessment, verification and validation in this assessment report (Environment Agency, 2016a).

The Environment Agency and Natural Resources Wales regulate the discharges of radioactive waste into the environment during normal operation, making sure that any radiation exposure of the public that may result is within the statutory dose limits and constraints. The Office for Nuclear Regulation (ONR) is responsible for regulating nuclear safety, including making sure that doses to the public resulting from direct radiation during normal operation are acceptable and below the statutory dose limits. Direct radiation is received directly from radioactive sources within a nuclear power station, instead of indirectly as a result of radioactive discharges.

This assessment report considers the information Hitachi-GE provided for its UK ABWR design. We appointed a Technical Specialist Contractor (TSC), (Quintessa) to review the information and make a technical assessment by validating the approach Hitachi-GE took and verifying the results. Our TSC, also carried out an independent assessment of the predicted environmental activity concentrations and radiological impact to people and wildlife from the UK ABWR at a generic site (Environment Agency, 2016a). The generic site was based on the one Hitachi-GE provided. However, the generic site for our independent assessment took into account the relevant characteristics of other UK locations where a UK ABWR might be constructed in future. Some variations in modelling assumptions and inputs from the generic site were applied in our independent assessment (Environment Agency, 2016a).

2. Radioactive Substances Regulation Environmental Principles (REPs)

In the REPS (Environment Agency, 2010) the following are partly or completely relevant to this assessment:

Fundamental Principle E – Protecting Human Health and the Environment

SEDP1 General RSR Principle for siting new facilities - When evaluating sites for a new facility, account shall be taken of the factors that might affect the protection of people and the environment from radiological hazards and the generation of radioactive waste.

We have produced a separate assessment report on the generic site proposed by Hitachi-GE and used in its assessment (Environment Agency, 2016c).

SEDP2 Movement of radioactive material in the environment - Data shall be provided to allow the assessment of rates and patterns of movement of radioactive materials in the air and the aquatic and terrestrial environments around sites.

RPDP1 Optimisation of protection - All exposures to ionising radiation of any member of the public and of the population as a whole shall be kept as low as reasonably achievable (ALARA), economic and social factors being taken into account.

RPDP2 Dose limits and constraints - Radiation doses to individual people shall be below the relevant dose limits and constraints.

RPDP4 Prospective dose assessments for radioactive discharges to the environment - Assessments of potential doses to people and to non-human species shall be made prior to granting any new or revised authorisation for the discharge of radioactive wastes into the environment.

2.1. Process and information document (P&ID)

In our P&ID (Environment Agency, 2013), we set out our requirements to a requesting party (RP). Table 1 shows the information that a requesting party is required to provide in its submission to address radiological assessment.

Table 1. Information required for prospective radiological assessment

Information required (Item 7)	Main REPs & references
A prospective radiological assessment at the proposed limits for discharges and for any on-site incineration. Include: • annual dose to most exposed members of the public for liquid discharges*; • annual dose to most exposed members of the public for gaseous discharges, identifying separately 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 • 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	REPs: RPDP2 and 4 References: Environment Agency et al., 2012

Information required (Item 7)	Main REPs & references
lifetime discharges, might have the potential to prejudice legitimate users or uses of the land or sea • collective dose up to 500 years to the UK, European and world populations • dose-rate to non-human species*# You should tell us which models you used to calculate these doses and why they are appropriate, and set out all the data and assumptions, with reasoning, that you used as input to the models. For those items marked with an asterisk (*), we recommend that you use our initial radiological assessment tool - IRAT (which is available on request), refining the default data to reflect the characteristics of your facility and generic site.	

3. Assessment

3.1. Our assessment method

Our overall assessment method included the following main steps:

- considering the generic environmental permit (GEP) submissions Hitachi-GE made, in particular the prospective dose assessment document (Hitachi-GE, 2016a)
- discussions with Hitachi-GE to clarify our understanding of the information presented and to explain any concerns we had with that information; where we believed information Hitachi-GE provided was still not enough, we considered raising Regulatory Issues (RIs), Regulatory Observations (ROs) or Regulatory Queries (RQs)
- verifying and validation of the assessment submitted Hitachi-GE submitted
- carrying out our own independent assessment (by TSC) using the information Hitachi-GE provided
- determining whether any potential GDA Issues or other issues should be carried forward from GDA

The prospective assessment of doses to members of the public requires 5 main activities:

- defining the environmental features of the generic site
- determining the input data and models, for example expected discharges of aqueous and gaseous radioactive waste (‘source term’) and models and methods for predicting environmental dispersion, concentrations and dose rates in the environment
- establishing the likely off-site radiation exposures from ‘direct radiation’
- calculating, using models, of the exposure situations, for example activity concentrations and external dose rates in the environment
- calculating doses to the public

3.2. Timeline of submissions and assessment

Hitachi-GE made 6 versions of its submission for the prospective dose assessment, which is part of the GEP. The changes to the submissions were influenced by activities in other parts of the GDA, in particular direct radiation, reactor chemistry and discharges arising from the source term. Table 2 below shows the prospective dose modelling/assessment submissions Hitachi-GE made.

Table 2 - Timeline of prospective dose submissions

Date	Document	Revision	Reviewed / assessed
December 2013	GA91-9901-0026-00001	A	Initial feedback.
March 2014	GA91-9901-0026-00001	B	RQs raised.
April 2014	GA91-9901-0026-00001	C	RQs raised
August 2014	GA91-9901-0026-00001 (First discharges source term). (Revised direct radiation) (RQs closed)	D	Initial assessment Verification, validation and independent assessment using TSC. Feedback provided to Hitachi-GE in meetings in February and March 2015.
February 2016	GA91-9901-0026-00001 (Second discharges source term)	E	Detailed assessment. Most verification and validation completed confirmation that RQ responses were present. New RQs raised.
July 2016	GA91-9901-0026-00001 (Third discharges source term) (RQs closed)	F	Detailed assessment. Finalisation of verification and validation. Independent assessment completed. Confirmation that RQ responses were present.

3.3. GDA Step 1

The first 3 submissions (Revisions A to C) were made under Step 1. We provided feedback on Revision A and raised formal RQs on Revisions B and C.

3.4. Modelling approaches

Mathematical models are used to calculate the dispersion of radionuclides in the environment and provide predictions of radionuclide concentrations in air, soil, food, water and sediment at future times. The predicted radionuclide concentrations are then combined with information on human habits such as occupancy times and food consumption data to build-up a picture of future potential doses.

Hitachi-GE proposed to use several models for predicting environmental dispersion. It proposed using the PC-CREAM 08 software system (Smith et al., 2009) in assessing the dispersion of radionuclides expected to be discharged over the expected generating lifetime of the reactor (60 years).

The PC-CREAM 08 software system (Smith et al., 2009) implements a series of models specifically designed for assessing environmental concentrations from continuous discharges of radioactive wastes made under normal operation. The models are suitable for assessing the fate of long-term continuous discharges, and calculates average concentrations of radionuclides over a number of years – of gases to air and of liquid waste to the water (aqueous) environment. The software uses the predicted concentrations to calculate the annual radiation doses to members of the public.

The environmental concentrations predicted by PC-CREAM 08 take into account build-up of discharged radionuclides over the period of discharges. Environmental concentrations can be calculated, allowing for build-up in soil, vegetation and farm animals, sea water, suspended sediment, sea bed sediment, fish and shellfish.

For the UK ABWR Hitachi-GE has provided information that indicates that the reactor systems are designed to recycle most liquid waste rather than discharge it. Therefore, discharges of radionuclides in liquid effluent are expected to be very low. The discharges made to the atmosphere are expected to be greater than those in liquid effluent.

In addition to the continuous discharges made at a constant rate, there is a need to consider elevated discharges over short periods as a result of foreseeable events, such as during shut-down or start-up.

The PC-CREAM 08 system is not designed for assessing short duration releases of gases. Other models are available to assess short duration releases to the atmosphere. Appropriate short duration release models include ADMS (CERC, 2012) and AERMOD (US EPA, 2004). Hitachi-GE has used the ADMS model version 5 (CERC, 2012). This model can provide estimates of transient concentrations of pollutants in air at ground level from a defined release over time frames of 30 minutes. Deposition onto the ground and through the environment, including in soil and the plants are derived from the short duration air concentrations.

Collective doses to the UK, Europe and the world from discharges also need to be assessed. This takes into account the distribution of radioactivity over these population groups. The PC-CREAM 08 system is suitable for calculating collective doses from gaseous discharges and liquid discharges. Hitachi-GE has used PC-CREAM 08 (Smith et al., 2009) to estimate collective doses over 500 years to these populations per year of discharge.

3.5. UK ABWR source term - discharges to air and to water

The UK ABWR source term and discharges to air and water is a main input to the prospective dose modelling assessment. The source term for discharges to air and water used in Revision F of the dose assessment is described in ‘Quantification of discharges and limits’ Revision F (Hitachi-GE, 2016c).

Hitachi-GE presented 3 source terms for discharges to air and water during the development of the GEP submission. Table 2 shows the 3 source terms for discharges to air and water that were used with the revisions of the prospective dose assessment.

The source term for discharges changes occurred as a result of Hitachi-GE’s changes to the full UK ABWR source term. It made the changes in response to RQs, ROs and an RI related to the full UK ABWR source term submitted to the ONR and the Environment Agency.

The full UK ABWR source term development by Hitachi-GE; the RQs, the ROs and the RI are not the subject of this part of the assessment. The discharges source term used by Hitachi-GE in Revision F (Hitachi-GE, 2016a) of the prospective dose modelling report is summarised in Appendix A. Revision F is the latest version and will be what the draft decision in the consultation is based on.

3.5.1. Discharges to air

The discharges to air occur via the main stack. The main stack is supplied by discharges from the off-gas system, the heating, ventilation and air conditioning system (HVAC) and the turbine gland steam system (TGS).

Discharges from the off-gas (OG) system are noble gases and carbon-14. The OG features charcoal decay beds that remove iodine and reduce the discharge of noble gases.

Discharges from the HVAC include iodine, tritium and particulates carrying metallic radionuclides such as chromium-51, cobalt-60 and caesium-137.

Most of the discharges from the TGS are of tritium.

3.5.2. Discharges as liquids

The discharges as liquids are expected to be very low in terms of quantity of liquid and amount of radionuclides. This is because the UK ABWR recycles much of the liquid as reactor make-up water. The main radionuclide discharged is tritium.

3.5.3. Result from GDA step 1

Twenty six RQs were raised during the assessment and are summarised in Table 3. The RQs were mostly related to the proposed dose assessment methods. This allowed Hitachi-GE to address RQs on the assessment method early and to allow it to include as much of the relevant information as possible before Hitachi-GE provided its submission for us to assess during our initial assessment stage.

Table 3 - Regulatory queries raised on the prospective dose modelling document Revisions B and C

RQ number	Content
RQ-ABWR-0061	Reason for using caesium-137 as a surrogate for other radionuclides in the source term for the assessment is needed.
RQ-ABWR-0062	Predicted build-up of radionuclides in the environment with time – reason for selecting radionuclides to present in the figures is needed.
RQ-ABWR-0063	Calculation of doses to the foetus is needed for the detailed assessment.
RQ-ABWR-0064	Reason for differences in dominant radionuclides (in terms of dose) between the Japanese ABWR and UK ABWR is needed.
RQ-ABWR-0065	Sources of information for expected discharges are not referenced correctly.
RQ-ABWR-0066	The method for undertaking a ‘top 2’ dose assessment is not presented.
RQ-ABWR-0067	Milk products omitted from Table 5.3-2 of the Hitachi dose assessment
RQ-ABWR-0068	Source of data.
RQ-ABWR-0069	Volumetric exchange rate for Stage 2 assessment.
RQ-ABWR-0108	Inconsistent presentation of particulate releases from short-term releases.
RQ-ABWR-0109	Provide references to support statements concerning a scaling factor.
RQ-ABWR-0110	Clarify the reason for selecting 57m for the stack height for the UK ABWR.

RQ number	Content
RQ-ABWR-0111	Clarification of footnotes to tables is needed.
RQ-ABWR-0112	Consideration of appropriate radionuclides to be shown in figure of seabed sediment concentrations is needed.
RQ-ABWR-0113	A more complete justification to support the statement that ‘it is concluded that the predicted radiological consequences will be independent of the duration of the discharges beyond 30 years is required.
RQ-ABWR-0114	More information is needed on which ‘radionuclides are of interest’ and why they are of interest.
RQ-ABWR-0115	Consideration of appropriate radionuclides to be shown in figure of soil concentrations is needed.
RQ-ABWR-0116	Justification for using PC-CREAM 08 for the Stage 3 assessment is needed.
RQ-ABWR-0117	Clarification of figure legends is needed.
RQ-ABWR-0118	Direct radiation exposure of the fisherman family (from external exposure to sediment) - reason why this has not been assessed is needed.
RQ-ABWR-0119	The relationship between Pasquill stability categories used and the ADMS 5 model parameters needs to be explained.
RQ-ABWR-0120	Clarification of the skin dose calculation methodology is needed.
RQ-ABWR-0121	Explanation of the environmental concentrations from short duration releases needs to be extended.
RQ-ABWR-0122	Explanation of the collective dose results needs to be improved.
RQ-ABWR-0123	Dose criteria and their application to prospective dose assessment in GDA needs to be presented more clearly.
RQ-ABWR-0124	The explanation of the potential impact on the future use of sea or land needs to be made clearer.

3.5.4. GDA – initial assessment

The first formal initial assessment was made of Revision D of the prospective public dose modelling. This involved a detailed technical review. The assessment objectives for the GDA process were:

- Is the radiological impact assessment Hitachi-GE carried out reasonable and justified?
- Can the radiological impact assessment Hitachi-GE carried out be independently validated and verified?
- Are the predicted doses to members of the public below the relevant dose constraints?

A TSC was employed to carry out this independent technical assessment. The aim of the independent assessment was to:

- validate the assumptions and method Hitachi-GE used in its dose assessments
- verify the results and repeat the dose assessments Hitachi-GE carried out
- carry out independent dose assessments to further demonstrate that the dose assessment provided by Hitachi-GE were appropriate

3.5.5. Initial assessment outcomes - Revision D

Several technical matters arose from the verification and validation. These are summarised in Table 4 below.

Table 4 - Technical matters related to verification and validation of the Prospective dose modelling report Revision D

Verification and validation activities
Verification activities
Doses from eating food grown on land affected by atmospheric release could not be verified for children and infants. Investigation suggests that this is because the adult intake rates have been used for infants and children.
Dose rates from beta irradiation by radionuclides deposited on the ground, following atmospheric discharge, differ significantly between the assessments for all age groups. Due to differences in beta dose factors from an older data library in an earlier version of PC-CREAM 08.
Doses from short-term discharges to atmosphere could not be verified. It was not clear which atmospheric dispersion modelling system (ADMS) parameters had been adopted. The conditions specified appeared unrepresentative of the stability conditions they were supposed to represent.
Soil concentrations, for a 60 year continuous gaseous discharge could not be verified for caesium-137, tellurium-125m (ingrown from antimony-125) and uranium-234 (ingrown from plutonium-238).
Air concentrations from a continuous gaseous release could not be verified for radioactive progeny (see glossary). It is suspected that this is related to the calculation method – Hitachi-GE scaled unit discharges, whereas the verification calculations used the specified discharge rate directly in PC-CREAM 08. However, it is not possible to be certain as the method Hitachi-GE used for determining the air concentrations of progeny is not described.
First pass collective doses for atmospheric discharges could not be verified due to the differences in the calculated external dose rate from beta emitters deposited on the ground. This is due to differences in beta dose factors from an older data library in an earlier version of PC-CREAM 08.
Validation activities
The validation activity compared the approach Hitachi-GE took in its dose assessment with the Principles for prospective public dose (Environment Agency et al., 2012). Four of the 13 principles were not completely addressed in the Hitachi-GE dose assessment: Principle 1 (Documentation) – In some cases, there is limited explanation and justification about why a particular assumption in the assessment has been made. Principle 2 (Exposure of workers) – Exposure of workers is unlikely to be directly relevant in GDA, however the potential exposure of such groups is not discussed. Principle 6 (Other sources of exposure) – No account has been taken of the potential contribution of other sources (nearby sites and residue from historic discharges) to an individual's exposure, however this principle is only indirectly relevant. Principle 13 (Uncertainty and variability) – There is no exploration of uncertainty and variability for the atmospheric discharge pathway, despite the calculated doses exceeding the 0.02 mSv/y criterion used to indicate the need for assessment of uncertainty and variability. There is some

Verification and validation activities
limited discussion of the sensitivity of doses from liquid discharges to marine properties. However, the doses from liquid discharges are very much less than the dose criterion.
There is no discussion of the basis for selecting the generic site parameters, or whether they are suitably cautious for the GDA. There is consequently limited insight into the rationale for the assessment basis.
The reasons for including seaweed ingestion as a pathway are not clear, and the selected consumption rate is a lower option without a supporting justification for using it.
The meteorological conditions assumed for the short-term discharge scenario to the atmosphere are unlikely to be sustainable for 24 hours. The assumption is mid-summer in the growing season, which is important for nuclides that can enter the food chain. Category D conditions would not be expected to be sustained for more than a few hours in mid-summer due to the energy input from strong sunshine. However, in the Hitachi-GE assessment category D for a given time of day and therefore insolation, were assumed to persist over a 24-hour period, with the only variation considered being a slight change in wind direction.
The assumption of category D conditions for gaseous short-term-releases over 24 hours maybe a non-conservative assumption, but is not justified by a supporting argument. We would expect this to be considered in a sensitivity analysis.

We reviewed the technical matters in Table 4 with Hitachi-GE in meetings in February 2015 and March 2015.

Hitachi-GE produced Revision D, E and F, taking into account changes to the source term.

3.5.6. GDA - Detailed assessment of Revision E

Hitachi-GE submitted Revision E of the GEP (Table 2), which took into account the first revision of the source term.

We carried out a detailed review of Revision E. This review considered the resolution of the RQs raised on Revisions B and C; technical matters raised on Revision D (Table 4) and an update of the verification and validation of the dose assessment.

The results of the review of Revision E showed that all except one of the RQs raised on Revisions B and C had been addressed. The majority of the technical matters raised on Revision D and presented in Table 4 had also been addressed in Revision E. One RQ (RQ-ABWR-0110) had not been addressed, so it was raised again as RQ-ABWR-0876.

The direct radiation assessment for members of the public considers sources of direct radiation that are known and exist on current ABWRs. For these the direct radiation dose rate can be assessed based on operational experience. However there will be additional sources of direct radiation that will be arise during future operations in the UK. These are currently at concept stage and therefore the doses to the public cannot easily be assessed. The direct radiation sources that have not been included because they are at concept stage have not been explicitly noted in the Revision E document. We have asked for these to be listed so they can be included in the assessment during site specific permitting.

The direct radiation assessment for members of the public had been updated, drawing on detailed information in a topic report on radiation protection matters. A review of the exposed groups used in the assessment of direct radiation Hitachi-GE provided may not be consistent with the groups considered for atmospheric discharges.

The verification of Revision E identified some changes in the predicted environmental concentrations that had not been documented. This was linked to model input data (marine sediment distribution coefficients (Kds)), which had been used to predict the concentrations of radionuclides in marine sediment and seawater. Therefore, an RQ was raised to establish what marine sediment Kds had been used, and which predicted environmental concentrations presented in Revision E and F had been updated to reflect the Kds.

Therefore, 4 new RQs were raised on Revision E as noted in Table 5.

Table 5. Regulatory Queries raised on the prospective dose modelling document Revision E

RQ number	Content
RQ-ABWR-0876	UK ABWR dose modelling - Stack height reference
RQ-ABWR-0923	Topic report - public dose evaluation from direct radiation for all relevant buildings, including those at concept stage
RQ-ABWR-0924	Receptor locations – consistency between those for direct radiation assessment and the discharge assessment.
RQ-ABWR-0978	Marine sediment Kds used

3.5.7. Detailed assessment of Revision F

The detailed assessment of Revision F consisted of:

- verifying and validating the short duration releases to atmosphere
- the final independent dose assessment

The verification and validation of the assessment in Revision E was taken to apply to Revision F as no further changes to the assessment approach had been declared by Hitachi-GE.

The results of the independent dose assessment were compared with the results presented in Revision F.

The predicted doses from Hitachi-GE's Revision F (Hitachi-GE, 2016a) and our independent assessment (Environment Agency, 2016a) are summarised and presented below. Detail of the doses, including a breakdown by radionuclide, are given in Appendix B.

Revision F included a change to the Hitachi-GE estimate of the discharge source terms.

Three RQs RQ-ABWR-0876, RQ-ABWR-0923 and RQ-ABWR-0924 had been answered in Revision F. Hitachi-GE has also responded to RQ-ABWR 0978 (although our RQ was submitted too late to allow Hitachi-GE's response to be included in Revision F).

4. Results

The results of the dose assessment were compared with the dose constraints for the public set by the Environmental Permitting Regulations 2010 for Radioactive Substances Activities (Schedule 23) (Stationery Office, 2010). The doses are also assessed against the dose limit for members of the public, set in EU legislation. The dose results may also be an input to decisions around BAT and abatement options.

There are no regulatory limits and constraints for collective dose. Collective dose is mainly an input to option comparisons. In addition, collective doses can be converted to per capita doses, which can be assessed against criteria set by Public Health England (PHE).

4.1. Doses from the UK ABWR from Revision F

Hitachi-GE followed 3 stages in its dose assessment as outlined in our dose principles document (Environment Agency et al., 2010). The 3 stages are initial assessment, refined initial assessment and detailed assessment.

4.2. Stage 1 and stage 2 dose assessment

The initial assessments provide an early indication of the size of doses and generally follow a very conservative and generic approach. The dose criterion for initial assessment is 20 µSv/y. Initial assessment of the impact and decisions can be made using a Stage 1 assessment. There is a need for a refined assessment at the second stage if doses are above 20 µSv/y. There is limited additional effort to refine the assessment. The second stage, therefore, is to refine the initial assessment using any more specific data related to expected dispersion or the source term. If doses from the second stage remain above 20 µSv/y, a third stage using a more detailed assessment is carried out using a more detailed model if appropriate.

Hitachi-GE reported the following doses for Stage 1 and 2 (Table 6):

Table 6. Hitachi-GE Stage 1 and Stage 2 doses

	Stage 1 doses (µSv/y)	Stage 2 doses (µSv/y)
Liquid discharges	0.003	0.0003
Gaseous discharges	143	24
Direct radiation	1	1
Total	144	24.5

The main reason for the change in predicted doses between Stage 1 and Stage 2 is due to changes in the modelling assumptions for environmental dispersion. For gaseous discharges, stage 1 assumes a ground level release for gaseous discharges. Stage 2 assumes an effective stack height of 19 m (See glossary for definition). Increasing the stack height leads to more dilution of the release and lower air concentration at ground level at the distances of interest.

Stage 1 for liquid discharges assumes a limited local dispersion of sea water at the releases point, while Stage 2 assumes greater initial dispersion and, therefore, lower radionuclide concentrations in the water.

4.3. Hitachi-GE Stage 3 dose assessment

Hitachi-GE carried out a detailed assessment (Stage 3), which is described below.

The predicted dose results Hitachi-GE produced in Revision F are summarised in the tables below. The source term used and how it was derived are summarised in Appendix A.

Table 7 shows the individual doses to the person most exposed to gaseous discharges were the highest. This person was a possible resident living close to the reactor and consuming local food (Table 7, part a). Their doses were predicted to range from 13 to 24 µSv/y. In addition, the residents were predicted to receive doses of between 0.3 to 0.9 µSv/y from direct radiation. This gives total doses in the range 14-24 µSv/y. Gaseous discharges contribute 90% or more of the overall dose. For all age groups, the main route of exposure from this source is consuming milk and milk products. These contribute up to 45% and 38% respectively of the dose from gaseous discharges for an infant. Carbon-14 is the main radionuclide, giving up to 90% of the total dose.

Individual doses from liquid discharges Hitachi-GE assessed are much lower than those from gaseous discharges. For the most exposed group to liquid discharges who have high beach occupancy and consume local seafood (Table 7, part b) doses are in the range 0.000005 to 0.0002 µSv/y. This group, who are also local to the reactor, are also projected to receive a dose from gaseous discharges (6-10 µSv/y) and between 0.3 and 1 µSv/y from direct radiation. For this group, the dose from gaseous discharges and direct radiation are higher than those received from liquid discharges.

Doses from short duration gaseous releases (Table 7, part c) range from 0.016 to 0.019 µSv/y. Hitachi-GE has assumed that the only radionuclides to be discharged in a short duration release under normal operation will be noble gases to the atmosphere. The assessment assumed a release lasting 24 hours, in summer, late in the growing season and before harvesting. Doses from noble gases arise mainly from external irradiation and are predicted to be low. Noble gases are not taken up in the food chain. Therefore, in this assessment, the time of year assumed for the release (that is, summer and before harvest) has no effect on the doses.

Therefore, the representative person (see glossary for definition) is a possible nearby resident exposed to gaseous discharges and direct radiation. Hitachi-GE's assessment shows that the total dose to the representative person is expected to be between 14 and 24 µSv/y from one reactor.

The potential doses are well below the statutory source dose constraint for the public of 300 µSv/y, (Stationary Office, 2010) and also below the dose constraint proposed by PHE of 150 µSv/y (HPA, 2009) for new nuclear power stations.

A number of the sites listed in the Nuclear National Policy Statement (DECC, 2011a; DECC, 2011b) as potentially suitable for a new nuclear power station are adjacent to existing nuclear power stations. In GDA, the specific site at which a UK ABWR will be located is not yet confirmed. However, it is, therefore, very unlikely that doses at the site will exceed the site dose constraint of 500 µSv/y or the overall dose limit for members of the public of 1000 µSv/y (1 mSv/y). However, if we receive an application for a permit for a site where UK ABWRs will operate, then we will make another dose assessment and compare with the site dose constraint and dose limit for the site.

Table 7. Summary of individual doses from a UK ABWR as reported in Hitachi-GE in Revision F (Prospective dose modelling; Hitachi-GE, 2016a)

7a Overall prospective dose µSv/y to the local fishing family (most exposed to liquid discharges)					
Age group	Liquid discharges	Gaseous discharges	Direct exposure	Total	Rounded* total
Adult	0.0002	6.0	0.9	6.9	7
Child	0.00006	6.7	0.5	7.1	7
Infant	0.000005	9.5	0.3	9.8	10

7b Overall prospective dose µSv/y to the local resident family (most exposed to gaseous discharges)					
Age group	Liquid discharges	Gaseous discharges	Direct exposure	Total	Rounded* total
Adult	0.000009	12.7	0.9	13.6	14
Child	0.000009	14.0	0.5	14.5	15
Infant	0.000002	23.5	0.3	23.8	24

7c Dose µSv to the local resident family (most exposed to gaseous discharges) for a short-term discharge of gases				
Age group	Cloud gamma	Cloud Beta	Total	Rounded* total
Adult	0.005	0.014	0.019	0.02
Child	0.003	0.014	0.017	0.02
Infant	0.002	0.014	0.016	0.02

* see glossary for more details

4.4. Build-up of radionuclides in the environment

Hitachi-GE has modelled the build-up of radionuclides in the environment (sea bed sediment and soil) from 60 years of discharges to the marine environment and to the air. Modelling build-up is to estimate the maximum predicted concentrations in the environment from ongoing discharges and to take them into account in the assessment. The modelling shows all radionuclides increase in concentration with time, some radionuclides such as iodine-131, tritium and zinc-65 are predicted to reach equilibrium within a few years. For marine sediment concentrations increased for longer, taking up to 50 years to reach equilibrium.

4.5. Collective dose

Hitachi-GE has estimated collective doses per year of discharge for the UK, Europe and the world. Collective dose is the sum of all individual effective doses over a defined period of space and time. The calculations are made taking into account the levels of radioactivity in the environment, including food, calculated using appropriate models, including global circulation. Results have been calculated for the UK, Europe and the world for 500 years for one year of discharge. The results are presented in Table 8. These range from 0.18 man-Sievert (manSv) per year of discharge for gaseous discharges in the UK to 30 manSv per year of discharge for the world population. Carbon-14 in gaseous discharges is the main contributor due to its global circulation. Collective doses from liquid discharges are very low, much less than 1 man Sv per year of discharge.

Table 8. Summary of collective doses (up to 500 years) man-Sv per year of discharge from a UK ABWR Hitachi-GE Revision F (Prospective dose modelling; Hitachi-GE, 2016a)

Population	Dose from liquid discharges		Dose from gaseous discharges		Total collective dose
		Rounded*		Rounded *	Rounded*
UK	0.0000004	0.0000004	0.43	0.4	0.4
EU-12	0.000002	0.000002	2.6	2.6	2.6
EU-25	--	--	2.9	2.9	2.9
World	0.00003	0.00003	29.9	30	30

* see glossary for more details

Collective dose can be used as an input into optimisation decisions, including decisions on abatement options.

Collective dose can be used as the basis of average annual individual (per caput) doses. Average annual individual doses for a population group in the nano-Sievert per year (nSv/y) range or below can be ignored in the decision making process as the associated risks are minuscule and the contribution to total doses to individuals will be insignificant. Higher annual doses, up to say a few micro-Sievert per year (µSv/y), can be considered trivial but may require some consideration, particularly if at the higher end of the range. Calculated annual average individual doses in excess of these values should prompt careful consideration of the discharge options being considered.

The Hitachi-GE assessed collective doses were converted to average dose. The average (per-caput) doses from a single UK ABWR unit are equal to 7.2 nano-Sv; 7.2 nano-Sv; 6.3 nano-Sv and 3 nano-Sv for populations of the UK, 12 European countries (EU-12); 25 European Countries (EU-25) and the World respectively.

The IAEA (IAEA, 2000) has previously stated that collective dose (manSv per year of discharge) could be added to an estimate of the relevant collective dose from occupational exposure to provide an estimate of the total collective dose. If the total collective dose is less than about 1 man Sv per year of discharge, it is unlikely to be worthwhile carrying out an extensive formal optimisation study.

Some of the components of collective dose may be characterised by substantial uncertainty. In particular, when radiation exposures from very long lived nuclides persist into the far future, the assessment of the total collective dose is highly speculative and this may invalidate the results of the analysis. In optimisation, however, it is the differences between collective doses for different control options that should be considered.

4.6. Independent assessment

Our independent assessment included an assessment at Stage 1, Stage 2 and in detail at Stage 3. For the initial assessment at Stage 1, our assessment outcome was 143 microsievert per year (µSv/y). For the initial assessment at Stage 2, our assessment outcome was 26 microsievert per year (µSv/y). These initial assessment outcomes are dominated by discharges to atmosphere and do not include direct radiation.

For the detailed assessment at stage 3, our independent assessment results are summarised in Table 9 (for individual doses) and Table 10 for collective doses. More details of the independent dose assessment will be published separately (Environment Agency, 2016a).

For gaseous releases, the independent assessment shows individual doses ranging from 13 to 24 µSv/y. Total doses that include all sources of discharge (gases and liquids) and direct radiation, range between 14 and 24 µSv/y.

Table 9. Summary of individual doses from a UK ABWR calculated in the independent dose assessment (using data from Hitachi-GE Revision F - (Prospective dose modelling; Hitachi-GE, 2016a)

9a Overall prospective dose µSv/y to the local resident family (most exposed to gaseous discharges)					
Age group	Liquid Discharges	Gaseous discharges	Direct radiation	Total	Rounded* total
Adult	0.000063	13.0	0.9	13.9	14
Child	0.000050	14.3	0.5	14.8	15
Infant	0.0000019	24.1	0.3	24.4	24

9b Overall prospective dose µSv/y to the local fishing family (most exposed to liquid discharges)					
Age group	Liquid Discharges	Gaseous discharges	Direct exposure	Total	Rounded* total
Adult	0.00049	7.5	0.9	8.4	8
Child	0.00013	8.8	0.5	9.3	9
Infant	0.000025	12	0.32	12.4	12

9c Dose µSv to the local resident family (most exposed to gaseous discharges) for a short-term discharge of gases						
Age group	Inhalation	External ground	External plume	Ingestion	Total	Rounded* total
Adult daily mean	0	0	0.0041	0	0.0041	0.004
Child daily mean	0	0	0.0028	0	0.0028	0.003
Infant daily mean	0	0	0.0026	0	0.0026	0.003
Adult 2h peak	0	0	0.002	0	0.002	0.002

* see glossary for more details

Doses to the group most exposed to liquid discharges are lower, ranging from 8 to 12 µSv/y. Most of the dose to the group exposed to liquid discharges was actually from gaseous discharges. Doses to this group from liquid discharges were very low - much less than 1 µSv/y.

Doses from short duration releases to atmosphere are between 0.002 and 0.004 µSv per event.

The results between the assessment Hitachi-GE provided (Hitachi-GE, 2016a) and our independent assessment (Environment Agency, 2016a) are broadly similar.

Our assessment confirms that:

- the potential dose will be below the dose limit and constraints
- gaseous discharges are the main component of the doses, with carbon-14 the dominant nuclide
- doses from short duration releases are very low

Table 10. Summary of collective doses from a UK ABWR (man-Sv per year of discharge), calculated in our independent dose assessment (based on Hitachi-GE Revision F - Prospective dose modelling; Hitachi-GE, 2016a)

Population	Dose from liquid discharges		Dose from gaseous discharges		Total collective dose
		Rounded*		Rounded*	Rounded*
UK	0.00000023	0.0000002	0.83	0.8	0.8
EU-25	0.0000011	0.000001	4.5	4.5	4.5

Collective dose per year of discharge due to liquid and gaseous discharges (up to 500 years)

* see glossary for more details

The independent results in Table 10 shows collective doses ranging from 0.8 manSv per year of discharge for the UK to 30 manSv per year of discharge to the world. Most of the collective dose is from carbon-14 in gaseous discharges.

The independent collective doses were used to calculate average annual individual (per caput) doses and compared with those calculated using the Hitachi-GE's estimate of collective dose.

The independent assessment of average annual individual (per caput) doses from a single UK ABWR unit (per year of discharge) are 14 nano-Sv; 9.8 nano-Sv and 3 nano-Sv for populations of the UK, 25 European countries (EU-25) and World respectively. These are similar to those calculated by Hitachi-GE.

4.7. Direct radiation doses

Estimates of direct radiation doses to the public were included in Hitachi-GE Revisions D, E and F (Hitachi-GE 2016a). Hitachi-GE has identified the main direct radiation sources and divided them into 2 groups. One group is direct radiation sources that are known, based on measurements around Japanese ABWRs. The other group are additional direct radiation sources likely to be part of the UK ABWR design but are still at the concept stage only. In GDA, direct radiation doses have been provided for the known sources only. The sources of direct radiation at concept stage are not included in the assessment. (See also Appendix C).

4.8. Conclusion

Hitachi-GE has completed its assessment of the prospective doses to the public from discharges of gaseous radioactive waste, liquid radioactive waste and direct radiation. There were several revisions of the assessment taking into account RQs we raised and changes to the expected discharges (source term).

The doses Hitachi-GE presented in its completed assessment at Revision F (Hitachi-GE, 2016a) are low. The highest doses from the detailed Stage 3, range from 14 to 24 μSv/y to adults and infants respectively. Most of the dose is from gaseous discharges. The main radionuclide is carbon-14. There is a small contribution of up to 1 μSv/y from direct radiation. Doses from liquid discharges are much less than 1 μSv/y due to the very small discharges because of the reactor liquid recycling systems (which minimises liquid discharges).

The doses Hitachi-GE predicted for the discharges from the UK ABWR at Stage 3 are well below the source dose constraint of 300 μSv/y (Stationary Office, 2010) and below the dose constraint of 150 μSv/y proposed by PHE for new nuclear build (HPA, 2009).

Doses from our independent dose assessment are similar to those from Hitachi-GE (Hitachi-GE, 2016a). They range from 14 to 24 μSv/y, mostly from gaseous discharges. Our independent assessment also shows very low doses from liquid discharges. The group most exposed to liquid discharges receives more dose from gaseous discharges and direct radiation than from liquid discharges.

It is unlikely that the doses from a UK ABWR at a site will exceed the site constraint of 500 μSv/y (Stationary Office, 2010) even taking into account future discharges from any other sources, such as nuclear power stations on adjacent sites. This will be re-assessed if a permit at a particular site is applied for. It is unlikely that the dose limit for members of the public of 1,000 μSv/y (Stationary Office, 2010; EC, 1996) will be exceeded even taking into account future discharges, direct radiation and the residues of any past discharges from other sources. This will be re-assessed if a permit at a particular site is applied for.

5. Compliance with Environment Agency requirements

Table 11. Compliance with Environment Agency requirements

P&ID Table 1 Section or REP	Compliance comments
REPs:	
Fundamental Principle E – Protecting human health and the environment SEDP1- General RSR Principle for siting new facilities -	We have produced a separate assessment report (Environment Agency 2016b) on the generic site Hitachi-GE proposed (Hitachi-GE, 2016b) and used in its assessment.
SEDP2 - Movement of radioactive material in the environment	The dose assessment includes information on the expected levels of radionuclides in the environment with time. The movement of air around the site and the movement of radionuclides in air is assumed to occur relatively quickly. Modelling of continuous discharges and short duration releases to atmosphere are also made, which provide an indication of the movement of radioactive material through the environment
RPDP2 - Dose limits and constraints - Radiation doses to individual people shall be below the relevant dose limits and constraints	RPDP2 has been met by the results of Hitachi-GE's prospective assessment and is confirmed by our independent assessment, verification and validation activity
RPDP4 - Prospective dose assessments for radioactive discharges to the environment - Assessments of potential doses to people and to non-human species shall be made prior to granting any new or revised authorisation for the discharge of radioactive wastes into the environment	RPDP4 has been met by Hitachi-GE's prospective assessment and is confirmed by our independent assessment, verification and validation activity
P&ID Section 7 A prospective radiological assessment at the proposed limits for discharges and for any on-site incineration	Hitachi-GE carried out an assessment that included assessing: • annual dose to the most exposed members of the public for liquid discharges • annual dose to the most exposed members of the public for gaseous discharges. On-site incineration is not 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

P&ID Table 1 Section or REP	Compliance comments
	• 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 • 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 legitimate users (or uses) of the land or sea • collective dose up to 500 years to the UK, European and world populations; The models used to calculate the doses are described and the reasons why the models are appropriate. The data and assumptions used as input to the models are set out, with reasoning.

6. Public comments

As at the end of 08 July 2016, we had received no public comments on the expected doses to the public assessed under GDA.

7. Conclusion

We conclude that all the doses Hitachi-GE assessed are below the source dose constraint for members of the public of 300 μSv/y. Doses are also below the dose constraint recommended by PHE for new nuclear build of 150 μSv/y.

We conclude that the sum of doses to the representative person at Hitachi-GE proposed limits is below the site dose constraint and the public dose limit.

A number of the sites listed in the Nuclear National Policy Statement (DECC, 2011a, DECC, 2011b) as potentially suitable for a new nuclear power station are adjacent to existing nuclear power stations. In GDA, the specific site at which a UK ABWR might be located is not defined.

Hitachi-GE's assessment shows that the highest total dose is expected to be between 14 and 24 μSv/y from one reactor.

Most of the dose to the public is from gaseous discharges of carbon-14.

Doses to the public from liquid discharges are very small, much less than 1 μSv/y from one reactor. The low doses are because the discharges of radioactivity as aqueous liquids are very small due to the arrangements for recycling and reusing most liquid waste.

It is, therefore, very unlikely that doses at any site where the UK ABWR is operated, even where there are several units operated together, will exceed the site dose constraint of 500 μSv/y. It is very unlikely that the dose limit of 100 μSv/y will be exceeded.

Our assessment was able to verify and validate Hitachi-GE's assessment.

We carried out an independent assessment. This took into account the sites listed in the Nuclear Policy Statement (DECC, 2011a; DECC, 2011b) and the environmental dispersion factors used. Our assessment found the highest doses from a single reactor to be between 14 and 24 μSv/y.

The assessment shows that most of the dose from discharge is from gaseous discharges of carbon-14. Therefore, careful consideration should be given to the current and future options for the abatement of carbon-14 in gaseous discharges.

In line with our usual procedures we will require a detailed site-specific impact assessment to be carried out during the site-specific permitting stage. The site-specific assessment should consider the actual environmental characteristics of the proposed site and the number of UK ABWR units that will be present. This will be to demonstrate that doses to members of the public and non-human species from the UK ABWR will be as low as reasonably achievable (ALARA) and below relevant dose constraint and dose limits. Comparison against the dose limit should be carried out at site-specific permitting when contributions from all sources of radiation can be included.

There are no potential GDA Issues or GDA Assessment Findings (AFs) arising from the prospective assessment of doses to the public. This is because the expected doses to the public from discharges and direct radiation are well below relevant dose criteria.

We have not made the need for a site-specific assessment a GDA finding because a site specific assessment is a requirement of the permitting process.

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List of abbreviations

Abbreviation	Details
ABWR	Advanced Boiling Water Reactor
ADMS	Atmospheric Dispersion Modelling System
ALARA	as low as reasonably achievable
ALARP	as low as reasonably practicable
BAT	best available techniques
GDA	generic design assessment
GEP	generic environmental permit
HVAC	heating ventilation and air conditioning system
OG	off-gas system
ONR	Office for Nuclear Regulation
P&ID	process and information document
PCSR	pre-construction safety report
PHE	Public Health England
REPs	Regulation Environmental Principles
RI	Regulatory Issue
RO	Regulatory Observation
RQ	Regulatory Query
TGS	Turbine Gland Steam System
TSC	Technical Specialist Contractor – employed by the regulator to provide specialist assessment support
UK ABWR	UK Advanced Boiling Water Reactor

Glossary

Word / Phrase	Meaning
Collective dose	The sum of the individual doses received by a specified population from exposure to a specified source of radiation in a given time period. Typically man-Sv truncated at 500 years from a discharge lasting for one year.
Direct radiation	Radiation emitted from fixed structures containing radioactivity and / or radioactive sources on a site, including the reactor circuit; source stores; spent fuel stores; radioactive waste stores.
Effective stack height (frequently used in the modelling of gaseous releases)	A representation of the release height of gases to atmosphere, which, where relevant, maybe affected by (or may take into account) the physical height of the release point; the wake effects or downdraught effects of nearby buildings of a similar height to or higher than the stack the exit velocity of the discharged gases the temperature of the discharged gases geography / terrain (hills or valleys nearby)
Gaussian (plume) model	One of the oldest (circa 1936) and commonly used model types for atmospheric dispersion of pollutants. It assumes that the air pollutant dispersion has a Gaussian distribution, meaning that the pollutant distribution has a normal probability distribution. Gaussian (plume) models are most often used for predicting the dispersion of continuous, buoyant air pollution plumes originating from ground-level or elevated sources. Gaussian models may also be used for predicting the dispersion of non-continuous air pollution plumes (called puff models). The primary algorithm used in Gaussian modelling is the Generalised Dispersion Equation For A Continuous Point-Source Plume (Paraphrased from Wikipedia)
Pasquill stability category (related to modelling dispersion of discharges to atmosphere)	An historically common method of categorising the amount of atmospheric turbulence present (dating from 1961). Atmospheric turbulence was categorised into six stability classes (A, B, C, D, E and F) with class A being the most unstable or most turbulent class, and class F the most stable or least turbulent class. (Paraphrased from Wikipedia)
Physical stack height (sometimes used in the modelling of gaseous releases)	The height of the top of the stack from which gaseous releases may occur relative to the ground.
Radioactive Progeny	The radioactive isotope that is the product atom formed during the radioactive decay. Also called radioactive daughter. In some cases the product atom may not be radioactive

Word / Phrase	Meaning
Representative person	Characterised individual, either hypothetical or specific, whose dose can be used for determining compliance with the relevant dose constraint. The representative person is ‘an individual receiving a dose that is representative of the more highly exposed individuals in the population.’ This term is the equivalent of and replaces the average member of the critical group. In selecting the characteristics including habits of the representative person, 3 important concepts should be borne in mind: reasonableness, sustainability, and homogeneity.
Rounded (number)	In this report estimated doses may be calculated to several decimal places. This suggests the result is known to a high level of precision, which is not correct given the uncertainties in the calculation. Therefore the results may be rounded to one or 2 significant figures. The standard rounding rules for decimals have been followed.

Appendix A - The UK ABWR source term used in the prospective assessment

A.1 Introduction

The prospective assessment of doses depends on the expected discharges of radioactivity, the 'source term for discharges', particularly the radionuclides, their form and quantity. The source term for discharges is derived from considering how radionuclides originate in the reactor and how they transfer to the various waste streams.

A.2. Liquid discharges

Liquid discharges are predicted to be very low (Table A1). The proposed discharge limits for the majority of radionuclides are less than 1 MBq/y, with the exception of tritium (0.76 TBq/y) and iron-55 (9.4 MBq/y). Overall, the low discharges resulted in low predicted doses.

Table A1. Liquid discharges used in Revision F of the dose assessment

Nuclide	Proposed discharge limits Bq/y	% of total
Ag-110m	5.70E+00	0.0000%
Am-241	1.10E-01	0.0000%
Ba-140	6.20E+03	0.0000%
Ce-141	4.50E+04	0.0000%
Ce-144	2.40E+05	0.0000%
Cm-242	2.10E+00	0.0000%
Cm-243	4.90E-03	0.0000%
Cm-244	4.50E-01	0.0000%
Co-58	8.20E+04	0.0000%
Co-60	8.20E+05	0.0001%
Cr-51	3.70E+04	0.0000%
Cs-134	5.70E+03	0.0000%
Cs-137	6.60E+03	0.0000%
Fe-55	9.40E+06	0.0012%
Fe-59	2.10E+04	0.0000%
H-3	7.60E+11	99.9983%
I-131	6.00E+04	0.0000%
La-140	7.00E+03	0.0000%
Mn-54	4.00E+05	0.0001%
Nb-95	1.80E+05	0.0000%

Nuclide	Proposed discharge limits Bq/y	% of total
Ni-63	8.60E+05	0.0001%
Pu-238	3.60E+00	0.0000%
Pu-239	5.70E-01	0.0000%
Pu-240	9.00E-01	0.0000%
Ru-103	2.70E+04	0.0000%
Ru-106	1.90E+04	0.0000%
Sb-122	1.20E+02	0.0000%
Sb-124	5.30E+04	0.0000%
Sb-125	8.20E+04	0.0000%
Sr-89	9.00E+03	0.0000%
Sr-90	4.50E+03	0.0000%
Te-123m	6.20E+01	0.0000%
Zn-65	1.10E+05	0.0000%
Zr-95	8.20E+04	0.0000%
Total		100.0000%

A.3. Gaseous discharges

Gaseous discharges are predicted to be low (Table A2). Discharges were above 1 TBq for only three radionuclides, argon-41, carbon-14 and tritium.

Table A2. Gaseous source term used in Revision F of the dose assessment

Nuclide	Proposed discharge limits Bq/y	% of total
Ag-110m	3.90E+01	0.0000%
Am-241	6.60E-04	0.0000%
Ar-41	5.20E+12	30.3815%
Ba-140	3.50E+04	0.0000%
C-14	1.70E+12	9.9324%
Ce-141	4.90E+04	0.0000%
Ce-144	4.50E+04	0.0000%
Cm-242	4.90E-01	0.0000%
Cm-243	4.90E-05	0.0000%
Cm-244	6.20E-03	0.0000%
Co-58	1.50E+05	0.0000%

Nuclide	Proposed discharge limits Bq/y	% of total
Co-60	1.50E+05	0.0000%
Cr-51	1.30E+05	0.0000%
Cs-134	9.40E+03	0.0000%
Cs-137	5.70E+03	0.0000%
Fe-59	2.40E+04	0.0000%
H-3	1.00E+13	58.4259%
I-131	3.20E+08	0.0019%
I-132	1.10E+08	0.0006%
I-133	7.30E+07	0.0004%
I-135	4.30E+07	0.0003%
Kr-85	1.30E+09	0.0076%
Kr-85m	1.00E+10	0.0584%
Kr-87	9.80E+03	0.0000%
Kr-88	9.30E+08	0.0054%
La-140	4.10E+04	0.0000%
Mn-54	9.00E+04	0.0000%
Nb-95	1.10E+05	0.0000%
Pu-238	9.40E-03	0.0000%
Pu-239	1.20E-03	0.0000%
Pu-240	1.90E-03	0.0000%
Sb-122	4.90E+02	0.0000%
Sb-124	4.90E+04	0.0000%
Sb-125	9.80E+03	0.0000%
Sr-89	4.10E+04	0.0000%
Sr-90	2.60E+03	0.0000%
Xe-131m	2.90E+09	0.0169%
Xe-133	2.00E+11	1.1685%
Xe-133m	1.80E+07	0.0001%
Zn-65	4.10E+04	0.0000%
Zr-95	5.30E+04	0.0000%
Total	1.71E+13	100.0000%

Table A2 shows the percentage contributions of each radionuclide discharges to the total in terms of activity. Tritium is the main nuclide discharged in terms of quantity, making up 58% of the total discharge, argon-41 at 30% and carbon-14 at 10% are also important in terms of quantity.

A.4 Short duration releases to the atmosphere

Radioactive discharges to the atmosphere may not always be made at a constant rate. Fluctuations and variations can occur within foreseeable margins. Fluctuations may be caused by the occasional failed fuel cladding or other events such as start up or shut down. The expected discharges are short duration enhanced discharges of noble gases released from fuel through damaged cladding. The expected enhanced discharges are shown in Table A3.

Table A3. Gaseous discharges of short duration used in Revision F of the dose assessment

Radionuclide	Activity discharged in 24h (Bq)	Fraction of proposed annual limit
Kr-85	1.10E+09	0.85
Kr-85m	5.50E+09	0.55
Kr-87	5.00E+03	0.51
Kr-88	5.50E+08	0.59
Xe-131m	2.60E+09	0.9
Xe-133	1.80E+11	0.9
Xe-133m	1.40E+07	0.78

Appendix B – Detail of predicted doses

B.1 Hitachi-GE assessment Revision F

The Hitachi-GE assessment shows that individual doses from gaseous discharges were the highest to residents living close to the reactor and consuming local food.

Their doses from gaseous discharges were predicted to range from 13 to 23.5 μSv/y.

In addition, the residents were predicted to receive doses of between 0.3 and 0.9 μSv/y from direct radiation. This gives total doses in the range 14-24 μSv/y (Table 6).

The highest dose of 24 μSv/y is to infants aged 1 year. Children receive a dose of 15 μSv/y and adults a dose of 14 μSv/y.

For the infant age group, doses from gaseous discharges are 23.5 μSv/y – (98.7% of the overall dose). Direct radiation doses to infants was 0.3 μSv/y (1.3% of the overall dose).

Doses to infants from aqueous liquid discharges is very small (much less than 1%).

For infants, the main radionuclides for doses are carbon-14 from gaseous discharges (90.6% of the dose) followed by iodine-131 (4.7%) and tritium (3.9%). The main dose pathway is consumption of milk and milk products (82% of the dose), followed by non-food pathways (8.2%).

For the adult age group, gaseous discharges contribute about 94% of the overall dose. For this age group, the main route of exposure from this source is also due to carbon-14, which dominates through the consumption of milk and milk products.

A breakdown of doses by pathway and by the main radionuclide for infants are shown in Table B1 and Table B2.

Table B1. Doses to infants from gaseous discharges by radionuclide

Nuclide	Dose μSv/y	Percentage
Ar-41	1.26E-01	0.54%
C-14	2.13E+01	90.63%
H-3	9.23E-01	3.93%
I-131	1.10E+00	4.68%
I-133	3.02E-03	0.01%
Others	4.99E-02	0.21%
Total	2.35E+01	100.00%

Table B2. Doses to infants by pathway μSv/y

Radio-nuclide	Dose by pathways μSv/y (grouped) and by main radionuclides							
	Sub-total						Total	%
	Non ingestion*	Cow meat	Cow milk	Fruit and veg	Sheep meat	Ingestion		
Ar-41	1.26E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.26E-01	0.54%
C-14	1.68E+00	3.12E-01	1.75E+01	1.72E+00	1.16E-01	1.97E+01	2.13E+01	90.63%
H-3	1.08E-01	6.01E-03	7.50E-01	5.69E-02	2.23E-03	8.15E-01	9.23E-01	3.93%
I-131	4.04E-03	1.67E-03	1.08E+00	1.43E-02	7.13E-04	1.10E+00	1.10E+00	4.68%
I-133	2.27E-04	1.14E-06	2.74E-03	4.92E-05	4.57E-07	2.79E-03	3.02E-03	0.01%
Others	0.00E+00	5.25E-04	4.86E-02	7.08E-04	0.00E+00	4.98E-02	4.99E-02	0.21%
Total	1.92E+00	3.20E-01	1.94E+01	1.79E+00	1.19E-01	2.16E+01	2.35E+01	100.00%
%	8.16%	1.36%	82.34%	7.61%	0.50%	91.82%	100.00%	100.00%

* Non-ingestion doses sub-total is the sum of doses from inhalation of radionuclides in the plume; external doses from radionuclides in the plume and external doses from radionuclides deposited on the ground.

Individual doses from liquid discharges are much lower than those from gases. For the most exposed group to liquid discharges who use the beach a lot and consume local seafood (Table 7 part b), doses are in the range 0.000005 to 0.0002 µSv/y. The highest dose from the liquid discharges is to an adult from cobalt-60 from external exposure to sediments.

This group also live near the reactor and are assumed to be exposed to gaseous discharges and direct radiation. The projected doses are 6 to 9.5 µSv/y and the doses from direct radiation are 0.3 to 0.9 µSv/y. This group's total dose is, therefore, dominated by doses not arising from liquid discharges.

Doses from short duration releases as gases range 0.016 to 0.019 µSv/y. These are shown in Table B3. The assessment shows that the dose is 25% from cloud gamma and 75% from cloud beta. 80% of the dose is from xenon-133.

Table B3 - doses to adults from short duration releases

Radionuclide	Adult cloud gamma dose (uSv)	Adult cloud beta dose (Sv)	Total dose (Sv)	Percentage
Kr-85	3.57E-06	3.31E-04	3.35E-04	1.80%
Kr-85m	5.08E-04	1.71E-03	2.21E-03	11.88%
Kr-87	2.68E-03	1.02E-08	1.29E-08	0.00%
Kr-88	7.20E-04	2.63E-04	9.83E-04	5.28%
Xe-131m	1.25E-05	2.37E-04	2.50E-04	1.34%
Xe-133	3.32E-03	1.15E-02	1.49E-02	80.11%
Xe-133m	2.43E-07	2.66E-06	2.90E-06	0.02%
Total	4.57E-03	1.41E-02	1.86E-02	100.00%
Percentage	24.57%	75.81%		

Appendix C Direct radiation dose to the public from the site

C.1 Introduction

There are a number of radioactive sources on the site that could give rise to direct radiation offsite. Generally, the radiation dose rate on site is likely to be higher close to the sources and, therefore, will expose workers on site. In some situations, a dose rate that may expose members of the public offsite can occur. The main sources are from the turbine hall and reactor area and the spent fuel store.

Direct radiation exposure of the public offsite is the regulatory responsibility of the ONR. However, the overall doses to the public from all sources on site, from discharges and direct radiation is our regulatory responsibility. Hitachi-GE provided the results of the direct radiation assessment to ONR. It is also included in the prospective dose assessment Hitachi-GE provided to us. We have, therefore, consulted with ONR on the direct radiation offsite and attended relevant meetings. Our main interest is to make sure that the assessment of doses from direct radiation is consistent with the assessment of doses from discharges, so that we can establish a complete picture of the doses to the public.

C.2. Assessment of direct radiation doses

There are a number of direct radiation sources for the UK ABWR design, some of which may give rise to offsite doses. The assessment of direction radiation was divided into 2 groups of sources.

The first group were those sources of direct radiation that already exist in other ABWRs in operation and the dose rates have been measured and are known. The first group is shown in Table C1:

Table C1. Sources of direct radiation in the first group

Source	Dose to public (µSv/y)
Reactor building	0.013
Turbine building	0.88
Radwaste building	0.025
Control building	0
Service building	0
Condensate storage tank	0.005
Suppression pool water surge tank	0.018
Total	0.94

The second group are those sources that could be specific to the UK ABWR. These are facilities declared as being still at the concept design stage. The second group is shown in Table C2:

Table C2. Sources of direct radiation in the second group

Spent fuel interim storage	Dose to public (µSv/y)
ILW storage facility	5[@]
Wet ILW processing facility	0.5[@]
Solid ILW processing facility	0.5[@]
Wet LLW processing facility (treatment facility)	0.5[@]
Solid LLW processing facility and temporary storage facility	0.5[@]

[@] These values are dose constraints because these facilities are still at design concept.

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