Environment Agency

Assessment report – Independent dose assessment of General Nuclear System's UK HPR1000

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Executive summary

The Office for Nuclear Regulation (ONR) and the Environment Agency (the Nuclear Regulators) are working together to ensure that any new nuclear power stations built in the UK meet the highest standard of safety, security, environmental protection and waste management. Together we have established a Generic Design Assessment (GDA) process to consider the acceptability of the new nuclear power plants. One of the stages in the process is consideration of the environmental acceptability of the design.

In the GDA process, we are carrying out detailed assessments of the environmental effects of each design, which will lead to a statement about the acceptability of the design. The statement on acceptability will be non-binding, but will give a strong indication of whether a design is likely to be acceptable in principle in the UK with respect to matters that the Environment Agency regulates.

General Nuclear System (GNSL), a subsidiary of EDF and China General Nuclear Power Corporation (CGN) has submitted its UK Hualong One Pressurised Water Reactor (UK HPR1000) nuclear power plant design for evaluation under the GDA arrangements. In its submission, GNSL assumed that the UK HPR1000 would be located at a generic site, such that the final selected site would be bounded by the generic site envelope. GNSL have proposed limits on discharges of radioactive wastes to atmosphere and as discharges as liquids. The proposed limits, on discharges of radioactive wastes to atmosphere are based on the annual maximum radioactive liquid and atmospheric discharges. The annual maximum radioactive liquid and atmospheric discharges were used as the basis for assessing doses to the local population and collective doses.

The GDA approach is outlined in our 'Process and Information Document for Generic Assessment of Candidate Nuclear Power Plant Designs' (P&ID).

As part of the GDA process, an independent assessment of the potential impact of liquid and gaseous discharges of radioactive wastes from the UK HPR1000 design has been carried out on behalf of the Environment Agency. This assessment takes account of the discharge information, design and the generic site description, provided by GNSL.

The aim of the independent assessment was to perform an independent estimate of doses and additional assessment of the radiological impact from the estimated discharges from the site. Stage 1 of the Initial Radiological Assessment (IRA) method calculated doses of 120 µSv y^{-1} from atmospheric discharges and 28 µSv y^{-1} from liquid discharges, whilst Stage 2 calculated doses of 22 µSv y^{-1} for both atmospheric and liquid discharges. Doses were calculated for the most exposed families to atmospheric discharges (local resident family) and liquid discharges (fishing family). The most exposed individuals from these families were the infant in the local resident family and the adult in the fishing family, who received doses of 21 µSv y^{-1} and 8.0 µSv y^{-1} respectively. The candidate for the “representative person” was determined to be the infant in the farming family. The assessment estimated that this individual received an annual dose of 29 µSv. Whilst this value is above the dose criterion of 20 µSv y^{-1} below which further assessment is not required, it is well below the dose constraint of 150 µSv y^{-1} for nuclear new build and 300 µSv y^{-1} for a single source. Almost all the dose was associated with discharges of C-14. Direct radiation contributed between 0.152 and 0.439 µSv y^{-1} to the total dose of the independent assessment, assuming 100% occupancy at 300 m from all buildings on site. The cautious habits assumed for the representative person (for example that they get all their food from sources close to the reactor) means that no other individuals could receive higher exposures, including other members of the public or non-nuclear workers.

The independent assessment of doses from short-term releases calculated total doses of 6.9 µSv, 6.0 µSv and 7.8 µSv to the adult, child and infant groups respectively. The total doses are dominated by the inhalation of the plume and ingestion of foods and the dominant radionuclide was C-14. The independent estimates of the collective radiation dose to the populations of Europe and the world were above the collective dose criterion historically proposed by the International Atomic Energy Agency (IAEA), of 1 manSv y^{-1} of discharge. However, more recently the IAEA has revised its guidance on collective dose and no longer offers a dose criterion. The collective radiation dose estimate for the UK population was below this value at 0.72 manSv. Estimates of exposures to wildlife did not indicate any doses that would be of concern.

The dose calculations in this study are applicable to the GDA generic site and to a single UK HPR1000 unit. If a site is selected and a permit applied for then a site specific assessment will need to be undertaken, taking account of site-specific factors and the number of UK HPR1000 units that will be operated.

Contents

1. Introduction

The Environment Agency and the ONR are using the GDA process to evaluate the new nuclear power station designs proposed for the UK. This report is concerned with the UK HPR1000 that has been submitted for assessment by GNSL (the requesting party).

ONR and the Environment Agency assess aspects of candidate nuclear power station designs, relevant to nuclear safety and environmental impact respectively. These reflect the regulatory remits. This report is concerned with the radiological impact to the public and wildlife of the anticipated maximum annual radioactive discharges from the UK HPR1000 - to both the atmosphere and the marine environment - over its projected operational lifetime. GNSL has also provided estimates of radiation doses to people and the environment from these discharges (General Nuclear System, 2020a).

The GDA process does not consider a specific site where a reactor might be operated. This is because one purpose of GDA is to establish if the design would be generally acceptable for operation in the UK. Therefore, a generic site has been proposed by GNSL for the assessment of the radiological impact of the expected radioactive discharges from the UK HPR1000. The generic site is coastal or located on large estuaries as the design assumes water is used for cooling. Other environmental characteristics of the site have been based on those found at sites identified as potential future sites for new nuclear power stations in the UK. GNSL has made additional assumptions about the people who might be most exposed to its radioactive discharges and used these in its assessment.

This report presents our own independent assessment of the radiation doses, undertaken to provide a separate and independent point of comparison with the GNSL assessment, discusses the main findings and presents the conclusions.

The appendices contain more detail on the following topics.

- Appendix A presents the overall approach to the independent dose assessment
- Appendix B shows how the IRA methodology was applied (Environment Agencies, 2012) to make an initial estimate of the doses to people from the discharges to atmosphere and the marine environment
- Appendix C describes the detailed dose assessment calculations for the anticipated atmospheric discharges
- Appendix D presents the dose assessment calculations for the anticipated liquid discharges
- Appendix E gives the calculated total dose to reference groups and the 'representative person' who is expected to be most exposed to the estimated discharges from the UK HPR1000. This includes doses from direct radiation and short-term releases, and compares the total dose with the regulatory criteria
- Appendix F contains an assessment of the potential doses from a short-term release of radioactivity to the atmosphere
- Appendix G describes the assessment of the dose for UK, European and world populations (the "collective dose")
- Appendix H presents an assessment of dose rates to wildlife (non-human species)
- Appendix I presents an assessment of direct radiation

2. Scope and Approach

The scope of the work is to confirm that the GNSL assessment of the potential radiological effects of discharges from the UK HPR1000 is suitable and sufficient (Environment Agencies, 2012). This is done through an independent assessment of radiation doses to members of the public and to non-human species from the proposed estimated discharges from the UK HPR1000 using the GNSL estimated maximum annual discharge rates. The assessments covered the different types of radioactive discharges (to the atmosphere and to the marine environment, short-term and long-term). Doses to the most exposed individuals (including a 'representative person'), to the wider population ('collective dose'), and to non-human species has also been assessed. The assessment has followed the relevant parts of the 'Principles for the Assessment of Prospective Public Doses' (Environment Agencies, 2012).

The Process and Information Document for Generic Assessment of Candidate Nuclear Power Plant Designs (P&ID) (Environment Agency, 2016) sets out the key information requirements for this stage of the GDA and thus the scope of this report. This states that the following require calculation:

- the annual dose to most exposed members of the public for estimated maximum annual liquid discharges
- the annual dose to most exposed members of the public for estimated maximum annual gaseous discharges
- the annual dose to the most exposed members of the public for all estimated maximum annual discharges from the facility
- the annual dose to the most exposed members of the public due to direct radiation
- the annual dose to the representative person for the facility
- the 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 the build-up of radionuclides in the local environment of the facility based on the anticipated lifetime discharges
- the total radiation dose to the UK, European and world populations, up to 500 years in the future
- the dose-rate to non-human species

3. Independent Dose Assessment

3.1. Scope and Approach

The independent assessment reported in this work has a similar scope to that undertaken by GNSL (General Nuclear System, 2020a). It involves making estimates of the potential doses to members of the public and non-human species from estimated discharges to atmosphere and liquid discharges to the marine environment. It addresses the principles for the assessment of prospective public doses (Environment Agencies, 2012). This assessment was designed to provide an independent view of the outcome of the estimated maximum annual discharges reported by GNSL (General Nuclear System, 2020a) and is for a single UK HPR1000 unit.

The tiered approach described in Environment Agency guidance (Environment Agency, 2006 a) was used. The first two stages of dose assessment were undertaken using the Initial Radiological Assessment Tool (IRAT) (Environment Agency, 2006 a). This provides a simple and conservative indication of the potential doses to members of the public, and can be used to decide if a detailed assessment is necessary. A detailed assessment is likely to be required if the estimated dose exceeds 20 μSv y^{-1}. This usually involves more specific modelling of discharges and, where available, the use of information about the habits of people including the amounts of locally produced food eaten.

There are various calculation methods available to assess doses to members of the public and non-human species. Existing software applications routinely used for the assessment of radioactive discharges that are also used in detailed independent dose assessments are:

- the PC CREAM 08 dose assessment software (Version 1.5.1.92, with database Version 2.0.0) for individual and collective doses to people from routine discharges to the atmosphere and marine environment (Smith & Simmonds, 2009). As a refinement of the dose assessment from Stage 1 and 2, it is reasonable to adopt an approach that uses the same models as those used in the IRAT. In the case of routine discharges, this is the PC CREAM 08 dose assessment code, which is widely used for the assessment of releases from nuclear sites in the UK and Europe. PC CREAM 08 is a well-established system that was specifically designed for the assessment of the effects of continuous discharges of radioactivity on people.
- the ADMS code for short-term discharges of radioactivity to the atmosphere (CERC, 2012). The National Dose Assessments Working Group (NDAWG) recommends the use of the ADMS code to evaluate atmospheric dispersion. ADMS is a significantly more sophisticated model than the PLUME model. ADMS calculates air concentrations and deposition rates at a given location.
- ERICA (Beresford, et al., 2007) for radiation doses to non-human species, supplemented by the Environment Agency's approach for the exposure of non-human species to noble gases (Copplestone, et al., 2001) (Vives i Batlle, Jones, & Copplestone, 2015). Activity concentrations calculated in PC CREAM 08 can be input into ERICA. This is widely used and can be readily applied to the predicted environmental concentrations. ERICA provides models and data that provide estimates of radiation doses to a range of non-human species typical of European wildlife.

The dose from direct radiation also needs to be taken into account when calculating total exposures for comparison with the dose constraints. Our assessment uses estimates of direct radiation calculated by GNSL (General Nuclear System, 2020a). The people who are most exposed to direct radiation are likely to be similar to, or the same people as those who are most exposed to atmospheric discharges due to their assumed close proximity to the site at all times. The consistency of the assessment approach for direct radiation with that for atmospheric discharges is considered in Appendix I.

3.2. Radioactive Discharges

Annual Discharges

The independent dose assessment uses the maximum annual discharges for releases of radioactivity to the atmosphere (Table 1) and the marine environment (Table 2) proposed in the GNSL submission (General Nuclear System, 2020a) for gaseous discharges and liquid discharges respectively. The assessment did not use the proposed limits presented in the GNSL submission (General Nuclear System, 2020b). However, the maximum annual discharges in Table 1 and Table 2 were the basis of the permit limits and are therefore the equivalent of the permit limits.

These maximum annual discharges include the annual discharges, headroom factors and contribution of expected events during normal operation.

The discharges were assumed to occur continuously over the year and to carry on for 60 years, (the operational lifetime of the UK HPR1000).

Table 1: Maximum annual discharges for releases to atmosphere by a single UK HPR1000, submitted by GNSL (Table T-7B-3) (General Nuclear System, 2020a)

Radionuclide	Discharge (Bq/y)	Radionuclide	Discharge (Bq/y)
H-3	$5.23\ 10^{12}$	Zr-95	671
C-14	$1.69\ 10^{12}$	Mo-99	$1.95\ 10^{4}$
Ar-41	$9.87\ 10^{8}$	Tc-99m	$5.14\ 10^{3}$
Kr-83m	$5.09\ 10^{7}$	Te-125m	785
Kr-85m	$2.36\ 10^{8}$	Te-127	269
Kr-85	$2.68\ 10^{11}$	Te-127m	0.00
Kr-87	$1.22\ 10^{8}$	Te-129	252
Kr-88	$3.79\ 10^{8}$	Te-129m	$1.45\ 10^{4}$
Xe-131m	$7.75\ 10^{8}$	Te-131m	$1.46\ 10^{3}$
Xe-133m	$1.81\ 10^{11}$	Te-132	$3.59\ 10^{3}$
Xe-133	$1.16\ 10^{13}$	Te-133m	$1.78\ 10^{3}$
Xe-135	$3.45\ 10^{12}$	Te-134	402
Xe-138	$2.56\ 10^{10}$	Cs-134	$1.67\ 10^{6}$
I-129	585	Cs-136	$8.77\ 10^{4}$
I-130	$5.88\ 10^{5}$	Cs-137	$1.93\ 10^{6}$
I-131	$8.57\ 10^{7}$	Cs-138	$2.76\ 10^{4}$
I-132	$1.97\ 10^{7}$	Ba-139	$1.10\ 10^{3}$
I-132m	$8.94\ 10^{4}$	Ba-140	933
I-133	$5.16\ 10^{7}$	La-140	47.6
I-134	$1.10\ 10^{7}$	Ba-137m	$3.00\ 10^{3}$
I-135	$4.78\ 10^{7}$	Cr-51	$9.36\ 10^{5}$

Radionuclide	Discharge (Bq/y)	Radionuclide	Discharge (Bq/y)
Br-82	$4.60\ 10^{5}$	Mn-54	$5.13\ 10^{5}$
Br-83	$3.11\ 10^{6}$	Fe-59	$1.21\ 10^{5}$
Br-84	$1.37\ 10^{6}$	Co-58	$1.64\ 10^{6}$
Rb-86	$2.32\ 10^{3}$	Co-60	$2.02\ 10^{6}$
Rb-88	$4.05\ 10^{4}$	Sb-122	$2.25\ 10^{4}$
Sr-89	$2.25\ 10^{3}$	Sb-124	$6.35\ 10^{4}$
Sr-90	958	Ag-110m	$3.14\ 10^{5}$
Sr-91	90.7	Ni-63	$1.64\ 10^{6}$
Sr-92	15.5	Na-24	$6.77\ 10^{4}$
Nb-95	373	**Total**	$2.24\ 10^{13}$

Table 2: Maximum annual discharges for releases to the marine environment from a single UK HPR1000, submitted by GNSL (Table T-7B-2) (General Nuclear System, 2020a)

Radionuclide	Discharge (Bq/y)	Radionuclide	Discharge (Bq/y)
H-3	$1.04\ 10^{14}$	La-140	195
Ag-110m	$2.47\ 10^{7}$	Mn-54	$1.73\ 10^{7}$
Ba-137m	173	Mo-99	$1.78\ 10^{5}$
Ba-139	$1.01\ 10^{3}$	Na-24	$2.09\ 10^{6}$
Ba-140	$3.40\ 10^{4}$	Nb-95	$8.60\ 10^{3}$
Br-82	$1.06\ 10^{3}$	Ni-63	$1.19\ 10^{8}$
Br-83	$5.38\ 10^{3}$	Rb-86	$2.52\ 10^{5}$
Br-84	930	Rb-88	$1.41\ 10^{4}$
C-14	$5.90\ 10^{10}$	Sb-122	$1.34\ 10^{6}$
Co-58	$6.53\ 10^{7}$	Sb-124	$8.79\ 10^{7}$
Co-60	$1.52\ 10^{8}$	Sr-89	$3.97\ 10^{4}$
Cr-51	$4.60\ 10^{8}$	Sr-90	$3.13\ 10^{3}$
Cs-134	$1.40\ 10^{7}$	Sr-91	109
Cs-136	$3.89\ 10^{6}$	Sr-92	18.3
Cs-137	$1.93\ 10^{7}$	Tc-99m	$8.18\ 10^{3}$
Cs-138	$6.79\ 10^{3}$	Te-125m	$1.24\ 10^{4}$
Fe-59	$5.28\ 10^{7}$	Te-127	324
I-129	1.37	Te-129	213
I-130	$2.97\ 10^{3}$	Te-129m	$3.46\ 10^{5}$
I-131	$1.61\ 10^{7}$	Te-131m	$1.89\ 10^{3}$
I-132	$7.40\ 10^{4}$	Te-132	$1.40\ 10^{3}$

Radionuclide	Discharge (Bq/y)	Radionuclide	Discharge (Bq/y)
I-132m	259	Te-133m	$2.27\ 10^{4}$
I-133	$4.86\ 10^{5}$	Te-134	252
I-134	$2.34\ 10^{4}$	Zr-95	$9.80\ 10^{3}$
I-135	$2.34\ 10^{5}$	**Total**	$1.04\ 10^{14}$

The full gaseous source term includes 61 radionuclides; similarly, the aqueous source term has a list of 49 radionuclides. Not all of the radionuclides listed in Table 1 and Table 2 will be important to the dose to members of the public due to the discharges being significantly less than the dominating radionuclides in the discharge inventory. The environmental assessment produced by GNSL shows that there is a small subset of the released radionuclides that contribute significantly (of the order of 98% of total) with the remaining radionuclides contributing very little (a total around 40-60 nuclides contributing 0.7% of dose).

With this in mind it was decided to screen and select the list of radionuclides considered for both aerial and aqueous release by using a cut off in the nuclides percentage contribution to the total dose.

When screening it was important to ensure that representative nuclides were included to cover the different sources of waste, i.e. to include for activation products (solids and gases) and fission products (noble gases and solids), such that any screened nuclide activity can be included in a representative category.

Finally, consideration has been made for any changes to nuclide concentration over time. It is shown in Appendix C and Appendix D that the activity concentrations of long lived radionuclides in soil and in seawater for both operational timescales and a look ahead time are constant or change so little in comparison to dose contribution that they do not require additional consideration.

PC CREAM 08 was used to calculate doses at 50 years from the first release for all the radionuclides listed in Table 1 and Table 2. PC CREAM default timescales of 50 years were used for this calculation; however, it is demonstrated in Appendices C2 and D2 that activity concentrations stabilise by this time. As such, it is acceptable to assume the dose contributions will remain in the same proportions at 60 years. The doses were then screened to identify the radionuclides with contributions of >0.001% of dose (over 99% of the total dose is due to C-14 and H-3). This screening has identified a list of 12 radionuclides for aerial releases and 10 radionuclides for aqueous releases. These are provided below in Table 3 and Table 4.

Table 3: Maximum annual discharges for releases to atmosphere by a single UK HPR1000 to be used in the independent dose assessment

Category	Nuclide	Annual Discharge (Bq/y)
Activated Metals/Solids	Ag-110m	$3.14\ 10^{5}$
Activated Gas	C-14	$1.69\ 10^{12}$
Activated Metals/Solids	Co-60	$2.02\ 10^{6}$
Fission Metals/Solids	Cs-134	$1.67\ 10^{6}$
Fission Metals/Solids	Cs-137	$1.93\ 10^{6}$

Category	Nuclide	Annual Discharge (Bq/y)
Activated Gas	H-3	$5.23\ 10^{12}$
Fission Metals/Solids	I-131	$8.57\ 10^{7}$
Fission Metals/Solids	I-133	$5.16\ 10^{7}$
Fission Noble Gas	Xe-133	$1.16\ 10^{13}$
Fission Noble Gas	Xe-133m	$1.81\ 10^{11}$
Fission Noble Gas	Xe-135	$3.45\ 10^{12}$
Fission Noble Gas	Xe-138	$2.56\ 10^{10}$

Table 4: Maximum annual discharges for releases to the marine environment by a single UK HPR1000 to be used in the independent dose assessment.

Category	Nuclide	Annual Discharge (Bq/y)
Activated Metals/Solids	Ag-110m	$2.47\ 10^{7}$
Activated Gas	C-14	$5.90\ 10^{10}$
Activated Metals/Solids	Co-58	$6.53\ 10^{7}$
Activated Metals/Solids	Co-60	$1.52\ 10^{8}$
Fission Metals/Solids	Cs-134	$1.40\ 10^{7}$
Fission Metals/Solids	Cs-137	$1.93\ 10^{7}$
Activated Metals/Solids	Fe-59	$5.28\ 10^{7}$
Activated Gas	H-3	$1.04\ 10^{14}$
Activated Metals/Solids	Mn-54	$1.73\ 10^{7}$
Fission Metals/Solids	Sb-124	$8.79\ 10^{7}$

For the independent dose assessment, it is assumed that all atmospheric discharges will be discharged via the main discharge stack, with no other discharge points. The atmospheric discharges will be assumed to be from a single 70 m high stack as this is the stack height of the design of Hualong Pressurised Reactor, which is under construction at Fangchenggang nuclear plant unit 3 (HPR1000 (FCG3)). According to the design of HPR1000 (FCG3), the height of the Reactor Building is about 60 m and therefore it can be assumed that the stack height will be higher than the Reactor Building.

The atmospheric dispersion model employed within PC-CREAM 08 is based on a typical Gaussian plume model that calculates downwind concentrations resulting from advection and dispersion processes on an unobstructed ideal flat plane. To include the effects of plume rise, terrain and building entrainment in these calculations, the concept of “effective stack height” was introduced. This represents the theoretical height of a stack that would result in the observed downwind dispersion taking into account all of the aforementioned factors. When calculations of concentrations resulting from a release from the stack are undertaken within PC-CREAM 08, the effective release height is used as a model input parameter, rather than the actual physical height of the stack.

To assist users of Gaussian plume models, the UK working group on atmospheric dispersion has provided guidance on the derivation of effective stack heights using the one-third reduction rule (Jones, 1983). The guidance states that for a site where entrainment may be an issue, the effective height can be approximated as 1/3 of the height of the building from where the release occurs. In the case of this independent dose assessment, this applies to the Reactor Building and the effective release height is thus 20 m. This value provides a high level of conservatism for the assessment such that the calculated doses can be considered as bounding. This is the same approach that has been taken by GNSL (General Nuclear System, 2020a). Cautiously, no account will be taken of the upwards velocity of the discharges into the atmosphere. By doing so, the dispersion that occurs higher in the atmosphere is not considered which leads to an increase of the ground level air concentration. This in turn increases the calculated dose to those who live closer to the reactor.

Short-Term Discharges

The dose assessment process will also consider the potential impact of the maximum estimated short-term release that could be expected to occur under normal operating conditions. For short duration releases, which will be to the atmosphere, the maximum monthly estimated discharges specified by GNSL (General Nuclear System, 2020b) will be used in the independent dose assessment. These are presented in Table 5. It is cautiously assumed that these radionuclides will be released uniformly over a short period of 24 hours. The possibility of a release happening over a shorter duration, for example 6 hours, and the effects of this shorter duration on doses will be considered within the sensitivity analysis (see Appendix F6). Due to the periodic nature of liquid discharges, which are already taken into consideration in the PC CREAM DORIS model, effects of short-term discharges to the marine environment are not considered here.

Table 5: Maximum short-term discharges to the atmosphere from a UK HPR1000, submitted by GNSL (Table T-7B-8) (General Nuclear System, 2020b)

Radionuclide	Discharge/ Bq	Radionuclide	Discharge/ Bq
H-3	$9.31\ 10^{11}$	Zr-95	97.4
C-14	$3.44\ 10^{11}$	Mo-99	$2.83\ 10^{3}$
Ar-41	$9.87\ 10^{8}$	Tc-99m	746
Kr-83m	$9.26\ 10^{6}$	Te-125m	114
Kr-85m	$4.29\ 10^{7}$	Te-127	39.0
Kr-85	$4.88\ 10^{10}$	Te-127m	0.00
Kr-87	$2.22\ 10^{7}$	Te-129	36.5
Kr-88	$6.90\ 10^{7}$	Te-129m	$2.11\ 10^{3}$
Xe-131m	$1.41\ 10^{8}$	Te-131m	212
Xe-133m	$3.29\ 10^{10}$	Te-132	522
Xe-133	$2.12\ 10^{12}$	Te-133m	258
Xe-135	$6.28\ 10^{11}$	Te-134	58.4
Xe-138	$4.66\ 10^{9}$	Cs-134	$2.43\ 10^{5}$
I-129	183	Cs-136	$1.27\ 10^{4}$
I-130	$1.84\ 10^{5}$	Cs-137	$2.80\ 10^{5}$
I-131	$2.68\ 10^{7}$	Cs-138	$4.00\ 10^{3}$
I-132	$6.17\ 10^{6}$	Ba-139	159
I-132m	$2.80\ 10^{4}$	Ba-140	135
I-133	$1.62\ 10^{7}$	La-140	6.91
I-134	$3.44\ 10^{6}$	Ba-137m	435
I-135	$1.50\ 10^{7}$	Cr-51	$1.36\ 10^{5}$
Br-82	$1.44\ 10^{5}$	Mn-54	$7.44\ 10^{4}$
Br-83	$9.75\ 10^{5}$	Fe-59	$1.76\ 10^{4}$
Br-84	$4.30\ 10^{5}$	Co-58	$2.38\ 10^{5}$
Rb-86	337	Co-60	$2.94\ 10^{5}$
Rb-88	$5.87\ 10^{3}$	Sb-122	$3.26\ 10^{3}$
Sr-89	327	Sb-124	$9.22\ 10^{3}$
Sr-90	139	Ag-110m	$4.55\ 10^{4}$
Sr-91	13.2	Ni-63	$2.37\ 10^{5}$
Sr-92	2.25	Na-24	$9.83\ 10^{3}$
Nb-95	54.1	Total	$4.11\ 10^{12}$

As per the assessment for continuous annual discharges it has been decided to screen and select the list of radionuclides considered for short-term aerial releases. A screening exercise was undertaken on the full list of radionuclides in Table 5 within ADMS 5 to ensure that there were no significant short-lived radionuclides that have an impact on dose from this short-term release (over 6 or 24 hours). This did not identify any significant radionuclides over those presented in Table 6.

Table 6: Maximum short-term releases to atmosphere by a single UK HPR1000 to be used in the independent dose assessment

Category	Nuclide	Discharge Bq
Activated Metals/Solids	Ag-110m	$4.55\ 10^{4}$
Activated Gas	C-14	$3.44\ 10^{11}$
Activated Metals/Solids	Co-60	$2.94\ 10^{5}$
Fission Metals/Solids	Cs-134	$2.43\ 10^{5}$
Fission Metals/Solids	Cs-137	$2.80\ 10^{5}$
Activated Gas	H-3	$9.31\ 10^{11}$
Fission Metals/Solids	I-131	$2.68\ 10^{7}$
Fission Metals/Solids	I-133	$1.62\ 10^{7}$
Fission Noble Gas	Xe-133	$2.12\ 10^{12}$
Fission Noble Gas	Xe-133m	$3.29\ 10^{10}$
Fission Noble Gas	Xe-135	$6.28\ 10^{11}$
Fission Noble Gas	Xe-138	$4.66\ 10^{9}$

3.3. Generic Site

The GDA process involves assessing the reactor design at a generic site. The generic site should be defined to reflect the constraints of potential sites. Cautious assumptions may include selecting a site that is appropriately representative of locations where nuclear power stations might be built in future. The habits of people at the generic site for inclusion in the assessment need to be identified that are suitable, reflect the main exposure pathways appropriately, and allow for higher exposure. The use of habits data is discussed in sub-section 3.4. Cautious assumptions about habits data may be included if they are appropriate for the envelope of potential sites in the UK at which the reactor could operate. Such an approach has been used in GDA studies for other reactor designs. It ensures that the dose assessment within the GDA will bound the potential effects of the UK HPR1000 at a range of sites.

The UK HPR1000 may be operated at several sites in the UK. For this independent assessment, the generic site used was derived following an examination of site characteristics for the eight nuclear sites that have previously been determined as potentially suitable for the deployment of new nuclear power stations in the UK (DECC, 2011) (Bradwell, Hartlepool, Heysham, Hinkley Point, Oldbury, Sellafield, Sizewell and Wylfa). The generic site needs to be defined based on reasonably cautious parameters from which to carry out the assessments, and take into account:

- atmospheric dispersion – land use, location of both human and non-human receptors, foodstuffs grown

- dispersion within the marine environment – retention and dispersion of radionuclides within the local marine compartments, use of the shoreline and water, and biota present.

Terrestrial parameters have been defined for the generic site using generic meteorological data for a UK coastal site (Clarke, 1979), covering wind speed and direction, Pasquill stability and washout coefficients. The topography of the site has been defined based on a reasonably conservative typical site. An analysis of atmospheric and terrestrial parameters for the generic site is presented in Appendices A2 and C2 respectively.

Marine parameters have been defined for the generic site based on a conservative UK potential site. The local marine compartment parameters including: volume, depth, coastline length, volumetric exchange rate, sedimentation rate, suspended sediment load etc., have broadly been defined by a review of local compartment parameter values for UK sites (PHE, 2019), taking into consideration that the HPR1000 site is likely to be located in Bradwell. This assumption is not unreasonable as the Bradwell local marine compartment has the most conservative values for the majority of parameters. The analysis of marine parameters is presented in Appendices A2 and D2. Data for the environment around nuclear sites in the UK and Europe are available in the description of models and data for the PC CREAM 08 code (Smith & Simmonds, 2009) and (PHE, 2019).

Our analysis of the environmental dispersion around the eight nuclear sites that have previously been determined as potentially suitable for the deployment of new nuclear power stations in the UK suggests that a generic site reflecting elements of the Bradwell site is not inappropriate. We have therefore adopted the Bradwell characteristics as the basis of the generic site.

3.4. Potentially Exposed People

As with the site characteristics, it is appropriate to make suitably cautious assumptions for the habits and behaviour of potentially exposed people near the site. The assumptions made should not be unrealistic. Members of the public can be exposed to radionuclides discharged to atmosphere or to the marine environment by a range of exposure pathways. The exposure pathways considered in the independent assessment are typical of those evaluated in radiological assessments of discharges from other nuclear sites. Guidance provided by the NDAWG (NDAWG, 2009) has also been taken into account.

Food consumption rates and occupancy assumptions for use in the prospective independent dose assessment have been based on established generic values for the UK from national survey data, see NRPB-W41 (Smith K. R., 2003).

The IRA methodology (Environment Agency, 2006 b) defines possible candidates for the representative person that provide a basis for this study. Details of their assumed behaviour, in respect of the exposure pathways described above, are presented in Appendix A (general information), Appendix C (exposure to estimated maximum annual atmospheric discharges) and Appendix D (exposure to estimated maximum annual liquid discharges).

3.5. Results

Initial Radiological Assessment of the UK HPR1000

The IRA methodology (Environment Agency, 2006 a) and (Environment Agency, 2006 b) was used to undertake an initial assessment of the estimated discharges from a single UK HPR1000. The assessment was carried out in two stages as detailed in Appendix B.

Stage 1 of the initial assessment makes very cautious assumptions about the dispersion of released radionuclides. Dose Per Unit Release (DPUR) values (Environment Agency, 2006 b) were multiplied by the estimated discharge rates (Table 1 and Table 2) to determine the calculated dose. The results are shown in Table 7. The total dose from discharges is above 20 μSv y^{-1}, indicating that further assessment is required.

Stage 2 of the IRA allows simple refinements to reflect site-specific characteristics that affect dose. The resulting Stage 2 doses are shown in Table 7.

The main change between the Stage 1 and Stage 2 assessments is that in a Stage 1 assessment the release to atmosphere assumes a ground level release whilst in the Stage 2 assessment the release was assumed to be via a stack with effective height of 20 m. In addition, a refined value for seawater exchange rate is used, from the conservative 100 m^3 s^{-1} in Stage 1 to a Bradwell specific value of 127 m^3 s^{-1} for the Stage 2 assessment.

The total dose from discharges remains above 20 μSv y^{-1}, indicating a detailed (Stage 3) assessment is appropriate. This is presented in subsequent sections.

Table 7: Doses (in μSv y^{-1}) from the discharges of a single UK HPR1000, estimated using the IRA methodology

Stage	Discharges	Food ingestion	External Irradiation	Inhalation	Total
Stage 1	Atmospheric Discharges	58	13	63	130
	Liquid Discharges	27	0.42		28
Stage 2	Atmospheric Discharges	19	0.035	2.5	22
	Liquid Discharges	22	0.34		22

Stage 3 Assessment – Individual doses to people most exposed to radioactive substances

In the Stage 3 detailed independent dose assessment, individual doses to groups of people most exposed to each of the main estimated maximum annual radioactive discharges from the UK HPR1000 were calculated. This was completed using PC CREAM 08 (Smith & Simmonds, 2009).

Doses were calculated on the basis of the maximum annual discharges for releases to the atmosphere and marine environment estimated by GNSL (see Table 1 and Table 2) for a period of 60 years. The site characteristics and human habits used in the calculations are described in detail in Appendix C (atmospheric releases) and Appendix D (liquid discharges). The total doses to members of the public most exposed to atmospheric discharge (the local resident) and marine discharges (the angler) are presented in Table 8, with details provided about the food type which contributes the most to the dose presented in Table 9. Further information on doses from food can be found in Appendix C.

Table 8: Summary of the total doses (in µSv y^{-1}) to people most exposed to atmospheric (the local resident) and liquid (the angler) discharges from a single UK HPR1000, calculated by the independent dose assessment

Group	Age	Inhalation	External	Dose from all foods	Total
Local resident (atmospheric discharges)	Adult	1.8	0.051	9.5	11
	Child	1.5	0.031	11	12
	Infant	1.2	0.025	19	21
Local Angler (liquid discharges)	Adult	$3.0\ 10^{-6}$	0.060	7.9	8.0
	Child	$3.3\ 10^{-7}$	$8.8\ 10^{-3}$	2.4	2.4
	Infant	$2.4\ 10^{-8}$	$8.8\ 10^{-4}$	0.61	0.61

Table 9: Details of the food type which contributes the most to the dose (in µSv y^{-1}) for the most exposed individuals to atmospheric (the local resident) and liquid (the angler) discharges.

Group	Age	Main food type	Dose from main food type	Dose from all foods
Local resident (atmospheric discharges)	Adult	Cow Milk Products	3.7	9.5
	Child	Cow Milk Products	3.9	11
	Infant	Cow Milk	9.5	19
Local Angler (liquid discharges)	Adult	Fish	4.4	7.9
	Child	Fish	1.2	2.4
	Infant	Fish	0.61	0.61

Stage 3 Assessment - Dose to the "representative person"

For a Stage 3 assessment it is necessary to calculate total doses to people most exposed from all exposure pathways. These exposure pathways are: exposure to estimated atmospheric discharges, exposure to estimated liquid discharges, direct radiation from the site and exposure to estimated short-term releases. The most exposed person to the combination of all of these pathways is referred to as the 'representative person'. The key criteria are the new build dose constraint of 150 µSv y^{-1} and the source-related dose constraint of 300 µSv y^{-1} (Environment Agencies, 2012).

The independent dose assessment evaluated two candidate families for the representative person, based on the local farmer and angler. These were used to assess doses from atmospheric and liquid discharges only, without considering direct radiation or short-term releases at this stage. The local farmer was assumed to spend a significant amount of time on land near the reactor in a house and outdoors, eat mainly food produced near the reactor, spend an average amount of time on the local beach and eat average amounts of local seafood. The angler was assumed to spend less time on land near the reactor, but to spend more time on the beaches, consume more fish and shellfish but lower amounts of locally produced terrestrial food than the local resident. The habits of the candidates for the 'representative person' are described in Appendix E.

Direct irradiation from radioactivity within the UK HPR1000 is not regulated by the Environment Agency, but needs to be included in the total dose. The dose due to direct radiation is considered in Appendix I. The contribution of doses from short-term releases should also be included in the total dose. The dose due to exposure to short-term releases is considered in Appendix F. The total dose, presented in Table 10, is the dose to the candidates for the ‘representative person’ combined with the dose from direct radiation and short-term releases. The dose from short-term releases includes consumption of food for a year following the release. Therefore there may be some duplication of dose between the dose calculated for ingestion of foods from routine releases and that from the short-term release. Radioactivity released to the atmosphere is the largest contributor to dose for all exposed individuals, except the adult in the fishing family. For all potentially exposed people, the dose is dominated by C-14 with cow’s milk and milk products being the principle ingestion pathways. For the infant in the farming family (assumed to consume 320 litres of milk per year) 69% of the total dose is associated with C-14, and 59% is associated with consuming milk and milk products.

Table 10: Summary of the total doses (in µSv y^{-1}) from a single UK HPR1000 to the candidates for the "representative person" including the dose due to direct radiation, calculated by the independent dose assessment

Group	Age	Atmos. Discharges	Liquid Discharges	Direct rad.*	Short-term Releases**	Total	Dose Const.
Local Farming Family	Adult	11	0.98	0.44	6.9	19	300
	Child	12	0.68	0.22	6.0	19	300
	Infant	21	0.43	0.15	7.8	29	300
Local Fishing Family	Adult	7.0	8.0	0.44	6.9	22	300
	Child	7.7	2.4	0.22	6.0	16	300
	Infant	9.8	0.61	0.15	7.8	18	300

Note: *The doses due to direct radiation are assessed at 300 m from the reactor. The sensitivity analysis for this distance can be found in Appendix I5.

** Units are µSv.

On the basis of the calculated doses for the assumed discharges, a single site could operate more than one HPR1000 and remain within the site-related constraint of 500 µSv y^{-1} (Environment Agencies, 2012). As a first estimate the total dose to an individual from discharges can be assumed to be proportional to the number of reactors.

The total doses calculated by GNSL (General Nuclear System, 2020a) for the candidate representative persons are shown in Table 11. The doses calculated in the independent dose assessment (Table 10) range from 16 to 24.5 µSv y^{-1} These are similar to but slightly higher than those calculated by GNSL which range from 10 to 24.5 µSv $y^{-1.}$ The actual total dose from a UK HPR1000 from gaseous discharges and direct radiation will depend on site-specific factors, including terrain, the habits of people and the location of the people including their houses relative to the reactor.

Table 11: Total doses (in µSv y^{-1}) from a single UK HPR1000 to the candidates for the "representative person" including the dose due to direct radiation, calculated by GNSL (Tables T-7.7-1 and T-7.7-2) (General Nuclear System, 2020a)

Group	Age	Atmospheric Discharges	Liquid Discharges	Direct radiation	Total
Local Farming Family	Adult	9.8	2.2	8.0	20.0
	Child	9.6	3.0	4.1	16.7
	Infant	15.1	0.6	2.8	18.5
Local Fishing Family	Adult	5.3	11.2	8.0	24.5
	Child	4.9	4.3	4.1	13.3
	Infant	6.5	0.9	2.8	10.2

Individual doses from potential short-term releases

Variation in radioactive discharges from an operating HPR1000 occurs due to short-term release events during the plant's normal operation. The principles for prospective dose assessment (Environment Agencies, 2012) require an assessment of the potential radiological consequences of such releases, to ensure dose constraints and limits are met.

The main expected short duration releases are to atmosphere. The characteristics of the release have been taken from GNSL (General Nuclear System, 2020a) and it has been assumed that these releases will occur over a 24 hour period. There are various numerical models available for assessing air concentrations for such a release, most of which rely on Gaussian plume dispersion. GNSL has used ADMS (CERC, 2012) which is one such model and which satisfies the guidance provided by NDAWG (NDAWG, 2019). ADMS has also been used in the independent dose assessment of a short-term release.

The results of the dose calculations are presented in Appendix F and are summarised in Table 12. Table 12 shows that the most exposed person is an infant and the results presented in Appendix F show that the dominant pathway to this dose is intake of C-14 from ingestion of food.

Table 12: Estimated doses (in µSv y^{-1}) from a short-term release calculated in the independent dose assessment

Exposed Group	Independent Dose Assessment
Adult	6.9
Child	6.0
Infant	7.8

Collective doses to exposed populations

The collective dose provides a measure of the exposure of all people to radioactive discharges. It is the sum of all doses to a defined population, over a defined time. Guidance (Environment Agencies, 2012) recommends that the populations considered should be UK residents, Europeans, and the global population, and that the time period over which doses are summed should be 500 years. Collective doses to these populations have been calculated in the independent study using PC CREAM 08, which provides models and data for the calculation of collective dose.

The collective dose results, described in more detail in Appendix G, are summarised in Table 13. There are no specific criteria against which the collective dose is compared, although collective doses are used to inform decisions on the permitting of discharges. However, it is noted that the average per caput dose may be informative (Environment Agencies, 2012). . It can be considered that per caput doses of less than 10 μSv y^{-1} represent a trivial level of individual risk (Smith , et al., 2007)

Table 13: Collective dose (manSv), truncated at 500 years, for each year of radioactive discharge from a single UK HPR1000 nuclear power plant for the independent dose assessment

Discharges	Dose Type	UK Population	EU Population	World population
Atmospheric Discharges	First Pass	0.53	2.7	-
	Global Circulation	0.18	1.4	30
	Total (atmospheric)	0.71	4.1	30
Liquid Discharges		0.013	0.078	0.74
Total		0.72	4.2	31

The independent dose assessment calculated collective doses per year of discharge from the UK, EU and global circulation of atmospheric and liquid releases that were closely matched by those given by GNSL (General Nuclear System, 2020a); see Table 14.

Table 14: Collective dose (manSv), truncated at 500 years, for each year of radioactive discharge from a single UK HPR1000 nuclear power plant calculated by GNSL (General Nuclear System, 2020a)Tables T-7.11-1 and T-7.11-2)

Discharges	Dose Type	UK Population	EU Population	World population
Atmospheric Discharges	First Pass	0.51	2.52	-
	Global Circulation	0.18	1.36	29.7
	Total (atmospheric)	0.68	3.88	29.7
Liquid Discharges		0.004	0.024	0.659
Total		0.684	3.90	30.4

Radiation Exposure of non-human species

Wildlife (non-human species) are exposed to radionuclides discharged to the environment. The Environment Agency process for the GDA (Environment Agency, 2016) requires that doses to the most exposed non-human species are assessed. This assessment has been undertaken using the same assumptions for the generic site and rates of discharge used in the assessment of doses to people.

Doses were assessed using the ERICA methodology (Beresford, et al., 2007), supplemented by the model for noble gases (Vives i Batlle, Jones, & Copplestone, 2015), for a wide range of non-human species.

Small and large mammals were deemed the most exposed non-human species for estimated annual atmospheric discharges. Cs-137 is the dominant radionuclide for these species. The dose rates were well below the screening value of 10 µGy h^{-1} to terrestrial animals, birds and reptiles and terrestrial plants. The most exposed non-human species assessed for estimated annual liquid discharges is the marine mammal, with an exposure rate of 0.023 µGy h^{-1} from the assessed nuclides. This is far below the 10 µGy h^{-1} screening level for aquatic organisms. The results are detailed further in Appendix H

3.6. Discussion

Direct Dose

Table 15 displays the comparison between the direct dose calculated at 100 m from the site in the assessment performed by GNSL (General Nuclear System, 2020a) and that calculated at 300 m used in the independent dose assessment as the location of the exposure group dwellings. The doses are not identical due to the different distances at which they were assessed. Justification of the use of 300 m as the distance from the site is given in Appendix I.

Table 15: Comparison of estimated doses (in µSv y^{-1}) from direct radiation at various distances from the site calculated in the independent dose assessment and by GNSL (General Nuclear System, 2020a) Table T-7.5-1

Exposed Group	Independent Dose Assessment (300 m)	GNSL (100 m)
Adult	0.44	8.0
Child	0.22	4.1
Infant	0.15	2.8

Stage 1 Assessment

Table 16 displays the comparison between the dose calculated at Stage 1 of the initial assessment for both the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a). The assessed doses are mainly identical, with the exception of the calculation of dose due to atmospheric discharge. This is due to the cautious substitutions made by the independent dose assessment when a radionuclide present in the both gaseous and liquid discharge inventory does not have a counterpart in the IRAT.

Table 16: Comparison of estimated doses (in µSv y^{-1}) calculated in Stage 1 of the initial assessment by the independent dose assessment and by GNSL (General Nuclear System, 2020a) Table T-7.6-1

Discharge Route	Independent Dose Assessment	GNSL
Atmospheric Discharges	130	120
Liquid Discharges	28	28

Stage 2 Assessment

Table 17 displays the comparison between the dose calculated at Stage 2 of the initial assessment for both the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a). The assessed doses by the independent dose assessment are marginally higher than those calculated by GNSL due to the selection of more cautious input data.

The difference in the dose from exposure to atmospheric discharges occurs due to the selection of different scaling factors for food ingestion for the effective stack height of 20 m. The independent dose assessment has used a scaling factor of 0.33 as recommended by the IRAT for a 20 m stack, whilst the assessment performed by GNSL uses a scaling factor of 0.27.

For the dose due to liquid discharges, this is due to the selection of a lesser volumetric exchange rate of 127 $m^3 s^{-1}$ for the Stage 2 assessment by the independent dose assessment. This is in comparison to 130 $m^3 s^{-1}$ volumetric exchange used by GNSL. The exchange rate used in the independent dose assessment is appropriate for Bradwell (Simmonds, Lawson, & Mayall, 1995) and is more cautious as it results in higher activity concentrations in the local compartment, and therefore higher exposures.

Table 17: Comparison of estimated doses (in µSv y^{-1}) calculated in Stage 2 of the initial assessment by the independent dose assessment and by GNSL (General Nuclear System, 2020a) Table T-7.6-2

Discharge Route	Independent Dose Assessment	GNSL
Atmospheric Discharges	22	18
Liquid Discharges	22	21

Stage 3 Assessment – Most Exposed Individuals

Table 18 displays the comparison between the dose calculated in the “Stage 3 – Most Exposed Individuals” part of the initial assessment for both the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a).

In the case of the local angler, the variation may occur due to the use of different marine parameters for the local compartment. The independent dose assessment uses updated data for use with the DORIS model based on a 2019 review (PHE, 2019). In addition, the GNSL assessment uses different habits data, with a higher beach occupancy time, taken from a habits survey report of Bradwell in 2015. The independent dose assessment has used data from generic values presented in NRPB-W41 (Smith K. R., 2003).

The difference in the assessed results for the local resident arises from the selection of different distances from the site at which the resident lives. It is demonstrated in Appendix I that 300 m (the distance used in the independent dose assessment) is a more realistic location to select than 100 m (the distance used in the GNSL assessment). In addition, the GNSL assessment did not consider the effect of consumption of locally produced milk products on the dose to the local resident.

Table 18: Comparison of estimated doses (in µSv y^{-1}) calculated in Stage 3 of the initial assessment to the most exposed individual by the independent dose assessment and by GNSL (General Nuclear System, 2020a) Table T-7.6-3

Discharge route – local resident (atmospheric discharges)

Exposed Group	Independent Dose Assessment	GNSL
Adult	11	9.8
Child	12	9.6
Infant	21	15.1

Discharge route – local angler (liquid discharges)

Exposed Group	Independent Dose Assessment	GNSL
Adult	8.0	11
Child	2.4	4.3
Infant	0.61	0.90

Stage 3 Assessment – Representative Person

Table 19 displays the comparison between the doses calculated in the "Stage 3 – Representative Person" part of the initial assessment for both the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a). The assessed doses are not identical. This is due to the same reasons as those that caused the variation in doses to the most exposed individuals, in combination with an increased direct dose contribution in GNSL's assessment as the candidate representative person lived at 100 m from the site. The candidate for the representative person for the independent dose assessment lived at 300 m from the site. In addition, the dose due to short-term releases is not included in the total for the GNSL assessment, whereas it is included for the independent dose assessment.

Table 19: Comparison of estimated doses (in µSv y^{-1}) calculated in Stage 3 of the initial assessment to the representative person by the independent dose assessment and by GNSL (General Nuclear System, 2020a) Tables T-7.7-1 and T-7.7-2

Discharge route – local farming family (atmospheric discharges)

Exposed Group	Independent Dose Assessment	GNSL
Adult	19	20
Child	19	17
Infant	29	19

Discharge route – local angling family (liquid discharges)

Exposed Group	Independent Dose Assessment	GNSL
Adult	22	25
Child	16	13
Infant	18	10

Short-term releases

Table 20 displays the comparison between the dose due to short-term releases as assessed by the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a).

The doses calculated are lower than those calculated by GNSL, which is due to a difference in the calculation method of integrated activity concentration of C-14 in foods used by GNSL and resulted in higher doses from the ingestion of C-14 in foods. The independent assessment has also identified a higher contribution to the total dose from the inhalation pathway. This is thought to be due to the independent assessment using the cautious assumption that that there is no indoor occupation during the passage of the plume for all age groups.

Table 20: Comparison of estimated doses (in µSv y^{-1}) from short-term releases calculated in the independent dose assessment and by GNSL (General Nuclear System, 2020a) Tables T-7A-23, T-7A-24 and T-7A-25

Exposed Group	Independent Dose Assessment	GNSL
Adult	6.9	8.7
Child	6.0	9.0
Infant	7.8	15

Collective Dose

Table 21 displays the comparison between the collective doses as assessed by the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a). The collective doses calculated by the independent dose assessment are broadly comparable to those calculated in the GNSL assessment.

Table 21: Comparison of estimated collective doses (in µSv y^{-1}) calculated in the independent dose assessment and by GNSL (General Nuclear System, 2020a) Table T-7.11-2

Exposed Group	Independent Dose Assessment	GNSL
UK Population	0.72	0.68
EU Population	4.2	3.9
World Population	31	30

Dose to Non-Human Species

Table 22 displays the comparison between the doses to non-human species due to the estimated maximum annual atmospheric discharges as assessed by the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a).

Table 22: Comparison of estimated doses (in µSv y^{-1}) to non-human species from estimated maximum annual atmospheric discharges calculated in the independent dose assessment and by GNSL (Table T-7A-35) (General Nuclear System, 2020a)

Exposed Group	Independent Dose Assessment	GNSL
Amphibian	0.09	0.141
Bird	0.046	0.144
Mollusc - gastropod	0.034	0.0517
Reptile	0.086	0.146
Annelid	0.08	0.0517
Arthropod - detritivore	0.082	0.0592
Flying insects	0.035	0.051
Grasses & Herbs	0.031	0.101
Lichen & Bryophytes	0.068	0.108
Mammal - large	0.13	0.147
Mammal - small-burrowing	0.13	0.142
Shrub	0.051	0.0991
Tree	0.034	0.142

Table 23 displays the comparison between the doses to non-human species due to the estimated maximum annual liquid discharges as assessed by the independent dose assessment and the assessment performed by GNSL (General Nuclear System, 2020a).

Table 23: Comparison of estimated doses (in µSv y^{-1}) to non-human species from estimated maximum annual liquid discharges calculated in the independent dose assessment and by GNSL (Table T-7A-34) (General Nuclear System, 2020a)

Exposed Group	Independent Dose Assessment	GNSL
Benthic fish	$6.6\ 10^{-4}$	$1.6\ 10^{-3}$
Bird	$6.5\ 10^{-4}$	$1.3\ 10^{-3}$
Crustacean	$9.8\ 10^{-4}$	$1.6\ 10^{-3}$
Macroalgae	$5.3\ 10^{-4}$	$1.5\ 10^{-3}$
Mammal	0.023	$1.5\ 10^{-3}$
Mollusc - bivalve	$6.3\ 10^{-4}$	$1.1\ 10^{-3}$
Pelagic fish	$5.8\ 10^{-4}$	$1.2\ 10^{-3}$
Phytoplankton	$2.9\ 10^{-4}$	$4.3\ 10^{-4}$
Polychaete worm	$2.8\ 10^{-3}$	$6.3\ 10^{-3}$
Reptile	$8.4\ 10^{-4}$	$1.5\ 10^{-3}$
Sea anemones & True coral	$6.9\ 10^{-4}$	$1.6\ 10^{-3}$
Vascular plant	$5.4\ 10^{-4}$	$1.4\ 10^{-3}$
Zooplankton	$2.7\ 10^{-3}$	$5.3\ 10^{-3}$

For the doses to non-human species due to atmospheric releases both the independent dose assessment and the GNSL assessment calculate the large Mammal to be the most exposed. However, for doses to non-human species due to liquid discharges the independent dose assessment has calculated the mammal as receiving the largest dose whereas the GNSL assessment calculated the polychaete worm as receiving the largest dose. This could be due to the selection of a different Concentration Ratio (CR) for Fe-59 between the two assessments.

Comparison with dose criteria

For the assessment of a single reactor undergoing the GDA process, the dose criteria (Environment Agencies, 2012) of importance are:

- 300 µSv y^{-1} source constraint for future discharges and direct radiation from the planned operation of the reactor.
- 20 µSv y^{-1} level below which no further work is required for the dose assessment.

In addition, there is a proposed dose constraint of 150 µSv y^{-1} for nuclear new build which was never formally taken into legislation (HPA, 2009).

For the candidate for the representative person, identified in the independent dose assessment as the infant in the farming family, the estimated dose received is 29 µSv y^{-1}. All estimated doses due to discharges from a singular HPR1000 are well below the dose constraint of 300 µSv y^{-1}. This level of dose from discharges means a site could operate more than one HPR1000 and remain within the site related constraint (to a first approximation, the total dose to an individual can be assumed to scale directly with the number of reactors).

Sensitivity Analysis

In order to ensure the assessment used the most appropriate parameters to calculate doses, sensitivity analyses were performed for model assumptions regarding site location, receptor location, and habits data used in the assessment.

The sensitivity analyses performed regarding the location of the site included:

- Comparison of the ground level activity in air concentrations at the different UK sites based on the Pasquill stability category for the site. Bradwell, with its Pasquill stability category of 65% D, resulted in a ground level activity in air concentration 7% higher than for a category of 70% D and 15% lower than for the most pessimistic category of 55% D (see Appendix C2)
- Comparison of the activity in seawater concentrations at the different UK sites. In this case, Bradwell, Oldbury and Hartlepool were the most pessimistic sites due to their low volumetric exchange rates (see Appendix D2)

It was determined that Bradwell would be the most appropriate site to use for the assessment as it is also the most likely location where the UK HPR1000 will be built.

The sensitivity analyses performed regarding the receptor location included:

- Varying the distance at which the receptor was placed to determine the location of the highest ground level activity in air concentration. It was found that 300 m from the stack gives the highest ground level activity in air concentration, which has been used in the main assessment (see Appendix C6)
- Varying stack height to demonstrate the effect this had on ground level activity in air concentrations at various distances from the stack. It was found that stack height plays a larger role closer to the stack, however, for large stack heights the receptor location with the highest ground level activity in air concentration moves further away (see Appendix C6)
- Determining the effect of varying the Pasquill stability category percentage on the ground level activity in air concentrations at different distances from the stack. It was found that at distances of 200 m or less from the stack, the variation of Pasquill stability category percentage had a large effect on ground level air concentration. However, at distances of 300 m or greater from the stack this effect was reduced (see Appendix C6)
- Considering the effect of moving the receptor location from 300 m to 100 m away from the reactor on the direct radiation component of the total dose. It was determined that whilst the direct radiation contribution to the total dose would increase, the dose associated with estimated atmospheric discharges peaked at 300 m from the site. As such, the most realistic position to locate the receptor is at 300 m from the reactor (see Appendix I5)

The sensitivity analyses performed regarding habits data included:

- Assessing the effect on dose when the diet of the most exposed individual does not include locally produced milk or milk products in line with local habits data (Smith K. R., 2003). The “top two” method was used on the remaining foodstuff without milk and milk products and was found to reduce the total dose (see Appendix C6)
- Assessing the effect on dose when an increased rate of fish consumption in children was used. This led to a 19% increase in the total dose to the child, from 2.4 to 3.0 µSv y^{-1}. This dose is significantly lower than the 20 µSv y^{-1} dose constraint (see Appendix D6)
- Assessing the effect on dose for a longer handling time of fishing gear in adults and children. This led to total dose increases in adults and children of less than 0.01%.

The doses were significantly below the 20 µSv y^{-1} dose constraint (see Appendix D6)

- Assessing the effect on dose for adult houseboat dwellers and infants with higher beach occupancy times. This led to increases in total dose for adults and infants of 1.9% and 3.8% respectively. The doses were significantly below the 20 µSv y^{-1} dose constraint (see Appendix D6)

Additional sensitivity analyses performed included:

- Assessing the dose uptake due to the short-term release inventory (see Table 5) being discharged over a 6 hour period as opposed to 24 hours. This led to a significant increase in the dose from exposure to short-term releases, due to an increased dose from consumption of foods. However, the doses were all well below the source dose constraint (see Appendix F6)
- Determining the activity in soil and seawater concentration of long-lived radionuclides in the discharge inventory for operational timescales and a look ahead time. This demonstrated that the activity concentrations in were constant or changed so little over timescales of 400 years that their dose contributions remain constant. Ingrowth need not be considered. (see Appendices C2 and D2)

4. Conclusions

An independent assessment has been undertaken of the estimated radioactive discharges from the UK HPR1000 that is being proposed for development in the UK by GNSL. The aim of the work was to independently estimate doses and other measures of radiological impact, such as activity concentrations in air or soil, due to the projected discharges from a single reactor site.

Stage 1 of the Initial Radiological Assessment (IRA) method calculated doses of 120 µSv y^{-1} from atmospheric discharges and 28 µSv y^{-1} from liquid discharges, whilst Stage 2 calculated doses of 22 µSv y^{-1} for both atmospheric and liquid discharges. Doses were calculated for the most exposed families to atmospheric discharges (local resident family) and liquid discharges (fishing family). The most exposed individuals from these families were the infant in the local resident family and the adult in the fishing family, who received doses of 21 µSv y^{-1} and 8.0 µSv y^{-1} respectively. The candidate for the "representative person" was determined to be the infant in the farming family. This individual was estimated to receive an annual dose of 29 µSv. This predicted dose is above the dose criterion of 20 µSv y^{-1} below which further assessment is not required, however, it is still well below the dose constraint of 300 µSv y^{-1} for a single source. Almost all of the dose is associated with discharges of C-14. Direct radiation contributed between 0.152 and 0.439 µSv y^{-1} to the total dose of the independent assessment, assuming 100% occupancy at 300 m from all buildings on site.

The independent assessment of doses from short-term releases calculated total doses of 7.0 µSv, 6.1 µSv and 7.8 µSv to the adult, child and infant groups respectively. The total doses are dominated by the inhalation of the plume and ingestion of foods and the dominant radionuclide contributing to the total dose was C-14. The independent estimates of the collective radiation dose to populations (Europe and the world) were above the collective dose criterion historically proposed by the International Atomic Energy Agency (IAEA) (IAEA, 1988), (IAEA, 2004 b) of 1 manSv y^{-1} of discharge. However, more recently the IAEA has revised its guidance on collective dose and no longer offers a dose criterion (IAEA, 2018). The collective radiation dose estimate for the UK population was below this value at 0.72 manSv. Estimates of exposures to wildlife did not indicate any doses that would be of concern.

The dose calculations in this study are applicable to the GDA and apply to a single HPR1000 unit. The results indicate that more than one unit could be accommodated at a site and still meet the legal dose criteria (the dose constraint of 300 μSv y^{-1} and site constraint of 500 μSv y^{-1}; or the dose limit of 1000 μSv y^{-1} allowing for radiation exposures from existing adjacent nuclear facilities).

Sensitivity analysis undertaken in the study shows that varying parameters such as meteorological data, stack height and habits of the representative person leads to similar or lower environmental concentrations and lower doses than those calculated for a site similar to Bradwell, which was used in this assessment. Sensitivity analysis showed that doses from direct radiation are higher when members of the public are located closer to the site.

If a site is selected for a new reactor of this design and an Environmental Permit applied for, then a site-specific assessment will be needed. This assessment will take account of site-specific factors and the number of UK HPR1000 units that will be operated.

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List of abbreviations

Abbreviation	Definition
ALARA	As Low As Reasonably Achievable
CGN	China General Nuclear Power Corporation
CR	Concentration Ratio
DEFRA	Department for Environment, Food and Rural Affairs
DPUR	Dose Per Unit Release
EC	European Commission
GDA	Generic Design Assessment
GNSL	General Nuclear System
UK HPR1000	UK Hualong One Pressurised Water Reactor
IAEA	International Atomic Energy Agency
IRA	Initial Radiological Assessment
IRAT	Initial Radiological Assessment Tool
LLWR	Low Level Waste Repository
NDAWG	National Dose Assessments Working Group
NRPB	National Radiological Protection Board
ONR	Office for Nuclear Regulation
PHE	Public Health England
P&ID	Process and Information Document

Appendix A: Approach to the independent dose assessment

A1 Requirements

The requirements for the GDA (Environment Agency, 2016) specify the need for the requesting party to undertake a dose assessment that calculates:

- the annual dose to the most exposed members of the public resulting from estimated maximum annual liquid discharges
- the annual dose to the most exposed members of the public resulting from estimated maximum annual atmospheric discharges
- the annual dose to the most exposed members of the public from both liquid and atmospheric discharges
- the annual dose to the representative member of the public local to the site
- potential short-term doses, including those received via the food chain, based on anticipated short-term discharges from the facility in normal operation
- a comparison of the calculated doses with the relevant dose constraints
- an assessment of the build-up of radionuclides in the environment, over the anticipated lifetime of the facility
- the collective radiation dose, truncated at 500 years, to the UK, European and world populations
- the dose to non-human species

An estimate of the annual dose from direct radiation to the public also needs to be included when calculating total doses that are compared with dose constraints. The calculation of these doses is discussed in Appendix I.

The independent dose assessment provides an independent view of the potential radiological impacts of a single UK HPR1000 located at a generic site in the UK. The independent dose assessment must therefore address the requirements presented above, applying good practice guidance.

This appendix describes key aspects: the approach taken to define a generic site and the assessment approach. Details that are specific to each particular assessment are discussed in the remaining appendices (Appendix B to H) which cover each of the aspects described above in turn.

A2 Characteristics of a generic site

The choice of the site at which the assessment is made is important because some of its characteristics influence the dispersion of discharged radioactivity. This determines the environmental concentrations and therefore the doses received.

For the GDA, it is necessary to make assumptions about the site that are cautious but realistic to ensure that all potential site conditions have been encompassed. One of the ways to do this is to base the generic site on an existing nuclear site. This approach has been adopted in previous independent dose assessments (Environment Agency, 2016) by basing the site characteristics on an existing nuclear site with the lowest environmental dispersions for the anticipated discharges. The same approach has been taken here. A review of the characteristics of the site has been performed to ensure the most appropriate site has been selected for the specifics of the UK HPR1000.

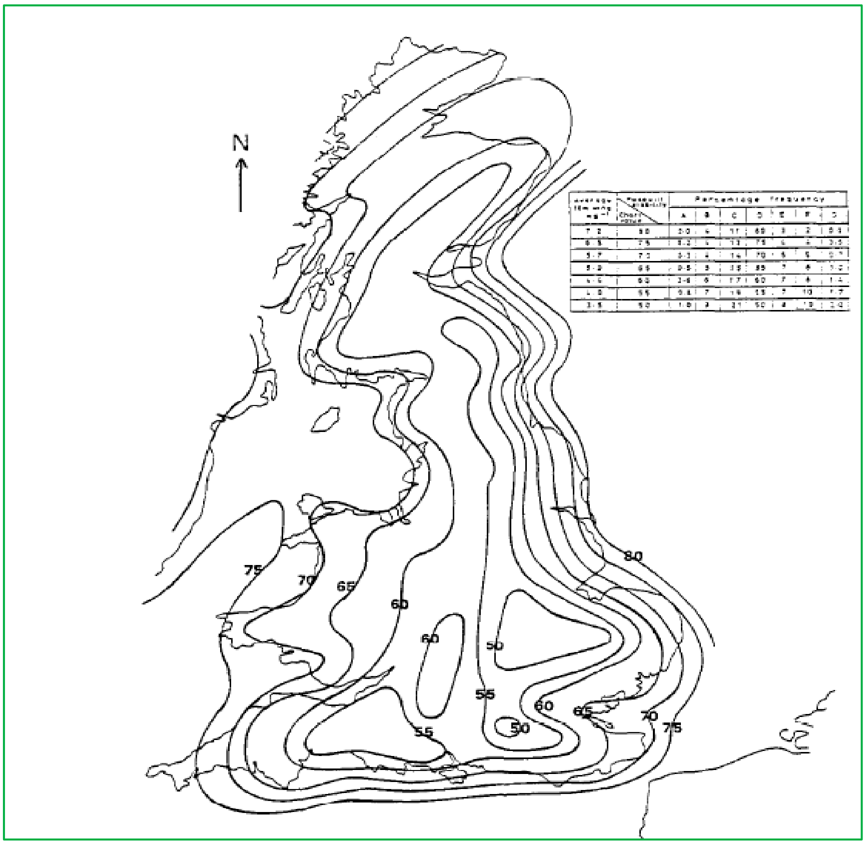


Figure A 1: Long-term average meteorological conditions in the UK according to Pasquill stability scheme (Clarke, 1979)

For discharges to the atmosphere, all but one of the eight nuclear sites that are potentially suitable for the deployment of new nuclear power stations are located on the coast or a coastal environment. Figure A 1 shows the long-term average meteorological conditions according to the Pasquill stability scheme for the UK. Taking the atmospheric conditions for each existing nuclear site and applying the atmospheric discharge rates assumed for the UK HPR1000 enables estimates to be made of ground level atmospheric concentrations of radioactivity.

Detailed descriptions of the assessment to identify the generic site parameters are presented in Appendices C2 and D2 for the dose assessment of atmospheric and marine discharges respectively. Based on this analysis, the site characteristics of Bradwell have been adopted for the generic site used in the independent dose assessment. The Bradwell site is the site identified as having the lowest dispersion for liquid discharges which leads to the highest activity concentrations in water and sediment of the potential sites (see Appendix D2). The Bradwell site also has a 65% D Pasquill stability category that is representative of the coastal location expected to be occupied by the UK HPR1000.

Suitably cautious (but not unrealistic) assumptions are also needed for people's behaviours and habits when assessing doses. At each existing nuclear site, there are groups of people that can be characterised as most exposed based on their habits, actual places of home and work, related exposure pathways and food intakes. These data are dependent on particular individuals and can readily change, especially over the course of more than half a century during which the UK HPR1000 is anticipated to operate (this would be considered at site specific permitting and during periodic permit reviews). Habits data around each nuclear site are collected by periodic habits surveys and these data may be used in assessments for a permit application. Habits data are also available from generic UK wide surveys (in particular food intake rates). Habits data used in the independent dose assessment are based on UK wide surveys – augmented by habits data taken from recent surveys around the Bradwell site.

The independent dose assessment therefore uses the land and water use assumptions and habits of people described in the IRA methodology (Environment Agency, 2006 a) (Environment Agency, 2006 b) and supporting studies, which combines habits data derived from national surveys and atmospheric and coastal dispersion factors. The derivation of human exposure assumptions is presented for each dose assessment in the appendices as part of the description of the specific dose assessment.

A3 Assessment approach

The discharges to be assessed are estimated releases to the atmosphere and the marine environment, and the receptors are human populations (individual and collective doses) and non-human species. In relation to the doses to people, 'Principles for the Assessment of Prospective Public Doses'" (Environment Agencies, 2012) describes a staged approach to the assessment of radiation doses, which has been applied in this study.

The initial dose assessment involves a simple and cautious assessment of the dose. There are two stages to the initial dose assessment.

- Stage 1 – initial radiological assessment using default data in the IRA methodology, and
- Stage 2 – initial radiological assessment using refined data.

If the resulting dose to the representative person is less than 20 µSv y^{-1} then no further assessment is likely to be needed. Where the initial dose assessment outcome exceeds 20 µSv y^{-1}, then a further assessment with suitable refinements to reflect the site may be appropriate. The methodology describes how the assessment can be refined at Stage 2; this involves scaling the dose to take account of local dispersion in the atmosphere or the marine environment.

If the doses calculated for the Stage 2 assessment remain above 20 µSv y^{-1} then a detailed assessment may be appropriate using site-specific models.

A3.1 Initial dose assessment (Stage 1 and 2)

Our independent initial dose assessment (Stage 1 and 2) is presented in Appendix B.

A3.2 Stage 3 (detailed) assessment

The dose assessment guidance (Environment Agency, Natural Resources Wales & ONR, 2019) does not specify models to be used in a Stage 3 detailed dose assessment. However, as a refinement of the dose assessment from Stage 1 and 2, it is reasonable to adopt an approach that uses the same models that are used in the previous stages. In the case of routine discharges, this is the PC CREAM 08 dose assessment code, which is widely used for the assessment of releases from nuclear sites in the UK and Europe.

PC CREAM 08 is a well-established system that was specifically designed for the assessment of the effects of continuous discharges of radioactivity on people. It was originally based on European Commission (EC) methodology (Simmonds, Lawson, & Mayall, 1995) and has been developed further since then (Smith & Simmonds, 2009). It is suitable for the purpose of assessing individual doses and collective doses to people from liquid and gaseous discharges. The main limitations of PC CREAM 08 are:

- the atmospheric dispersion module, PLUME embedded in PC CREAM 08 is for continuous releases, and its implementation means that it is not suitable for the assessment of short-term releases (as discussed by NDAWG (NDAWG, 2020)); and
- it does not include algorithms for the calculation of radiation doses to non-human species.

For short duration releases to the atmosphere our approach follows the NDAWG guidance, which recommends the use of the ADMS code to evaluate atmospheric dispersion. ADMS is a significantly more sophisticated model than the PLUME model which provides more detailed outputs. This can require a higher amount of input data, which enables more specific atmospheric conditions such as might be encountered during a short-term discharge to be defined. ADMS can be used to calculate air concentrations and deposition rates at a given location.

For the assessment of exposures to non-human biota, PC CREAM 08 can be used to estimate environmental concentrations. The exposure of non-human species can then be assessed using the ERICA approach (Beresford, et al., 2007). This is widely used and can be readily applied to the predicted environmental concentrations. ERICA provides models and data that deliver estimates of radiation doses to a range of non-human species. ERICA does not include models for the exposure of non-human species by noble gases, for which an alternative approach has been used as described in Appendix H.

Appendix B: Initial Dose Assessment

B1 Introduction

This appendix presents the initial dose assessment of the estimated radioactive discharges from the UK HPR1000. The IRA methodology (Environment Agency, 2006 a) (Environment Agency, 2006 b) has been used for this assessment. This recommends two stages to the assessment.

- Stage 1 - initial radiological assessment using default data
- Stage 2 - initial radiological assessment using refined data

The guidance describes how the assessment can be refined at Stage 2; this involves scaling the dose to take account of local dispersion in the atmosphere or the marine environment.

Both assessments use the annual discharges presented in Table 1 and Table 2 of the main report. These are the equivalent of the annual permit limits. The assessments used the default DPUR factors presented in the IRA documentation (Environment Agency, 2006 b). Some radionuclides included in the GNSL inventory did not have corresponding DPUR release factors. However, upon substituting alternative radionuclides with similar properties, as shown in Table B 1 and Table B 2, it was found that their contribution to the dose was minimal in most cases. For simplicity, these radionuclides have been omitted from the liquid release Stage 1 assessment and both liquid and gaseous release Stage 2 assessments, which has had no effect on the result. For the gaseous release Stage 1 assessment, the substitution of Ar-41 for both Xe-133m and Xe-135 led to dose contributions greater than 0.1% of the total dose and as such were included for this stage of the assessment.

Table B 1: Radionuclide substitutions used in the Stage 1 and 2 assessments of atmospheric discharges

Radio-nuclide	Category	Substitute	Radio-nuclide	Category	Substitute
Kr-83m	Noble Gas	Ar-41	Te-125m	Metalloid	Sb-125
Kr-87	Noble Gas	Ar-41	Te-127	Metalloid	Sb-125
Kr-88	Noble Gas	Ar-41	Te-127m	Metalloid	Sb-125
Xe-131m	Noble Gas	Ar-41	Te-129	Metalloid	Sb-125
Xe-133m	Noble Gas	Ar-41	Te-129m	Metalloid	Sb-125
Xe-135	Noble Gas	Ar-41	Te-131m	Metalloid	Sb-125
Xe-138	Noble Gas	Ar-41	Te-132	Metalloid	Sb-125
I-130	Reactive Nonmetal	I-129	Te-133m	Metalloid	Sb-125
I-132m	Reactive Nonmetal	I-129	Te-134	Metalloid	Sb-125
Br-83	Reactive Nonmetal	I-129	Cs-138	Alkali Metal	Cs-134
Br-84	Reactive Nonmetal	I-129	Ba-139	Alkaline Earth Metal	Ra-223
Rb-86	Alkali Metal	Cs-134	Ba-137m	Alkaline Earth Metal	Ra-223
Rb-88	Alkali Metal	Cs-134	Sb-122	Metalloid	Sb-125
Sr-91	Alkaline Earth Metal	Ra-223	Sb-124	Metalloid	Sb-125
Sr-92	Alkaline Earth Metal	Ra-223			

Table B 2: Radionuclide substitutions used in the Stage 1 and 2 assessments of liquid discharges

Radio-nuclide	Category	Substitute	Radio-nuclide	Category	Substitute
Ba-137m	Alkaline Earth Metal	Sr-90	Sb-124	Metalloid	Sb-125
Ba-139	Alkaline Earth Metal	Sr-90	Sr-91	Alkaline Earth Metal	Sr-90
Br-83	Reactive Nonmetal	P-32	Sr-92	Alkaline Earth Metal	Sr-90
Br-84	Reactive Nonmetal	P-32	Te-125m	Metalloid	Sb-125
Cs-138	Alkali Metal	Cs-137	Te-127	Metalloid	Sb-125
I-130	Reactive Nonmetal	P-32	Te-129	Metalloid	Sb-125
I-132	Reactive Nonmetal	P-32	Te-129m	Metalloid	Sb-125
I-132m	Reactive Nonmetal	P-32	Te-131m	Metalloid	Sb-125
I-134	Reactive Nonmetal	P-32	Te-132	Metalloid	Sb-125
Rb-86	Alkali Metal	Cs-137	Te-133m	Metalloid	Sb-125
Rb-88	Alkali Metal	Cs-137	Te-134	Metalloid	Sb-125
Sb-122	Metalloid	Sb-125			

B2 Stage 1 Initial Radiological Assessment

The IRA methodology presents DPUR values (μSv y^{-1} per Bq y^{-1}) for atmospheric releases and for liquid discharges to a marine environment.

In Stage 1 of the methodology, the atmospheric releases are assumed to be discharged at ground level, which is a very cautious assumption that will tend to lead to higher doses. Liquid discharges are assumed to occur into a local marine compartment with low dispersion. This is represented with volumetric exchange rate of seawater of 100 $m^3 s^{-1}$, which is at the low end of the rates found around existing nuclear sites in England and Wales.

The results calculated using the Stage 1 DPUR values for the proposed annual discharges for the UK HPR1000 are presented in Table B 3 and Table B 4.

The total dose from atmospheric discharges is above the 20 μSv y^{-1} criterion, indicating a Stage 2 assessment is required. C-14 is the dominant radionuclide contributing to dose (via inhalation and ingestion) and Xe-135 dominates the dose contribution from external radiation. The doses for liquid discharges are much lower than the atmospheric release doses; however, they are still above the criterion for further assessment. The dominant radionuclides for liquid discharges are C-14 (ingestion) followed by Co-60 (external radiation).

Table B 3: Estimated Stage 1 doses (in µSv y^{-1}) from atmospheric discharges from a single UK HPR1000

Radio-nuclide	Food Ingestion	External Irradiation	Inhalation	Total	% of Total	Age Group
H-3	1.4	0.0	3.6	5.0	3.8	Offspring
C-14	56	<0.10	59	120	86	Infant
Xe-133	0.0	0.81	0.0	0.81	0.61	Adult
I-131	0.35	<0.10	<0.10	0.39	0.29	Infant
Xe-133m*	0.0	0.58	0.0	0.58	0.44	Adult
Xe-135*	0.0	11	0.0	11	8.3	Adult
Total	58	13	63	130		

Note: Only radionuclides contributing more than 0.1% of the total dose and only doses greater than 0.1 µSv y^{-1} are shown

*There is no DPUR value for these radionuclides in the IRAT, therefore the DPUR value for Ar-41 was substituted.

Table B 4: Estimated Stage 1 doses (in µSv y^{-1}) from liquid discharges to the marine environment from a single UK HPR1000

Radionuclide	Seafood Ingestion	External Irradiation	Total	% of Total	Age Group
H-3	0.093	0	0.093	0.33	Offspring
Ag-110m	0.096	$3.0\ 10^{-3}$	0.099	0.36	Adult
C-14	27	$9.4\ 10^{-6}$	27	98	Offspring
Co-60	0.011	0.41	0.43	1.5	Adult
Total	27	0.43	28		

Note: Only radionuclides contributing more than 0.1% of the total dose are shown

B3 Stage 2 Initial Radiological Assessment

Stage 2 of the IRA involves enhancements to the assessment to include refined information about site-specific characteristics. The guidance in the methodology was used (Environment Agency, 2006b) which involves applying scaling factors. These factors relate to site-specific conditions, for example, variation in the initial dispersion of radionuclides in the atmosphere due to the height of the stack, or the dispersion in the marine environment due to the seawater exchange rate. These factors consequently affect the environmental concentrations and doses.

Scaling factors for inhalation, external radiation and food ingestion are provided in the IRA methodology for atmospheric releases to reflect stack height. Using an effective release height of 20 m (see Section 3.2 in the main report), the following scaling factors were used:

- 0.040 for inhalation/external radiation, and
- 0.33 food ingestion.

These have been applied to give the Stage 2 results shown in Table B 5.

For the liquid discharges, the main factor is the seawater exchange rate in the local marine environment. The Stage 1 calculations adopt a value of 100 $m^3 s^{-1}$. Using data from Table 4.5 of RP-72 (Simmonds, Lawson, & Mayall, 1995), a value appropriate for the generic site is 127 m^3 s-1 (this is discussed in Appendix A2 and is the recommended value for the Stage 2 assessment*). The Stage 2 results are shown in Table B 6.

The total dose from atmospheric discharges is slightly above the 20 μSv y^{-1} criterion indicating a detailed (Stage 3) assessment is appropriate. The dominant radionuclide and pathway is C-14 in foods. The doses from liquid discharges are also above this criterion. The dominant radionuclides for liquid discharges are C-14 and Co-60, and the dominant pathway is the ingestion of seafood.

The Stage 3 assessment of individual doses from atmospheric discharges is presented in Appendix C. A Stage 3 assessment of liquid discharges is presented in Appendix D.

Table B 5: Estimated Stage 2 doses in (μSv y^{-1}) from atmospheric discharges from a single UK HPR1000

Radio-nuclide	Food Ingestion	External Irradiation	Inhalation	Total	% of Total	Age Group
H-3	0.47	0.0	0.14	0.61	2.8	Offspring
C-14	18	<0.10	2.4	21	94	Offspring
Xe-133	0.0	<0.10	0.0	<0.10	0.15	Adult
I-131	0.12	<0.10	<0.10	0.12	0.53	Infant
Xe-133m⁺	0.0	<0.10	0.0	<0.10	0.10	Adult
Xe-135⁺	0.0	0.44	0.0	0.44	2.0	Adult
Br-83**	<0.10	<0.10	<0.10	<0.10	0.13	Infant
Total	19	<0.10	2.5	22		

Note: Only radionuclides contributing more than 0.1% of the total dose and only doses greater than 0.1 μSv y^{-1} are shown

⁺There is no DPUR value for these radionuclides in the IRAT, therefore the DPUR value for Ar-41 was substituted.

**There is no DPUR value for this radionuclide in the IRAT, therefore the DPUR value for I-129 was substituted.

Table B 6: Estimated Stage 2 doses (in μSv y^{-1}) from liquid discharges to the marine environment from a single UK HPR1000

Radionuclide	Seafood Ingestion	External Irradiation	Total	% of Total	Age Group
H-3	<0.10	0.0	<0.10	0.33	Offspring
Ag-110m	<0.10	<0.10	<0.10	0.36	Adult
C-14	21	<0.10	21	98	Offspring
Co-60	<0.10	0.32	0.34	1.5	Adult
Total	22	0.34	22		

Note: Only radionuclides contributing more than 0.1% of the total dose and doses greater than 0.1 μSv y-1 are shown.

Appendix C: Detailed independent dose assessment of atmospheric discharges

C1 Introduction

This appendix describes the detailed (Stage 3) assessment of radiation doses from the estimated maximum annual atmospheric discharges from a UK HPR1000 nuclear power plant. A detailed assessment has been undertaken because the Stage 1 and 2 dose assessment for atmospheric discharges (Appendix B) gave results that exceeded the 20 µSv y^{-1} criterion described in EA guidance (Environment Agency, 2006 a).

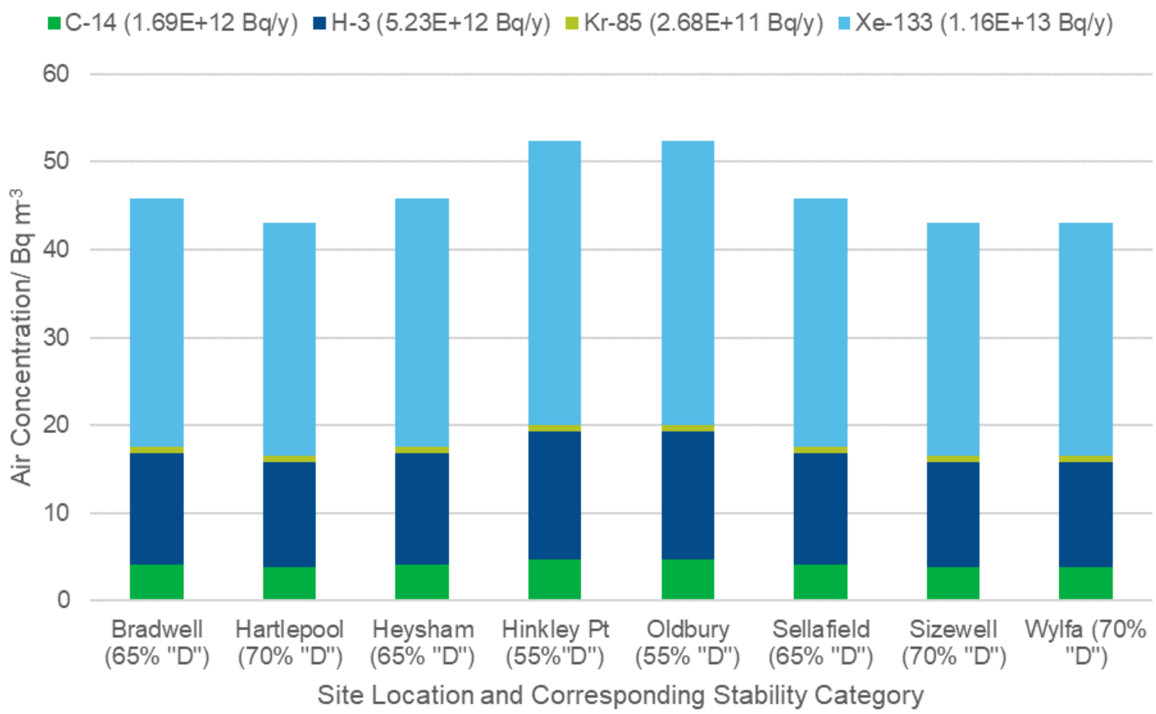
The estimated discharges used in the assessment are those presented in Table 3 and Table 4 of the main report. The overall scope and assessment approach is described in Appendix A, and reflects the principles (Environment Agency et al., 2012) and relevant guidance.

C2 Site Characteristics

For discharges to atmosphere, the atmospheric conditions at a site will affect the dispersion of gaseous discharges. The NRPB report NRPB-R91 (Clarke, 1979) presents the long-term average meteorological conditions for the Pasquill stability scheme for the UK. Categorising meteorological conditions using the Pasquill stability scheme is a historically common method of grouping atmospheric conditions 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. The long-term meteorological conditions in the UK range from 50% D to 80% D as is shown in Figure A 1, Appendix A. The PC CREAM 08 PLUME module which uses the modelling in NRPB R-91 (Clarke, 1979) was run for the eight nuclear sites determined as potentially suitable for the deployment of new nuclear power stations in the UK (DECC, 2011) (Bradwell, Hartlepool, Heysham, Hinkley Point, Oldbury, Sellafield, Sizewell and Wylfa). Long-term average atmospheric conditions from NRPB-R91 and an effective release height of 20 m were used for the four radionuclides that have the highest estimated annual discharge rates for the UK HPR1000 (H-3, C-14, Kr-85 and Xe-133). PLUME calculated the ground level activity concentrations in air at 300 m from the stack, the results of which are presented in Figure C 1. Figure C 1 also shows the frequency of stability category D at each site. Figure C 1 has identified that an increase in the frequency of occurrence of stability category D will reduce the predicted ground level air concentration and therefore the sites Hinkley Point and Oldbury (with the lowest stability category D level of 55% D) have the highest ground level air concentrations. Sites with 70% D have the lowest concentrations (Hartlepool, Sizewell and Wylfa). At these latter sites (with stability category 70% D), the air concentrations are predicted to be 25% lower than those where 55% D is appropriate.

In the independent dose assessment, the site characteristics of Bradwell were adopted for the generic site. The selection of the Bradwell site with a 65% D stability is a realistic selection as it is representative of the coastal location expected to be occupied by the UK HPR1000.

Figure C 1: Concentrations of radionuclides in air for continuous releases, calculated assuming the UK HPR1000 discharges occur at existing nuclear sites in the UK (using Pasquill atmospheric stability categories)

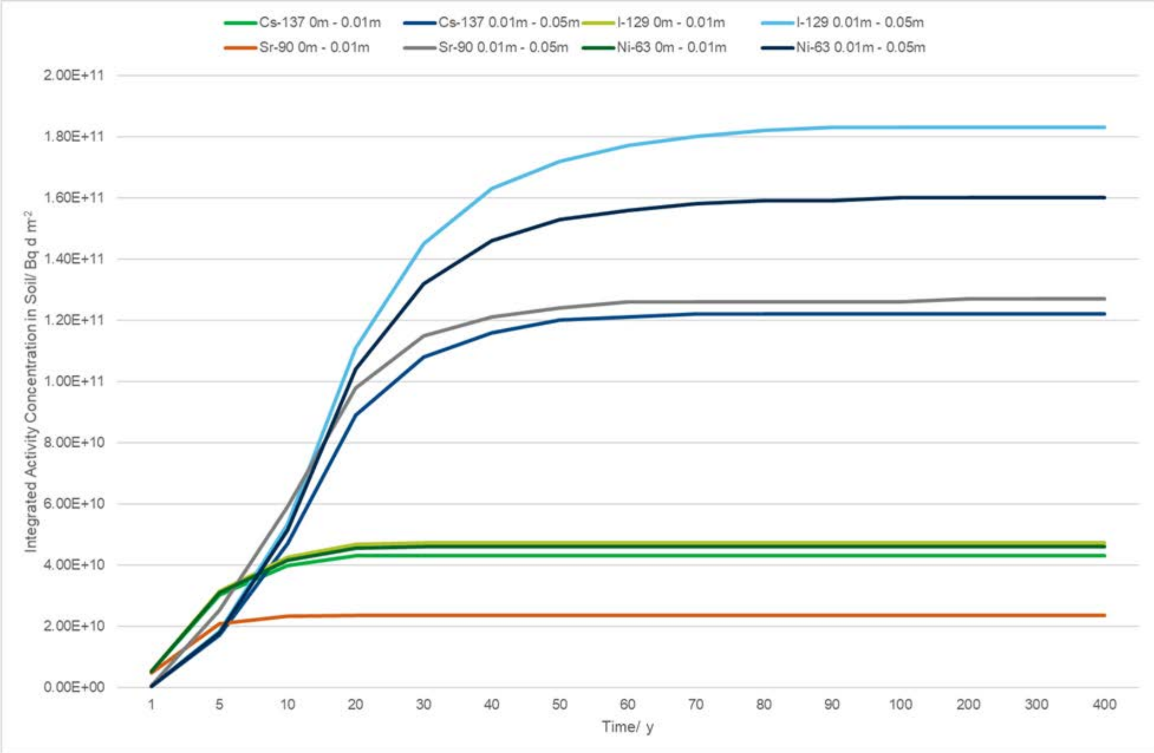


A uniform distribution of wind direction has been assumed for this assessment.

It is assumed that an agricultural area is present around the UK HPR1000 generic site where crops are grown for human consumption and grazing animals are farmed for their meat. The surface roughness value used for defining agricultural areas is 0.3. The habits data for Bradwell do not detail milk production in the local area. As such, a sensitivity analysis has been performed (see Appendix C6) which explores the effect on the dose of including and excluding consumption of locally produced milk and milk products from the diet.

Figure C 2 shows that the activity concentrations in soil for long lived radionuclides discharged from the UK HPR1000 are constant or change so little over timescales of 400 years that their dose contributions remain constant. Ingrowth need not be considered.

Figure C 2: Integrated activity concentrations in soil over time for long-lived radionuclides discharged by the HPR1000.



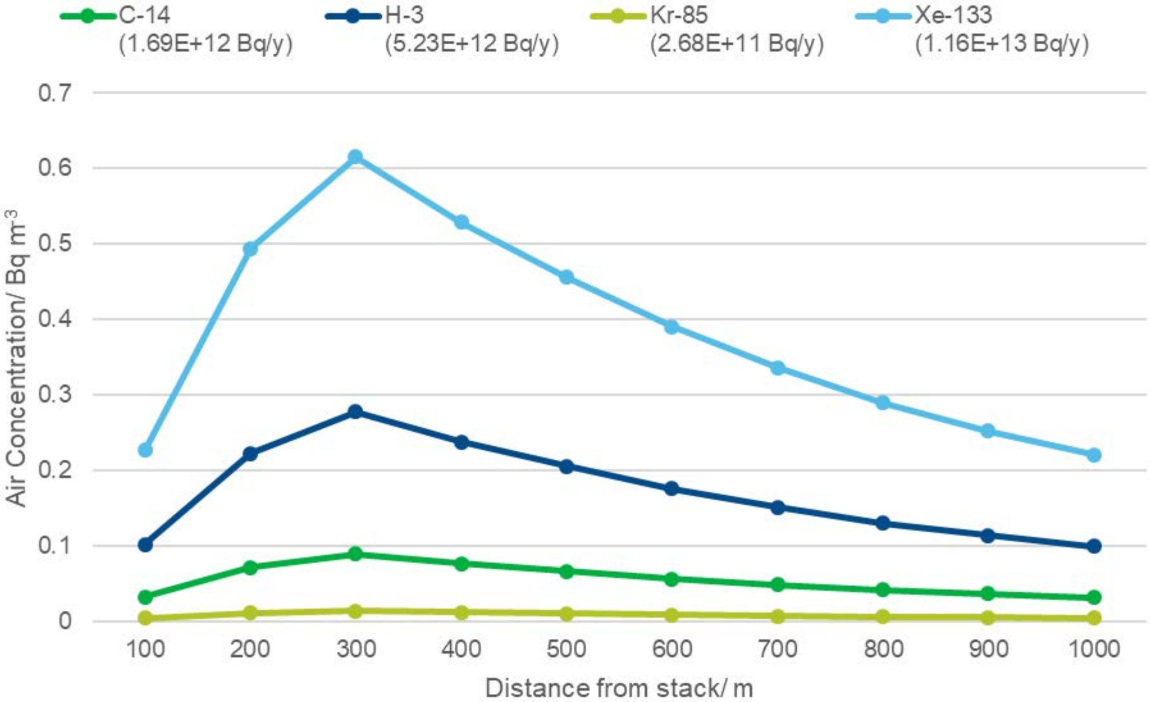
C3 People most exposed to atmospheric discharges

For discharges to atmosphere, the independent assessment will consider the following exposure pathways:

- inhalation of radionuclides discharged to atmosphere;
- ingestion of radionuclides in locally produced foods following the deposition onto farmland of radionuclides discharged to atmosphere; and
- external irradiation from radionuclides in the atmosphere and deposited on the ground following discharge to atmosphere.

The most exposed group is assumed to live close to where the ground level air concentration is a maximum and have a range of exposure pathways. This group will therefore be a family living close to the site, in which the adults are farmers, home workers or carers for small children and will therefore spend almost all of their time at home. Children and infants are assumed to be at home. Furthermore, it is cautious but reasonable to assume that the family farms the land and therefore they obtain much of their food from a local source. GNSL has assumed (General Nuclear System, 2020a) that the family live 100 m from the discharge point, with food being obtained at 500 m. For the independent dose assessment a simple assessment has been undertaken to identify the distance for the location where the family could reside. The assessment calculated air concentrations at distances up to 1000 m from the discharge point to identify the distance of peak activity concentrations in air at ground level. This assessment has found that a distance of 300 m is where peak activity concentrations in air occur. The results of this assessment are presented in Figure C 3.

Figure C 3: Identification of the distance of peak activity concentration in air from the discharge point (65% "D")



The independent dose assessment will therefore assume that the local resident family live 300 m from the discharge point and that food is obtained 500 m from the discharge point. Sensitivity analysis of the balance between the increased dose contribution due to direct radiation from the site when the family is assumed to live 100 m from the site against the reduced ground level air concentration at this point is considered in Appendix I.

Food consumption rates and occupancy assumptions for use in the independent dose assessment are based on generic values presented in NRPB-W41 (Smith K. R., 2003). Guidance from NDAWG on the use of habits data in prospective dose assessments (NDAWG, 2009) states that where site-specific habits data are not available (as in the case of an assessment under GDA), generalised UK habits data can be used. It would be overly cautious to assume that people eat all food types at high rates. The NDAWG Guidance (NDAWG, 2009) suggests that a reasonable assumption, when using generalised habits data, is that the two foodstuffs that contribute most to a person’s dose should be taken to be consumed at a high rate, with the others at average rates. This is called the “top two” method. As part of the Independent Dose Assessment, PC CREAM 08 was run with all foods consumed at the high rates to allow the top two dominant foodstuffs to be identified. Grain has been excluded from the assessment because there is little evidence to indicate that grain in the UK is grown, milled and consumed on a local scale. Grain is bulked and combined with other grain at regional millers and so will be significantly diluted prior to entry into the consumer market. Table C 1 presents the foods included in the independent dose assessment and the 97.5th percentile (high) and average consumption rates for these.

Table C 1: Generalised terrestrial food consumption rates (average and high)

Consumption Pathway	Adult Average (kg/y)	Adult High (kg/y)	Child Average (kg/y)	Child High (kg/y)	Infant Average (kg/y)	Infant High (kg/y)
Cow liver	2.8	10	1.5	5.0	0.5	2.8
Cow meat	15	45	15	30	3.0	10
Cow milk	95	240	110	240	130	320
Cow milk products	20	60	15	45	15	45
Fruit	20	75	15	50	9.0	35
Green veg	35	80	15	35	5.0	15
Root veg	60	130	50	95	15	45
Sheep liver	2.8	10	1.5	5.0	0.5	2.8
Sheep meat	8.0	25	4.0	10	0.8	3.0

To find out which foods give the highest and second highest ingestion dose when eaten at critical consumption rates, a calculation was performed using all foods eaten at critical consumption rates for adult, child and infant. The results of this analysis are shown in pie charts in Figure C 4, Figure C 5 and Figure C 6.

Figure C 4: Percentage of total dose to the adult by consumption of terrestrial foods at critical rates

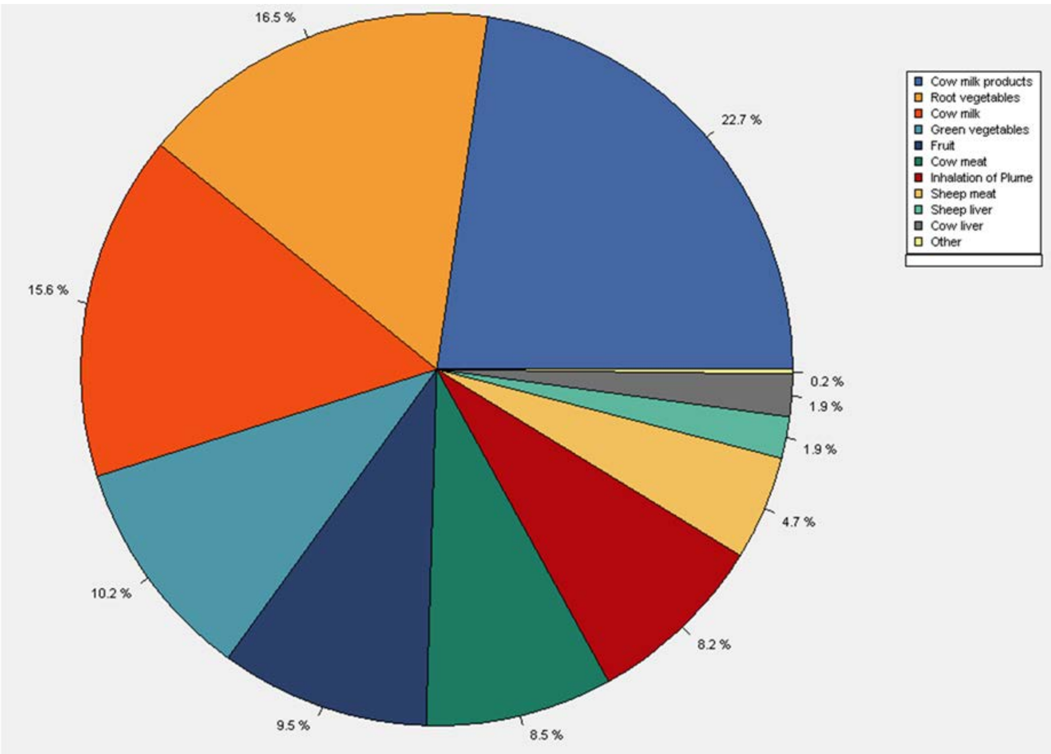


Figure C 5: Percentage of total dose to the child by consumption of terrestrial foods at critical rates

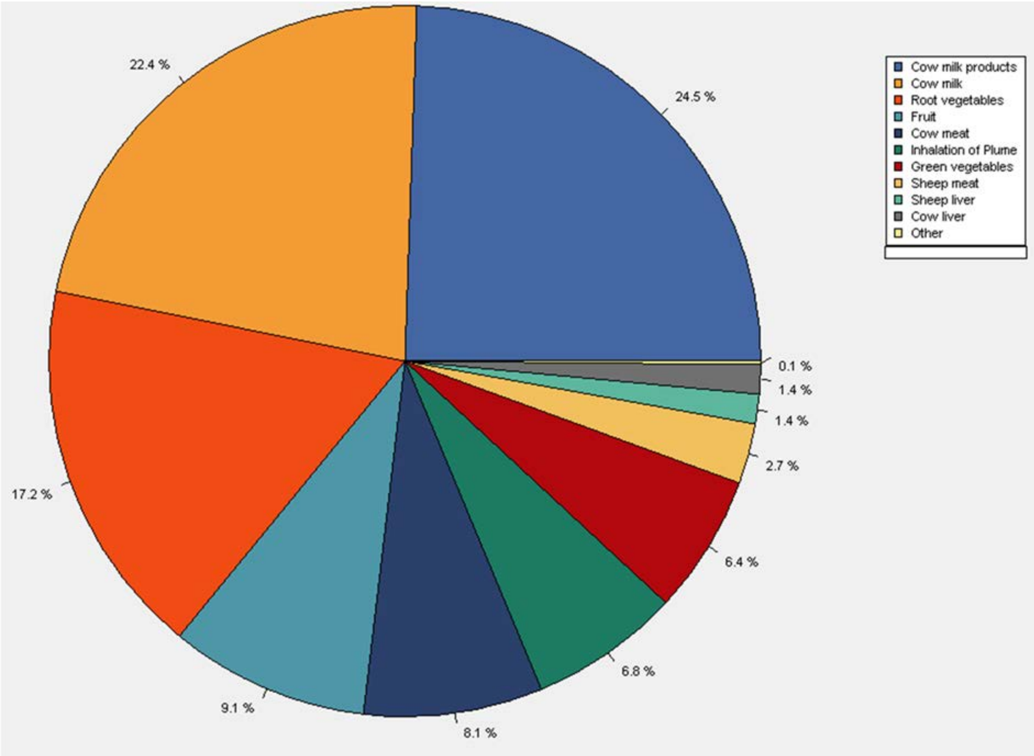
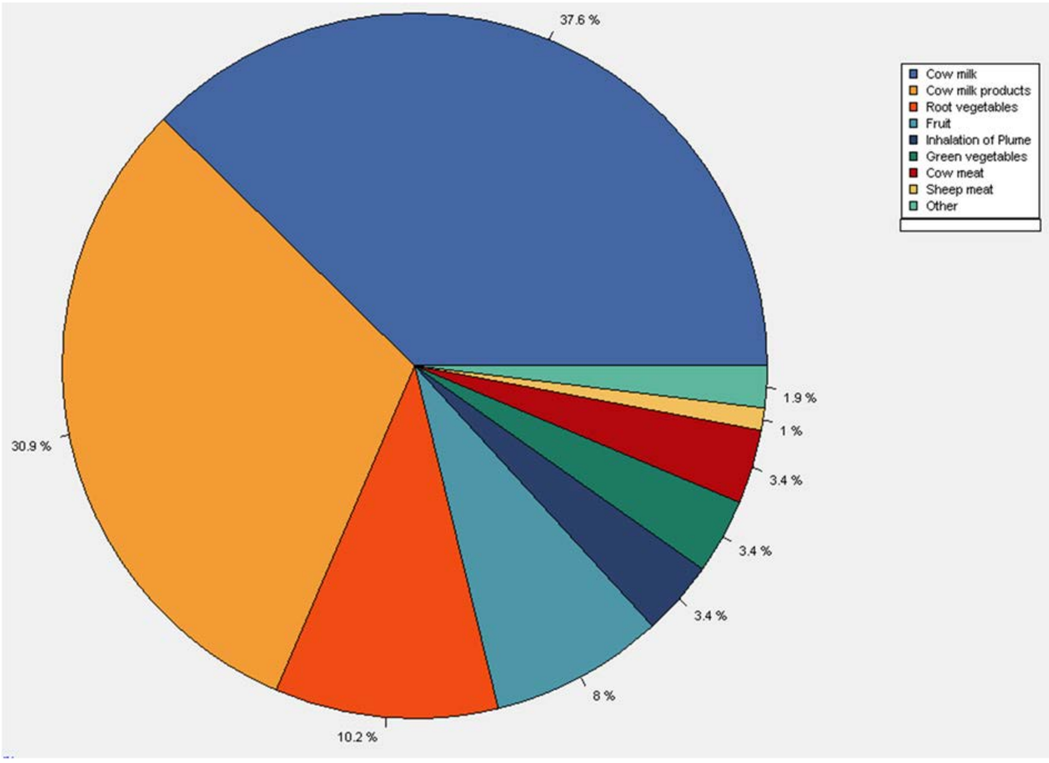


Figure C 6: Percentage of total dose to the infant by consumption of terrestrial foods at critical rates



The highest two doses from ingestion of food are presented in Table C 2.

Table C 2: Terrestrial food types that contribute the most to doses for the different age groups.

Age	Food with highest dose	Food with second highest dose
Adult	Cow milk products	Root vegetables
Child	Cow milk	Cow milk products
Infant	Cow milk	Cow milk products

For the detailed assessment of dose, the two highest ingestion doses from the individual foods will be kept at critical consumption rate where the remainder will be set to average consumption rates.

A review has been undertaken of the habits data identified for the Bradwell site (Cefas, 2016) to identify if there are any habits that could be more conservative compared to the generic UK data. For food consumption, it has been identified that in the local areas surrounding the Bradwell site there is no consumption of locally produced milk. It can therefore be concluded that consumption of locally produced milk products will also not occur. This is because there is currently limited dairy farming near the Bradwell site, although in the past some dairy farming did occur. Examination of the sensitivity of the model assumptions investigates the impact of excluding these two pathways (milk and milk products) on the results of the independent dose assessment. This analysis is shown in Appendix C6. However, for the main assessment these two pathways are retained in order to keep the assessment generic and to account for the potential for these farming practices to recur in the 60 years operational life of the facility.

For the calculation of doses from inhalation of radionuclides discharged to atmosphere and external irradiation from radionuclides in the atmosphere and deposited on the ground, the occupancy, inhalation rates, food consumption rates and shielding factors from NRPB-W41 presented in Table C 3 will be used (Smith K. R., 2003).

Table C 3: Occupancy times, inhalation rates, food consumption rates and shielding factors for the local resident family exposed to atmospheric discharges

Parameter	Adult	Child	Infant
Occupancy at the habitation (h)	8760	8760	8760
Fraction of time indoors	0.5	0.8	0.9
Inhalation rate (m3/h)	1.12*	0.64	0.22
Inhalation rate (m3/y)	9818	5610	1929
Cow liver consumption (kg/y)	2.8	1.5	0.5
Cow meat consumption (kg/y)	15	15	3
Cow milk consumption (kg/y)	95	240	320
Cow milk products consumption (kg/y)	60	45	45
Fruit consumption (kg/y)	20	15	9.0
Green veg consumption (kg/y)	35	15	5.0
Root veg consumption (kg/y)	130	50	15
Sheep liver consumption (kg/y)	2.8	1.5	0.5
Sheep meat consumption (kg/y)	8.0	4.0	0.8
Cloud shielding factor	0.2	0.2	0.2
Shielding factor for deposited radionuclides	0.1	0.1	0.1

*The adult breathing rate is based upon Table 9 in NRPB-W41 (Smith K. R., 2003). The “24 hour total” value for a heavy worker is used, cautiously assuming the individual in question farms the local land and performs heavy work outdoors all day. This breathing rate includes eight hours of sleep, eight hours of heavy work and eight hours of non-occupational activity. This gives an adult breathing rate of 27 m^3 in 24 hours, or an average of 1.12 $m^3 h^{-1}$.

C4 Modelling approach

The independent dose assessment of atmospheric discharges was undertaken using the PC CREAM 08 modelling code. The code includes a Gaussian plume atmospheric dispersion model for the assessment of routine discharges to the atmosphere, PLUME. The model calculates ground level air concentrations and deposition rates for a range of user-specified stack heights and meteorological conditions. The PLUME model results were then used in the ASSESSOR module to determine individual doses.

The meteorological properties for the generic site, specified in Appendix A2 and based on Bradwell, were used. It should be noted that the PLUME model does not represent the vertical discharge velocity of the discharge, or the turbulent effects of nearby buildings. The former is cautiously ignored in the assessment. The latter has been accounted for by specifying an effective release height lower than the actual stack height as has been determined appropriate through the comparison of models with experimental data. It can be shown that using an effective release height of one-third the height of the building gives “the best prediction of concentration distribution observed near buildings” (Jones, 1983). Other parameters were set to default values defined for PC CREAM 08 (Smith & Simmonds, 2009).

The calculated air concentrations, after 60 years of continuous releases at the rates presented in Table 3, are shown in Table C 4. Soil concentrations, after 60 years of continuous discharges, are shown in Table C 5.

Table C 4: Air concentrations calculated by PC CREAM 08, 300 m distance from a 20 m high stack, assuming 65% Pasquill Category D conditions and a uniform windrose

Radio-nuclide	Discharge Rate (Bq y^{-1})	Conc in Air (Bq m^{-3})	Radio-nuclide	Discharge Rate (Bq y^{-1})	Conc in Air (Bq m^{-3})
Ag-110m	$3.14\ 10^{5}$	$1.7\ 10^{-8}$	**Xe-133^**	I-133	$2.7\ 10^{-10}$
C-14	$1.69\ 10^{12}$	0.090	**Xe-133m^**	I-133	$6.6\ 10^{-10}$
Co-60	$2.02\ 10^{6}$	$1.1\ 10^{-7}$	**Xe-133**	$1.16\ 10^{13}$	0.62
Cs-134	$1.67\ 10^{6}$	$8.9\ 10^{-8}$	**Xe-133m**	$1.81\ 10^{11}$	$9.6\ 10^{-3}$
Cs-137	$1.93\ 10^{6}$	$1.0\ 10^{-7}$	**Xe-133^^**	Xe-133m	$9.6\ 10^{-7}$
Ba-137m*	Cs-137	$2.6\ 10^{-8}$	**Xe-135**	$3.45\ 10^{12}$	0.18
H-3	$5.23\ 10^{12}$	0.28	**Cs-135“**	Xe-135	$1.1\ 10^{-13}$
I-131	$8.57\ 10^{7}$	$4.5\ 10^{-6}$	**Xe-138**	$2.56\ 10^{10}$	$1.3\ 10^{-3}$
Xe-131m**	I-131	$2.0\ 10^{-10}$	**Cs-138“”**	Xe-138	$3.1\ 10^{-5}$
I-133	$5.16\ 10^{7}$	$2.7\ 10^{-6}$			

Note: *Ingrown from Cs-137 **Ingrown from I-131 ^Ingrown from I-133 ^^Ingrown from Xe-133m
“Ingrown from Xe-135 “”Ingrown from Xe-138

Table C 5: Soil concentrations calculated by PC CREAM 08, 300 m distance from a 20 m high stack, assuming 65% Pasquill Category D conditions and a uniform windrose

Radio-nuclide	Discharge Rate (Bq y^{-1})	Conc in Soil (Bq m^{-2})	Radio-nuclide	Discharge Rate (Bq y^{-1})	Conc in Soil (Bq m^{-2})
Ag-110m	$3.14\ 10^{5}$	$1.5\ 10^{-9}$	**Xe-133^**	I-133	0.0
C-14	$1.69\ 10^{12}$	0.0	**Xe-133m^**	I-133	0.0
Co-60	$2.02\ 10^{6}$	$2.2\ 10^{-9}$	**Xe-133**	$1.16\ 10^{13}$	0.0
Cs-134	$1.67\ 10^{6}$	$2.0\ 10^{-9}$	**Xe-133m**	$1.81\ 10^{11}$	0.0
Cs-137	$1.93\ 10^{6}$	$2.4\ 10^{-9}$	**Xe-133^^**	Xe-133m	0.0
Ba-137m*	Cs-137	$3.9\ 10^{-15}$	**Xe-135**	$3.45\ 10^{12}$	0.0
H-3	$5.23\ 10^{12}$	0.0	**Cs-135”**	Xe-135	$1.4\ 10^{-21}$
I-131	$8.57\ 10^{7}$	$5.5\ 10^{-10}$	**Xe-138**	$2.56\ 10^{10}$	0.0
Xe-131m**	I-131	0.0	**Cs-138””**	Xe-138	$4.4\ 10^{-15}$
I-133	$5.16\ 10^{7}$	$5.9\ 10^{-11}$			

Note: *Ingrown from Cs-137 **Ingrown from I-131 ^Ingrown from I-133 ^^Ingrown from Xe-133m
“Ingrown from Xe-135 “”Ingrown from Xe-138

C5 Radiation doses to individuals

The annual effective dose to the hypothetical local resident family considered to be most exposed to the radioactive discharges from the UK HPR1000 was calculated using the approach described above. A summary of the calculated doses is shown in Table C 6. The highest dose of 20.6 μSv y^{-1} to the infant is well below the source-related dose constraint of 300 μSv y^{-1} (Environment Agency et al., 2012).

The infant local resident is the most exposed person for atmospheric discharges as a result of their high intake of milk and milk products. The contribution of radionuclides and pathways to their exposure is shown in Table C 7. This illustrates that the dominant pathways are consumption of milk and milk products, with the most important radionuclide being C-14.

Table C 6: Doses (μSv y^{-1}) to the local resident family

Age	Inhalation	External Radiation	Meat and Meat Products	Milk and Milk Products	Fruit and Veg	Total
Adult	1.8	0.051	0.89	4.8	3.9	11
Child	1.5	0.031	0.94	7.4	2.3	12
Infant	1.2	0.025	0.41	17	1.7	21

Table C 7: Contribution of radionuclides and pathways to the doses to the infant (μSv y^{-1}) in the local resident family from radioactive discharges

Radio-nuclide	Inhalation	External Radiation	Meat and Meat Products	Milk and Milk Products	Fruit and Veg	Total	% of Total
C-14	1.1	$7.1\ 10^{-6}$	0.41	17	1.6	20	96
H-3	0.039	0.0	$4.1\ 10^{-3}$	0.38	0.029	0.45	2.2
I-131	$6.2\ 10^{-4}$	$1.1\ 10^{-4}$	$6.1\ 10^{-4}$	0.28	$3.7\ 10^{-3}$	0.28	1.4
Xe-133	0.0	$8.0\ 10^{-3}$	0.0	0.0	0.0	$8.0\ 10^{-3}$	0.039
Xe-135	0.0	0.016	0.0	0.0	0.0	0.016	0.076
Total	1.2	0.025	0.41	17	1.7	21	100

Note: Only radionuclides contributing 0.01% or more to the total dose are shown. Noble gases only contribute by external radiation pathways.

C6 Exploring sensitivity to model assumptions

Long-term exposure to atmospheric discharges is related to the average calculated air concentrations and deposition of radionuclides over the course of a typical year. These are defined by the atmospheric dispersion characteristics of the stack and the site. The stack height is a key factor, as it determines the ground level concentrations, particularly those close to the site, where there is least dispersion. The site's location determines the strength of the wind and factors like the frequency of different meteorological conditions (for example different boundary layer heights).

These factors can be varied in the PC CREAM 08 code and so have been examined to illustrate their significance for the independent dose assessment. The variation in air concentration with distance is shown in Figure C 3, illustrating key radionuclides. In these calculations, the site meteorological conditions were the same as for the independent dose assessment. An additional test of the variation of air concentration with distance was performed, only this time with a stability category “D” of 55%, which leads to less dispersion. This is displayed in Figure C 7 and shows that the distance from the stack at which peak air concentrations occur remains at 300 m.

Figure C 7: Identification of the distance of peak activity concentration in air from the discharge point for Pasquill Stability category frequency of 55% "D"

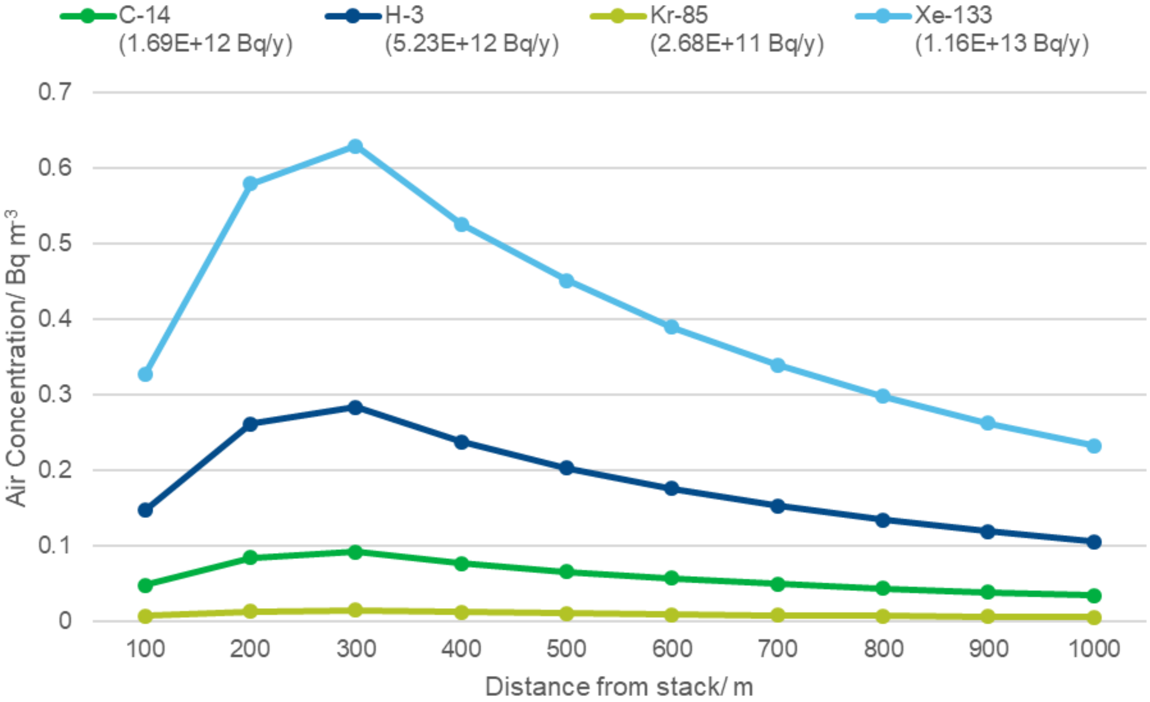
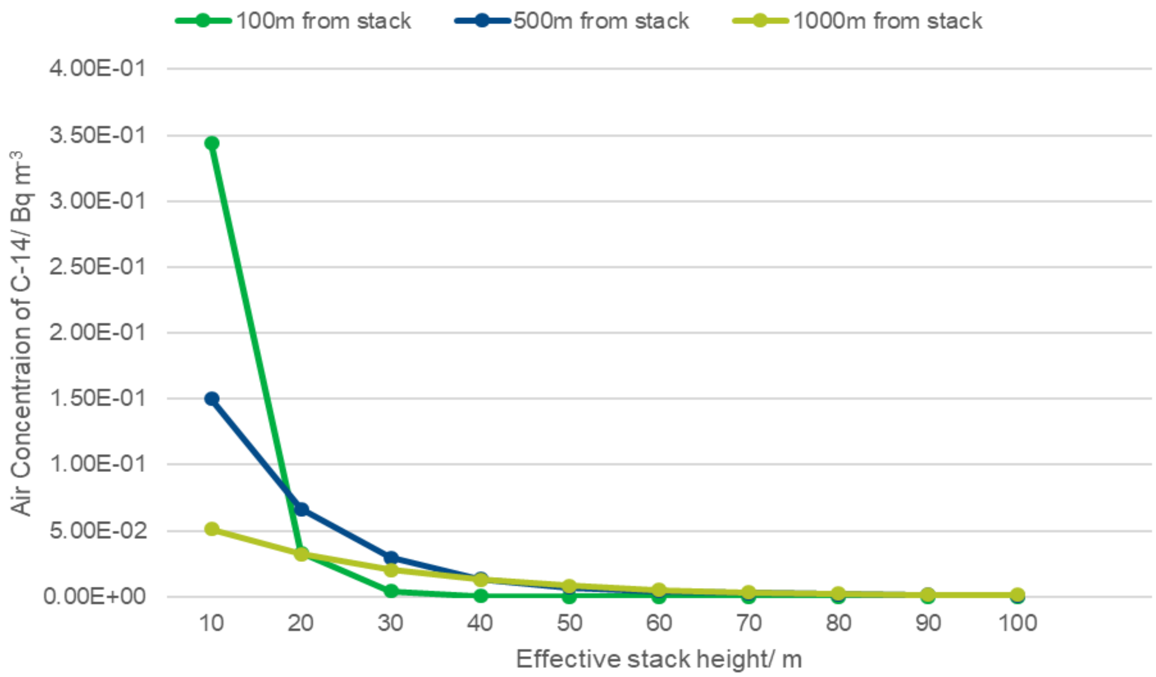


Figure C 8 shows that the effective discharge height is a key factor, particularly close to the stack. In the independent dose assessment, the release height is assumed to be 20 m (corresponding to the building height of 60 m, to take account of the effects of building wake effects). This figure also shows that concentrations close to the stack are more sensitive to stack height as the 'skip distance' (before the plume reaches ground level) increases. For stacks more than approximately 25 m high the highest concentrations may occur several hundred metres from the stack.

Figure C 8: Variation in ground level air concentration of C-14 at one year with height of the stack at various distances from the point of release. Assumed continuous release of maximum estimated annual discharge specified in Table 3 and 65% Category D conditions



Another parameter that could affect the dose due to atmospheric discharges is the type and frequency of the Pasquill stability categories. Category D is the most frequent category and so is used for the assessment. This has been varied between 55% and 80% for C-14, H-3 and Xe-133 at a range of distances from the stack. The results of this analysis are displayed in Figure C 9, Figure C 10 and Figure C 11 respectively.

The analysis demonstrates that at 300 m, where the local resident family live, the activity concentrations in air are relatively similar for all stability categories. As the site is likely to be located at Bradwell with a stability category of 65% D, it is reasonable to assume this stability category in the independent dose assessment.

Figure C 9: Effect of stability category on the activity concentration of C-14 in air at varying distances from the stack. Assumed continuous release of maximum estimated annual discharge specified in Table 3, 65% Category D conditions and a stack height of 20 m

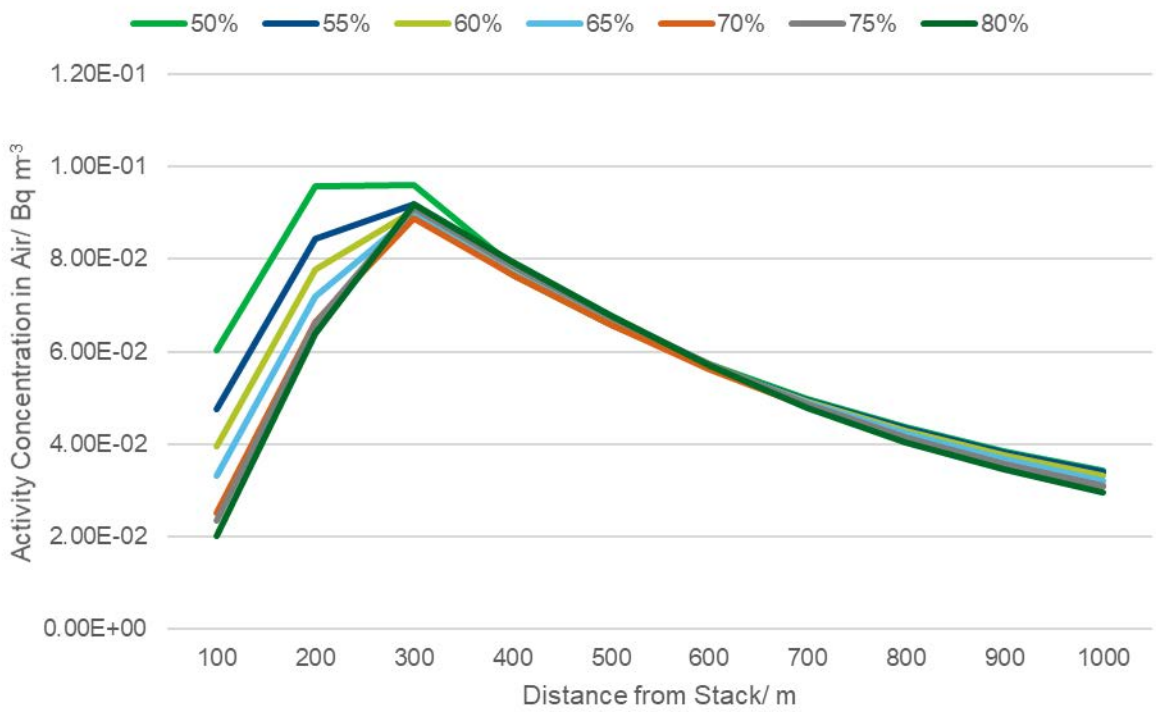


Figure C 10: Effect of stability category on the activity concentration of H-3 in air at varying distances from the stack. Assumed continuous release of maximum estimated annual discharge specified in Table 3, 65% Category D conditions and a stack height of 20 m

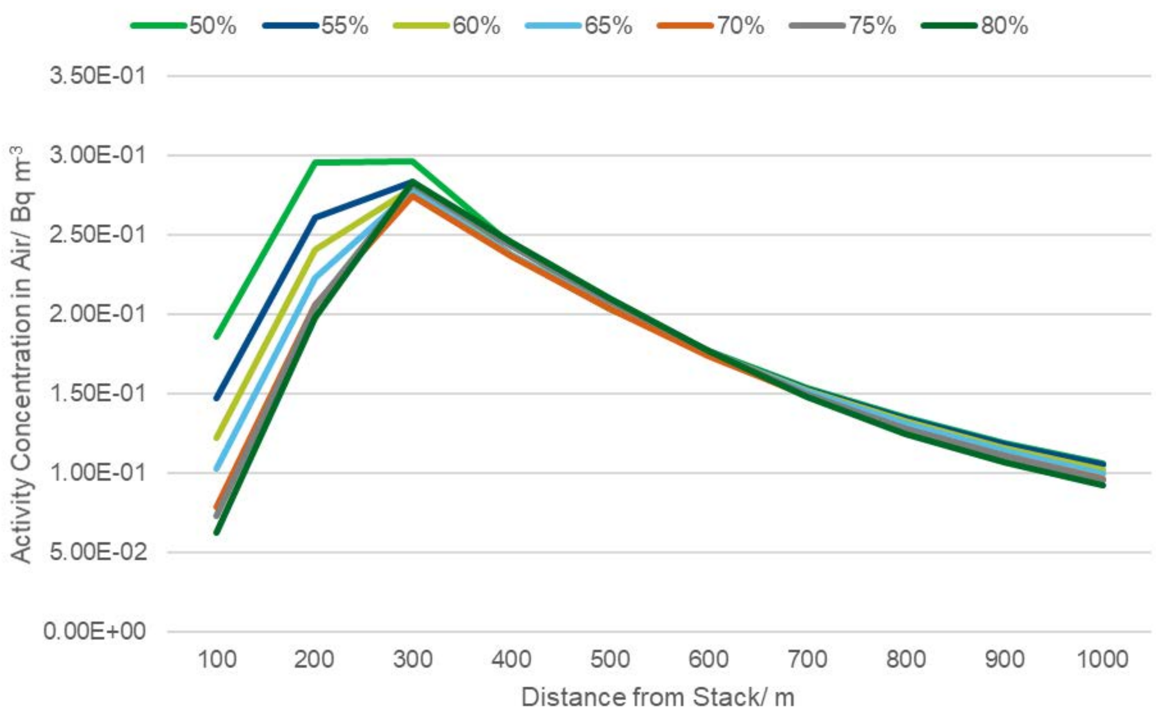
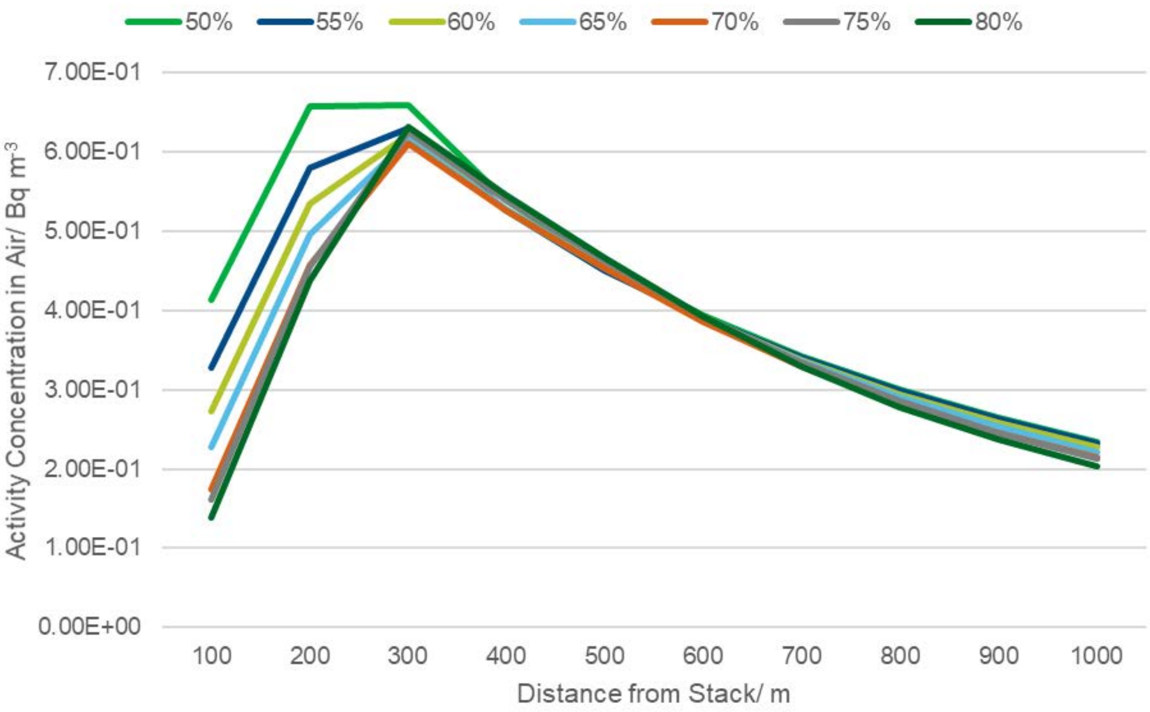


Figure C 11: Effect of stability category on the activity concentration of Xe-133 in air at varying distances from the stack. Assumed continuous release of maximum estimated annual discharge specified in Table 3 and 65% Category D conditions and a stack height of 20 m



Finally, the habits data for Bradwell suggests that there are no local sources for cow milk and cow milk products; however, there is evidence for the consumption of other animal products, e.g. beef, mutton and liver. Table C 8 presents the dose from ingestion of the remaining foodstuffs excluding cow milk and cow milk products.

Table C 8: Dose to the local resident family due to ingestion of foodstuffs excluding cow milk and cow milk products

Age	Cow liver	Cow meat	Fruit	Green veg	Root veg	Sheep liver	Sheep meat	Total
Adult	0.31	1.4	1.6	1.7	2.7	0.31	0.78	8.8
Child	0.21	1.2	1.4	1.0	2.7	0.21	0.43	7.3
Infant	0.24	0.86	2.0	0.87	2.6	0.24	0.26	7.1

This shows that if cow milk and cow milk products are not included, the new top 2 foods for an adult would be green veg and root veg. For a child or infant the top 2 foods change from milk and milk products to root veg and fruit.

Excluding cow Milk and cow milk products decreases the overall dose from ingestion so the assessment including cow milk and cow milk products bounds any results with these new top two foods. Additionally, local food production and consumption habits in 60 years could be quite different to those currently exhibited.

Appendix D: Detailed independent assessment of individual doses from liquid discharges

D1 Introduction

The Stage 1 and 2 dose assessment for the estimated maximum annual liquid radioactive discharges from a UK HPR1000 nuclear power station (Appendix B) gave results that required further analysis, and as such a detailed (Stage 3) assessment has been undertaken. This enables a comparison with the results calculated by GNSL (General Nuclear System, 2020a) for the most exposed members of the public for liquid discharges.

The site has been assumed to be at a coastal location and the discharge assumed to be to the marine environment. The annual estimated discharges described in Table 4 have been used. The overall scope and assessment approach is described in Appendix A, and reflects our principles (Environment Agencies, 2012) and relevant guidance.

D2 Characteristics of the marine environment

In relation to liquid discharges, the coastline and near-shore currents determine the amount of dispersion that occurs for effluents containing radioactivity. To identify the site with the lowest dispersion, the PC CREAM 08 DORIS module has been run for the eight nuclear sites that have been determined as potentially suitable for the deployment of new nuclear power stations in the UK (DECC, 2011) (Bradwell, Hartlepool, Heysham, Hinkley Point, Oldbury, Sellafield, Sizewell and Wylfa). The DORIS module was used to calculate the activity concentration in water in the local compartment for the five radionuclides that have the highest annual liquid discharge rates for the UK HPR1000 (H-3, C-14, Co-60, Cr-51 and Ni-63). The modelling used the local compartment parameter values recommended in PHE-CRCE-051 (PHE, 2019) for each of the eight sites. The results are presented in Figure D 1, Figure D 2 and Figure D 3. This has identified that the site with the lowest dispersion is Bradwell. This result would be expected as this site has the lowest volumetric exchange of marine water between its local and regional compartments and the longest mean residence time of seawater in the local compartment.

Figure D 1: Concentrations of H-3 in seawater calculated by assuming the UK HPR1000 discharge occurs at existing nuclear sites in the UK

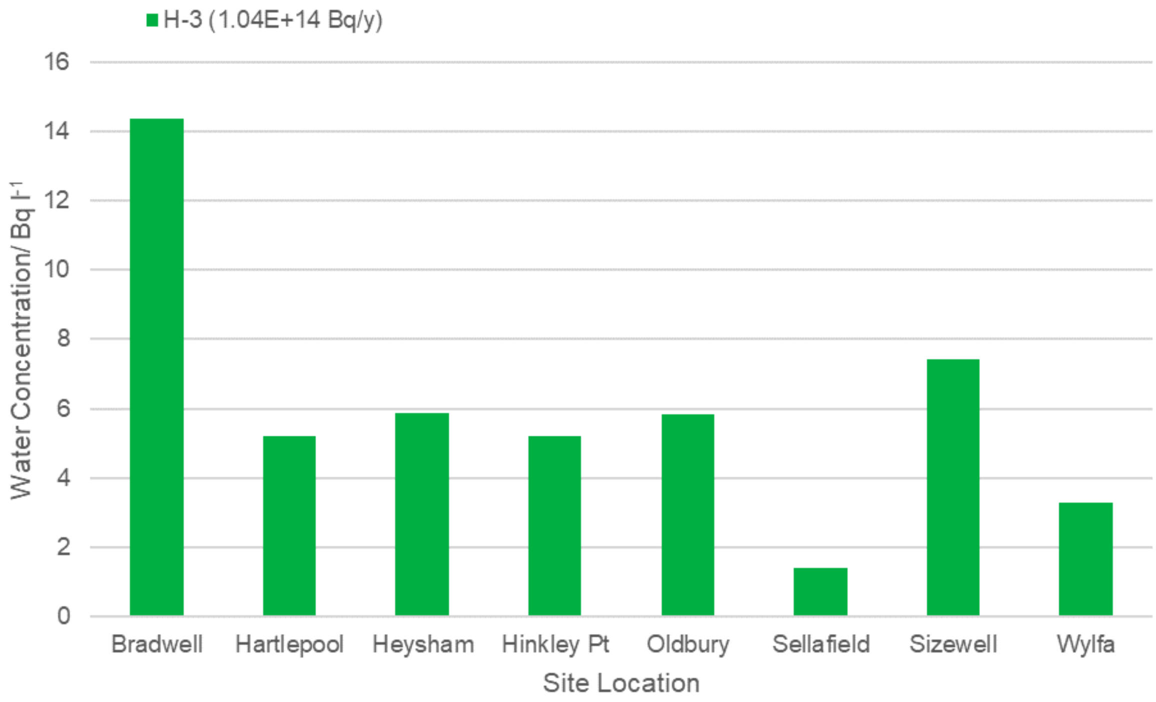


Figure D 2: Concentrations of C-14 in seawater calculated by assuming the UK HPR1000 discharge occurs at existing nuclear sites in the UK

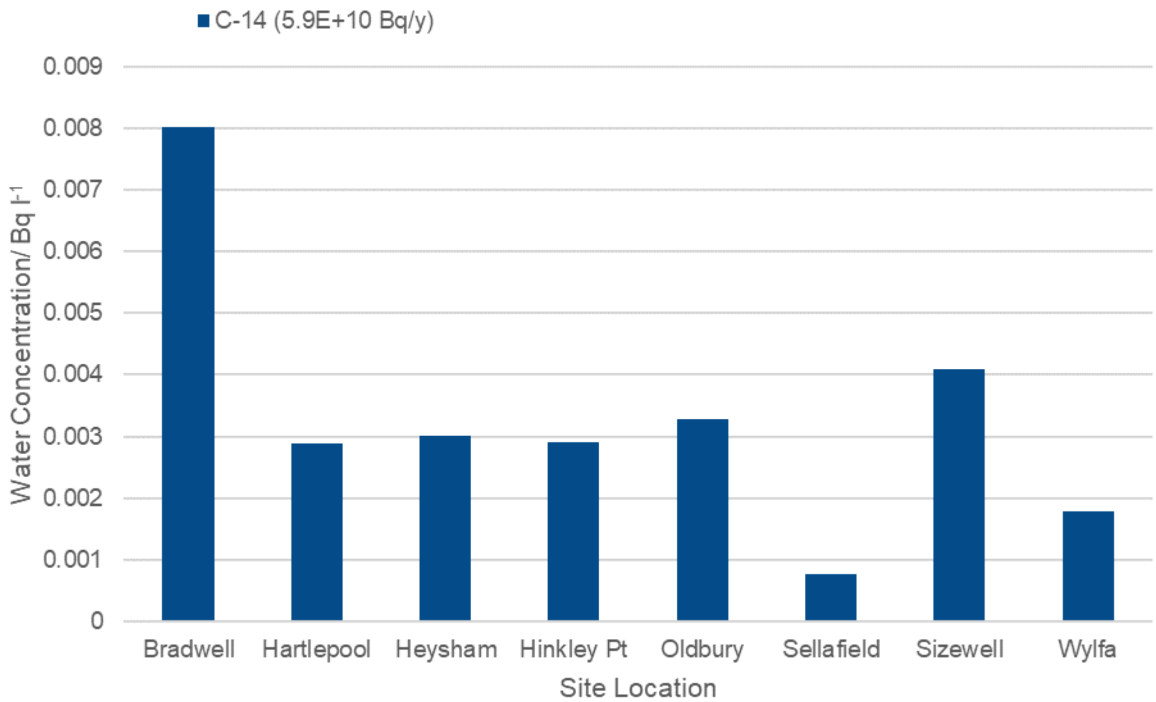
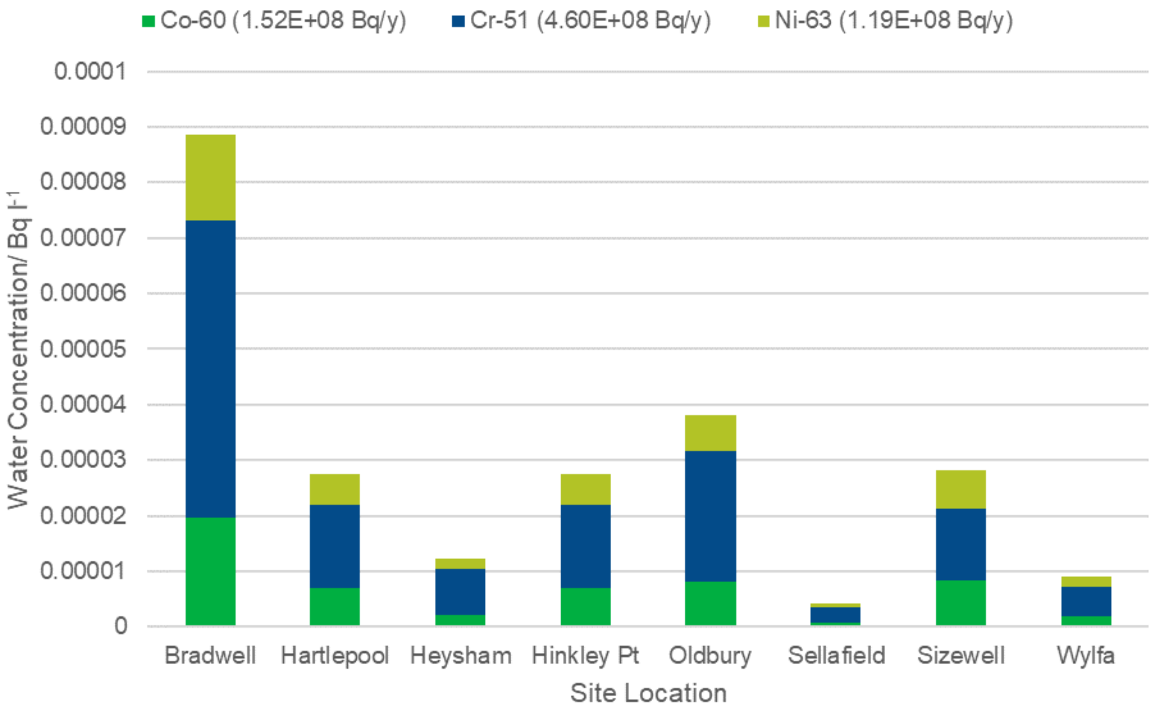


Figure D 3: Concentrations of radionuclides in seawater calculated by assuming the HPR1000 discharge occurs at existing nuclear sites in the UK



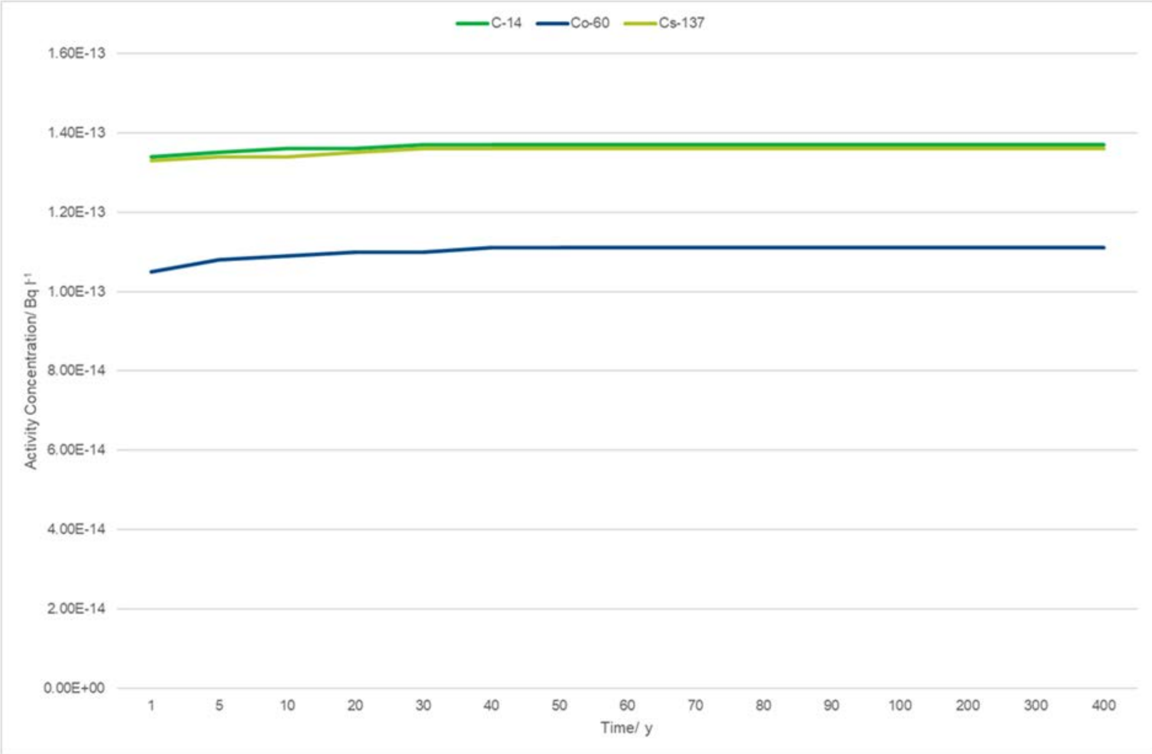
The generic site properties of the marine environment used in the detailed model (PHE, 2019) are presented in Table D 1. These values are a further refinement of the parameters used for Stage 2 based on a more current review of site parameters.

Table D 1: Local compartment characteristics to be used in the independent dose assessment of liquid discharges from the UK HPR1000

Parameter	Value	Parameter	Value
Volume (m3)	$1.00\ 10^{8}$	Suspended sediment (t/m^3)	$3.80\ 10^{-5}$
Depth (m)	4	Sedimentation rate ($t/y/m^2$)	$8.00\ 10^{-4}$
Coastline length (m)	$1.40\ 10^{4}$	Sediment density (t/m^3)	2.6
Seawater exchange rate (m3/y)	$7.30\ 10^{9}$	Diffusion rate (m^3/y)	0.0315

Figure D 4 shows that the activity concentrations in seawater for long lived radionuclides discharged from the UK HPR1000 are constant or change so little over timescales of 400 years that their dose contributions remain constant. Ingrowth need not be considered.

Figure D 4: Activity concentrations in seawater over time of long lived radionuclides discharged from the UK HPR1000 assuming a continuous release over 60 years of the annual discharges specified in Table 4.



D3 People most exposed to liquid discharges

For discharges of liquids to the marine environment, the independent assessment considers the following exposure pathways:

- inhalation of contaminated seawater in the form of sea spray;
- ingestion of radionuclides in locally caught fish and shellfish; and
- external irradiation from radionuclides in coastal sand/sediment (at the beach), including exposure from handling contaminated fishing gear.

For the independent dose assessment, fishing from the local and regional compartment are assumed to take place in the vicinity of the UK HPR1000. NRPB-W41 [12] presents generic ingestion rates that are representative of coastal communities as distinct from those of the population as a whole. The most exposed people to liquid discharges are assumed to be an angler and their family (including children and infants). The exposure group has been assumed to spend time on beaches and intertidal areas, and consume locally caught fish and shellfish (crustaceans and molluscs) at high intake rates. It is assumed that 50% of fish will be obtained from the local compartment and 50% from the regional compartment. All crustaceans and molluscs are assumed to come from the local compartment. As per the assessment for aerial discharges, food consumption rates and occupancy assumptions for use in the independent dose assessment are based on generic values presented in NRPB-W41 [12] and these are presented in Table D 2.

Table D 2: Food consumption, inhalation rates, occupancy times and time spent handling fishing gear for the angler and family most exposed to liquid discharges

Parameter	Adult	Child	Infant
Crustacean - consumption rate (kg/y)	20	5	0
Crustacean - fraction caught in local compartment	1.0	1.0	1.0
Fish - consumption rate (kg/y)	100	20	5
Fish - fraction caught in local compartment	0.5	0.5	0.5
Mollusc - consumption rate (kg/y)	20	5	0
Mollusc - fraction caught in local compartment	1.0	1.0	1.0
Beach occupancy (local compartment) (h)	2000	300	30
Time spent handling fishing gear (local compartment) (h)	2000	0	0
Inhalation rate (m^3/h)	1.12	0.64	0.22
Inhalation rate (m^3/y)	9818	5610	1929

D4 Modelling Approach

The PC CREAM 08 code (version 1.5.1.92, database version 2.0.0) has been used to undertake the independent dose assessment. It includes a representation of the marine model for Europe, developed by the EC (Smith & Simmonds, 2009) and widely used for radioactive discharge modelling. The marine modelling component of PC CREAM 08, DORIS, can represent different 'local' marine compartment properties into which initial discharges from a nuclear site occur. The properties given in Table D 1 have been used for this assessment, and the annual estimated discharges described in Table 4 have been assumed. All other parameter values used are PC CREAM 08 default data (Smith and Simmonds, 2009).

Activity concentrations in environmental media (seawater and sediment) were calculated assuming discharges lasted for 60 years at the annual rate specified in Table 4. The highest concentrations were in the local coastal waters and sediment, and it was assumed that this area was fished by the local angler. The calculated environmental concentrations for the local compartment at the selected site, Bradwell, are presented in Table D 3.

Table D 3: Environmental concentrations of key radionuclides in the local compartment marine environment calculated by the DORIS module

Radionuclide	Discharges (Bq y^{-1})	Unfiltered Seawater (Bq l^{-1})	Seabed Sediment (Bq l^{-1})
Ag-110m	$2.5\ 10^{7}$	$3.3\ 10^{-6}$	$2.0\ 10^{-4}$
C-14	$5.9\ 10^{10}$	$8.1\ 10^{-3}$	14
Co-58	$6.5\ 10^{7}$	$6.5\ 10^{-6}$	$2.6\ 10^{-3}$
Co-60	$1.5\ 10^{8}$	$1.7\ 10^{-5}$	0.13
Cs-134	$1.4\ 10^{7}$	$1.9\ 10^{-6}$	$8.0\ 10^{-4}$
Cs-137	$1.9\ 10^{7}$	$2.6\ 10^{-6}$	$5.1\ 10^{-3}$
Fe-59	$5.3\ 10^{7}$	$5.5\ 10^{-6}$	$1.0\ 10^{-3}$
H-3	$1.0\ 10^{14}$	14	25
Mn-54	$1.7\ 10^{7}$	$1.8\ 10^{-6}$	$3.0\ 10^{-3}$
Sb-124	$8.8\ 10^{7}$	$1.1\ 10^{-5}$	$1.7\ 10^{-4}$

D5 Radiation doses to individuals

Effective doses to infants, children and adults have been calculated with the ASSESSOR module in PC CREAM 08. This combines the assumed behaviour of people (Table D 2) with the discharges and calculated environmental concentrations (Table D 3). A summary of the calculated doses is shown in Table D 4. All the calculated doses are below 20 µSv y^{-1}.

A breakdown of the doses to the adult in the fishing family is shown in Table D 5. This illustrates that the dominant exposure pathway for the aqueous discharges is the consumption of seafood, with the most important radionuclide being C-14.

Table D 4: Doses (µSv y^{-1}) to the local fishing family from liquid discharges

Age	Seafood	Beach	Fishing Gear	Total
Adult	7.9	0.059	1.8 10-3	8.0
Child	2.4	$8.8\ 10^{-3}$	0.0	2.4
Infant	0.61	$8.8\ 10^{-4}$	0.0	0.61

Table D 5: Contribution of radionuclides and pathways to the doses to the adult member of the fishing family (in µSv y^{-1}) from liquid radioactive discharges

Radio-nuclide	Crust-aceans	Fish	Molluscs
Ag-110m	$8.9\ 10^{-4}$	$2.2\ 10^{-4}$	$1.8\ 10^{-3}$
C-14	1.8	4.4	1.8
Co-60	$1.3\ 10^{-3}$	$3.4\ 10^{-4}$	$6.6\ 10^{-4}$
Fe-59	$3.4\ 10^{-4}$	$8.6\ 10^{-5}$	$2.1\ 10^{-3}$
H-3	$5.2\ 10^{-3}$	0.013	$5.8\ 10^{-3}$
Total	**1.8**	**4.4**	**1.8**

Note: Only radionuclides contributing 0.01% or more to the total dose are shown.

Table D 6 continued: Contribution of radionuclides and pathways to the doses to the adult member of the fishing family (in µSv y^{-1}) from liquid radioactive discharges

Radio-nuclide	Ext. Beach	Ext. Gear	Sea-spray	Total	% of Total
Ag-110m	$1.0\ 10^{-4}$	$1.1\ 10^{-6}$	$1.9\ 10^{-10}$	$3.0\ 10^{-3}$	0.038
C-14	$2.0\ 10^{-4}$	$1.2\ 10^{-3}$	$1.2\ 10^{-7}$	7.9	99
Co-60	$4.6\ 10^{-4}$	$4.7\ 10^{-6}$	$1.2\ 10^{-9}$	0.059	0.74
Fe-59	0.056	$5.8\ 10^{-4}$	$1.5\ 10^{-10}$	$2.7\ 10^{-3}$	0.034
H-3	$2.2\ 10^{-4}$	$2.5\ 10^{-6}$	$2.9\ 10^{-6}$	0.023	0.29
Total	0.059	$1.8\ 10^{-3}$	$3.0\ 10^{-6}$	70	100

Note: Only radionuclides contributing 0.01% or more to the total dose are shown.

D6 Exploring sensitivity to model assumptions

A review has been undertaken of the specific habits data identified for the Bradwell site (Cefas, 2016) to identify if there are any habits that could be more conservative compared to the generic data. For food consumption, it has been identified that there is a higher consumption rate of fish by children compared to the generic values presented in NRPB-W41 (Smith K. R., 2003) and there is an increased time spent handling fishing gear by adults and children. The habits surveys at Bradwell have also identified the presence of adult houseboat dwellers on intertidal areas and increased intertidal occupancy rates for infants. Comparisons of the doses received in these scenarios are presented in Table D 6, which demonstrates that the majority of the changes result in a change to the dose of < 4%. The analysis of the higher consumption rate of fish that a child eats leads to a 19% change in the total dose from 2.4 µSv y^{-1} to 3.0 µSv y^{-1}. This is still far below the 20 µSv y^{-1} dose criterion above which further analysis is required. As such, the habits data used in the independent dose assessment are reasonable.

Table D 7: Comparison of effective doses based on sensitivity analysis habits data

Sensitivity Scenario	Assessment parameter	Sensitivity Analysis Parameter	Assessment Dose due to parameter ($\mu Sv\ y^{-1}$)	Sensitivity Dose due to parameter ($\mu Sv\ y^{-1}$)	% difference to Total Dose
Child - higher consumption rate of fish	20 kg y^{-1}	29.5 kg y^{-1}	1.2	1.8	**19**
Adult – longer handling time of fishing gear	2000 h y^{-1}	2151 h y^{-1}	$1.8\ 10^{-3}$	$2.0\ 10^{-3}$	**0.0020**
Child – longer handling time of fishing gear	0 h y^{-1}	144 h y^{-1}	0.0	$1.3\ 10^{-4}$	**$5.4\ 10^{-3}$**
Adult – Houseboat Dweller (Beach Occupancy)	2000 h y^{-1}	7424 h y^{-1}	0.059	0.22	**1.9**
Infant – Increased Beach Occupancy	30 h y^{-1}	849 h y^{-1}	$8.8\ 10^{-4}$	0.025	**3.8**

For illustrative purposes, the same information in Table D 6 is displayed in a different manner in Table D 7, which shows the percentage of the total dose made up by the parameter both before and after the habits data is amended. As can be seen, the only pathway with a significant contribution to the total dose is the rate at which a child consumes fish. The contribution to the total dose of the consumption of fish increases from 50% to 60% when it is assumed the child eats fish at a higher rate than in the original assessment.

Table D 8: Percentage contributions of the pathways explored in this sensitivity analysis to the total dose, before and after the habits data is altered

Sensitivity Scenario	Altered Parameter	% contribution of Independent Assessment Dose	% contribution of Sensitivity Dose
Child - higher consumption rate of fish	29.5 kg y^{-1}	50	60
Adult – longer handling time of fishing gear	2151 h y^{-1}	0.023	0.025
Child – longer handling time of fishing gear	144 h y^{-1}	0.0	0.0054
Adult – Houseboat Dweller	7424 h y^{-1}	0.73	2.7
Infant – Increased Beach Occupancy	849 h y^{-1}	0.14	3.9

Appendix E: Radiation exposure of representative persons and assessment of total dose

E1 Introduction

The Stage 1 and 2 dose assessment for the estimated maximum annual radioactive discharges from a UK HPR1000 nuclear power station (Appendix B) gave results that exceeded the 20 μSv y^{-1} dose criterion for atmospheric discharges and liquid discharges to the marine environment. Therefore a more detailed (Stage 3) assessment using refined parameters has been undertaken. The detailed assessment considers doses to the most exposed members of the public for atmospheric and liquid discharges (Appendix C and Appendix D) but also doses to the 'representative person'. The latter assessment incorporates exposures from estimated discharges and from direct radiation and short-term releases where present, as required in the dose principles (Environment Agencies, 2012) and the requirements for GDA (Environment Agency, 2016).

The representative person is an individual receiving a dose that is representative of the most highly exposed individuals in the population (Environment Agency et al., 2012). It differs from the 'most exposed persons' assessed in Appendix C and Appendix D in that the representative person is exposed to all sources of radioactivity emanating from the nuclear facility (atmospheric discharges, liquid discharges, direct radiation and short-term releases) and is assessed using a realistic combination of habits.

The doses to representative person has been calculated using the models and data for atmospheric and liquid discharges (Appendix A, Appendix C and Appendix D) and using a combination of habits consistent with the definition of a representative person. This appendix presents the assumptions and the resulting doses.

E2 Definition of representative persons

For prospective dose assessments, it is not possible to assess doses to existing individual members of the public. For this reason, doses are assessed to a ‘representative person‘ who has behaviours that lead them to be amongst the most highly exposed individuals in the population from a nuclear facility. The dose to the representative person can be compared with the key criteria (such as the source-related dose constraints, site constraints and dose limits) in the process of determining discharge permits or authorisations (Environment Agency et al., 2012).

For the purposes of assessing doses to the candidate for the representative person, the site assumptions described in Appendix A have been used. The dose assessment models, and the resulting environmental concentrations, are as described in Appendix C and Appendix D. The assessment of direct radiation doses are described in Appendix I and the assessment of short-term release doses are described in Appendix F.

In order to determine the representative person, two candidates have been considered - one with greater exposure to atmospheric discharges and direct radiation:

- The local farming family

and one with greater exposure to liquid discharges:

- The local fishing family

E2.1 Local Farming Family

The local farming family is assumed to live close to the boundary of the site. The location is 300 m from the discharge stack which is the approximate position where ground level air concentrations are highest. The surrounding land is farmed and local produce consumed. It is assumed that the produce is grown at an average distance of 500 m from the stack and is consumed in the "top two" manner described in Appendix C. They are also assumed to visit the beach and ingest locally sourced seafood at average rates. This representative person is therefore a variant of the local resident used in the assessment of the most exposed person for atmospheric discharges, with additional pathways to account for liquid discharges, direct irradiation and short-term releases. The exposure characteristics for the local farming family are presented in Table E 1. External dose rates are presented in Appendix I and doses due to short-term releases are presented in Appendix F.

Table E 1: Exposure Characteristics for a candidate representative person based on the local farming family

Table E 1a: Resident (home) – 300m from site

Parameter	Source	Adult	Child	Infant
Indoors, home (300m from site) (h/y)	Atmospheric	4380	7008	7884
Outdoors, home (300m from site) (h/y)	Atmospheric	4080	1452	846

Table E 1b: Farmland – 500m from site

Parameter	Source	Adult	Child	Infant
Cow liver consumption (kg/y)	Atmospheric	2.75	1.5	0.5
Cow meat consumption (kg/y)	Atmospheric	15	15	3
Cow milk consumption (kg/y)	Atmospheric	95	240*	320*
Cow milk products consumption (kg/y)	Atmospheric	60*	45*	45*
Fruit consumption (kg/y)	Atmospheric	20	15	9
Green veg consumption (kg/y)	Atmospheric	35	15	5
Root veg consumption (kg/y)	Atmospheric	130*	50	15
Sheep liver consumption (kg/y)	Atmospheric	2.75	1.5	0.5
Sheep meat consumption (kg/y)	Atmospheric	8	4	0.8

Table E 1c: Marine environment

Parameter	Source	Adult	Child	Infant
Crustacean consumption (kg/y)	Liquid	1.75	1.25	0
Fish consumption (kg/y)	Liquid	15	6	3.5
Mollusc consumption (kg/y)	Liquid	1.75	1.25	0
Beach occupancy (h/y)	Liquid	300	300	30

Note: The indoors occupancy at home is taken to be 50% of the year for adults, 80% for children and 90% for infants, based on Environment Agency's IRA methodology (Environment Agency, 2006 b). The time spent outdoors is the remainder minus the time spent at the beach. 50% of fish was assumed to be obtained from the local compartment and 50% from the larger regional compartment. All crustaceans and molluscs were assumed to come from the local compartment.

*These foods are consumed at high rates, in line with the “top two” analysis performed in Appendix C

E2.2 Local Fishing Family

The local fishing family is a variant of the group used in the assessment of the most exposed person for liquid discharges (Appendix D). Additional pathways have been included to account for potential exposures to atmospheric discharges, direct irradiation and short-term releases. The family is assumed to live at the site boundary and obtain food from surrounding farmland, in addition to spending time on the beach and fishing. The exposure characteristics for the local fishing family are presented in Table E 2.

Table E 2: Exposure Characteristics for a candidate representative person based on the local fishing family

Table E 2a: Resident (home) – 300m from site

Parameter	Source	Adult	Child	Infant
Indoors, home (300m from site) (h/y)	Atmospheric	4380	7008	7884
Outdoors, home (300m from site) (h/y)	Atmospheric	2380	1452	846

Table E 2b: Farmland – 500m from site

Parameter	Source	Adult	Child	Infant
Cow liver consumption (kg/y)	Atmospheric	2.75	1.5	0.5
Cow meat consumption (kg/y)	Atmospheric	15	15	3
Cow milk consumption (kg/y)	Atmospheric	95	110	130
Cow milk products consumption (kg/y)	Atmospheric	20	15	15
Fruit consumption (kg/y)	Atmospheric	20	15	9
Green veg consumption (kg/y)	Atmospheric	35	15	5
Root veg consumption (kg/y)	Atmospheric	60	50	15
Sheep liver consumption (kg/y)	Atmospheric	2.75	1.5	0.5
Sheep meat consumption (kg/y)	Atmospheric	8	4	0.8

Table E 2c: Marine environment

Parameter	Source	Adult	Child	Infant
Crustacean consumption (kg/y)	Liquid	20	5	0
Fish consumption (kg/y)	Liquid	100	20	5
Mollusc consumption (kg/y)	Liquid	20	5	0
Beach occupancy (h/y)	Liquid	2000	300	30
Handling fishing gear (h/y)	Liquid	2000	0	0

Note: The indoors occupancy at home is taken to be 50% of the year for adults, 80% for children and 90% for infants, based on the Environment Agency's IRAT methodology (Environment Agency, 2006). The time spent outdoors is the remainder minus the time spent at the beach. 50% of fish was assumed to be obtained from the local compartment and 50% from the larger regional compartment. All crustaceans and molluscs were assumed to come from the local compartment.

E3 Radiation doses to representative person

Effective doses to infants, children and adults from the two groups for the candidate representative person have been calculated using the ASSESSOR module in PC CREAM 08. A summary of the doses is shown in Table E 3 (the farming family) and Table E 4 (the fishing family). In most cases, the dominant exposure pathway is from atmospheric discharges. However, for the adult in the fishing family the liquid discharges result in the most significant exposure pathway. The infant in the farming family is the most exposed, owing to the intake of cow's milk and milk products (59% of the total dose). The dominant radionuclide is C-14 (69% of the total dose). The calculated doses to the farming family infant are shown in more detail in Table E 5.

Table E 3: Doses (µSv y-1) to the local farming family candidate representative persons

Age	Atmospheric Discharges	Liquid Discharges	Direct Radiation	Short-Term Releases*	Total
Adult	11	0.98	0.44	7.0	19
Child	12	0.68	0.22	6.1	19
Infant	21	0.43	0.15	7.8	29

* The dose due to short-term releases is calculated in Appendix F

Table E 4: Doses (µSv y-1) to the local fishing family candidate representative persons

Age	Atmospheric Discharges	Liquid Discharges	Direct Radiation	Short-Term Releases*	Total
Adult	7.0	8.0	0.44	7.0	22
Child	7.7	2.4	0.22	6.1	16
Infant	9.8	0.61	0.15	7.8	18

* The dose due to short-term releases is calculated in Appendix F

Table E 5: Doses (µSv y-1) from continuous atmospheric and liquid discharges to the representative person (infant in the farming family)

Radio-nuclide	Inh. Home	Ext. Home	Inh. Beach	Ext. Beach	Non food total
C-14	1.1	$7.1\ 10^{-6}$	$1.2\ 10^{-9}$	$2.9\ 10^{-6}$	1.1
H-3	0.039	0.0	$2.2\ 10^{-8}$	0.0	0.039
I-131	$6.3\ 10^{-4}$	$1.1\ 10^{-4}$	-	-	$7.4\ 10^{-4}$
Xe-133	0.0	$8.0\ 10^{-3}$	-	-	$8.0\ 10^{-3}$
Xe-135	0.0	0.016	-	-	0.016
Total	**1.14**	**0.025**	**$2.3\ 10^{-8}$**	**$2.9\ 10^{-6}$**	**1.16**

Note: Only radionuclides contributing more than 0.01% are shown.

Table E 6 cont: Doses (µSv y-1) from continuous atmospheric and liquid discharges to the representative person (infant in the farming family)

Radio-nuclide	Non food total	Meat	Milk	Veg	Sea-food	Total	% of Total
C-14	1.1	0.41	17	1.6	0.42	20.5	96.2
H-3	0.039	$4.1\ 10^{-3}$	0.38	0.029	$1.2\ 10^{-3}$	0.45	2.1
I-131	$7.4\ 10^{-4}$	$6.1\ 10^{-4}$	0.28	$3.7\ 10^{-3}$	-	0.28	1.3
Xe-133	$8.0\ 10^{-3}$	0.0	0.0	0.0	-	$8.0\ 10^{-3}$	0.04
Xe-135	0.016	0.0	0.0	0.0	-	0.016	0.08
Total	**1.16**	**0.41**	**17.7**	**1.6**	**0.42**	**21.3**	**100**

Note: Only radionuclides contributing more than 0.01% are shown.

E4 Comparison with dose criteria

During the planning for the development of a new nuclear facility such as the UK HPR1000, the Environment Agency compares assessed doses with radiation protection criteria to determine what controls may be required over the discharges (Environment Agency et al., 2012). The criteria that apply to nuclear sites are:

- the As Low As Reasonably Achievable (ALARA) dose constraint of 20 µSv y^{-1}, below which no further assessment needs to occur
- the PHE recommended dose constraint for nuclear new build of 150 µSv y^{-1} (HPA, 2009)
- the source-related dose constraint of 300 µSv y^{-1} (which applies to a single source such as a single UK HPR1000 unit)
- the site-related dose constraint of 500 µSv y^{-1} (i.e. the total dose from multiple sources on the site)

Application of these constraints ensures that no individual person should receive a radiation dose from man-made sources of radioactivity that exceeds the public dose limit of 1 mSv y^{-1} (1,000 µSv y^{-1}).

The total dose to the candidate for the representative person (Table E 3) can be compared with these criteria. The representative person dose is 29 µSv y^{-1} to the infant in the farming family. All doses are well below the PHE recommended criterion. This level of dose from discharges means a site could operate more than one UK HPR1000 and remain within the site-related constraint (to a first approximation, the total dose to an individual can be assumed to scale directly with the number of reactors.)

Appendix F: Individual doses from short-term discharges

F1 Introduction

This appendix considers the effect of estimated short duration increases in discharges of radioactivity from the HPR1000 reactor. It considers discharges of radioactivity to air only. In their submission GNSL (General Nuclear System, 2020a) have stated that the design prevents spikes of short-term activity being released to the marine environment. Liquid discharges from the UK HPR1000 design are made on a batch basis, via storage tanks - which are sampled prior to final discharge to the environment. If activity values exceed the prescribed limits, the effluent can be returned to the effluent waste management system for further treatment until levels are acceptable for release into the environment.

The dose assessment process considers the potential impact of the maximum short-term release that could be expected to occur under normal operating conditions. For short duration releases, which will be to the atmosphere, the maximum monthly discharges specified by GNSL will be used and are presented in Table 5. It is conservatively assumed that these radionuclides will be released uniformly over a short period of 24 hours. The possibility of a release happening over a shorter duration, for example 6 hours, and the effects of this shorter duration on doses will be considered within the sensitivity analysis.

The methodology used to calculate doses from short-term releases follows that described in NDAWG guidance (NDAWG, 2020). The assessment methodology is based on that described in NRPB-W54 (Smith J G, 2004).

The atmospheric dispersion model ADMS 5 (CERC, 2012) is used to estimate air concentrations, deposition rates (wet, dry and total deposition) and cloud gamma dose rates for each release for the radionuclides identified in Table 5. ADMS 5 does not consider location factors (shielding when indoors) when assessing the cloud gamma dose rates so these have been considered in subsequent calculations, described in section F4, using the ADMS 5 outputs.

F2 Meteorological conditions and dispersion parameters

For the short-term release assessment, the realistically conservative meteorological conditions presented in NRPB-W54 (Smith J G, 2004) have been used and are presented in Table F 1. These are conservative but not extremely cautious. The report demonstrates that adoption of these meteorological conditions is shown to result in representative group doses at 1 km downwind of the release point being in the upper part of the overall distribution, generally around the 70th percentile. The wind is assumed to blow towards a hypothetical resident family and food crops. Fluctuation in wind direction during the release was taken into account using the approach adopted in report NRPB-W54 (Smith J G, 2004) and it was estimated that on average the wind deviates over an angle of about 60 degrees over the 24 hour period of release.

Table F 1: Short-term discharge assessment meteorological parameters

Rainfall Rate (mm h^{-1})	Wind Speed (m s^{-1})	Mixing Layer Height (m)	Reciprocal of the Monin-Obukhov length (m^{-1}) *	Wind rose
0.10	3.0	800	0.0	Wind blows towards resident family and food crop.

* New generation atmospheric dispersion models like ADMS do not define atmospheric stability in terms of categories. Instead the reciprocal of the Monin-Obukhov length is used. A value of 0 m^{-1} may be used to represent the stability category D as defined in NRPB-R91 (Clarke, 1979).

The dispersion parameters used in this assessment are the same as those presented by GNSL in their submission (General Nuclear System Ltd., 2020a). The effective stack height has been set at 20 m. The default values of stack diameter (1 m) and temperature of gases (15°C) in ADMS 5 will be used, and the discharge velocity set as 10 m s^{-1}.

F3 Habits data

The location of resident family from the release point has been assumed to be at a distance of 300 m from the release point and food production assumed to be at 500 m from the release point.

The resident family have been assumed to source all of the food they consume locally. The food consumption rates presented in Table F 2 will be used and again the “Top Two” approach used where the two foodstuffs that contribute most to a person’s dose is taken to be at a high rate, with the others at average rates. For adults the top two foods were cows milk and sheep meat, for children and infants the top two foods were cow milk and cow meat, these are identified in bold in Table F 2.

Table F 2: Location and food consumption parameters for the hypothetical local resident family exposed to short-term atmospheric discharges

Distance of residence from release point – 300m

Distance of food production location from release point – 500m

Fraction of food that is locally produced – 1.0

Parameter	Adult Average	Adult High	Child Average	Child High	Infant Average	Infant High
Cow liver consumption (kg y^{-1})	2.8	10	1.5	5.0	0.5	2.8
Cow meat consumption (kg y^{-1})	15	45	15	**30***	3.0	**10***
Cow milk consumption (kg y^{-1})	95	**240***	110	**240***	130	**320***
Fruit consumption (kg y^{-1})	20	75	15	50	9.0	35
Green veg consumption (kg y^{-1})	35	80	15	35	5.0	15
Root veg consumption (kg y^{-1})	60	130	50	95	15	45
Sheep liver consumption (kg y^{-1})	2.8	10	1.5	5.0	0.50	2.8
Sheep meat consumption (kg y^{-1})	8.0	**25***	4.0	10	0.80	3.0

* High consumption rates used for the top two foodstuffs for each age group that contribute most to a person's dose.

The occupancy, inhalation rates and shielding factors used in the assessment are presented in Table F 3, which are the assumptions for a cautious short-term release from NDAWG Guidance (NDAWG, 2019). For this assessment it has been cautiously assumed that there is no indoor occupation during the passage of the plume for all age groups.

Table F 3: Occupancy, inhalation rates and shielding factors for the hypothetical local resident family exposed to short-term atmospheric discharges

Parameter	Adult	Child	Infant
Time spent at location for deposited gamma/resuspension (h) (fraction of year)	8760 (1)	8760 (1)	8760 (1)
Fraction of time indoors (of year)	0.5	0.8	0.9
Location factor for deposited gamma	0.1	0.1	0.1
Exposure time in plume (inhalation & cloudshine) (h)	24 or 6*	24 or 6*	24 or 6*
Fraction of time indoors (plume passage)	0	0	0
Inhalation rate in plume (m3 h^{-1})	1.69	0.87	0.31
Dose reduction factor	0.5	0.5	0.5
Location factor cloudshine	0.2	0.2	0.2

* Duration of release

F4 Dose calculations

The radiological assessment of short-term discharges considers the following exposure pathways:

- Inhalation and external gamma radiation from plume; and
- Ground external radiation and ingestion of terrestrial foodstuffs for a year following the release.

The doses have been calculated using the approach outlined in Appendix I of NRPB W54 (Smith J G, 2004) as detailed below.

For the assessment of inhalation dose and cloud gamma dose from the plume, the assessment has assumed that there is no indoor occupancy during the passage of the plume. The assessment of these dose pathways does not include any consideration of the indoor occupancy time and dose reduction factor related to this.

Inhalation dose

Equation 1

$$DoseInh_n = Act_n \times H_{inh,n} \times Inh \times T_{od}$$

Where:

$DoseInh_n$:	Inhalation dose for radionuclide n (Sv);
Act_n :	Activity concentration in air of radionuclide n during the passage of the plume (Bq m^{-3});
$H_{inh,n}$:	Inhalation Dose coefficient to calculate committed effective dose for radionuclide n (Sv Bq^{-1});
Inh :	Breathing rate (m^3h^{-1});
T_{od}:	Occupancy outdoors (h).

Act_n is calculated from:

Equation 2

$$Act_n = R_n \times C_n$$

Where:

Act_n :	Activity concentration in air of radionuclide n during the passage of the plume (Bq m^{-3}), presented in Table 42;
R_n :	Release rate of radionuclide n (Bq s^{-1});
C_n :	Activity concentration in air of radionuclide n per unit release rate (Bq m^{-3} per Bq s^{-1} release), presented in Table 43.

Cloud Gamma Dose

Equation 3

$$External\ Dose_n = Dose_{unit,n} \times R_n \times T \times 3600 \times T_{od}$$

Where:

$External\ Dose_n$:	Individual effective dose due to external gamma exposure from radionuclide n in the cloud (Sv) (cloud gamma);

$Dose_{unit,n}$: Individual effective dose rate at distances downwind due to external gamma exposure from the cloud per unit release rate of radionuclide (Sv s^{-1} per Bq s^{-1}), presented in Table 43;

R_n : Release rate of radionuclide n (Bq s^{-1});

T : Release duration (h);

T_{od}: Occupancy outdoors (h).

Ground dose

Equation 4

$$External\ Dose_n = \left(\frac{1 - e^{-\lambda nt}}{\lambda n}\right) Dep_{n,r} \times DC_{ext} \times [(LF_{id} \times F_{id}) + (LF_{od} \times F_{od})]$$

Where:

$External\ Dose_n$: Effective dose (Sv) received over the exposure time to the total deposit of radionuclide n on the ground that occurs during the passage of the plume;

λn : Radioactive decay constant 1/h for radionuclide n;

t : Exposure time (h);

$Dep_{n,r}$: Activity concentration in the ground resulting from the deposition of the plume (Bq m^{-2});

DC_{ext} : External dose coefficient (Sv h^{-1} per Bq m^{-2});

LF_{id} and LF_{od} : Indoors (id) and outdoors (od) location factors;

F_{id} and F_{od} : Fraction of time spent indoors (id) and outdoors (od) in location.

$Dep_{n,r}$ is calculated from:

Equation 5

$$Dep_{n,r} = R_n \times T \times C_{dep,n}$$

Where:

$Dep_{n,r}$: Activity concentration in the ground resulting from the deposition of the plume (Bq m^{-2}), presented in Table 42;

R_n : Release rate of radionuclide n (Bq s^{-1});

T : Release duration (s);

$C_{dep,n}$: Deposition rate of the radionuclide n per release rate (Bq m^2 s^{-1} per Bq s^{-1}), presented in Table 43.

Ingestion dose

Doses from ingestion of food are calculated using either integrated activity concentrations in food per unit deposit or per activity concentration in air which have been taken from Table A3 (NDAWG, 2020). For all the radionuclides assessed in the independent dose assessment excluding C-14, integrated activity concentrations in food per unit deposit have been used. The calculation of dose from ingestion of C-14 in food used the integrated activity concentrations in food per activity concentration in air.

Equation 6

$$Dose_{T,n,r} = \sum_{f=1}^{f=F} \sum_{t=1}^{t=T} Dep_{n,r} \times IntAct_{t,f,n} \times IngRate_{t,f} \times DPUI_n \times LocPcnt_f$$

Where:

$Dose_{T,n,r}$: Individual effective dose (Sv) to the chosen age group received from the food consumption, over time (T), of all food (F), for the radionuclide (n) and release (r);

$Dep_{n,r}$: Total deposition Bq m^{-2} from the passage of the plume (as calculated in equation 5)[1];

$IntAct_{t,f,n}$: Integrated activity concentration per unit deposit (Bq.y kg^{-1} per Bq m^{-2}) in food f over time t[2];

$IngRate_{t,f}$: Ingestion rate (kg y^{-1}) of food f over time t for the chosen age group presented in Table F2;

$DPUI_n$: Dose per unit intake (Sv Bq^{-1}) for the radionuclide and chosen age group;

$LocPcnt_f$: The percentage of food f that is locally produced, assumed to be 100%.

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[1] For C-14 Act_n Activity concentration in air of radionuclide n during the passage of the plume (Bq m^{-3}), presented in Table 42 (as calculated in Equation 2) was used.

[2] For C-14 the integrated activity concentration per activity concentration in air (Bq.y kg^{-1} per Bq m^{-3}) was used.

Table F 4: Activity concentrations in air during the passage of the plume and on the ground from deposition of the plume at the 300m and 500m receptor points

Radionuclide	Air (Bq/m3) 300m	Air (Bq/m3) 500m	Ground (Bq/m2) 300m	Ground (Bq/m2) 500m
H-3	130	48	0.97	0.63
C-14	46	18	0.0	0.0
Xe-133m	4.4	1.7	0.0	0.0
Xe-133	290	110	0.0	0.0
Xe-135	84	33	0.0	0.0
Xe-138	0.61	0.23	0.0	0.0
I-131	$3.6\ 10^{-3}$	$1.4\ 10^{-3}$	$2.8\ 10^{-5}$	$1.8\ 10^{-5}$
I-133	$2.2\ 10^{-3}$	$8.3\ 10^{-4}$	$1.7\ 10^{-5}$	$1.1\ 10^{-5}$
Ag-110m	$6.1\ 10^{-6}$	$2.3\ 10^{-6}$	$4.7\ 10^{-8}$	$3.1\ 10^{-8}$
Cs-134	$3.3\ 10^{-5}$	$1.3\ 10^{-5}$	$2.5\ 10^{-7}$	$1.7\ 10^{-7}$
Cs-137	$3.8\ 10^{-5}$	$1.5\ 10^{-5}$	$4.1\ 10^{-9}$	$1.8\ 10^{-8}$
Co-60	$4.0\ 10^{-5}$	$1.5\ 10^{-5}$	$4.3\ 10^{-9}$	$1.9\ 10^{-8}$

Table F 5: Activity concentration in air, deposition rate and individual effective dose rate due to external gamma exposure from the cloud per unit release rate of 1Bq/s

Radionuclide	Receptor Point	Air Concentration (Bq/m3)	Deposition rate (Bq/m2/s)	Gamma (Sv/s)
H-3	300m	$1.2\ 10^{-5}$	$9.0\ 10^{-8}$	0.0
	500m	$4.5\ 10^{-6}$	$5.8\ 10^{-8}$	0.0
C-14	300m	$1.2\ 10^{-5}$	0.0	0.0
	500m	$4.5\ 10^{-6}$	0.0	0.0
Xe-133m	300m	$1.2\ 10^{-5}$	0.0	$1.4\ 10^{-21}$
	500m	$4.5\ 10^{-6}$	0.0	$2.2\ 10^{-21}$
Xe-133	300m	$1.2\ 10^{-5}$	0.0	$1.9\ 10^{-21}$
	500m	$4.5\ 10^{-6}$	0.0	$3.1\ 10^{-21}$
Xe-135	300m	$1.2\ 10^{-5}$	0.0	$1.2\ 10^{-20}$
	500m	$4.5\ 10^{-6}$	0.0	$1.9\ 10^{-20}$
Xe-138	300m	$1.1\ 10^{-5}$	0.0	$4.3\ 10^{-20}$
	500m	$4.2\ 10^{-6}$	0.0	$6.6\ 10^{-20}$
I-131	300m	$1.2\ 10^{-5}$	$9.0\ 10^{-8}$	$1.8\ 10^{-20}$
	500m	$4.5\ 10^{-6}$	$5.9\ 10^{-8}$	$2.7\ 10^{-20}$
I-133	300m	$1.2\ 10^{-5}$	$9.0\ 10^{-8}$	$2.7\ 10^{-20}$
	500m	$4.5\ 10^{-6}$	$5.9\ 10^{-8}$	$4.2\ 10^{-20}$
Ag-110m	300m	$1.2\ 10^{-5}$	$9.0\ 10^{-8}$	$1.2\ 10^{-19}$
	500m	$4.5\ 10^{-6}$	$5.9\ 10^{-8}$	$1.8\ 10^{-19}$
Cs-134	300m	$1.2\ 10^{-5}$	$9.0\ 10^{-8}$	$6.7\ 10^{-20}$
	500m	$4.5\ 10^{-6}$	$5.9\ 10^{-8}$	$1.1\ 10^{-19}$
Cs-137	300m	$1.2\ 10^{-5}$	$1.3\ 10^{-9}$	0.0
	500m	$4.5\ 10^{-6}$	$5.5\ 10^{-9}$	0.0
Co-60	300m	$1.2\ 10^{-5}$	$1.3\ 10^{-9}$	$1.0\ 10^{-19}$
	500m	$4.5\ 10^{-6}$	$5.5\ 10^{-9}$	$1.6\ 10^{-19}$

F5 Estimated doses

Potential radiation doses to a hypothetical exposure group, living 600 m from the point of an atmospheric release have been calculated using the equations and data presented in the preceding sections. The doses from short-term discharges are calculated for the adult, child and infant groups and the results are presented in Table F 6, Table F 7 and Table F 8 respectively.

The results show total doses of 6.9 µSv, 6.0 µSv and 7.8 µSv to the adult, child and infant groups respectively. The total doses are dominated by the inhalation of the plume and ingestion of foods. For adults the contribution of dose from these two pathways is 3.8 µSv

(55.3%) and 3.1 µSv (44.5%) for inhalation and ingestion of foods respectively. For children the contribution of dose from these two pathways is 2.8 µSv (45.9%) and 3.2 µSv (53.9%) for inhalation and ingestion of foods respectively. For infants the contribution of dose from these two pathways is 2.3 µSv (29.7%) and 5.5 µSv (70.2%) for inhalation and ingestion of foods respectively. The total doses are dominated by C-14 which contributes 6.8 µSv (98.5%), 6.0 µSv (98.8%) and 7.8 (99.2%) to the dose to the adult, child and infant groups respectively.

NDAWG Guidance (NDAWG, 2019) states that the doses assessed for operational short-term releases should be compared with the source constraint (maximum of 0.3 mSv y^{-1}) and the dose limit (1 mSv y^{-1}), taking into account other relevant contributions. The total dose for the “representative person”, including the contribution from direct radiation and short-term releases for the different age groups are presented in Table 10 in the main report.

Table F 6: Estimated doses in µSv to adult from short-term releases from the UK HPR1000

Radionuclide	Inhalation of plume	Gamma from plume	Ingestion of foods	Gamma from ground	Total
H-3	0.091	0.0	$5.6\ 10^{-6}$	0.0	**0.091**
C-14	3.8	0.0	3.1	0.0	**6.8**
Xe-133m	0.0	$4.5\ 10^{-5}$	0.0	0.0	**$4.5\ 10^{-5}$**
Xe-133	0.0	$4.1\ 10^{-3}$	0.0	0.0	**$4.1\ 10^{-3}$**
Xe-135	0.0	$7.6\ 10^{-3}$	0.0	0.0	**$7.6\ 10^{-3}$**
Xe-138	0.0	$2.0\ 10^{-4}$	0.0	0.0	**$2.0\ 10^{-4}$**
I-131	$1.1\ 10^{-3}$	$4.7\ 10^{-7}$	$2.4\ 10^{-7}$	$3.3\ 10^{-5}$	**$1.1\ 10^{-3}$**
I-133	$1.3\ 10^{-4}$	$4.3\ 10^{-7}$	$2.8\ 10^{-8}$	$3.9\ 10^{-6}$	**$1.4\ 10^{-4}$**
Ag-110m	$1.9\ 10^{-6}$	$5.3\ 10^{-9}$	$6.2\ 10^{-10}$	$7.9\ 10^{-6}$	**$9.8\ 10^{-6}$**
Cs-134	$8.7\ 10^{-6}$	$1.6\ 10^{-8}$	$2.0\ 10^{-8}$	$3.3\ 10^{-5}$	**$4.1\ 10^{-5}$**
Cs-137	$7.0\ 10^{-6}$	0.0	$1.5\ 10^{-9}$	$4.8\ 10^{-9}$	**$7.0\ 10^{-6}$**
Co-60	$1.6\ 10^{-5}$	$3.0\ 10^{-8}$	$1.1\ 10^{-10}$	$9.3\ 10^{-7}$	**$1.7\ 10^{-5}$**
Total	3.8	0.012	3.1	$7.8\ 10^{-5}$	**6.9**

Table F 7: Estimated doses in μSv to child from short-term releases from the UK HPR1000

Radionuclide	Inhalation of plume	Gamma from plume	Ingestion of foods	Gamma from ground	Total
H-3	0.060	0.0	$5.9\ 10^{-6}$	0.0	0.060
C-14	2.7	0.0	3.2	0.0	6.0
Xe-133m	0.0	$4.5\ 10^{-5}$	0.0	0.0	$4.5\ 10^{-5}$
Xe-133	0.0	$4.1\ 10^{-3}$	0.0	0.0	$4.1\ 10^{-3}$
Xe-135	0.0	$7.6\ 10^{-3}$	0.0	0.0	$7.6\ 10^{-3}$
Xe-138	0.0	$2.0\ 10^{-4}$	0.0	0.0	$2.0\ 10^{-4}$
I-131	$1.4\ 10^{-3}$	$4.7\ 10^{-7}$	$5.1\ 10^{-7}$	$1.9\ 10^{-5}$	$1.4\ 10^{-3}$
I-133	$1.7\ 10^{-4}$	$4.3\ 10^{-7}$	$6.0\ 10^{-8}$	$2.1\ 10^{-6}$	$1.7\ 10^{-4}$
Ag-110m	$1.5\ 10^{-6}$	$5.3\ 10^{-9}$	$9.9\ 10^{-10}$	$4.4\ 10^{-6}$	$5.9\ 10^{-6}$
Cs-134	$3.6\ 10^{-6}$	$1.6\ 10^{-8}$	$1.3\ 10^{-8}$	$1.8\ 10^{-5}$	$2.2\ 10^{-5}$
Cs-137	$2.9\ 10^{-6}$	0.0	$1.0\ 10^{-9}$	$2.6\ 10^{-9}$	$2.9\ 10^{-6}$
Co-60	$1.2\ 10^{-5}$	$3.0\ 10^{-8}$	$3.0\ 10^{-10}$	$5.2\ 10^{-7}$	$1.3\ 10^{-5}$
Total	2.8	0.012	3.2	$4.4\ 10^{-5}$	6.0

Table F 8: Estimated doses in μSv to infant from short-term releases from the UK HPR1000

Radionuclide	Inhalation of plume	Gamma from plume	Ingestion of foods	Gamma from ground	Total
H-3	0.045	0.0	$1.1\ 10^{-5}$	0.0	0.045
C-14	2.3	0.0	5.5	0.0	7.8
Xe-133m	0.0	$4.5\ 10^{-5}$	0.0	0.0	$4.5\ 10^{-5}$
Xe-133	0.0	$4.1\ 10^{-3}$	0.0	0.0	$4.1\ 10^{-3}$
Xe-135	0.0	$7.6\ 10^{-3}$	0.0	0.0	$7.6\ 10^{-3}$
Xe-138	0.0	$2.0\ 10^{-4}$	0.0	0.0	$2.0\ 10^{-4}$
I-131	$1.9\ 10^{-3}$	$4.7\ 10^{-7}$	$2.1\ 10^{-6}$	$1.4\ 10^{-5}$	$1.9\ 10^{-3}$
I-133	$2.9\ 10^{-4}$	$4.3\ 10^{-7}$	$3.0\ 10^{-7}$	$1.6\ 10^{-6}$	$2.9\ 10^{-4}$
Ag-110m	$1.3\ 10^{-6}$	$5.3\ 10^{-9}$	$2.1\ 10^{-9}$	$3.3\ 10^{-6}$	$4.5\ 10^{-6}$
Cs-134	$1.8\ 10^{-6}$	$1.6\ 10^{-8}$	$1.2\ 10^{-8}$	$1.4\ 10^{-5}$	$1.5\ 10^{-5}$
Cs-137	$1.5\ 10^{-6}$	0.0	$1.0\ 10^{-9}$	$1.9\ 10^{-9}$	$1.5\ 10^{-6}$
Co-60	$1.0\ 10^{-5}$	$3.0\ 10^{-8}$	$7.6\ 10^{-10}$	$3.8\ 10^{-7}$	$1.0\ 10^{-5}$
Total	2.3	0.012	5.5	$3.3\ 10^{-5}$	7.8

F6 Exploring sensitivity to model assumptions

It has been assumed that the maximum monthly discharged estimated by GNS for the UK HPR1000 is discharged over a 24 hour period, however, a scenario where this discharge is released over a much shorter period has been assessed. The assessment looked at the impact on doses with the source term presented in Table 5 released over 6 hours. All the same assumptions presented in sections F2 and F3 remained the same. The assessment identified a significant increase in doses for this discharge scenario, these are presented in Table F 9. The increase in doses are 176% to 19 µSv, 162% to 16 µSv and 211% to 24 µSv for adult, child and infant respectively. This increase in dose is due to an increased dose from consumption of foods. This increase in dose affects the total dose to the representative person. For the Local Farming Family the total doses are 31 µSv, 29 µSv and 46 µSv to adult, child and infant respectively. For the Local Fishing Family the total doses are 34 µSv, 26 µSv and 35 µSv to adult, child and infant respectively. Despite the increases in contribution from short-term releases, these total doses remain well below the source dose constraint.

Table F 9: Estimated doses in µSv from short-term releases over a 6 hour duration from the UK HPR1000

Age	Inhalation of plume	Gamma from plume	Ingestion of foods	Gamma from ground	Total
Adult	3.8	0.012	15	$5.7\ 10^{-5}$	**19**
Child	2.8	0.012	13	$6.3\ 10^{-5}$	**16**
Infant	2.3	0.012	22	$6.9\ 10^{-5}$	**24**

Appendix G: Collective doses

G1 Introduction

The total exposure from radioactive discharges to a population is referred to as the 'collective dose' and is assigned the unit of manSv per year of discharge. It is the sum of the doses to all individuals that are exposed over a specified period. The period can be more than a person's lifetime as many radionuclides are persistent in the environment.

This section presents the assessment of the collective dose from a UK HPR1000 resulting from both atmospheric and liquid estimated discharges. The annual estimated discharges proposed by (General Nuclear System, 2020a) and screened for the independent dose assessment have been used in the calculation (Table 3 and Table 4).

G2 Scope and approach

Although collective doses involve large populations, they are nevertheless dependent on the point of release. For the purposes of the assessment, the generic site characteristics are the same as used in the assessment of individual doses from atmospheric and marine discharges (see Appendix A). The same atmospheric and marine dispersion parameters used for individual dose calculations (as described in Appendix C and Appendix D) were used.

PC CREAM 08 includes models for the calculation of collective dose, which have been used in the independent dose assessment. The collective dose for each pathway was calculated in the following way.

- For liquid discharges, the DORIS model calculates the dispersion of radionuclides in the marine environment globally. Each region of the world's oceans is represented in the model, as are the transfers between them, and the models and data are presented in the HPA report (Smith & Simmonds, 2009). The resulting marine water and sediment concentrations can be used to estimate the collective radiation dose resulting from the ingestion of seafood and exposure on beaches from each region.
- For atmospheric discharges, radiation exposures from the “first pass” of the dispersed plume are calculated with the same suite of models as used in the assessment of individual doses, albeit for much larger distances. In addition, the long-term global circulation of gaseous radionuclides that remain in the atmosphere needs to be accounted for. PC CREAM 08 includes atmospheric global circulation models for H-3, C-14 and Kr-85 and I-131 (Smith & Simmonds, 2009) which have been used in the calculation.

Over time, radioactive discharges to the atmosphere and the marine environment can spread far, indeed throughout the entire world. Collective doses therefore require the calculation of exposures to large populations. For the purposes of regulatory authorisation the populations of the UK, Europe and the World require consideration (Environment Agencies, 2012). This guidance also recommends that the total dose be estimated, truncated for a period of 500 y (to account for the persistence of radionuclides in the environment even after discharges have ceased). These assumptions have been used in our assessment.

PC CREAM 08 includes default datasets of population distribution and habits (Smith & Simmonds, 2009) which have been used in the calculations. It is noted that there are various definitions of European nations in the results provided by PC CREAM 08, reflecting the gradual expansion of the Union over the period in which PC CREAM has been developed. For atmospheric discharges EU-25 has been used and for liquid discharges, EU-12. This is also due to some EU countries not having a coastline and therefore exploring the effect of liquid discharges is not applicable.

G3 Collective radiation doses

The calculated collective doses for a 500 y period are presented in Table G 1 for a range of populations. On all measures, the dominant contributor to collective dose is the atmospheric discharges, with the key radionuclide being C-14 (Table G 2) and the main exposure pathway being ingestion of grain. For the less significant liquid discharges, the dominant radionuclide is also C-14 (Table G 3).

Table G 1: Collective dose (manSv), truncated at 500 years, for one year of radioactive discharges from a single UK HPR1000

Discharges	Dose Type	UK population	EU population	World population*
Atmospheric	First Pass	0.53	2.7	-
Atmospheric	Global circulation	0.18	1.4	30
Atmospheric	Total (atmospheric)	0.71	4.1	30
Liquid	-	0.013	0.078	0.74
Total	-	0.72	4.2	31

*Global circulation models only consider H-3, C-14 and Kr-85.

Table G 2: Collective dose (manSv), truncated at 500 years, for individual radionuclides following one year of radioactive atmospheric discharges from a single UK HPR1000

Radionuclide	UK	EU-25	World*
Ag-110m	$3.9\ 10^{-7}$	$2.0\ 10^{-6}$	-
C-14	0.70	4.1	30
Co-60	$4.3\ 10^{-6}$	$6.4\ 10^{-6}$	-
Cs-134	$5.4\ 10^{-6}$	$1.7\ 10^{-5}$	-
Cs-137	$6.6\ 10^{-6}$	$1.8\ 10^{-5}$	-
H-3	$5.1\ 10^{-3}$	0.015	$1.7\ 10^{-3}$
I-131	$4.3\ 10^{-5}$	$4.0\ 10^{-5}$	-
I-133	$2.8\ 10^{-7}$	$3.3\ 10^{-7}$	-
Xe-133	$1.6\ 10^{-4}$	$3.3\ 10^{-4}$	-
Xe-133m	$2.1\ 10^{-6}$	$3.7\ 10^{-6}$	-
Xe-135	$1.7\ 10^{-4}$	$2.1\ 10^{-4}$	-
Xe-138	$1.5\ 10^{-7}$	$2.0\ 10^{-7}$	-

*Global circulation models only consider H-3, C-14 and Kr-85

Table G 3: Collective dose (manSv), truncated at 500 years, for individual radionuclides following one year of radioactive liquid discharges from a single UK HPR1000

Radionuclide	UK	EU-12	World
Ag-110m	$4.3\ 10^{-6}$	$2.7\ 10^{-5}$	$3.1\ 10^{-5}$
C-14	0.013	0.077	0.74
Co-58	$1.6\ 10^{-7}$	$1.0\ 10^{-6}$	$1.2\ 10^{-6}$
Co-60	$2.3\ 10^{-6}$	$1.4\ 10^{-5}$	$1.6\ 10^{-5}$
Cs-134	$1.3\ 10^{-7}$	$7.6\ 10^{-7}$	$1.2\ 10^{-6}$
Cs-137	$1.7\ 10^{-7}$	$9.7\ 10^{-7}$	$1.7\ 10^{-6}$
Fe-59	$4.4\ 10^{-6}$	$2.7\ 10^{-5}$	$2.9\ 10^{-5}$
H-3	$4.5\ 10^{-5}$	$2.7\ 10^{-4}$	$3.7\ 10^{-3}$
Mn-54	$3.3\ 10^{-7}$	$2.0\ 10^{-6}$	$2.2\ 10^{-6}$
Sb-124	$9.2\ 10^{-8}$	$6.3\ 10^{-7}$	$1.0\ 10^{-6}$

Using estimated population data from (Smith & Simmonds, 2009) the average dose to each person in the exposed population can be calculated for illustrative purposes. This is presented in Table G 4 and shows that it is around 0.012 μSv y^{-1} (12 nSv y^{-1}) for the UK, 0.009 μSv y^{-1} (9 nSv y^{-1}) for EU 25 and 0.003 μSv y^{-1} (3 nSv y^{-1}) for the world. Calculated average annual individual doses for a population group in the 10 nSv range or less can be ignored in the decision making process (Environment Agencies, 2012) and so will not be considered further in this assessment.

Table G 4: Average doses per person (per caput) (μSv y-1), truncated at 500 years, following one year of radioactive discharges from a single UK HPR1000

Population Group	Population	Per Caput dose (μSv y^{-1}) Atmospheric Discharges	Per Caput dose (μSv y^{-1}) Liquid Discharges	Per Caput dose (μSv y^{-1}) Total
UK	$6.0\ 10^{7}$	0.012	$2.2\ 10^{-4}$	**0.012**
EU12	$3.6\ 10^{8}$	-	$2.2\ 10^{-4}$	**$2.2\ 10^{-4}$**
EU25	$4.6\ 10^{8}$	$8.9\ 10^{-3}$	-	**$8.9\ 10^{-3}$**
World	$1.0\ 10^{10}$	$3.0\ 10^{-3}$	$7.4\ 10^{-5}$	**$3.1\ 10^{-3}$**

Appendix H: Radiation exposure of non-human species

H1 Introduction

This Appendix presents the assessment of exposure to non-human species living in close proximity to the generic envelope site as a result of estimated discharges from a single UK HPR1000 reactor. Assessment of exposure to discharged radionuclides was calculated using the modelling code ERICA (Beresford, et al., 2007) for all considered nuclides with the exception of noble gases which were assessed using Radiological Impact Assessment for Terrestrial Ecosystems Version 2 (also known as Ar, Kr, Xe) (Vives i Batlle, Jones, & Copplestone, 2015).

H2 Model Assumptions

In order to assess the environmental impact on non-human species it was necessary to determine the environmental concentrations in various media due to atmospheric and liquid discharges. Data from PC CREAM model runs (Appendix C and Appendix D) were input to the ERICA and Ar, Kr, Xe models.

H2.1 Atmospheric Discharges

Atmospheric Discharges were modelled using PC CREAM 08 to determine activity concentrations in air (PLUME) and soil (GRANIS). Activity concentrations in non-human species were derived by ERICA. The receptor location chosen was at the peak deposition distance of 300 m.

An uncertainty factor of 3 was assumed in these assessments

Radioecology Parameters

In determining the appropriate radioecology parameters for each of the radioelements considered in this study, ERICA default CRs were selected. Where empirical data was not already available the method used to derive the CRs followed the ERICA recommended process.

Default Radiation Weighting factors for alpha, beta/gamma and low beta emitters were assumed, i.e. 10, 1 and 3 respectively.

Xenon Assessments

ERICA is not capable of assessing exposures to non-human species from noble gases; therefore, it was necessary to use a separate modelling code for this assessment. The activity concentrations in air of Xe-131m and Xe-133 were taken from PLUME to assess exposures. All other input values in the Ar, Kr, Xe spreadsheet were left as default.

H2.2 Liquid Discharges

Estimated marine discharges were modelled using the DORIS model within PC CREAM 08 to determine activity concentrations in unfiltered seawater and sediment in the local marine compartment defined in Appendix D above. Activity concentrations in non-human species were derived by ERICA utilising the CRs and distribution coefficients (Kd) selected for the radioelements of interest.

Radioecology Parameters

As for atmospheric discharges, the CRs were selected using ERICA defaults where available. Where empirical data was not already available the method used to derive the CRs followed the ERICA recommended process.

As iron (Fe-59) was not a standard nuclide within ERICA, there is no CR or Kd data for iron. A Kd for iron of 3 10^8 l kg-1 was taken from TRS422 (IAEA, 2004) for the Ocean Margin region. Where CRs were available in TRS422 relevant to biota in ERICA these were used in the assessment (Table H 1). For species where data was not available in TRS422 CRs were determined by taking the maximum CR for all elements included within ERICA. The element providing the maximum CR is provided in parenthesis within Table H 1.

Table H 1: Summary of CRs for Fe-59 used in assessment for non-human species

Species	CR (TRS422)	CR (max)
Benthic fish	3.00 10^4	
Bird		7.75 10^4 (Po)
Crustacean	5.00 10^5	
Sea anemones & True coral		2.13 10^5 (Po)
Mammal	1.00 10^7 (pinnipeds – muscle)	
Mollusc - bivalve	5.00 10^5	
Pelagic fish	3.00 10^4	
Reptile		7.75 10^4 (Po)
Polychaete worm		4.62 10^5 (Po)
Macroalgae	2.00 10^4	
Phytoplankton	4.00 10^5	
Vascular plant		5.34 10^4 (Tc)
Zooplankton	1.00 10^5	

H2.3 Direct Radiation Exposures

As Terrestrial non-human species could be located at any distance from the site buildings, including within the site boundary, this assessment has assumed that the non-human species are located at 50 m from all buildings specified as a source for direct radiation on the UK HPR1000 site. These buildings are the Reactor Building (BRX); Nuclear Auxiliary Building (BNX); Fuel Building (BFX); Radioactive Waste Treatment Building (BWX); Intermediate Level Waste Interim Store (BQZ), and the Spent Fuel Interim Store (BQF). Dose rate data at this distance has been taken from (CNPDC, 2019). The dose rate data presented in (CNPDC, 2019) is given at three elevations: 1 m, 10 m and 20 m. The dose rate from each building on the generic site will differ depending on the topography of the site. As the orientation of the buildings on the site is not known and the most relevant elevation for non-human species is at or close to ground level, data for an elevation of 1 m has been used in this assessment.

All dose rates are assumed attributable to gamma radiation; therefore, conversion from the presented dose rates in Sieverts to non-human species exposures in Gray is a simple 1:1 ratio. Exposure times for non-human species have been taken to be 8760 h y^{-1}. Transient sources, such as package transfers across and off site have been excluded from this assessment as the data on dose rate from a package is currently only based on package dose limits, so are subject to change. Frequency and period of transfers is also not yet known. These transient sources will not be a significant contributor to total exposure for non-human species when compared to ongoing exposures from the site buildings. The direct radiation exposure calculated is species independent.

H3 Non-human species considered in the assessment

H3.1 Species in the terrestrial environment

The non-human species of interest in this study have been taken to be all default terrestrial species present in ERICA. It has been determined that these species are sufficiently representative of species that may be present on a generic UK site. The species assessed are detailed in Table H 2.

Table H 2: Non-human species from the terrestrial environment considered in the independent dose assessment

Organism (animal)	Organism (plant)
Amphibian	Grasses & Herbs
Bird	Lichen & Bryophytes
Mollusc - gastropod	Shrub
Reptile	Tree
Annelid	
Arthropod - detritivorous	
Flying insects	
Mammal - large	
Mammal - small-burrowing	

The default occupancies of each species were used, i.e. fractions of time in soil, on soil and in air.

These same species were selected for the xenon assessments.

H3.1 Species in the marine environment

The Non-Human Species of interest in this study have been taken to be all default marine species present in ERICA. It has been determined that these species are sufficiently representative of species that may be present in the marine environment close to a generic UK site. The species assessed are detailed in Table H 3.

Table H 3: Non-human species from the marine environment considered in the independent dose assessment.

Organism (animal)	Organism (plant)
Benthic fish	Macroalgae
Bird	Phytoplankton
Crustacean	Vascular plant
Sea anemones & True coral	Zooplankton
Mammal	
Mollusc - bivalve	
Pelagic fish	
Reptile	
Polychaete worm	

The default habits (occupancy factors) for each species were used, i.e. fractions of time in water, at the water surface, on the sediment surface and in sediment.

H4 Radiation doses to non-human species

H4.1 Atmospheric Discharges

The calculated dose rates for the exposure of terrestrial biota to noble gases discharged from a UK HPR1000 (using the Ar, Kr, Xe model) and all other gaseous discharges (using ERICA) are given in Table H 4. The calculated doses due to noble gases are extremely low across all species. The atmospheric doses to non-human species from all other gaseous discharges are well below the screening value of 10 μGy h^{-1} to terrestrial animals, birds and reptiles and terrestrial plants. Cs-137 is the dominant radionuclide for birds, lichen & bryophytes, large and small mammals, trees and shrubs. For all other terrestrial non-human species, Co-60 was calculated to be the dominant nuclide.

The calculated dose rates to terrestrial biota following exposure to atmospheric discharges, and the corresponding risk quotients (RQ), are given in Table H 5*.* The most exposed non-human species assessed in this study is the large mammal, with an exposure rate of 0.13 μGy h-1 from the assessed nuclides. This is far below the 10 μGy h^{-1} screening level for terrestrial species with an RQ of 0.013.

Table H 4: Calculated dose rates (in µGy h-1) to terrestrial biota resulting from the atmospheric discharges

Nuclide	Amphibian	Bird	Mollusc - gastropod	Reptile	Annelid
Cs-135 (Xe-135)	$3.80\ 10^{-4}$	$2.30\ 10^{-4}$	$1.20\ 10^{-4}$	$3.80\ 10^{-4}$	$3.20\ 10^{-4}$
Cs-138 (Xe-138)	$3.90\ 10^{-9}$	$4.80\ 10^{-9}$	$3.40\ 10^{-10}$	$4.80\ 10^{-9}$	$6.80\ 10^{-10}$
I-133	$2.10\ 10^{-3}$	$1.20\ 10^{-3}$	$7.80\ 10^{-4}$	$2.00\ 10^{-3}$	$1.80\ 10^{-3}$
I-131	0.018	0.010	$7.40\ 10^{-3}$	0.017	0.016
H-3	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$
Cs-137	0.027	0.016	$9.10\ 10^{-3}$	0.027	0.023
Cs-134	$5.50\ 10^{-3}$	$2.70\ 10^{-3}$	$2.00\ 10^{-3}$	$5.30\ 10^{-3}$	$5.30\ 10^{-3}$
Co-60	0.032	0.012	0.012	0.030	0.032
C-14	$3.40\ 10^{-3}$	$3.60\ 10^{-3}$	$1.10\ 10^{-3}$	$3.60\ 10^{-3}$	$1.10\ 10^{-3}$
Ag-110m	$1.30\ 10^{-3}$	$6.20\ 10^{-4}$	$5.30\ 10^{-4}$	$1.20\ 10^{-3}$	$1.40\ 10^{-3}$
Xe-131m	$6.20\ 10^{-6}$	$5.10\ 10^{-6}$	$6.80\ 10^{-6}$	$6.00\ 10^{-6}$	$1.60\ 10^{-9}$
Xe-133	$8.40\ 10^{-16}$	$5.90\ 10^{-16}$	$1.00\ 10^{-15}$	$7.90\ 10^{-16}$	$2.50\ 10^{-19}$
Total	**0.09**	**0.046**	**0.034**	**0.086**	**0.08**

Table H 4 (cont) Calculated dose rates (in µGy h-1) to terrestrial biota resulting from the atmospheric discharges

Nuclide	Arthropod-detritivore	Flying insects	Grasses & Herbs	Lichen & Bryophytes	Mammal - large
Cs-135 (Xe-135)	$3.20\ 10^{-4}$	$1.30\ 10^{-4}$	$1.10\ 10^{-4}$	$3.40\ 10^{-4}$	$1.30\ 10^{-3}$
Cs-138 (Xe-138)	$8.70\ 10^{-10}$	$8.70\ 10^{-10}$	$4.40\ 10^{-14}$	$3.10\ 10^{-8}$	$2.90\ 10^{-8}$
I-133	$1.90\ 10^{-3}$	$8.90\ 10^{-4}$	$6.00\ 10^{-4}$	$7.30\ 10^{-4}$	$1.20\ 10^{-3}$
I-131	0.017	$8.20\ 10^{-3}$	$5.90\ 10^{-3}$	$6.90\ 10^{-3}$	0.010
H-3	$3.40\ 10^{-4}$	$3.20\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$
Cs-137	0.023	$9.80\ 10^{-3}$	$8.00\ 10^{-3}$	0.041	0.088
Cs-134	$5.30\ 10^{-3}$	$2.10\ 10^{-3}$	$1.90\ 10^{-3}$	$4.00\ 10^{-3}$	0.015
Co-60	0.032	0.012	0.012	0.012	0.01
C-14	$1.10\ 10^{-3}$	$1.10\ 10^{-3}$	$2.30\ 10^{-3}$	$2.30\ 10^{-3}$	$3.60\ 10^{-3}$
Ag-110m	$1.30\ 10^{-3}$	$5.00\ 10^{-4}$	$4.80\ 10^{-4}$	$5.00\ 10^{-4}$	$7.20\ 10^{-4}$
Xe-131m	$7.40\ 10^{-6}$	$7.00\ 10^{-6}$	$1.40\ 10^{-5}$	$8.20\ 10^{-6}$	$1.60\ 10^{-6}$
Xe-133	$1.40\ 10^{-15}$	$1.20\ 10^{-15}$	$2.10\ 10^{-15}$	$1.90\ 10^{-15}$	$1.90\ 10^{-16}$
Total	**0.082**	**0.035**	**0.031**	**0.068**	**0.13**

Table H 4 (cont) Calculated dose rates (in µGy h-1) to terrestrial biota resulting from the atmospheric discharges

Nuclide	Mammal - small-burrowing	Shrub	Tree
Cs-135 (Xe-135)	$9.40\ 10^{-4}$	$3.50\ 10^{-4}$	$1.40\ 10^{-4}$
Cs-138 (Xe-138)	$2.90\ 10^{-8}$	$1.70\ 10^{-8}$	$1.10\ 10^{-9}$
I-133	$2.00\ 10^{-3}$	$6.00\ 10^{-4}$	$7.80\ 10^{-4}$
I-131	0.018	$5.50\ 10^{-3}$	$7.30\ 10^{-3}$
H-3	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$	$3.40\ 10^{-4}$
Cs-137	0.062	0.028	$9.70\ 10^{-3}$
Cs-134	$8.50\ 10^{-3}$	$3.10\ 10^{-3}$	$2.10\ 10^{-3}$
Co-60	0.03	0.011	$9.50\ 10^{-3}$
C-14	$3.60\ 10^{-3}$	$2.30\ 10^{-3}$	$3.50\ 10^{-3}$
Ag-110m	$1.30\ 10^{-3}$	$4.60\ 10^{-4}$	$7.10\ 10^{-4}$
Xe-131m	$1.30\ 10^{-9}$	$8.30\ 10^{-6}$	$5.80\ 10^{-6}$
Xe-133	$1.60\ 10^{-19}$	$2.00\ 10^{-15}$	$6.20\ 10^{-16}$
Total	**0.13**	**0.051**	**0.034**

Table H 5: Calculated dose rates (in µGy h-1) to terrestrial biota and corresponding risk quotients from atmospheric discharges

Terrestrial Biota	Total dose rate	Risk Coefficient (expected)*	Risk Coefficient (conservative)^
Amphibian	0.090	$9.0\ 10^{-3}$	0.027
Bird	0.046	$4.6\ 10^{-3}$	0.014
Mollusc - gastropod	0.034	$3.4\ 10^{-3}$	0.010
Reptile	0.086	$8.6\ 10^{-3}$	0.026
Annelid	0.080	$8.0\ 10^{-3}$	0.024
Arthropod - detritivore	0.082	$8.2\ 10^{-3}$	0.025
Flying insects	0.035	$3.5\ 10^{-3}$	0.011
Grasses & Herbs	0.031	$3.1\ 10^{-3}$	$9.4\ 10^{-3}$
Lichen & Bryophytes	0.068	$6.8\ 10^{-3}$	0.02
Mammal - large	0.13	1.3 10-2	0.039
Mammal - small-burrowing	0.13	1.3 10-2	0.038
Shrub	0.051	$5.1\ 10^{-3}$	0.015
Tree	0.034	$3.4\ 10^{-3}$	0.01

Note: * Calculated using a screening value of 10 µGy h^{-1} for terrestrial animals, birds and reptiles and 400 µGy h^{-1} for terrestrial plants.

^Calculated by applying an uncertainty factor of 3 to the expected risk coefficient.

H4.2 Liquid Discharges

The calculated total dose rates to marine biota from estimated liquid discharges from the UK HPR1000 are given in Table H 6. Table H 7 displays the summary dose rates and the corresponding RQs. The most exposed non-human species assessed in this study is the mammal, with an exposure rate of 0.023 µGy h^{-1} from the assessed nuclides. This is far below the 10 µGy h^{-1} screening level for aquatic organisms.

Table H 6: Calculated dose rates (in µGy h-1) to marine biota resulting from the liquid discharges

Nuclide	Benthic fish	Bird	Crustacean	Macroalgae	Mammal
Sb-124	$2.00\ 10^{-6}$	$3.30\ 10^{-5}$	$1.20\ 10^{-6}$	$6.00\ 10^{-7}$	$7.00\ 10^{-5}$
Mn-54	$8.90\ 10^{-7}$	$5.90\ 10^{-7}$	$5.90\ 10^{-6}$	$1.00\ 10^{-6}$	$2.10\ 10^{-6}$
H-3	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$
Fe-59	$2.00\ 10^{-5}$	$6.60\ 10^{-5}$	$3.90\ 10^{-4}$	$9.30\ 10^{-6}$	0.023
Cs-137	$8.00\ 10^{-7}$	$2.40\ 10^{-7}$	$7.60\ 10^{-7}$	$8.80\ 10^{-7}$	$1.90\ 10^{-7}$
Cs-134	$3.60\ 10^{-7}$	$2.00\ 10^{-7}$	$3.40\ 10^{-7}$	$3.70\ 10^{-7}$	$2.40\ 10^{-7}$
Co-60	$9.70\ 10^{-5}$	$2.00\ 10^{-6}$	$9.40\ 10^{-5}$	$9.10\ 10^{-5}$	$6.60\ 10^{-6}$
Co-58	$3.20\ 10^{-6}$	$3.40\ 10^{-7}$	$2.70\ 10^{-6}$	$1.10\ 10^{-6}$	$1.10\ 10^{-6}$
C-14	$4.10\ 10^{-4}$	$4.10\ 10^{-4}$	$3.30\ 10^{-4}$	$3.10\ 10^{-4}$	$4.10\ 10^{-4}$
Ag-110m	$6.70\ 10^{-6}$	$1.90\ 10^{-5}$	$2.80\ 10^{-5}$	$1.30\ 10^{-6}$	$6.50\ 10^{-5}$
Total	**$6.60\ 10^{-4}$**	**$6.50\ 10^{-4}$**	**$9.80\ 10^{-4}$**	**$5.30\ 10^{-4}$**	**0.023**

Table H 6 cont: Calculated dose rates (in µGy h-1) to marine biota resulting from the liquid discharges

Nuclide	Mollusc - bivalve	Pelagic fish	Phyto-plankton	Polychaete worm
Sb-124	$1.30\ 10^{-6}$	$2.10\ 10^{-6}$	$6.60\ 10^{-7}$	$1.10\ 10^{-5}$
Mn-54	$1.20\ 10^{-6}$	$2.60\ 10^{-7}$	$4.90\ 10^{-8}$	$1.50\ 10^{-6}$
H-3	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$
Fe-59	$2.40\ 10^{-4}$	$2.20\ 10^{-5}$	$1.10\ 10^{-4}$	$2.10\ 10^{-4}$
Cs-137	$8.40\ 10^{-7}$	$4.00\ 10^{-8}$	$2.60\ 10^{-9}$	$1.70\ 10^{-6}$
Cs-134	$3.60\ 10^{-7}$	$3.10\ 10^{-8}$	$2.60\ 10^{-9}$	$7.40\ 10^{-7}$
Co-60	$9.70\ 10^{-5}$	$1.70\ 10^{-5}$	$2.40\ 10^{-6}$	$1.90\ 10^{-4}$
Co-58	$2.20\ 10^{-6}$	$2.90\ 10^{-6}$	$3.70\ 10^{-7}$	$3.40\ 10^{-6}$
C-14	$1.50\ 10^{-4}$	$4.10\ 10^{-4}$	$5.60\ 10^{-5}$	$2.30\ 10^{-3}$
Ag-110m	$1.20\ 10^{-5}$	$7.70\ 10^{-6}$	$7.00\ 10^{-6}$	$8.00\ 10^{-6}$
Total	**$6.30\ 10^{-4}$**	**$5.80\ 10^{-4}$**	**$2.90\ 10^{-4}$**	**$2.80\ 10^{-3}$**

Table H 6 cont: Calculated dose rates (in µGy h-1) to marine biota resulting from the liquid discharges

Nuclide	Reptile	Sea anemones & True coral	Vascular plant	Zoo-plankton
Sb-124	$6.90\ 10^{-5}$	$3.00\ 10^{-7}$	$7.00\ 10^{-7}$	$1.90\ 10^{-6}$
Mn-54	$2.10\ 10^{-6}$	$7.00\ 10^{-7}$	$2.10\ 10^{-6}$	$4.40\ 10^{-8}$
H-3	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$	$1.20\ 10^{-4}$
Fe-59	$1.70\ 10^{-4}$	$8.90\ 10^{-5}$	$2.70\ 10^{-5}$	$2.50\ 10^{-4}$
Cs-137	$4.00\ 10^{-7}$	$9.30\ 10^{-7}$	$8.20\ 10^{-7}$	$4.20\ 10^{-8}$
Cs-134	$5.20\ 10^{-7}$	$4.00\ 10^{-7}$	$3.50\ 10^{-7}$	$2.20\ 10^{-8}$
Co-60	$6.50\ 10^{-6}$	$8.90\ 10^{-5}$	$8.80\ 10^{-5}$	$4.60\ 10^{-6}$
Co-58	$1.10\ 10^{-6}$	$8.50\ 10^{-7}$	$8.00\ 10^{-7}$	$7.90\ 10^{-7}$
C-14	$4.10\ 10^{-4}$	$3.90\ 10^{-4}$	$3.00\ 10^{-4}$	$2.30\ 10^{-3}$
Ag-110m	$6.40\ 10^{-5}$	$1.90\ 10^{-7}$	$1.60\ 10^{-6}$	$9.60\ 10^{-7}$
Total	**$8.40\ 10^{-4}$**	**$6.90\ 10^{-4}$**	**$5.40\ 10^{-4}$**	**$2.70\ 10^{-3}$**

Table H 7: Calculated dose rates (in µGy h-1) to marine biota and corresponding risk quotients from liquid discharges

Marine Biota	Total dose rate	Risk Coefficient (expected)*	Risk Coefficient (conservative)^
Benthic fish	$6.6\ 10^{-4}$	$6.6\ 10^{-5}$	$2.0\ 10^{-4}$
Bird	$6.5\ 10^{-4}$	$6.5\ 10^{-5}$	$1.9\ 10^{-4}$
Crustacean	$9.8\ 10^{-4}$	$9.8\ 10^{-5}$	$2.9\ 10^{-4}$
Macroalgae	$5.3\ 10^{-4}$	$5.3\ 10^{-5}$	$1.6\ 10^{-4}$
Mammal	2.3 10-2	$2.3\ 10^{-3}$	$7.0\ 10^{-3}$
Mollusc - bivalve	$6.3\ 10^{-4}$	$6.3\ 10^{-5}$	$1.9\ 10^{-4}$
Pelagic fish	$5.8\ 10^{-4}$	$5.8\ 10^{-5}$	$1.7\ 10^{-4}$
Phytoplankton	$2.9\ 10^{-4}$	$2.9\ 10^{-5}$	$8.8\ 10^{-5}$
Polychaete worm	$2.8\ 10^{-3}$	$2.8\ 10^{-4}$	$8.5\ 10^{-4}$
Reptile	$8.4\ 10^{-4}$	$8.4\ 10^{-5}$	$2.5\ 10^{-4}$
Sea anemones & True coral	$6.9\ 10^{-4}$	$6.9\ 10^{-5}$	$2.1\ 10^{-4}$
Vascular plant	$5.4\ 10^{-4}$	$5.4\ 10^{-5}$	$1.6\ 10^{-4}$
Zooplankton	$2.7\ 10^{-3}$	$2.7\ 10^{-4}$	$8.1\ 10^{-4}$

Note: * Calculated using a screening value of 10 µGy h^{-1} for aquatic organisms.

^Calculated by applying an uncertainty factor of 3 to the expected risk coefficient.

H4.3 Direct Radiation Exposures

Direct radiation dose rate from all buildings on site at 50 m from all buildings is calculated to be 3.3 nGy h^{-1} for all identified static sources. This is far below the 10 µGy h^{-1} screening level for terrestrial organisms.

Appendix I: Assessment of direct radiation

I1 Introduction

Dose rates have been calculated by GNSL (General Nuclear System Ltd., 2020a) at the required receptor locations for each of the buildings of interest (CNPDC, 2019). Given that the precise layout of the site is not available a generalised and bounding approach has been adopted to assess the dose to the public.

I2 Methodology and Input Data

To assess dose to the public a bounding assumption that the member of the public is exposed to the radiation from all buildings at the same distance. Exposures at both 100 m and 300 m are assessed using the following formula.

Equation 7

$$Direct\ Dose = D_{rs} \times [(S_{fo} \times T_{fo)} + (S_{fi} \times T_{fi})]$$

Where:

Direct Dose = Dose to the member of the public (µSv y^{-1})

D_{rs} = External dose rate from direct radiation (µSv y^{-1})

S_{fo} = Shielding factor for outdoors (1)

S_{fi} = Shielding factor for indoors (0.1)

T_{fo} = Time Spend Outdoors (as a factor of 8760 hours)

T_{fi} = Time spent indoors (as a factor of 8760 hours)

Table I 1 presents the factors used for each age group assessed.

Table I 1: Table of values used to calculate dose to members of the public

Age	S_{fo}	S_{fi}	T_{fo}	T_{fi}
Adult	1.0	0.1	0.5	0.5
Child	1.0	0.1	0.2	0.8
Infant	1.0	0.1	0.1	0.9

Dose rates were calculated for various elevations, with peak dose rates at 1 m, 10 m or 20 m elevation depending on the building (and location of the sources of radiation within that building). For consistency, dose rates at 1 m elevation have been used to calculate public dose from direct radiation. Table I 2 presents the sum of all dose rates from buildings on the UK HPR1000 site for distances of 100 and 300 m.

Table I 2: Sum of all dose rates from buildings (µSv h-1) at distances of 100 m and 300 m from the UK HPR1000 site

Elevation/ m	100 m Distance	300 m Distance
1.0	$1.7\ 10^{-3}$	$9.1\ 10^{-5}$

I3 Radiation Doses

Using the Methodology described in Appendix I2 the doses to members of the public have been calculated and are presented in Table I 3.

Table I 3: Dose (in µSv y-1) due to direct radiation from buildings on the UK HPR1000 site to resident families for 100 m or 300 m distances

Age	100 m Distance	300 m Distance
Adult	8.0	0.44
Child	4.1	0.22
Infant	2.8	0.15

I4 Discussion

Dose to members of the public from direct radiation is higher at a distance of 100 m from the site than at 300 m from the site, which is expected. The difference between the doses to each age group is due to the different amount of time spent indoors and outdoors. Total dose to the public includes doses via inhalation and ingestion of contaminated foodstuffs.

I5 Exploring sensitivity to model assumptions

Assessment of public dose assumed that the representative families (local resident Farmer and Angler) lived 300 m from the stack. To confirm that direct radiation dose does not significantly change the assessed dose should the resident families live closer to the site a sensitivity study on the distance of the resident families has been performed.

Table I 4 and Table I 5 present the total doses from the estimated atmospheric release (excluding ingestion) as well as the direct radiation doses from buildings on the UK HPR1000 site for families living at 100 m and 300 m from the discharge point respectively. Dose from ingestion is assumed to be the same in both cases as the location of food sources (terrestrial and marine) won't change based on where the resident families are living.

Table I 4: Dose comparison between the doses (in µSv y-1) from the atmospheric discharges of a single UK HPR1000 and direct radiation to resident families living 100 m from the site

Age	Atmospheric Discharges	Direct Radiation	Total
Adult	0.79	8.0	8.8
Child	0.61	4.1	4.7
Infant	0.49	2.8	3.2

Table I 5: Dose comparison between the doses (in µSv y-1) from the atmospheric discharges of a single UK HPR1000 and direct radiation to resident families living 300 m from the site

Age	Atmospheric Discharges	Direct Radiation	Total
Adult	1.9	0.44	2.3
Child	1.5	0.22	1.7
Infant	1.2	0.15	1.4

It is clear from the above assessments that the direct radiation dose rate at 100 m is significantly higher than most other pathways. It is unlikely that a member of public would live as close as 100 m from each of the buildings in the reactor site.

Doses from atmospheric releases to the local resident family living near the site have been shown to be greatest at 300 m from the stack. As such, it has been assumed that the resident family lives 300 m from the main release point to atmosphere. Therefore direct radiation doses at 300 m have been used in the assessment of doses to this group for consistency.

The direct radiation assessment suitably bounds consideration of resident families' at greater distances from the UK HPR1000 site.

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