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## **Technical Advice to inform proposed Regulatory Justification decisions on new nuclear power stations**

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IDM68-2009.11

November 2009

# decision?



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### Executive Summary

The purpose of Regulatory Justification is to ensure that a new Class or Type of Practice resulting in exposure to ionising radiation is justified in advance of being first adopted or first approved by its economic, social or other benefits in relation to the health detriment it may cause.

A Consultation has taken place on the Nuclear Industry Association's (NIA) Application for the Regulatory Justification of four reactor designs, namely the AP1000 reactor designed by Westinghouse, the EPR designed by Areva, GE-Hitachi's ESBWR and the ACR1000 reactor from AECL. These four designs remain under consideration for Regulatory Justification and are therefore addressed as part of this technical review.

A previous study by IDM-NNL published alongside the consultation on the NIA's Application examined the benefit and detriment attributes of the range of technology which could be used to generate electricity by nuclear fission. It concluded that from a consideration of technical characteristics, there was likely to be little variation between the detriment/benefit relationship across a wide range of technologies, and found no technical reason to recommend more than one Class or Type of Practice. However, following the consultation, the Justifying Authority concluded that it would not be right to assess such a broad class or type of practice, and the process is therefore proceeding on the basis of four Classes or Types of Practice based on the four individual designs.

This paper does not comment on the legal or regulatory position of the NIA Application, but seeks to examine the benefits and detriments of nuclear power generation in general, and of the four designs in particular, from a technical standpoint, taking into account issues raised by some respondents to the consultation on the NIA's application. We believe that the relevant commentary and arguments are adequately referenced, but the conclusions reached are those of the authors.

Though the previous study by IDM-NNL had concluded that the benefit-detriment relationship was unlikely to vary greatly over the four reactor types, some consultation responses pointed to differences in several aspects of the design, operation and fuel cycle of the applicant reactors and raised issues about the numbers and capacity of the new nuclear reactors actually installed. IDM-NNL was commissioned to further examine the differences between existing reactors and the four applicant designs and to address specific issues raised in the consultation.

In assessing the benefits and detriments of the generation of electricity by nuclear fission, there is a strong, though not universal, consensus on the International Commission on Radiological Protection's methodology for calculating doses to people from radioactive discharges and the associated generalised risk factors of

0.05 per Sievert<sup>1</sup> for fatal radiation-induced cancers and 0.01 per Sv for hereditary disease. These are commonly added to give a total risk factor of 0.06 per Sv.

The accepted method of regulating risks from nuclear operations is by using dose constraints with single source and site public dose constraints set at 0.3mSv/y and 0.5mSv/y respectively. The NIA's application confirms that the four reactor designs could operate within a critical group dose<sup>2</sup> to the public of 0.15mSv per year, which would equate to a total individual risk of fatal cancer or hereditary disease of about 1 in 100,000 ( $10^{-5}$ ) per year. Examination of the doses from the operation of Sizewell B, which are likely to be similar to the four applicant reactors, indicate a maximum critical group dose of 15 $\mu$ Sv/y, which is many times lower than the constraints required by regulation.

Radioactive discharges disperse into the environment, and can then give very small doses to large numbers of people over significant periods of time. The summation of these doses is termed 'collective dose' which has been used to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with these doses. The use of collective dose has been reviewed by ICRP and the UK regulators, who have concluded that such calculations are not appropriate in relation to radiological protection. However, such calculations can be undertaken and are referenced in the public domain. The authors have reproduced a worked example on collective dose from spent fuel reprocessing activities at Sellafield. While involving much higher discharges than are predicted for a programme of new nuclear power stations in the UK, it demonstrates that although significant numbers of statistical fatalities can be calculated, the large majority are associated with individual risk levels of the order of one in a trillion ( $10^{-12}$ ) per annum. The average doses to UK, EU and world populations are low enough that most if not all of them could be considered trivial under current regulatory guidance.

Several respondents to the consultation commented that the assessment of the benefits and detriments of a Class or Type of Practice definition should reflect the full extent of the fuel cycle, with particular reference to the mining and milling of uranium. Although the authors understand that the approach taken by the Government is that a Regulatory Justification decision takes account only of activities in the UK, this technical advice reviewed the radiological consequences of the entire fuel cycle for nuclear power generation using current reactor designs, and illustrated that the dose and detriment from the operation of a nuclear reactor is a relatively small part of the overall detriment - around 4% in the example used. Whilst over 90% of the radiological detriment is associated with uranium mining and milling, the major uranium suppliers to the UK, for example Australia and Canada, have very similar regulatory regimes to the UK, and apply the same radiological protection principles and dose limits.

This technical advice also examined the fuel cycle stages of each of the four reactors in comparison to previous and existing UK reactor designs: Magnox, AGR, and Sizewell B. The key findings are:

- Uranium usage: Magnox reactors have around twice the uranium usage compared to other reactors, with current PWR designs (e.g. Sizewell B) using slightly less uranium than AGR. The applicant reactors show further slight reductions, which would be expected to be able to be matched by further optimisation of fuel use in Sizewell B.
- Enrichment: Magnox has essentially no enrichment needs, existing AGR reactors, current PWRs and projected new build LWRs have very similar enrichment demand, while ACR uses lower enrichment fuel and has enrichment needs around 30% less than the LWRs.
- Fuel requirements: the amount of fuel required is approximately proportional to the fuel burnup<sup>3</sup>. Magnox requires by far the most fuel with LWRs (Sizewell B, AP1000, EPR, ESBWR) requiring the

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<sup>1</sup> Sievert (Sv) a unit of radiation dose – 1Sv = 1000 millisievert (mSv) = 1,000,000 microsieverts ( $\mu$ Sv)

<sup>2</sup> The group of members of the public who are representative of people receiving the highest doses due to where they live and their habits.

<sup>3</sup> Burnup is the heat output per tonne of uranium in the fuel

lowest amount followed by AGR and ACR. The burnup achieved is a feature of the fuel rather than the reactor design, so Sizewell B fuel could be expected to achieve similar burnup to that predicted for AP1000 and EPR.

- Radiotoxicity: the relative overall toxicity of spent fuel can be assessed using the concept of Ingested Toxic Potential. This is the volume of water required to dilute a given amount of radioactive material to a concentration that would be safe for people to drink if a population were to use the mixture as its sole source of water. The radiotoxicity of spent fuel from a given amount of electrical generation is within a factor of two for all existing and applicant reactors after 50 year cooling time. Current PWRs and all four potential new build reactor designs are also well within a factor of two after cooling for 10,000 years.
- Heat output of spent fuel: the total heat output of fuel is roughly proportional to the total amount of power produced, so the heat output of fuel for a given amount of generation would be expected to be fairly constant. Though ACR has a higher fuel mass per GW(e)y, it has a slightly lower heat output overall, with very small differences between current PWRs and projected new build LWRs (AP1000, EPR, ACR1000).
- Spent fuel storage and disposal: while the radiotoxicity and heat output for any of the four reactor designs will be very similar, and directly proportional to the overall amount of power generated by the programme, the amount of fuel used will vary by around a factor of 3. Any difference in geological disposal volume will depend on the trade-off between heat output and packaged fuel volume for any given repository design. All fuels from the applicant reactors use zirconium alloy (Zircaloy) as their cladding material, which is extremely resistant to corrosion in water, and also in air at moderate temperatures. This has been demonstrated by the storage of many thousands of tonnes of spent fuel over decades, with some currently stored fuel dating from the 1960s.

It is estimated that the overall power output from new reactors would be twice that of previous UK nuclear power stations when normalised to the same installed capacity. While it should be noted that these preliminary calculations were made using assumed discharges and therefore do not take account of the range of possible locations and sites for new nuclear power stations, the Health Protection Agency have agreed that even if 20 stations equivalent to Sizewell B were built (and met the current regulatory constraints on doses to critical groups), then the annual per caput dose to the UK population would be at the microsievert (uSv) level - a thousand times less than the current annual dose limit for members of the public of 1 millisievert (mSv) and therefore would be of low concern.

One of the major perceived benefits of nuclear energy production is the reduced amount of carbon which would be emitted in comparison with electricity generation using fossil fuels. The carbon emissions associated with the construction of nuclear power stations, provision of their fuel and subsequent decommissioning and waste management mean that nuclear power is not wholly "carbon free". However, using a minimum carbon saving for nuclear generation of 363gCO<sub>2</sub>/kWh with respect to gas, the average annual output of Sizewell B (9,023.25 GWh) translates to a carbon benefit of around 3.275 million tonnes of CO<sub>2</sub> per annum.

If this is assessed using the UK Low Carbon Transition Plan 'traded' carbon values ranging from £25 (range £14 - £31) in 2020, via £70 (range £35 - £105) in 2030, to £200 (range £100 - £300) for 2050, the corresponding carbon reduction values range from £46 - £983 million.

This advice also discusses methodologies which can allow the health detriment of radioactive discharges to be assessed in monetary terms. Such valuations are inevitably contentious – in that the economic valuation of human life, and particularly its discounting with time, is an emotive subject. The methods rely on financial valuations of human life or life expectancy reduction based either on a valuation of economic output lost, or on how much people are willing to pay to prevent such life reduction. Using different

methodologies which have been applied in the UK nuclear sector, a range of valuations of between £7,100<sup>4</sup> and £807,000<sup>5</sup> per annum have been assessed for the annual detriment from the operation of Sizewell B. When it is considered that all these methodologies rely on “*the aggregation of very low individual doses over extended time periods*”, then it is clear that any credible valuation of the radiological health detriment from the operation of Sizewell B is likely to be very much lower than the valuation of the carbon benefit it provides when replacing electricity generation which would otherwise come from fossil fuels (gas or coal).

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<sup>4</sup> ExternE YOLL not truncated at 3% discount, 10% discounting gives a further reduction to £370

<sup>5</sup> ExternE VOSL not truncated, not discounted

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## 1. Introduction

The purpose of Regulatory Justification is to ensure that a new Class or Type of Practice resulting in exposure to ionising radiation is justified in advance of being first adopted or first approved by its economic, social or other benefits in relation to the health detriment it may cause.

A Consultation [Ref 1] has taken place on the Nuclear Industry Association's (NIA) Application for the Regulatory Justification of four reactor designs, namely the AP1000 reactor designed by Westinghouse, the EPR designed by Areva, GE-Hitachi's ESBWR and the ACR1000 reactor from AECL. These designs were also submitted to the Regulators' Generic Design Assessment (GDA) process, and Stage 1 of this assessment found no shortfalls in any designs which would, at that stage, rule out their eventual construction on licensed sites in the UK. AECL withdrew the ACR1000 from the process on 4 April 2008 and GE-Hitachi subsequently suspended its involvement on 11 September 2008. Regulators are now undertaking a detailed assessment of the two remaining designs, which is expected to conclude in June 2011.

All four designs remain under consideration for Regulatory Justification and are therefore addressed as part of this technical review.

A previous study by IDM-NNL [Ref 2] published alongside the consultation on the NIA's Application [Ref 1] examined the benefit and detriment attributes of the range of technology which could be used to generate electricity by nuclear fission. It concluded that from a consideration of technical characteristics, there was likely to be little variation between the detriment/benefit relationship across a wide range of technologies, and found no technical reason to recommend more than one Class or Type of Practice. After extensive analysis, the study gave the view that:

*“Logically, an increase in the number of CTPs should reflect a perception that the benefit/detriment relationship (using the same benefit/detriment parameters) of one reactor type or group of reactor types is materially different at the level required for Justification. This should lead to a consideration of how a variation in any given parameter would affect the Justification ‘score’.*

*Given the fact that all four reactor designs submitted for potential deployment in the UK have been subject to several decades of development by their respective vendors and are considered fit for optimised deployment in the same competitive world marketplace, it would not be surprising if the benefits and detriments associated with the competing designs were broadly similar, at least when viewed at the high level of scrutiny appropriate to Justification. If this were judged to be so, it would point to the high-level CTP I definition based on thermal fission, light or heavy water moderated, light water cooled reactors”.*

However, following the consultation, the Justifying Authority concluded that:

*Where a class or type of practice covers multiple designs, Justification is of the class or type of practice, not of individual reactor designs. This means that in the case of such a class or type of practice the Justifying Authority might need to identify relevant information on all the designs which fall within it, and their benefits and detriments. Accordingly in the event that the class or type of practice was defined more broadly so that it encompassed designs other than the four designs identified in the NIA application, then it*

*is likely that the Justifying Authority would need to assess information in relation to designs other than those referred to in the NIA application. Such a broad class or type of practice would differ quite significantly from that contained in the NIA application and would be likely to require the Justifying Authority to acquire significant further information. The Government therefore concluded that it would not be right to assess such a broad class or type of practice*<sup>6</sup>.

The Regulatory Justification process is therefore proceeding on the basis of four Classes or Types of Practice based on the four individual designs. This paper does not comment on the legal or regulatory position of the NIA Application, but seeks to examine the benefits and detriments of nuclear power generation in general, and of the four designs in particular, from a technical standpoint, taking into account issues raised by some respondents to the consultation on the NIA's application.

The benefit achieved by reducing carbon emissions will be offset by the carbon emissions involved in constructing the four reactor designs, their fuel cycle, and their decommissioning and waste management. The IDM>NNL Study [Ref 2] concluded that the benefit-detriment relationship was unlikely to vary greatly over the four reactor types. However, some consultation responses pointed to differences in several aspects of the design, operation and fuel cycle of the applicant reactors, and raised issues about the number and capacity of new nuclear reactors actually installed, implying that the relationship between benefits and detriments would be influenced by technical variations between the four reactor designs, and the number of them which were installed.

IDM>NNL was commissioned to further examine the differences between existing reactors and the four applicant designs. To address the specific issues raised by respondents to the consultation, IDM>NNL needed to review other methods of assessing health detriment from radiological discharges, together with the overall detriment from the nuclear fuel cycle. This could then be compared with the likely benefit in terms of the reduced amounts of carbon emitted by nuclear generation using the four reactor designs in comparison to that which would be emitted by fossil fuel generation. Although the Justifying Authority is not bound to consider overseas practices, an examination of the fuel cycle does provide a more complete background to the assessment of benefits and detriments.

## **2. New Build Reactor Regulatory Justification and the Nuclear Life Cycle**

### **2.1 Assessment and Regulation of Health Risks from Nuclear Operations**

The benefits and detriments of nuclear power are subjects which often promote a polarised debate. While there are varied and frequently dissenting views, there is a strong consensus among Governments, health, environmental and safety regulators and inter-government organisations (for example WHO, IAEA, OECD, NEA) on the benefits and detriments of the various stages and processes that make up electricity generation by nuclear fission using uranium fuel in light or heavy water moderated, light water cooled reactors.

In particular, the methodology for calculating doses to people from radioactive discharges is essentially the same worldwide, and though there is still controversy on the relationship between radiological dose to humans and the risk incurred, there is a consensus, shared by the large majority of scientific opinion, around the values derived by the International Commission on Radiological Protection (ICRP). In the UK this consensus is assessed and interpreted by the Radiation Protection Division of the Health Protection Agency (HPA-RPD formerly NRPB).

In classical radiation protection research the risk increases of cancer and other ailments seen in groups which have suffered high doses are used to predict the risks at lower doses by extrapolating both dose and

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<sup>6</sup> Ref 1, para 4.5, page 20

risk back to zero. This assumes that no matter how small the dose is it will have a corresponding risk. This is termed the Linear No Threshold assumption.

HPA and ICRP define a dose/risk regime [Ref 3] which is described below:

*“Assuming linearity between dose and effect, at the levels of dose typical of routine discharges of radionuclides, the relationships between dose and effect given by ICRP in Publication 60 can be used to estimate the incidence of particular health effects. ICRP have recommended a risk factor of 0.05 per Sv<sup>7</sup> for fatal radiation-induced cancers for radiation protection purposes. This value is appropriate for the general population, assuming a mix of ages. It is calculated as an average value for five populations (Japan, UK, USA, Puerto Rico and China) based on transferring both absolute and relative risks across populations.”*

Using this risk factor, a dose of 1mSv per year is equivalent to an additional risk of fatal cancer of one in twenty thousand (0.005%)<sup>2</sup> per year.

*“ICRP have also recommended a risk factor for hereditary disorders for exposure of the whole population of 0.01 per Sv. This is based on a risk following exposure of either parent of hereditary disorders of 0.024 per Sv expressed over all generations. However, the genetically significant exposure in a population and hence the risk, will be less than this because a proportion of the population are older than child bearing age. If the mean age of child bearing is 30 years and average life expectancy is 75 years then the probability of genetic harm resulting from exposure of the entire populations is  $30/75 \times 0.024 = 0.01$ .”*

The two risk factors, 0.05 per Sv for fatal radiation-induced cancers and 0.01 per Sv for hereditary disease, are commonly added to give a total risk factor of 0.06 per Sv.

Radioactive discharges disperse into the environment, and can then give very small doses to large numbers of people over significant periods of time. The summation of these doses is termed 'collective dose', and in the past these collective doses have been used to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with these doses.

The ICRP has examined the appropriateness of the use of collective dose in radiological protection, and the Commission's latest Guidance [Ref 4] states that:

*“Because of this uncertainty on health effects at low doses, the Commission judges that it is not appropriate, for the purposes of public health planning, to calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long periods of time”*

The current UK regulatory guidance [Ref 5], concurring with ICRP's Guidance, recommends the use of the highest average<sup>8</sup> individual doses ('per caput' doses) for any given population group over any given time period rather than using collective dose. The Guidance was underpinned by work carried out by Smith et al for the European Commission on disaggregation of collective doses [Ref 6]. This examined the distribution of per caput doses over different populations and timescales, using radioactive discharge data from the reprocessing plants at Sellafield in the UK and Cap La Hague in France.

The UK guidance concludes:

*“In this respect, calculated average annual individual doses for a population group in the nanosievert (nSv/y) range or below should be ignored in the decision making process as the associated risks are minuscule and the contribution to total doses to individuals will be insignificant. Higher annual doses,*

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<sup>7</sup> 0.05/Sv = 5%/Sv = 0.005%/mSv

<sup>8</sup> The highest annual total collective dose to the UK population from the discharge divided by the UK population.

*up to say a few microsievert ( $\mu\text{Sv}/\text{y}$ ) can be considered trivial but may require some consideration particularly if at the higher end of the range. Calculated annual average individual doses in excess of these values should prompt careful consideration of the discharge options being considered.”*

This is in line with HSE advice on individual risk [Ref 7], which defines a Broadly Acceptable risk as:

*“HSE believes that an individual risk of death of one in a million per annum for both workers and the public corresponds to a very low level of risk and should be used as a guideline for the boundary between the broadly acceptable and tolerable regions.”*

UK environmental regulation also ensures that individual risks will be maintained at a low level by specifying the maximum dose that may be delivered to the group of the public most affected by the discharges of any nuclear operation or site. The regulations stipulate that for any nuclear site this ‘critical group’ [Ref 8] must receive a dose no higher than 0.5mSv in a year<sup>9</sup>, within a Public Dose Limit of 1mSv in a year. Single facilities and new nuclear installations are limited to a dose constraint of 0.3mSv in a year. Using the accepted dose-risk factor of 0.06 per Sv<sup>10</sup> (see Section 2.1) gives a risk of death to the critical group at the site constraint for multiple facilities of  $3 \times 10^{-5}$  per annum with a risk derived from the public dose limit of  $6 \times 10^{-5}$ .

The HPA [Ref 9] has recently recommended a dose constraint for members of the public of 0.15 mSv a year for a single new source. This would give a total individual risk of fatal cancer or hereditary disease of some 1 in 100,000 ( $10^{-5}$ ) per year.

The regulators thus ensure that both individual and average population doses are assessed, and the regulatory process of optimisation is used to keep doses as low as reasonably practicable (ALARP).

## **2.2. Applicability of Collective Dose Calculations**

As discussed above, using dose constraints is the accepted way of regulating risk from nuclear operations. However, the concept of collective dose has often been applied by integrating doses over the large populations (for example the world) and over long, and sometimes infinite, timescales. This can lead to high values for the collective dose, which can in turn be used to predict high numbers of statistical fatalities. While the ICRP and UK regulators agree that this is not appropriate, (see Section 2.1), the absence of such calculations was commented on by respondents to the consultation on the NIA’s application. It is therefore instructive to examine such calculations to see if they can be put into perspective to further inform the detriment/benefit relationship for new nuclear reactors.

An extensive UK stakeholder study [Ref 10] carried out just such a worked example. This was performed before the development of the per caput concept [Refs 5, 6], and sought to answer the question ‘*for a collective dose of, say, 100 man sieverts (which, using the Linear No Threshold assumption, will give a predicted detriment of 6 fatalities), what annual doses are individuals actually receiving?*’. This aimed to help to provide a context for the radiological detriments from nuclear operations in comparison with their socio-economic benefits. The work, by Westlakes Research Institute [Ref 11], provided an indicative disaggregation into individual dose bands of the collective dose due to potential future radioactive discharges from the nuclear fuel reprocessing site at Sellafield. The example postulated an extensive programme of spent fuel reprocessing at Sellafield with associated discharges being very much higher than those which would be predicted for a programme of new nuclear power stations in the UK.

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<sup>9</sup> This ‘site constraint’ applies to the aggregate exposure from a number of sources at a single location.

<sup>10</sup> Note that this factor includes an allowance for genetic effects and non-fatal cancers, when detriment is restricted to individual fatality risk a factor of 0.05 per Sv is used (see Section 2.1)

The Westlakes study concluded that the collective doses from radioactive discharges to local, regional and world populations are dominated by very small doses of radiation over very long times to large populations.

The initial conclusion reached was that the bulk of the collective dose was delivered at very low individual doses, as illustrated in Table 1 (Reproduced from Table 8 of Reference 11).

Individual dose range ( $\mu\text{Sv y}^{-1}$ )	Collective dose (personSv)	Percentage of total
<0.015	3500	95.4
0.015-0.15	120	3.3
0.15-1.5	17	0.5
1.5-10	20	0.5
>10	12	0.3
World Total	3700	100

**Table 1. Breakdown of 500 year collective dose for scenario SF3, broken down into individual effective dose bands (Table 8 of Ref 11)**

Using the accepted dose-risk factor of 0.06 per Sv (total of fatal radiation-induced cancer plus hereditary disease) indicates that 95.4% of the detriment is delivered at risks to the individual of less than 1 in 1,100 million per annum. The study was also able to conclude that ‘for aerial discharges, collective dose at individual effective dose rates exceeding  $0.015 \mu\text{Sv y}^{-1}$  is only incurred within the UK, and at effective dose rates exceeding  $1.5 \mu\text{Sv y}^{-1}$  is only incurred within about 20 km of Sellafield. The geographical distribution of collective dose from liquid discharges is harder to assess, but it appears that collective dose incurred outside the UK is at levels of individual effective dose rate below  $1.5 \mu\text{Sv y}^{-1}$ , with the majority being incurred at rates of  $0.002 \mu\text{Sv y}^{-1}$  or less’<sup>11</sup>.

Further work enabled an indicative breakdown of dose into dose bands for various times and geographical areas [Ref 10, Appendix 10], and the results are summarised below. The data has also been re-examined here to calculate an average dose for each member of the population considered over the time for which integration was performed. This is a very crude ‘average’ but does show the order of magnitude of the doses that contribute to the collective dose. Using the total risk factor of 0.06 per Sv, these doses can be used to calculate the corresponding risk levels for these average individual doses, which are given as the average risk of fatality per year.

Population examined	Integration time	Collective Dose (man Sieverts)	Average per caput dose (microsieverts per year, $\mu\text{Sv/a}$ )	Statistical fatalities calculated from Collective Dose.	Risk level corresponding to dose (annual risk of fatality)
Minimum $10\mu\text{Sv/year}$ individual dose (2)	500 years, infinity	12	>10(1)	0.72	$6.0 \times 10^{-7}$
UK (2002 Pop 59M)	500 years	120	0.0041	7.2	$2.4 \times 10^{-12}$
EU (2002 Pop 379M)	500 years	520	0.0027	31.2	$1.6 \times 10^{-12}$
World (2002 Pop 6.2B)	500 years	3,700	0.0011	222	$5.9 \times 10^{-13}$
UK	infinity	330	-	19.8	-
EU	infinity	1,900	-	114	-
World	infinity	29,000	-	1,740	-

1. Note that all UK, EU and World doses are  $<10\mu\text{Sv/y}$  beyond 500 years, so the figures over an infinite timescale will be unchanged from those at 500 years.

2. The risk of ‘one in a million per annum’ equates to an annual dose of around 17 microsieverts ( $0.017\text{mSv}$ ).

<sup>11</sup> Using the 0.06 per Sv dose-risk factor, a dose of  $0.002 \mu\text{Sv y}^{-1}$  equates to an annual risk of around one in 8 billion.

## **Table 2. Doses and Risks, Spent Fuel Example**

Table 2 shows that if the total collective dose for any given population is converted into statistical fatalities through a Linear No Threshold assumption, then the calculated number of statistical fatalities over the long timescales and large populations can appear significant. Such figures have been historically quoted as providing evidence of significant health detriment from nuclear power and the nuclear fuel cycle. However, Table 2 also shows that in such cases the average member of any population incurs an infinitesimally small dose and a correspondingly small risk.

### **2.3. Doses and Detriment within the UK Regulatory Regime**

The overall understanding to be gained from examining the 'Spent Fuel Example' doses against the current regulatory regime is:

- The maximum doses predicted to the UK population are low, and only a very small proportion is likely to be delivered at individual risk levels which can be judged at anything other than 'broadly acceptable' under safety regulatory risk limits
- The average doses to UK, EU and world populations are low enough that most if not all of them could be considered trivial under current regulatory guidance
- The use of long integration times over large populations can give rise to a large calculated number of statistical fatalities, but these will be overwhelmingly derived from doses which, under the current Regulatory Guidance [Ref 5] "*should be ignored in the decision making process*" or at most "*can be considered trivial*".

This analysis would support the logic of the view expressed in the NIA Application [Ref 12], which argues that meeting regulatory limits and constraints ensures that health detriments of a Class or Type of Practice will be small. It states that:

*"On the basis that UK regulation is framed so as to reduce potential radiological health impacts to the public to a low level and that regulatory constraints can be easily met, this therefore substantiates the argument that any radiological health detriment from the proposed class of practice will be very small".*

### **2.4. Doses from Reactor Operation**

The NIA application quotes radiological dose data from Sizewell B operations, and references a recent Environment Agency radiological assessment [Ref 13] as part of the Discharge Authorisation Review 2005/6, which, together with "*evidence prepared by the National Radiological Protection Board (NRPB) at the request of the Hinkley Point C Public Inquiry Inspector provides a helpful illustration of the level of radiation dose resulting from a modern water moderated and cooled nuclear reactor station meeting UK standards*"<sup>12</sup>.

In the Sizewell B assessment, at the authorised limits, *the critical group dose ..... was 15 µSv/y to local residents (infant), of which 5 µSv/y was from discharges and 10 µSv/y from direct radiation*. This is many times lower than the 0.3mSv/y and 0.5mSv/y single source and site public dose constraints required by regulation, and discussed in Section 2.1.

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<sup>12</sup> Reference 1, para 4.41, page 39

The assessment also derived collective doses per year of discharge for Sizewell B at the authorised limits<sup>13</sup>. These were summed over 500 years and vary greatly for different populations. A collective dose of 0.136 man Sv for the UK increased to 1.17 man Sv for Europe, and a dose to the world population of 9.8 man Sv.

Per caput doses were also derived<sup>14</sup>:

*“Average per caput doses are presented .... (truncated at 500 years). At proposed limits, the average per caput dose to the UK from Sizewell B was 2.4 nSv, those to Europe 1.7 nSv and to the World were less than 1 nSv.”*

The assessment confirmed that<sup>15</sup>:

*“The Health Protection Agency (formerly the National Radiological Protection Board) has stated that discharges giving rise to per caput doses of less than a few nanosieverts per year of discharge can be regarded as trivial”*

This stance has been reiterated by the HPA in their recent advice on Application of the 2007 Recommendations of the ICRP to the UK [Ref 9] and the NIA has also confirmed that the reactors in its application could operate within the dose constraint for members of the public of 0.15mSv a year as recommended by the HPA.

## **2.5. Fuel Cycle Doses, Risks and Detriments**

Several respondents to the consultation commented that the assessment of the benefits and detriments of a Class or Type of Practice definition should reflect the full extent of the fuel cycle, with particular reference to the mining and milling of uranium. Although the authors understand that the approach taken by the Government is that a Regulatory Justification decision takes account only of activities in the UK, this technical advice reviewed the radiological consequences of the entire fuel cycle for nuclear power generation using current reactor designs.

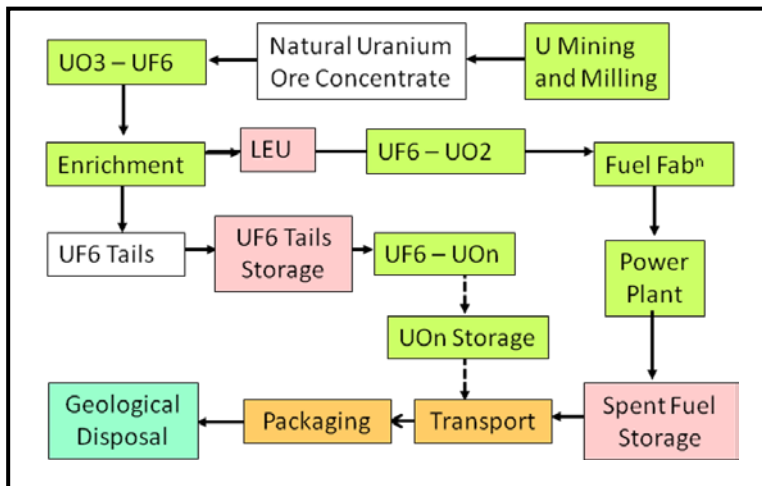
The four reactors named in the Application all use thermal fission, using low enriched uranium dioxide fuel contained in zirconium alloy cans and cooled with water. As spent fuel is considered to be stored and disposed rather than reprocessed, a simple ‘once through’ cycle is being envisaged, as seen in Figure 1 below.

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<sup>13</sup> Reference 11, Table A3.7

<sup>14</sup> Reference 11, para A3.12

<sup>15</sup> Reference 11, para A3.13



**Figure 1. Indicative once-through fuel cycle** (note: there are various proposals to convert tails  $UF_6$  to uranium oxide for storage and ultimate disposal – these may involve  $U_3O_8$  or  $UO_2$ , and  $UO_n$  is used here)

Discharges of radioactive substances can occur during all stages of such a fuel cycle, and the effect of these doses of radioactivity, and the consequent health detriment to the public, can be both estimated and measured. Such an analysis has been performed for Sizewell B and its fuel cycle [Ref 14]. The health detriments are expressed in terms of Years of Life Lost (a concept discussed more fully in Section 7) and are shown in Table 2. The dose has been integrated over 500 years, a time period which accords with regulatory advice [Ref 5] and the sum of small individual doses has been used in the valuation process. The purpose of Table 2 is to illustrate that the dose and detriment from the operation of a nuclear reactor is a relatively small part of the overall fuel cycle radiological health detriment, in this example around 4%.

	Damage - mECU/kWh using YOLL (0% discount)	% of fuel cycle
Mining and Milling	1.9	91.87
Conversion + Fuel Fabrication	0.0092	0.44
Enrichment	0.00000108	$5.2e^{-5}$
Power generation	0.079	3.82
Total Fuel Cycle	2.068201	100

**Table 2. Radiological dose detriment from a PWR fuel cycle**

Several respondents to the consultation were of the opinion that uranium mining and milling detriments represented a significant health detriment, and from the PWR fuel cycle assessment above, the radiological doses from mining and milling do constitute over 90% of the total. However, the major uranium suppliers to the UK, for example Australia and Canada, have very similar regulatory regimes to the UK, and apply the same radiological protection principles and dose limits.

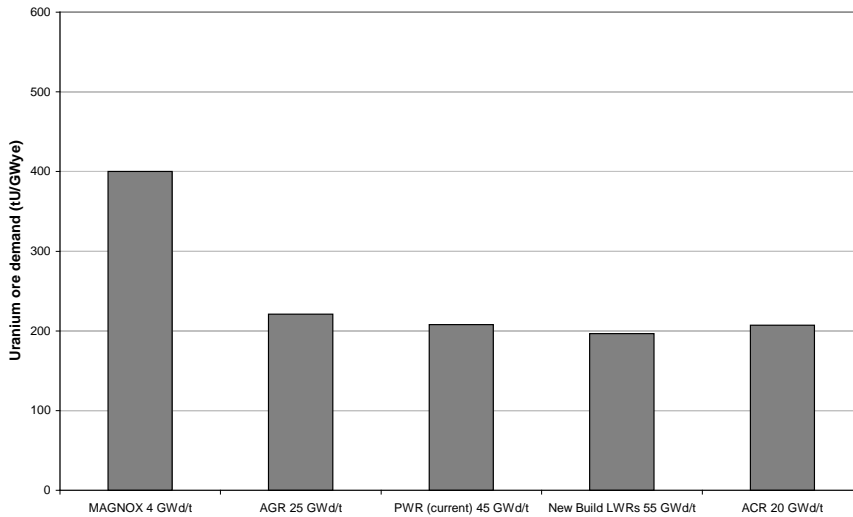
This overview highlights the relatively minor role of generation in the overall health detriments from the nuclear fuel cycle, and also clarifies that an examination of the whole fuel cycle will give a better context to the possible differences in the benefits and detriments of different reactor types and designs. The following section examines the fuel cycle stages for the applicant reactors in comparison to previous UK designs.

### 3. Fuel Cycle Comparisons of Reactor Designs

#### 3.1. Uranium Usage

The four applicant reactors use low enriched uranium dioxide fuel, and the enrichment process produces 'tails' of low  $^{235}\text{U}$  content which is retained for future use or eventual disposal. In contrast, the first generation of UK reactors, the Magnox stations, used natural uranium metal fuel. In view of the relative importance of uranium mining and milling to the overall health detriment of the fuel cycle (see Table 2), it is useful to examine the overall amount of uranium used to produce a given amount of electrical power.

In Figure 3, the amount of uranium required to produce 1 gigawatt-year of electrical power (GW(e)y)<sup>16</sup> is shown. Magnox reactors require around 400te of uranium to produce 1 GW(e)y, compared to values around half this figure for the second generation AGR reactors. Current PWR designs (similar to Sizewell B) use slightly less uranium than AGRs, and projections for new build LWR (AP1000, EPR and ESBWR) and ACR reactors show slight further reductions in uranium usage. It is anticipated that existing PWR reactors (including Sizewell B) will also be able to achieve similar reductions.

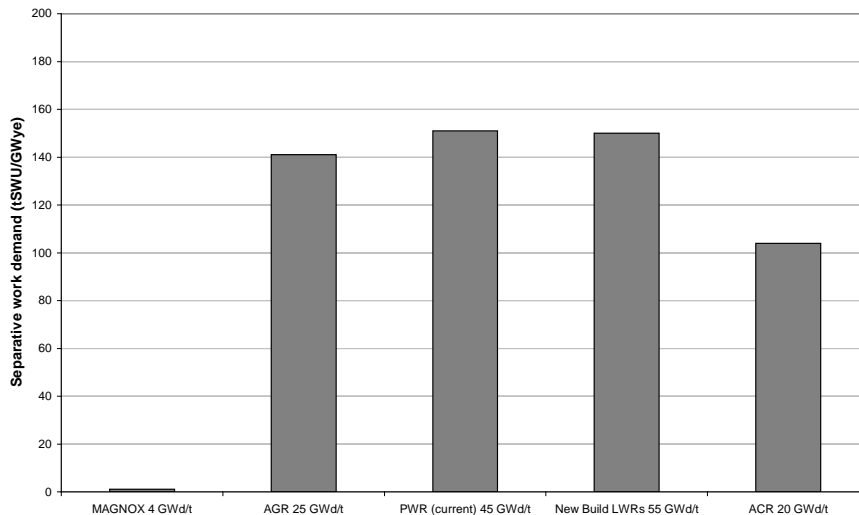


**Figure 3: Uranium ore demand for new and existing reactors (teU/ GW(e)y)**

#### 3.2. Enrichment

As seen in Table 2, uranium enrichment produces an extremely small fraction of the overall fuel cycle dose. Figure 4 below examines the enrichment requirements per GW(e)y of electrical output for existing and applicant designs.

<sup>16</sup> The amount of electrical power that would be produced by a 1 gigawatt (1000 megawatt) power station running continuously for 1 year



**Figure 4: Separative work demand for existing and applicant reactors (teSWU/ GW(e)y)**

While Magnox has essentially no enrichment needs (though in fact the two remaining Magnox stations are now using small amounts of very low enriched fuel<sup>17</sup>), existing AGR reactors, current PWRs and projected new build LWRs have very similar enrichment demands. ACR uses lower enrichment fuel and has enrichment needs around 30% less than the LWRs.

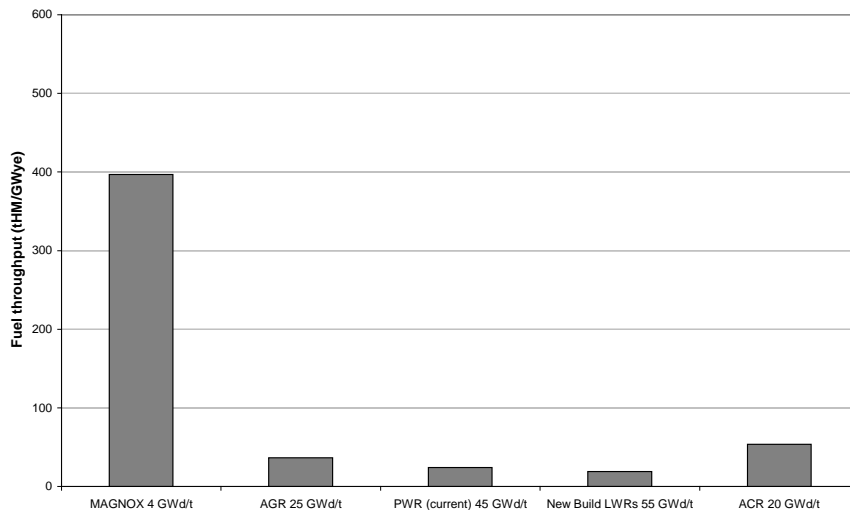
### 3.3. Fuel Requirements and Spent Fuel Properties

The amount of fuel required to generate a given amount of electrical power is proportional to the burnup of the fuel (the heat output per teU of fuel) and the thermal efficiency of the reactor (i.e. the percentage of the thermal output that is turned into electricity). As noted in the previous IDM-NNL Advice [Ref 2], the thermal efficiencies of the four applicant reactors are similar, so the amount of fuel required will be proportional to the burnup. This is illustrated in Table 3 and Figure 5, which show that Magnox requires by far the most fuel, with more modern designs requiring less fuel for the same electrical output. The fuel usage is indeed shown to be proportional to burnup, with the LWRs requiring the lowest amount of fuel followed by AGR and ACR.

	MAGNOX 4 GWd/t	AGR 25 GWd/t	PWR (current) 45 GWd/t	New Build LWRs 55 GWd/t	ACR 20 GWd/t
Burnup (GWd/t)	4	25	45	55	20
Fuel throughput (teHM/GWye)	396.7	36.5	23.9	19.0	53.7

**Table 3. Fuel requirement per GW(e)y (teHM/ GW(e)y)**

<sup>17</sup> Current enrichment for Magnox is <14teSW/GWye, but over the lifetime (most stations ran totally on natural uranium) the enrichment was much less.



**Figure 5: Fuel requirement per GW(e)y (teHM/ GW(e)y)**

The other main dependence in generating heat and then electricity from the thermal fission of uranium fuel, is that the heat developed is roughly proportional to the number of atoms being fissioned. This means that, in generating a given amount of heat, the fuel in the four applicant reactors will undergo very similar numbers of fissions. Spent fuel from new nuclear power stations will therefore contain similar amounts and types of radionuclides to those found in the spent fuel used to generate an equivalent amount of power in current designs of light water reactors (LWRs).

The steady rate of development of fuel technology is apparent from the steadily increasing discharge burnups of LWRs. The burnups have increased from about 30 GWd/t in the 1970s to the 50 GWd/t which are prevalent currently. High burnups are advantageous for utilities because they improve operational flexibility and give significant economic savings. An OECD-NEA report [Ref 15] has reviewed whether the trend towards increasing burnups will continue further. The study concluded that technically it may be beneficial to extend burnups to 70 GWd/t or more, but that some technological developments will be needed to achieve this. It is considered that future LWRs will aim to achieve mean discharge burnups ranging at least up to 65 GWd/t.

The increasing burn-ups being achieved by PWR reactors will mean that both new reactors and Sizewell B will be producing comparatively fewer spent fuel elements to be managed for a given amount of power generated. An individual element will have a higher heat output and external radiation dose rate beyond a period of about one month after discharge, compared with fuel elements discharged from PWRs at lower burnups.

As the total radioactive content of the spent fuel from the applicant reactors to generate a given amount of electricity will be similar, its total radiotoxicity and total heat output will also be similar. For example, though the radiotoxicity per tonne of spent ACR fuel would be expected to be less than that of a tonne of spent PWR fuel, the total radiotoxicity per GW(e)y of electrical generation would be expected to be comparable.

The radiotoxicity of the fuel is its ability to cause harm to people. In the UK, this is measured using the concept of Ingested Toxic Potential (ITP)<sup>18</sup>. ITP calculates the volume of water required to dilute a given amount of radioactive material to a concentration that would be safe for people to drink if a population were

<sup>18</sup> ITP is the basis of waste equivalence calculations for Intermediate Level Waste substitution, and these arrangements were consulted on by DTI in 2004. ITP is also the basis for calculation of hazard in the Prioritisation Procedure used by the Nuclear Decommissioning Authority.

to use the mixture as its sole source of water<sup>19</sup>. The methodology ‘normalises’ the different radioisotopes with respect to their potential dose impact to man. High ITP values indicate that a large volume of water is required to dilute the material to be safe for people to drink; conversely lower ITP values indicate that smaller volumes of water are sufficient to make the material safe to drink. ITP will reduce as the radioactivity decays. ITP forms the basis of the Nuclear Decommissioning Authority’s measure of Hazard Potential [Ref 16] (part of the NDA Prioritisation Procedure), and also the Integrated Toxic Potential methodology used to calculate the equivalence of substituted Intermediate Level Waste (ILW) for return to overseas reprocessing customers [Ref 17].

In Table 4, the ITP radiotoxicity of the five fuel types for the spent fuel produced in generating 1GW(e)-year is given at storage times of 50 years, and after disposal at 10,000 years.

	Radiotoxicity per GW(e)y generated by reactor type (m <sup>3</sup> )				
	Magnox	AGR	Current PWR	New Build LWR	ACR
Burnup	4GWd/t	25GWd/t	45GWd/t	55GWd/t	20GWd/t
Fuel throughput (teHM/GWye)	396.7	36.5	23.9	19.0	53.7
50 year cooling	2.2e12	1.5e12	2.4e12	2.3e12	1.5e12
10,000 year cooling	2.5e11	6.5e10	8.2e10	7.0e10	8.4e10

**Table 4. ITP Radiotoxicity per GW(e)y (m<sup>3</sup> water)**

This shows that the radiotoxicity of fuel per 1GW(e)y are within a factor of two for all reactors after 50 year cooling, and that current PWR and all four potential new build reactor designs are also well within a factor of two after 10,000 years. In terms of ITP radiotoxicity, which for materials on a typical nuclear site will span many orders of magnitude, these differences are unlikely to have any practical significance. The total heat output of fuel is also roughly proportional to the total amount of power produced, so again, the heat output of fuel for a given amount of generation would be expected to be fairly constant, as illustrated in Table 5.

	Magnox	AGR	Current PWR	New Build LWR	ACR
Burnup	4GWd/t	25GWd/t	45GWd/t	55GWd/t	20GWd/t
Fuel throughput (teHM/GWye)	396.7	36.5	23.9	19.0	53.7
Decay heat per GW(e) generated - 50 year cooling	18.8kW	12.8kW	19.7kW	19.6kW	14.1kW

**Table 5. Heat output per GW(e)y (kW – 50-year cooling)**

Thus though ACR has a higher fuel mass per GW(e)y, it has a slightly lower heat output overall. The figures also emphasise the very small difference between current PWRs and projected new build LWRs (AP1000, EPR, ACR1000) when viewed on a ‘per amount of electricity generated’ basis.

### 3.4. Spent Fuel Storage and Disposal

Respondents to the consultation on the NIA’s application expressed concerns about the volume, storage time and heat output of new build spent fuel and consequent impacts on the storage and disposal of radioactive waste in the UK. From the discussions in Section 3.3 above, it is clear that the radiotoxicity and

<sup>19</sup> The Procedure also includes methodologies to account for materials where the key hazard pathway is not ingestion

heat output for any of the four reactor designs will be very similar, and directly proportional to the overall amount of power generated by the programme. There will, however, be a difference in the amount of fuel used, covering a factor of around 3. Any difference in geological disposal volume will depend on the trade-off between heat output and packaged fuel volume for any given repository design.

NDA's Radioactive Waste Management Directorate has examined the impacts of the applicant designs on disposed waste volumes, and concludes that:

*"In the case of spent fuel, the dimensions of the underground disposal area are also influenced by the heat output from the wastes at the time of disposal. This is because each disposal container has to have sufficient separation from adjacent containers to ensure that the temperatures of components in the isolating engineered barrier system stay below levels at which the components' performance might be compromised. This consideration of heat output is strongly conditioned both by the length of time that the power station operator will hold the spent fuel in interim storage, allowing the radioactivity and associated heat generation to decrease, and by the thermal properties of the rocks at a GDF site. A smaller number of fuel elements would be used in the EPR or AP-1000 reactors to generate the same amount of electricity than in earlier designs of pressurised water reactors; however the heat output from each spent fuel element would be greater. Therefore the requirements for underground space for the disposal of spent fuel from the EPR or AP-1000 are thought likely to be broadly similar to those that would have been required for spent fuel used to generate an equivalent amount of electrical energy from an earlier design of pressurised water reactor" [Ref 18].*

The similarity of thermal output per GWe generated (as shown in Table 5), will mean that the requirements for cooling will be comparable across the four applicant designs while the amount of fuel may vary.

All fuels from the applicant reactors use zirconium alloy (Zircaloy) as their cladding material, which is extremely resistant to corrosion in water, and also in air at moderate temperatures. This has been demonstrated by the storage of many thousands of tonnes of spent fuel over decades, with some currently stored fuel dating from the 1960s<sup>20</sup>. However, when fuel is newly removed from the reactor and heat output is high, adequate water cooling must be provided. An accident occurred at the Paks nuclear power plant in Hungary in 2003 where inadequate cooling provision during a fuel cleaning operation caused fuel damage [Ref 19] but this is the only relevant example known.

#### **4. Effect of Programme Size**

The size of any projected programme of new build reactors in the UK can usefully be compared with the output from the past and existing nuclear power stations, normalised to the same installed capacity. This is done in Table 6 below.

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<sup>20</sup> Zircaloy fuel was irradiated in both BWRs and PWRs at least from the very early 1960s. The initial fuel from the first BWR, Dresden, is stored in dry casks on the reactor site. The first PWR fuel, from the Shippingport reactor, is stored at the Idaho Nuclear Technology Center (INTEC) in underground dry wells.

UK Reactor Programme	Installed Capacity (MWe)	Generation (GW(e)y)	Relative Output
Magnox	4690	114.0	
AGR	8380	183.7	
Sizewell B	1188	42.0	
Total Major Programmes	14,258	339.7	
Total Major Programmes (normalised to 10GWe)	10,000	237.8	1.00
Other (PFR, SGHWR, etc.)		2.2	
Total Current Programme		341.9	
Assumed 10GWe New Build		540.0	2.27

**Table 6. Electrical Output of Reactor Programmes**

This assumes currently licensed programmes for the existing reactors (i.e. ignores potential future life extensions) and for new build assumes a 60-year lifetime and a conservative 90% load factor.

All the applicant designs, in IDM-NNL's view, have been found to involve small and very similar detriments in the context of Regulatory Justification. The overall detriment of a programme, while being largely directly proportional to programme size and electricity generation, is unlikely to become large enough to materially affect Regulatory Justification. IDM-NNL discussed the effect of discharges from multiple new build reactors on dose to the UK population with the Health Protection Agency (HPA) in terms of the potential collective or population dose to the public based on current data associated with Sizewell B (which was likely to be representative of the operating regime of new nuclear power stations). While it should be noted that these preliminary calculations were made using assumed discharges and therefore do not take account of the range of possible locations and sites for new nuclear power stations, HPA agreed that even if 20 equivalent stations were built (and met the current regulatory constraints on doses to critical groups), the annual per caput dose to the UK population would be at the microsievert (uSv) level - a thousand times less than the current annual dose limit for members of the public of 1 millisievert (mSv) and therefore would be of low concern.

## 5. Carbon Benefits

As discussed in Section 1, one of the major perceived benefits of nuclear energy production is the reduced amount of carbon which would be emitted in comparison with electricity generation using fossil fuels. The carbon emissions associated with the construction of nuclear power stations, provision of their fuel and subsequent decommissioning and waste management mean that nuclear power is not wholly 'carbon free'. This has been discussed in previous Consultations, with the 2008 White Paper [Ref 20] concluding that:

*"We continue to believe that the range of figures presented in the consultation document – 7-22 gCO<sub>2</sub>/kWh emissions ...represents a prudent and conservative judgement which is fully in line with authoritative research published by the OECD and the IAEA. It is also broadly in line with analysis carried out by the World Energy Council (WEC) in 2004 which presented a range of CO<sub>2</sub> emissions of 5-40g kWh emissions for the nuclear lifecycle (with the highest figure being based on enrichment carried out entirely through the inefficient and increasingly obsolete diffusion method rather than the centrifuge process which is deployed at Capenhurst in the UK). The WEC's figures were endorsed by the Inter-Governmental Panel on Climate Change (IPCC)'s Working Group III in its Fourth Assessment Report of October 2007, which states that "Total lifecycle GHG (Green-House Gas) emissions are below 40 gCO<sub>2</sub>/kWh (10 gC-eq/kWh), similar to those for renewable energy sources."*

The comparable values for fossil fuels were 385 g/kWh for lifecycle CO<sub>2</sub> emissions from a gas-fired electricity power station, and 755 g/kWh for lifecycle CO<sub>2</sub> emissions from a coal-fired electricity power station [Ref 20]<sup>21</sup>. These values give a minimum carbon saving for nuclear generation of 363gCO<sub>2</sub>/kWh with respect to gas. Using the average annual output of Sizewell B of 9,023.25 GWh, this will translate to a carbon benefit of around 3.275 million tonnes of CO<sub>2</sub> per annum.

## 6. Valuation of Health Detriments

One respondent to the consultation pointed out that comparing benefits in Pounds Sterling (£) with the radiation doses measured in sieverts (Sv) is not a like for like comparison. The detriments to human health from radiation doses will certainly arise in very different forms, and over different timescales, to the benefits, for example, of reducing the adverse effects of climate change by carbon discharge reduction.

There are well-documented methodologies based on Cost Benefit Analysis (CBA) and Cost Effectiveness Analysis (CEA) which attempt to relate both carbon benefits and dose detriments to financial values. The different derivations of these metrics will give a range of values and such valuations are inevitably contentious – in that the economic valuation of human life, and particularly its discounting with time, is an emotive subject.

Such methods rely on the financial valuation of human life or life expectancy reduction, by means based either on a valuation of economic output lost, or based on how much people are willing to pay to prevent such life reduction. Simple measures such as the Value of Life Lost (VOLL), Value of a Statistical Life (VOSL) and Value of Life Year (VOLY – also quoted as Year of Life Lost, YOLL) have been joined by more sophisticated measures designed to modify financial valuation by a factor reflecting the quality of life. For example Quality Adjusted Life Years (QALY) and Disability Adjusted Life Years (DALY) are measured and subsequently valued in UK healthcare assessments. Much of the decision making on healthcare and transport policy is underpinned by such concepts.

In these policy areas, assessment is fairly straightforward, as health detriments (identified illnesses, accident fatalities etc.) can be measured directly. For operational radioactive discharges, dose levels are much lower than those required to produce individually identifiable effects. The doses which will occur from the discharges must be calculated from models, and the detriments can only be determined by reference to epidemiological studies and statistical assessments of populations who have experienced much higher doses – for example survivors of the Hiroshima and Nagasaki atomic bombs.

All attempts to value radiation dose ultimately rely on valuing the integrated total of health effects predicted by using collective dose and the linear-no-threshold assumption that dose, no matter how small, has a deleterious effect. As discussed in Section 2.2, current regulatory guidance [Ref 5], would recommend ignoring the large majority of these doses or dismissing them as trivial.

However, there have been attempts to value detriment from radioactive discharges, and a growing body of academic and regulatory work has produced economic valuations by various methods [see for example References 21, 22], all of which ultimately involve this aggregation of the effects of small doses. IDM>NNL believe that, while the valuation of life remains an emotive concept, particularly when applied to the nuclear sector, it is still instructive to review such assessments as part of assessing the economic, social or other benefits of a new Class or Type of Practice in relation to the health detriment it may cause.

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<sup>21</sup> See Section 2.10, p48

### 6.1. NRPB “Valuation for the 1990s”

In 1993, the National Radiological Protection Board (NRPB) [Ref 23] recommended a valuation of £20,000 for 1 man Sievert of collective dose. It was not universally applied to operational discharge regulation, and has subsequently been overtaken by the developments in the use of collective dose discussed in Section 2.2.

In today’s money, this valuation would be around £30,000 per man sievert. Applying this figure to the annual collective dose from Sizewell discharges (truncated at 500 years) [Ref 13] produces valuations of health detriment as seen in Table 7. It should be noted, however, as the dose estimates are modelled at the maximum of the Discharge Authorisation, they will overestimate the doses which would arise from normal operation.

Population	Collective Dose (man Sv)	Valuation (£)
UK	0.136	4,100
Europe	1.17	35,000
World	9.8	290,000

**Table 7. Collective dose and dose valuation using £30,000 per man Sievert**

Table 7 shows valuations of collective dose per year of operation between £4,100 and £290,000. Sizewell B electrical output averaged 9023.25 GW(e)h, (equivalent to 1.029 GW(e)y) in the period 1999-2008<sup>22</sup>, so the valuations are almost exactly a ‘per GW(e)y’ figure. This simple example does not consider the complexity that the detriment is predicted to occur over a 500-year period. Instead, the valuation is applied as if the detriment all occurred in year 1, so in effect the valuation assumes a zero discount rate.

### 6.2. ExternE Valuation

The European Commission ExternE project has been running for well over 15 years, and is the most established study of the external costs of energy in Europe (indeed probably the world). The use of the ExternE values has now crossed over from the academic literature into policy use, e.g.:

- With the incorporation of the values in cost-benefit analysis in the European Commission (e.g. in the supporting impact assessment of new air quality legislation, or recommended for CBA by the EU IPPC bureau), and
- As part of the consideration of taxes, charges and subsidies (e.g. in the allowable state aid for renewables).

Most of the policy uses of the values have centred on the ExternE air quality methodology and results. However, the UK has developed its own methods for external cost analysis. These draw heavily on the ‘impact pathway’ approach developed by ExternE, but use UK specific functions and values. The values therefore differ slightly from ExternE. The UK Government has adopted a more explicit use of economics in policy making than any other European country, and uses external costs in routine policy appraisal.

In line with this, the UK Government has published recommended external cost values for use in policy appraisal in the UK. These include a recommended social cost of carbon (a global warming externality – see Section 2.5), and a set of values for combustion related air pollutants (e.g. SO<sub>2</sub>, NO<sub>x</sub>, PM).

For its UK nuclear power assessment [412] the ExternE Project used Sizewell B data and used the Euro’s predecessor, the ECU, as its unit of currency. It assesses overall fuel cycle detriments, including the

<sup>22</sup> From IAEA PRIS Database at <http://www.iaea.org/programmes/a2/>

detriment from small doses using calculations of collective dose and the linear no threshold hypothesis. Thus the estimates include the whole of the radiological detriment from the fuel cycle, which was given in Table 1.

The detriment valuation results obtained (which include all health detriments from the generation stage) varied depending on the valuation technique (Year of Life Lost, YOLL, or Value of a Statistical Life, VOSL), whether or not the analysis was truncated at 500 years, and the discount rate applied to damage in the future. At zero discount rate, the damage derived varied only from 0.039 mECU/kWh (YOLL truncated 500 years), via 0.079 mECU/kWh 'YOLL not truncated' to 0.099 mECU/kWh (VOSL not truncated)<sup>23</sup>.

Assuming that the ExternE Project data is at 1998 money values, converting these values into 2009 pounds via a purchasing power parity conversion and an appropriate GDP deflator produces a conversion factor of 1ECU = £0.93<sup>24</sup>. Thus 1mECU/kWh equates to £8.15M/GW(e)y.

This gives damage costs per GW(e)y of £318,000 (YOLL truncated 500 years), £644,000 (YOLL not truncated) and £807,000 (VOSL not truncated). The disparity between the YOLL and VOSL values illustrates the differences which occur between using CBA and CEA techniques, and therefore the difficulty of establishing a generally accepted cost model.

The effect of discount rate is very large, and in the YOLL methodology, damage cost reduces from £644,000 undiscounted (YOLL not truncated) to £7,100 at 3% discount, and to £370 at 10% discounting<sup>25</sup>. The application of discounting to health effects and other detriments is central to much of the current debate on climate change, notably highlighted by the Stern Report [Ref 24]. Certainly, the use of extreme discount rates (e.g. 10% per annum) will significantly devalue future detriments and is likely to be unsatisfactory.

## 7. Financial Comparisons of Benefits and Detriments

As Section 6 suggests, Sizewell B can be estimated to give a minimum carbon saving of 363gCO<sub>2</sub>/kWh with respect to gas. Using the average annual output of Sizewell B of 9,023.25 GWh, this would translate to a saving of around 3,275,000 tonnes of CO<sub>2</sub> per annum if it replaces electricity generation which would otherwise come from the use of gas. The savings would approximately double if it was considered to replace coal generation without carbon capture and storage (CCS).

The Government has recently revised the method by which it is valuing carbon reductions [Ref 25] as part of the UK Low Carbon Transition Plan [Ref 26], with a 'traded' carbon value ranging from £25 (range £14 - £31) in 2020, via £70 (range £35 - £105) in 2030, to £200 (range £100 - £300) for 2050. Notably, all these figures would have relevance to a 60-year life nuclear reactor starting up in around 2018. Using the Sizewell B annual CO<sub>2</sub> saving as an example, the traded carbon value for the various assumed prices is given in the Table below.

Year	Traded Price		
	Lower £M	Central £M	Upper £M
2020	45.9	81.9	101.5
2030	114.6	229.3	327.5
2050	343.9	655.0	982.5

**Table 8. CO<sub>2</sub> saving - valuation per annum, Sizewell B example**

<sup>23</sup> Reference 12, Table 7.36

<sup>24</sup> The authors are grateful to HPA for deriving this conversion factor.

<sup>25</sup> Calculated from Table 7.37 of Reference 12

This can be compared with a range of health detriment valuations from £245,000 (using 1990s NRPB valuation, world population, truncated to 500 years), £3.400 (using 1990s NRPB valuation, UK population, truncated to 500 years) and £320 (ExternE valuation, YOLL at 10% discounting).

When it is considered that the NRPB methodology has fallen out of favour because it largely relied on “*the aggregation of very low individual doses over extended time periods*”, then it is clear that any credible valuation of the radiological health detriment from the operation of Sizewell B is likely to be very much lower than the valuation of its carbon benefit.

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