Siting Considerations relating to Land at Boundary Hall, Tadley

Proof of Evidence

prepared by

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Summary and Conclusions

S.1 CONTEXT OF THE EVIDENCE

S.1 The HSE has, on public safety grounds, advised against the planning application to redevelop, for mixed use including residential, the Boundary Hall site adjacent to the licensed nuclear installation at the Atomic Weapons Establishment (AWE) Aldermaston.

S.2 One of the bases for objection is that the existence of a controlled ‘Low Population Zone’ around a nuclear licensed site is important and represents a buffer between the nuclear licensed site boundary and more concentrated centres of population. The HSE refers to the existence and application of long-standing National Government siting policy for new nuclear installations and for subsequent development controls in the vicinity of licensed nuclear sites, comments that the proposed development site is located in an area around AWE Aldermaston where the current population density already substantially exceeds even the least restrictive nationally determined limits applied to nuclear installations, and considers that the proposed development would further exacerbate the already excessive population within the inner nuclear safeguarding zone set for AWE Aldermaston.

S.3 The HSE further considers that there are national and international implications if the proposed development is permitted. At a national level, the HSE considers that there would be precedential implications for control of offsite populations liable to be affected at the AWE Aldermaston site and other licensed nuclear sites around the UK. At an international level, the HSE considers that implications arise because the existing siting policy and arrangements have been repeatedly relied upon by UK Government in its triennial report on the measures that it has taken to implement each of the obligations of the Conventions on Nuclear Safety and the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. However, it is recognised by HSE that AWE Aldermaston is not within the scope of these two conventions, though it is said to be subject to the same land-use planning arrangements.

S.2 APPROACH

S.4 Based on a review of the historical development of siting guidelines applicable to nuclear installations in the UK, I have found the HSE objections to the proposed development on siting grounds to be unsupported by precedent or appropriate analyses. My detailed conclusions are set out below.

S.3 INAPPLICABILITY OF THE EXISTING GUIDELINES TO AWE ALDERMASTON

S.5 Siting criteria in the UK were developed solely in the context of the siting of nuclear power reactors. Furthermore, those guidelines were developed primarily to control the **siting** of such installations. Their use to control **developments** in the vicinity of existing installations has been given much less consideration. In particular, there do not appear to have been any policy or technical analyses of their role in achieving the primary policy requirement that once a site has been accepted for a nuclear station, arrangements are made to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. It is not self-evident that the same numerical criteria should be used in an initial siting evaluation as in the control of developments. In particular, it is noted that the burden of compliance in the two cases lies mainly with different stakeholders.

S.6 AWE Aldermaston came into existence before any formal criteria for the siting of nuclear power reactors had been defined. In developing the criteria, no reference was made to the type of activities undertaken at AWE Aldermaston and the criteria did not give any consideration to the population distribution around AWE Aldermaston.

S.7 Current UK international obligations on siting under the Conventions on Nuclear Safety and the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, as expressed through the United Kingdom's Fourth National Report on compliance with Article 17: Siting of the Convention on Nuclear Safety obligations (HSE, 2007), relate entirely to power-generating nuclear reactors. They do not relate to several other types of nuclear installation (e.g. research reactors). Furthermore, the HSE recognises that AWE Aldermaston is not within the scope of the two conventions.

S.8 With new build, the key consideration is that the nuclear power station could be constructed at any location within the potential site. Therefore, the siting analysis properly considers each potential location in turn. Through this analysis, HSE can come to a view as to whether any parts of the potential site are inappropriate for construction. However, if a power station were subsequently constructed at a location deemed suitable, future developments around the site would be assessed using a calculation centred on a point representing the actual location of the power station. In the case of AWE Aldermaston, HSE has undertaken the same type of analysis, arguing that the location of sources on the site is unspecified. However, this is not a risk-informed approach, since every off-site location is evaluated by reference to its own worst-case source location. This is excessively penalising to developments and there is nothing in policy that requires this approach.

S.9 The AWE Aldermaston site undertakes well defined operations in various specialised facilities. Thus, the determination of possible locations of potential accidents under current and projected operational arrangements should be straightforward, just as is the case at other nuclear licensed sites. If AWE Aldermaston wished in future to substantially modify its operational procedures, the revised procedures would require evaluation at the time to ensure that they did not compromise the safety of populations around the site. If issues arose in this respect, the proposed operational changes could be denied, or subject to any conditions necessary for the maintenance of safety.

S.10 Based on the above, it seems clear that any proposals for developments in the vicinity of AWE Aldermaston can, and should, be decided on their own merits, having regard to the general obligation to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. This does not preclude the use of numerical analyses, but any such analyses should only be used as guidance to inform decision making, which needs to take into account numerous other factors, some of which may be unquantifiable. In particular, those factors include socio-economic considerations.

S.11 There are technical aspects of the existing guidelines that can properly be used to evaluate whether developments in the vicinity of all nuclear licensed sites, including AWE Aldermaston, are appropriate. In particular, when evaluating the overall impact of a potential accident, it is appropriate to give consideration to the cumulative weighted population downwind (i.e. the accumulation over distance of the product of the number of people exposed at each distance and a quantity proportional to the radiological impact on people present at that distance). However, the aspect of the current guidelines for nuclear power reactors that cannot be used is the limiting population densities adopted. This is because those densities are conditioned on the types of accidents that could occur at nuclear power reactors and their associated likelihoods of occurrence. These types of accidents are not, in general, relevant at other licensed nuclear sites.

S.12 Whenever quantitative calculations are undertaken, it is important to bear in mind that those calculations are for the purpose of making comparisons with guidelines. Those guidelines are intended to inform judgements made by the HSE, e.g. in relation to the acceptability of proposed developments in the vicinity of a site. In the context of such developments, local authorities are required to consult with the HSE, but any criteria based upon population distribution are used only for guidance, and the HSE cannot necessarily insist on rigid adherence to demographic constraint limits. Specifically, local considerations may take precedence over any numerical criteria. Just as the Inspectorate has not in the past required rigid adherence to quantitative demographic constraint limits, so it cannot require local authorities to apply such rigid adherence, since those authorities have a responsibility to take into account other unquantifiable factors. Such factors may enhance or diminish the desirability of a particular development.

S.4 COMPARISON OF POTENTIAL ACCIDENTS AT AWE ALDERMASTON WITH THOSE AT NUCLEAR POWER STATIONS AND OTHER LICENSED NUCLEAR SITES

S.13 The radiological impact of the reference worst-case accident for a nuclear power reactor is a factor of 5,390 larger than the radiological impact of the reference worst-case accident for AWE Aldermaston.

S.14 Overall, AWE Aldermaston should be considered more closely comparable to a research reactor site than to a power reactor site. For research reactor sites, no specific constraints on local population density have ever been imposed in the UK.

S.5 EVALUATION OF EXISTING AND PROJECTED POPULATION DENSITIES IN THE VICINITY OF AWE ALDERMASTON

S.15 There is no justification for using a population density constraint lower than the semi-urban value of 5,000 persons per km^2 for AWE Aldermaston and there are strong arguments, based on the types of accidents that could occur at the site, that a much higher population density constraint should be used.

S.16 The existing population density around the site does not violate the semi-urban constraint value, irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. Therefore, there should not be any concern that the existing population density is prejudicial to public safety.

S.17 The population density around the site including the additional population associated with the proposed development at Boundary Hall would also not violate the semi-urban constraint value. Therefore, there should not be any concern that the change in population would be prejudicial to public safety.

S.18 The increment in population due to the proposed development at Boundary Hall would constitute a small perturbation to the population pattern in the area. It would increase the limiting population density by about 8% irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. This arises because the population density in the 175 to 205 degree sector and distance range 1 to 2 km is increased from 3596 to persons per km^2 to 3,937 persons per km^2. This is an increase of 9.5%.

S.19 In the event of a severe accident at AWE Aldermaston with the wind blowing towards Boundary Hall, the proposed development would increase the societal impact of the accident by no more than 6.2%. In fact, the increase would be less than this because the impact beyond 5 km from the site is neglected in this calculation and because no account is taken of the effectiveness of sheltering local to the site.

S.20 A consideration of the wind rose for the nearest Meteorological Station to AWE Aldermaston shows that the wind blows preferentially away from the proposed development and that there is no requirement to reduce acceptable population densities because of wind speed and atmospheric stability effects.

S.6 OVERALL OPINION

S.21 Overall, it is my opinion that the HSE has not provided a suitably argued basis on public safety grounds, for refusing to permit development of the Boundary Hall site for mixed use including residential. Existing policy on siting relates to nuclear power reactors only and does not apply to AWE Aldermaston for which the magnitudes of potential major accidents are much smaller than those that could occur at nuclear power reactors. Furthermore, the quantitative criteria used in relation to nuclear power reactors only constitute guidance and local factors may take priority. Thus, the proposed development should be evaluated on its own merits. It constitutes an infill development on an available site broadly consistent with land use in the immediate area. Thus, if it were to be implemented, the general characteristics of the site (i.e. the area in the immediate vicinity of AWE Aldermaston) would be preserved. This is the fundamental intent of siting and development policy. The numerical criteria that have been developed by the HSE are intended to inform judgements related to this fundamental principle, but analyses against these criteria have also to be informed by consideration of other unquantifiable factors. Taking these considerations into account, I am of the opinion that there are no issues arising from national siting and development policy that should prevent the proposed development at the Boundary Hall site from being implemented.

Contents

Michael Charles Thorne will say:

1. Introduction

1.1 My name is Michael Charles Thorne. I have a First Class Honours Degree in Physics and a PhD in Experimental High Energy Physics from the University of Sheffield, England. I have 35 years experience in radiological protection, having worked both with the Medical Research Council and with various engineering companies. Since April 2001, I have been the Director of my own company, Mike Thorne and Associates Limited. I am a former member of Committee 2 of the International Commission on Radiological Protection, a former Scientific Secretary to the Commission and a former President of the Society for Radiological Protection. I am currently a Visiting Fellow at the University of East Anglia and a member of the Editorial Board of the Journal of Radiological Protection. I am a Fellow of the Society for Radiological Protection and a Fellow of the Institute of Physics. I am also a Chartered Radiation Protection Professional and a member of the UK National Dose Assessment Working Group. I have appeared as an expert witness in the US District Courts, before the US Nuclear Regulatory Commission and at a Public Inquiry in Scotland relating to radioactive waste disposal. I have undertaken various studies relating to the safety and siting of nuclear installations, and was Principal Investigator for a study undertaken by Electrowatt Engineering (UK) Limited for the HSE (Electrowatt, 1997) that is referred to in the following proof of evidence.

1.2 My full CV is provided in Appendix A.

1.3 The evidence which I have prepared and provide for this inquiry (reference APP/H1705/V/10/2124548) in this proof of evidence, is true and has been prepared and is given in accordance with the guidance of my professional institution (the Society for Radiological Protection) and I confirm that the opinions expressed are my true and professional opinions.

2. Background

2.1 THE ROLE OF THE HEALTH AND SAFETY EXECUTIVE IN RELATION TO AWE ALDERMASTON

2.1.1 Under UK law (the Health and Safety at Work etc. Act 1974) employers are responsible for ensuring the safety of their workers and the public. This responsibility is reinforced for nuclear installations by the Nuclear Installations Act 1965, as amended. Under the relevant statutory provisions of the Nuclear Installations Act, a site cannot have nuclear plant on it unless the user has been granted a site licence by the Health and Safety Executive (HSE). This licensing function is administered on behalf of the HSE by its Nuclear Directorate (ND) comprising the Nuclear Installations Inspectorate (NII), the Office for Civil Nuclear Security (OCNS) and the UK Safeguards Office (UKSO).

2.1.2 For civil nuclear safety policy matters in England and Wales, the Health and Safety Commission (HSC) together with the HSE advise the Secretary of State for Business, Enterprise and Regulatory Reform, and for defence-related nuclear safety matters HSC/HSE advise the Secretary of State for Defence. ND may be called on to contribute to advice on nuclear safety and security matters to HSE and HSC and, on their behalf, to Ministers.

2.1.3 ND acts for HSE and sets the safety and security standards to be used on nuclear sites in the UK. This includes the regulation of defence nuclear facilities through the work of Division 3 of the ND. This work includes inspections of such facilities. The Quarterly Report for 1 January to 31 March 2010 relating to AWE Aldermaston and Burghfield defines that such inspections are undertaken for the purpose of monitoring compliance with: the conditions attached by HSE/NII to nuclear site licenses; the Health and Safety at Work etc. Act 1974; regulations made under that Act, e.g. the Ionising Radiations Regulations 1999 and the Management of Health and Safety at Work Regulations 1999.

2.1.4 HSE has developed a standard suite of licence conditions (LCs) that are attached to all nuclear site licences. Although some LCs impose specific duties, the majority require the licensee to devise and implement adequate arrangements in particular areas. The issues covered range from processes for ensuring the safety of plant and for controlling operations to management issues such as the supervision and training of staff.

2.1.5 The Conditions are non-prescriptive and set goals that the licensee is responsible for meeting, amongst other things by applying detailed safety standards and establishing safe procedures for the facilities. Each licensee can develop compliance arrangements that are appropriate to the scale and nature of its activities. Compliance arrangements may need to be adapted over the lifecycle of a site to ensure they remain relevant and proportionate as the facility progresses from initial design and installation through operation to final decommissioning.

2.1.6 As a non-statutory consultee, HSE/NII provides advice to Local Authorities with regard to planning applications near nuclear sites. The advice provided in relation to the Boundary Hall site is set out in Section 2.2.

2.2 THE POSITION OF THE HEALTH AND SAFETY EXECUTIVE IN RELATION TO THE PROPOSED REDEVELOPMENT OF THE BOUNDARY HALL SITE

2.2.1 The HSE has, on public safety grounds, advised against the planning application to redevelop, for mixed use including residential, the Boundary Hall site (hereafter referred to as "the Site") adjacent to the licensed nuclear installation at the Atomic Weapons Establishment (AWE) Aldermaston.

2.2.2 One of the bases for objection is that the existence of a controlled 'Low Population Zone' around a nuclear licensed site is important and represents a buffer between the nuclear licensed site boundary and more concentrated centres of population. The HSE refers to the existence and application of long-standing National Government siting policy for new nuclear installations and for subsequent development controls in the vicinity of licensed nuclear sites, comments that the proposed development site is located in an area around AWE Aldermaston where the current population density already substantially exceeds even the least restrictive nationally determined limits applied to nuclear installations, and considers that the proposed construction of 115 dwellings (which together with 945m^2 of commercial development is referred to hereafter as "the Proposed Development") would further exacerbate the already excessive population within the Inner nuclear safeguarding zone set for AWE Aldermaston.

2.2.3 The HSE further considers that there are national and international implications if the proposed development is permitted. At a national level, the HSE considers that there would be precedential implications for control of offsite populations liable to be affected at the AWE Aldermaston site and other licensed nuclear sites around the UK. At an international level, the HSE considers that implications arise because the existing siting policy and arrangements have been repeatedly relied upon by UK Government in its triennial report on the measures that it has taken to implement each of the obligations of the Conventions on Nuclear Safety and the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. However, it is recognised by HSE that AWE Aldermaston is not within the scope of these two conventions, though it is said to be subject to the same land-use planning arrangements.

2.2.4 Herein, a review is provided of the historical development of policy and guidance on the siting of nuclear licensed sites and controls on developments in their vicinity (Section 3). It is demonstrated that the current guidance has been developed only in the context of commercial nuclear power production, so it is not applicable to AWE Aldermaston (where the primary activities relate to the development and production of nuclear weapons). This means that developments around AWE Aldermaston have to be considered on their own merits and not with reference to guidelines for nuclear power stations. To inform judgements on this matter, an evaluation is provided of the radiological consequences of major accidents that could occur at AWE Aldermaston in comparison with the radiological consequences of major accidents that could occur at nuclear power plants (Section 4).

2.2.5 Although the current guidance is not applicable to AWE Aldermaston, some aspects of the technical arguments upon which it is based can be used. Therefore, following the account of the existing guidance applicable to nuclear power plants and the evaluation of major accidents that could occur at AWE Aldermaston, an analysis is presented that applies relevant aspects of the current guidance to determine the significance of the increase in population in the vicinity of AWE Aldermaston due to the proposed development relative to the existing population density (Section 5).

2.2.6 Finally, I draw conclusions that relate to the appropriateness of the HSE position, as set out above (Section 6), and give my overall opinion on whether the proposed development at the Boundary Hall site is appropriate in relation to controls on developments in the vicinity of licensed nuclear sites (Section 7).

3. The Development of Siting Guidelines applicable to Nuclear Power Plant

3.1 INTRODUCTION

3.1.1 The historical development of siting guidelines is relevant because it demonstrates that those guidelines have been developed solely and explicitly for nuclear power reactors, and cannot be assumed to apply to other nuclear licensed sites. Thus, this historical development is summarised and commented upon in Section 3.2. However, as noted in Section 2, some technical aspects of the guidelines are relevant to other nuclear licensed sites. Therefore, full technical details of the current guidelines are set out in Section 3.3, to provide a basis for understanding as to how appropriate components of those guidelines have been used in the analyses presented in Section 5 of this proof of evidence.

3.2 HISTORICAL DEVELOPMENT OF SITING GUIDELINES APPLICABLE TO NUCLEAR POWER PLANT

3.2.1 Gronow (1978) provides a useful account of the early development of siting policy for nuclear power stations in the UK. At the start of the first programme of nuclear power development, the Government adopted a policy of siting nuclear power stations remote from population centres. However, the most remote sites available were too far from the major demand centres in England and Wales to be of practical use. Therefore, a standard was adopted aimed at achieving the maximum degree of remoteness judged to be compatible with securing sufficient sites that were technically practicable for the introduction of a programme of nuclear power in the UK (Gronow, 1978, page 1). It is emphasised that this initial policy was related entirely to the siting of nuclear power stations and did not address other types of nuclear installation.

3.2.2 In the context of AWE Aldermaston, it is important to note that the United Kingdom began work on its atomic bomb project at Fort Halstead in June 1947. The intention was to produce a nuclear device '…similar to the [one] that destroyed Nagasaki...'. Over the five years this took, improvements emerged and differences between the American design and British equivalent crept in. When it entered service, there was little left of the original except a general resemblance (**www.awe.co.uk/aboutus/our_history_f77a4.html**).

3.2.3 To make the core for the weapon, new facilities for handling plutonium were needed, but Fort Halstead was too small. In September 1949, an airfield near the village of Aldermaston in Berkshire was allocated. On April 1st 1950, it re-opened as the headquarters of the British atomic weapon programme (**www.awe.co.uk/aboutus/our_history_f77a4.html**). Thus, the Aldermaston site was selected for activities related to nuclear weapons production well before any siting policy for nuclear installations had been developed in the UK. Interestingly, the siting standards developed in the mid-1950s were entirely directed to the siting of installations for nuclear power production, though the authors of the earliest criterion document identified (Marley and Fry, 1955) were well aware of the location of the Aldermaston site and of the type of activities that were undertaken there.

3.2.4 The earliest expression of the 'remote' siting policy at the beginning of the first programme of nuclear power development in the early 1950s was based on the simple exclusive principle that a site should be at least five miles away from a population centre of more than 10,000 people and ten miles away from 100,000 people (Gronow, 1978, page 1).

As noted above, these criteria were refined by Marley and Fry (1955). They proposed that sites should be classified on a comparative scale of A to D, with Class D sites being recommended for the Magnox reactors in steel pressure vessels.

3.2.5 Limiting population characteristics of Class D sites were set for any ten degree sector and for the population all around the site. For any ten degree sector, the requirements were: (1) few people within 0.3 mile; (2) 500 within 1.5 miles; (3) 10,000 within 5 miles; 100,000 within 10 miles. For all round the site, the corresponding criteria were: (1) few people within 0.3 mile; (2) 3,000 within 1.5 miles; (3) 60,000 within 5 miles; 600,000 within 10 miles (Gronow, 1978, page 1).

3.2.6 The objectives of these early siting criteria were summarised by Gronow (1978, page 2). They were to locate sites such that in the event of a reactor accident: (i) very few people would be exposed to extreme risks; (ii) protracted evacuation or severe restriction on living conditions would not be imposed on any but small population centres; (iii) temporary evacuation or restriction on activities would not be imposed on more than 10,000 people, except in the most adverse weather conditions.

3.2.7 These broad principles seem very reasonable, but it should be noted that the quantitative criteria were set on the basis of consideration of reactor accidents at Magnox power stations (not for a site with the characteristics of AWE where there are now no reactors with significant net power production) and imply a judgement on the magnitude of radiation doses arising at different distances off-site as a result of such accidents, as well as on the appropriate response to such doses. It should also be noted that the objectives are closely related to considerations addressed in emergency planning, rather than representing a separate line of defence in depth, *i.e.* the use of multiple barriers or lines of argument to provide assurance of safety.

3.2.8 Gronow (1978, page 2) goes on to comment that a more refined method of assessing sites was proposed by F R Farmer (1960). This introduced population weighting factors based on the calculated consequences of accidental releases of radioactivity and gave greater emphasis to persons living nearest to reactors. A site rating factor was calculated for each site based on the highest thirty degree sector value of the summation of the products of population between successive 1 mile boundaries and the appropriate weighting factor out to a distance of 12 miles. This method made possible the comparison of sites with widely differing population characteristics and a site rating scale was developed that placed sites into four classes I to IV. Class I was broadly equivalent to the earlier Class D and corresponded to 6% of the maximum UK urban population density in the most highly populated thirty degree sector. Classes II, III and IV corresponded to 12%, 25% and 50% of the maximum UK urban population density, respectively.

3.2.9 It is of interest that the criteria proposed in 1960 related only to the total weighted population to 12 miles and not to the weighted population at sub-distances within that total distance. Thus, the use of population weighting was seen to remove the need for criteria disaggregated by distance. This is reasonable because weighting takes account of both the contributing numbers of persons and the degree to which they would be impacted by an accident. However, it should be noted that the distance weighting was devised before modern methods of atmospheric dispersion calculation or radiological impact assessment were developed.

3.2.10 Although Magnox sites conformed to Class I, it was proposed that relaxations in siting restrictions should be based on evaluation of the relative safety of reactors with different design features. Thus, enclosure of the gas-cooled reactor core and heat exchangers in a pre-stressed concrete pressure vessel, as compared with earlier designs having steel pressure vessels and heat exchangers external to the concrete shielding, was considered to confer a sufficient increase in overall safety to permit these reactors to be located on Class II sites. A similar policy was adopted for the first Advanced Gas-Cooled Reactor (AGR) stations (Gronow, 1978, pages 2 and 3). Throughout, the emphasis was on sites associated with nuclear reactors for power production and the guidance did not address other types of nuclear facility.

3.2.11 Thus, from 1960, the use of total weighted population to 12 miles strongly suggests that the primary consideration in siting had become the collective radiological impact of an accident. Furthermore, the use of different criteria depending on the relative likelihood of accidents of different magnitudes strongly indicates a risk-informed judgement rather than a simple consideration of the hazard. Thus, for example, criteria for AGR stations were less restrictive than those for early Magnox stations, even though their power output and radionuclide inventory were much larger, because it was perceived that the frequency of accidents with significant off-site consequences would be less. It is also important to keep in mind that the siting criteria are closely related to the impacts of accidents at nuclear reactors and are not tied in to accidents at other types of nuclear installations. It is emphasised that this position was taken at the peak of atmospheric weapons testing activities when operations at AWE Aldermaston are likely to have been particularly intensive.

3.2.12 The site rating factor for assessing sites was adopted by Government in 1961 (Gronow, 1978, page 3).

3.2.13 The siting standards adopted for the early nuclear power stations made it difficult however for the Generating Boards to acquire suitable sites. It was recognised that strict adherence to a remote siting policy with a continued programme of nuclear stations would be difficult to maintain and involve a steeply rising rate of injury to amenity. In addition, it was recognised that the population distribution in England and Wales is such that 'if a significant release of fission products should occur at a nuclear site a large number of people could be exposed to the radioactive plume and the factor of safety to be gained by the remotest practicable siting is limited.'(Gronow, 1978, page 3).

3.2.14 In view of these considerations, 'a thorough review of the safety and siting policy for power reactors was undertaken by the Government in consultation with the Nuclear Safety Advisory Committee (NuSAC). This resulted in a new policy which re-affirmed that the main safeguard to the public was derived from attention given to the design, construction and operation of nuclear plants and under which reactors of approved designs could be sited nearer to urban developments.' (Gronow, 1978, pages 3 and 4). Again, siting policy can be seen at this time to be risk informed, i.e. safer reactors can be located closer to urban developments, and remains entirely directed to nuclear power reactors rather than giving consideration to other types of nuclear installations.

3.2.15 The adoption of the new siting policy introduced difficulties in the assessment and control of development around sites. Gronow (1978, page 4) comments that '(t)he site rating factor method could only be usefully applied to remote sites where the bulk of the population was generally confined to a single 30^{o} sector. A characteristic of semi-urban sites is that they are likely to have population centres distributed about them in all directions and would therefore be more likely to have persons affected by a release of radioactivity than a site with only one such population centre. A method of combining these aspects in terms of site and sector risk characteristics was developed by Charlesworth and Gronow (1967, Ref. 16.4). Their approach is described in more detail below, since it is the precursor to current siting policy. However, it is relevant to note that Gronow (1978) relates the new approach to considerations of risk. Specifically, Gronow (1978, page 4) describes the criterion curves proposed as relating to site and sector risk factors.

3.2.16 On a separate point, Gronow (1978, page 5) emphasises that decisions on siting of nuclear power reactors are closely related to capabilities for emergency response. Specifically, he states that 'site and sector limiting characteristic curves used in the evaluation of sites exclude the use of sites in or near large centres of population, not least because it would be difficult to carry out effective emergency countermeasures for people at greater risk in the unlikely event of a release of radioactivity.' The implication of this would seem to be that the limiting characteristic curves would need to be reconsidered if either the risks differed from those envisaged when they were formulated for nuclear power stations or because the ease of implementing emergency countermeasures differed.

3.2.17 However, set against this risk-informed approach, Gronow (1978, page 6) recognises what would now be considered an argument based on the precautionary principle, *viz.* 'If a reactor system new to the UK was approved for development it would be expected that a cautious siting policy would be adopted. The initial installations would be located on relatively remote sites and any relaxation to allow the use of more populated sites would be based on the experience gained in design and operation of these installations.' Thus, safe design and operation have to be established in practice before siting criteria can be relaxed. A corollary of this would seem to be that when safe design and operation have been demonstrated at a site then restrictions on the growth of population around that site could be relaxed.

3.2.18 Charlesworth and Gronow (1967) developed distance-related population weighting factors based on considerations of dispersion. In general terms they argued (pages 147 and 148) that 'atmospheric dispersion of airborne material, in stable air conditions gives a dilution factor of 10^2 from 100 yards out to a distance of one mile, a further factor of 10 being attained at a distance of 5 miles. Thereafter dispersion is slow and a further factor of 10 is attained at approximately 50 miles. Thus, for a large release, a significant public hazard would extend to several tens of miles and would embrace large groups of the population. Control of milk supplies and growing crops will be necessary out to distances of hundreds of miles. There would also be a severe hazard close to the site which may result in lethal or very damaging effects to those persons exposed.' They further considered that 'siting alone can never be relied upon to safeguard the public in the UK' and, in developing siting criteria primarily emphasised 'unforeseen minor accidents involving irradiated fuel' that 'could result in a comparatively small release of a few thousand curies [about 1 10^{14} Bq] of gaseous and volatile fission products.' For such releases, they considered that 'siting can mitigate the consequences to the public and differences between sites can be recognized' and that '(t)he selection of a site for a given reactor design must therefore take into account both the risk to the population and that of the individual residing near the site.'

3.2.19 Although Charlesworth and Gronow (1967) discuss the principles for establishing weighting factors in general terms, the actual calculations of weighting factors are based on a single specific scenario (Charlesworth and Gronow, 1967, page 149). Bearing in mind the potential importance of releases of iodine-131 (^{131}I) from operating nuclear reactors and the consideration that the highest concentrations close to a site will arise from ground-level releases in stable atmospheric conditions at low wind speeds, they define the accident as a release of 1000 curies of ^{131}I, together with associated gaseous and volatile fission products, at ground level under Pasquill atmospheric stability Category F conditions (see NRPB, 1979, for a description of atmospheric stability categories). The release is taken to be uniformly distributed into a 30^o sector, narrowing to 15^o at 100 km downwind. Furthermore, '(t)he cumulative population dose to the thyroid in the most densely populated sector can be taken to indicate the sector risk factor of the site, while the sum of each sector risk factor will represent the total risk factor of the site.' For later reference, it is important to note that they state, but do not subsequently use, the guidance that '(i)n such an assessment account can be taken of the relative prevalence of different wind directions and the frequency of different weather categories in those directions where these may have significance.' Also, they use a wind speed for category F conditions of 2 m s^{-1} (see their Table 5).

3.2.20 Based on the work of Charlesworth and Gronow (1967) and a subsequent paper by Gronow (1969), Gronow (1978, Appendix 1) sets out the siting criteria used for the siting of AGRs. The sector characteristic of a proposed site is derived by plotting the value of $\Sigma_{i=1,n} p_i w_i$ against the outer radius of the ith zone, where p_i is the population within a zone and w_i is the weighting factor for the same zone. A similar approach is adopted for the whole (360^o) site population, using the total population in each annulus. The numerical values of the weighting factors used are listed in Tables 3.1 and 3.2.

Table 3.1: Sector Weighting Factors and Limits (Gronow, 1978, Appendix 1)

Zone	Distance (Miles)	Sector Weighting Factor (w)	Limiting Sector Population
1	0 – 1	32.4	63,000
2	1 – 1.5	17.6	137,000
3	1.5 – 2	10.5	198,000
4	2 – 3	6.4	305,000
5	3 – 5	3.3	482,000
6	5 – 10	1.31	812,000
7	10 - 20	0.46	1,274,000

Table 3.2: Zonal Weighting Factors and Limits (Gronow, 1978, Appendix 1)

Zone	Distance (Miles)	Zonal Weighting Factor (w)	Limiting Zonal Population
1	0 – 1	40	190,000
2	1 – 1.5	22.5	411,000
3	1.5 – 2	13.75	595,000
4	2 – 3	8.75	917,000
5	3 – 5	4.75	1,448,000
6	5 – 10	2.0	2,436,000
7	10 - 20	0.75	3,823,000

3.2.21 These weighting factors and limits were subsequently revised and updated. Results to 8 km were given in Hansard (1988) and values out to 30 km are given in Table 2 of Highton and Senior (2008), as applicable to Magnox and AGR reactor stations. These values are set out in Tables 3 and 4 below.

Table 3.3: Sector Weighting Factors and Limits (Highton and Senior, 2008)

Distance (km)	Sector Weighting Factor	Limiting Sector Population (Magnox)	Limiting Sector Population (AGR)
0 – 2	26.0	23,000	96,000
2 – 3	12.0	37,000	170,000
3 – 5	5.6	48,000	290,000
5 – 8	2.8	56,000	430,000
8 – 15	1.3	82,000	700,000
15 - 30	0.5	170,000	1,100,000

Table 3.4: Site Weighting Factors and Limits (Highton and Senior, 2008)

Distance (km)	Site Weighting Factor	Limiting Site Population (Magnox)	Limiting Site Population (AGR)
0 – 2	26.0	45,000	290,000
2 – 3	12.0	69,000	520,000
3 – 5	5.6	120,000	870,000
5 – 8	2.8	180,000	1,300,000
8 – 15	1.3	340,000	2,100,000
15 - 30	0.5	650,000	3,400,000

3.2.22 The key context-setting text reproduced from Hansard (1988) and as also cited by Highton and Senior (2008) is given below.

> 'Mr Michael Spicer: ...Once a site has been accepted for a nuclear station, arrangements are made to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved, and therefore local authorities consult the inspectorate with regard to any proposed development which might lead to an increase in population close to the site and on large developments further from the site. Limiting criteria based upon population distribution are used only for guidance and the inspectorate would not necessarily insist on rigid adherence to them. Other unquantifiable factors are also taken into account.
>
> The limiting criteria are in the form of cumulative weighted populations out to various distances all around the site and in any 30 degree sector. To assess a site against the criteria at a certain distance, the population for a given band distance is multiplied by the appropriate weighting factor and the values up to the distance being evaluated are added together.'

3.2.23 This statement from the Secretary of State for Energy is the closest approach that exists to a direct Government statement of policy. However, it is important to note that it is primarily a description of the then current practice by the Nuclear Installations Inspectorate rather than a direction to the Inspectorate. Furthermore, a considerable degree of latitude is afforded, since the limiting criteria are used only for guidance. The statement that the Inspectorate ‘would not necessarily insist on rigid adherence’, implies that the degree of latitude primarily relates to a relaxation of the criteria if there are relevant unquantifiable factors to be taken into account.

3.2.24 By the mid-1980s, considerable developments in atmospheric dispersion modelling and radiological impact assessment had occurred. These were commented upon by Tildsley (1985) whose remarks are here taken to reflect thinking in the Nuclear Installations Inspectorate (NII) shortly before the statement by the Secretary of State discussed above.

3.2.25 Tildsley states at page 8 that ‘(i)t cannot be over-emphasised that the safety of nuclear power stations depends primarily on achieving high standards of design, construction, commissioning and operation, nevertheless it is prudent to make use of the limited contribution to public safety which can be gained from site selection in a densely populated country like the UK.’ In relation to the siting criteria based on weighting factors and limiting curves discussed above, he comments at page 9 that ‘(t)hese criteria have proved to be a useful practical tool for the initial assessment of sites and for subsequent control of development near to the sites... In practice the Inspectorate has not required rigid adherence to them but has been flexible in their application; they have been treated as guidelines to which exceptions may be made in either direction. Some sites may possess compensatory features which allow them to be accepted even though they may not fall strictly within the guidelines, whilst the opposite may be true in other cases. For example the Committee [i.e. the Advisory Committee on the Safety of Nuclear Installations (ACSNI)] in the past has been requested to endorse relaxations at Sizewell and Bradwell.’

3.2.26 Turning to recent scientific developments, Tildsley commented at pages 9 and 10 that ‘(t)he more ready availability of powerful computers and the development of sophisticated computer programs modelling the consequences of radioactive releases from reactors (such as the MARC code developed by the National Radiological Protection Board, NRPB) has permitted a comprehensive examination of the effect the various factors contributing to the radiological impact of a release may have on the community. It is therefore timely to utilise these codes to carry out a more extensive evaluation of the radiological impact to see whether it is possible to improve upon the present criteria based on weighted population distribution.’ However, after reviewing studies carried out for the Inspectorate on 23 UK sites (existing power stations, some locations with the potential to become nuclear power station sites and a metropolitan location) using six postulated accidental releases (a Magnox reference accident and five Pressurised Water Reactor (PWR) accidents ranging from design basis accidents to large degraded core accidents) and considering both early and late health effects, Tildsley at page 12 concluded that it had not been possible to draw other than tentative conclusions so far from the examination of the results of these studies. Furthermore, he commented that although such studies can provide deeper technical insights they can also greatly complicate matters whilst not necessarily aiding in decision making. This was found to be due not only to the vast amount of data generated, but also because ‘significant changes in the ranking of sites can occur depending upon the characteristics of the releases, the type of consequence considered, judgements on the levels of individual dose or risk to be taken into account, assumptions in cut-off factors and so on.’ Thus, these detailed assessment studies clearly did not significantly affect the siting criteria for nuclear power reactors stated in Hansard (1988) and used subsequently. Interestingly, a similar detailed evaluation of the impacts of various types of accidents at a wide range of nuclear licensed sites was undertaken by Electrowatt (1997). This study also appears to have had little impact on policy developments and is cited in Highton and Senior (2008) only in a footnote to their Table 2 to justify the weighting factors and limiting constraints listed for distances of 8-15 and 15-30 km.

3.2.27 However, it is of interest to note that the Electrowatt study clearly stated (at page 15) that the current guidelines:

- Do not address the full range of nuclear installations present in the UK;
- Give no consideration to the range of accident types that can occur for different installations and their probabilities of occurrence;
- Do not take into account the influence of different weather conditions at the time of release;
- Are based on outdated metabolic, dosimetric and health effects models;
- Are derived by reference to thyroid doses and, therefore, address only one component of radiological impact;
- Can be manipulated to derive implied constraints on population density that are not coherent.

3.2.28 The Electrowatt report was provided to me by the HSE for the purpose of preparing this proof of evidence. In the covering letter, HSE made it clear that the report represented a scoping review that was never implemented. This comment by HSE applies to the approach proposed for updating the guidelines set out in that report. This position is accepted and, for this reason, that proposed approach is not discussed further in this proof of evidence (though some data from the Electrowatt report are used in Section 4). However, it is important to note that the above criticisms of the current guidelines were not challenged by the HSE when the report was reviewed by them.

3.2.29 In considering the significance of different endpoints in defining siting policy, it is also relevant to draw attention to conclusions drawn by Anthony (1981, pages 8 through 12) in relation to radiological aspects of siting. Recognising that radiological considerations are only one aspect of siting, he pointed out that there are a number of quantitative relationships that can be considered in the radiological aspects of siting. These relate to early health effects, late health effects (primarily cancer), the numbers of people likely to be affected by countermeasures, and areas of land contaminated. For the first of these, the number of people affected is a function not only of the characteristics of the site, but also of the size and type of accident considered. This and the number of people affected by countermeasures were found to be the main discriminator between sites for nuclear power reactors. In contrast, there was very little variation in the incidence of late effects between sites for all the releases considered. Similarly, the areas of ground contaminated did not exhibit great site dependence. The review provided by Anthony was undertaken subsequent to the accident at Three Mile Island and gave consideration to the more restrictive siting guidelines for nuclear power reactors being promulgated in the USA at that time. Overall, the review considered (page 7a) that accidents with some off-site effects on health 'might possibly occur once or twice in the 30 year currency of the nuclear power programme, but did not recommend any changes in the semi-urban siting policy for AGR reactors.'

3.3 CURRENT GUIDELINES APPLICABLE TO NUCLEAR POWER PLANT

3.3.1 Highton and Senior (2008, page 2) identify that the current position with regard to Government siting policy is stated in the United Kingdom's Fourth National Report on compliance with Article 17: Siting of the Convention on Nuclear Safety obligations (HSE, 2007). The general introduction to Article 17 material in this report (paragraphs 17.1 and 17.2) does not specify the types of nuclear installations to which it relates. Paragraph 17.2 states that the factors that should be considered in assessing sites cover three main aspects:

- The location and characteristics of the population around the site, and the physical factors affecting the dispersion of released radioactivity that might have implications for radiological risk to people;
- External hazards that might preclude the use of the site for its intended purpose; and
- The suitability of the site for the engineering and infrastructure requirements of the facility.

3.3.2 The commentary on national laws and regulations for the planning and licensing process (paragraphs 17.3 to 17.8) refers only to power generating stations, the material on Government siting policy (paragraphs 17.9 to 17.15) refers only to reactors and the text makes clear that it relates to Magnox reactors and AGRs (see paragraph 17.14). The following section relates to considerations in the initial siting of nuclear installations (paragraphs 17.16 to 17.22). Paragraph 17.23 relates to the role of the initial design of a nuclear power plant in optimising the radiation exposure to the workers and general public, while paragraph 17.24 relates to the use of both plant design and location data in evaluating radiological risk to the general public, and emphasises the importance of effective emergency arrangements. Paragraph 17.25 relates to targets for radiation exposure in design base fault sequences. Paragraph 17.26 relates to societal risk and states that as a measure of societal concerns that would result from a major accident, a target based on a representative accident leading to 100 or more fatalities is defined. However, the report makes clear that this target does not cover all the factors related to societal concerns and that, in making an As Low As Reasonably Practicable (ALARP) demonstration, the consequences in terms of other societal effects must also be considered. In particular '(t)he safety case should identify accidents that result in source terms that could cause 100 or more deaths. The total risk should be calculated taking account of the frequency distribution of the source terms together with probabilistic weather conditions. In estimating the risks, fatalities both on-site and off-site should be included.' The issue as to how societal risk should be represented is addressed in more detail below. Paragraph 17.27 identifies that topography and geology should be considered in evaluating the dispersion of activity released in the event of an accident.

3.3.3 All the material in paragraphs 17.3 through to 17.27 relates to nuclear power plants. There is no indication that any consideration has been given to other types of nuclear licensed sites. In particular, there is no evidence that the text is applicable to AWE Aldermaston, since this site lies outside the scope of the applicable convention (see paragraph 2.3).

3.3.4 Paragraphs 17.28 onward relate to the ongoing controls to be imposed once a site has been established. Paragraph 17.28 relates to the statement by the Secretary of State for Energy on 11 March 1988 that 'once a site has been accepted for a nuclear station, arrangements are to be made to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved.' Paragraph 17.29 states that the planning and public enquiry processes should address and discuss all relevant issues. It further requires that 'HSE must be satisfied that the size, nature and distribution of the population around the site are properly taken into consideration' and that 'there will be planning controls to ensure that significant and unacceptable population growth does not occur. In the UK, the area requiring these restrictive controls is out to 8 km from the nuclear site.'

3.3.5 Paragraph 17.30 relates to re-evaluation of external hazards and emergency plans. Paragraph 17.31 addresses the issue of proposed developments specifically and is cited in full below.

> '17.31. Local authorities consult the HSE with regard to any proposed development that might lead to an increase in population close to the site and on large developments further from the site. Limiting criteria based upon population distribution are used only for guidance, and the HSE cannot necessarily insist on rigid adherence to demographic constraint limits.'

3.3.6 Paragraphs 17.32 and 17.34 relate to the types of development in the vicinity of hazardous installations on which HSE should be consulted. Amongst other matters, these paragraphs state that HSE's nuclear installation inspectors assess such planning applications to determine whether a proposed development would raise the population to near the constraint limits set out in the Government's siting policy for nuclear installations. For a proposed development within the emergency planning zone, the HSE is to refer the application to the licensee, who must, in turn, liaise with those bodies having responsibilities under the off-site emergency plan to find: (a) whether the development can be incorporated into the emergency plan; or failing that (b) whether the emergency plan could be modified such that the development could be incorporated into the emergency plan. In this context, HSE requires assurances that the developments in the immediate vicinity of a nuclear installation can be accommodated by the existing emergency preparedness arrangements to satisfy REPPIR [Radiation (Emergency Preparedness and Public Information) Regulations, 2001] requirements.

3.3.7 Paragraph 17.34 relates to actions to be followed if local authorities do not follow HSE's advice as a statutory consultee. Paragraph 17.35 relates to monitoring by the licensee and HSE of any phenomena that might affect safety. Specifically, it notes that HSE maintains a database of estimated population around nuclear installations, based upon the most recent ten-yearly population census, updated to take account of subsequent planning applications for residential developments. It is stated that '(t)his database is used to compare the projected population, following a proposed residential development, with government demographic guidelines, before HSE advises a local authority on the acceptability of such a planning application.'

3.3.8 Paragraphs 17.36, 17.37 and 17.38 relate to Discharge Authorisations, periodic safety reviews, and transmission of information to the European Commission and Member States of the European Union. They are of little relevance in the current context.

3.3.9 Highton and Senior (2008, page 1) describe the intent of their paper as being to 'explore the background to the Hansard demographic siting criteria in current usage in the United Kingdom' and state that it 'offers proposals for revised demographic siting criteria for application to both reactor and non-reactor nuclear facilities.' Thus, the paper does not comprise a definitive statement of policy.

3.3.10 Highton and Senior (2008, page 2) identify two main objectives of siting: (i) ensuring the technical and economic feasibility of the plant; and (ii) minimising potential adverse impacts on the community and the environment. It is relevant to note that adverse impacts are not limited to radiological impacts, e.g. Highton and Senior (2008, page 2) lists economic and socio-economic factors. Thus, both potential health risks from accidents and economic and socio-economic impacts from sterilisation of development have to be given due weight in evaluating either initial siting or developments in the vicinity of an existing site.

3.3.11 Highton and Senior (2008, page 3) recognise that 'the major contribution to public safety lies in the standards achieved in the design, construction and operation of the nuclear plant'. However, they also consider that 'there are further benefits in reducing societal risk through control of the population in the immediate locality of the installation.' They do not define the term societal risk, but the HSE has published a report by the Institution of Chemical Engineers for the Interdepartmental Task Group on Societal Risk (HSE, 2006a, paragraph 3.1) that states that individual risk does not, by itself, provide sufficient information to assess those risks where many people could be killed in one incident and that the latter is termed societal risk.[1]

3.3.12 The report goes on to state in paragraph 3.2 that the most common way, accepted by both HSE and industry, of calculating societal risk is by using methodology based on Quantified Risk Analysis (QRA), with the results expressed graphically or by a Risk Integral (RI).

3.3.13 Two forms of graphical expression can be used (HSE, 2006a, Section 4):

(a) The frequency, f (in chances per million per year – cpm), of an individual event represented by a particular set of circumstances, (release type, wind, weather, etc.) which lead to N fatalities can be plotted. Individual pairs of f-N data are shown graphically on a log-log scale as a scattering of individual points which at the left hand side starts at the frequency of 1 fatality and terminates at its right hand extremity at the frequency of the maximum number of fatalities representing the "worst case" scenario.

(b) However, to more clearly demonstrate how society in general might regard this concept, the results are more commonly shown graphically, usually on log-log scales, as the cumulative frequency, F (also in cpm), of all circumstances leading to N or more fatalities. Individual F(N) points describe a stepped graph. In practice these are frequently represented as a smooth FN curve.

3.3.14 Thus, the societal risk due to radiological impacts of an accident at a nuclear installation can be expressed in terms of the cumulative frequency of accidents giving rise to different numbers of fatalities, *i.e.* it relates to the collective or population risks from a site, taking into account both the hazards present and the likelihood that those hazards will be expressed in terms of accidents.

[1] Societal risk can be defined more broadly, in terms of overall adverse impacts on society. However, the number of people killed in an incident can be considered as an appropriate surrogate for this overall impact, i.e. the overall impact is taken to be proportional to the number of people killed.

3.3.15 Highton and Senior (2008, page 4) equate the Magnox and AGR demographic siting criteria with remote and semi-urban sites. However, it is important to recognise that the Magnox criteria relate primarily to the first generation of nuclear power stations and that a later generation of stations of this type could have been located in a semi-urban context. The key considerations are the risk predicted to be associated with the type of installation and experience with the safety of such installations in operation. In the context of AWE Aldermaston, which was already operational before siting criteria were developed and is not the site of a nuclear power reactor, there is no prior basis in policy to determine what demographic criteria (if any) apply. In this context it is relevant to note that siting criteria less restrictive than semi-urban have been applied in the UK. Specifically, research reactors have been located in urban settings. Thus, from 1964 until 1982 Queen Mary College maintained a nuclear reactor, the first to be built for a UK university, that was initially sited beneath Mile End Road, but was moved to the new Nucleonics Laboratory in Marshgate Lane in 1967, upgraded in 1968, and decommissioned in 1982, with the site licence surrendered in November 1983 (HSE, 1984).

3.3.16 Highton and Senior (2008, page 4) trace the population weighting factors back to the work of Charlesworth and Gronow (1967), as described above. They determine that the semi-urban 30^{o} sector constraint limits for nuclear power reactors in Hansard (1988) can be derived on the basis of (i) an exclusion zone with zero population for two thirds of a mile and (ii) a uniform population density of 20 people per acre (corresponding to 12,800 per square mile, or 4,942 per square kilometre that is then rounded to 5,000 per square kilometre for application). No exclusion zone is listed in Hansard (1988), so this stipulation presumably arises from the early comment of Marley and Fry (1955) that only a few people should be located within 0.3 of a mile (500 to 1.5 miles).

3.3.17 The all around site constraint limits are three times the 30^{o} sector limits.

3.3.18 Highton and Senior (2008, page 5) comment correctly that the remote siting population constraint limits for nuclear power reactors were not based on consideration of a maximum acceptable uniform population density. Rather, they were defined *a posteriori* by drawing a bounding envelope for existing Magnox sites, i.e. remote was defined as a location where siting of a Magnox power station had been deemed to be acceptable on unspecified grounds that were thought to have taken the remoteness of the situation into account.

3.3.19 Highton and Senior (2008, page 5) state that ‘(c)urrent custom and practice in the UK, requires that general site demographic characteristics as they exist at the time of licensing are maintained throughout the entire life cycle of the plant with an allowance for future developments to account for natural growth whilst restricting inward migration. For residential and commercial developments, therefore, planning control guidelines are in place with local authorities to ensure that the general site characteristics are preserved.’ On this topic they cite an extract from R D Anthony, Chief Inspector Nuclear Installations (Sizewell ‘B’ Public Inquiry, Daily Transcripts Days 56-60). This states, in relation to nuclear power stations, that:

> ‘A site is acceptable only if the surrounding population together with any likely future development remains consistent with the siting policy. For this purpose a proposed site is assessed by comparing the expected future population around it with established criteria using a standardising method which lays greater emphasis on population densities close to the site than on those further away.

The distribution of population around a site is also an important factor in the assessment. Others are the location of schools and hospitals, local communications, population mobility and any other special features which might affect emergency countermeasures which might be necessary should an accident occur. Once a site has been accepted for a nuclear station, arrangements are made to ensure that residential and industrial developments are so controlled that the general site characteristics of the site are preserved, and local authorities consult the Inspectorate with regard to any proposed new development falling outside guidelines which have been laid down. These guidelines were laid down in letters sent by the Department of the Environment in 1961 to local authorities.'

3.3.20 Highton and Senior (2008, pages 5 and 6) state that '(t)he June 1961 letter by the then Minister of Housing and Local Government identified three safeguarding zones (inner, middle and outer) around each site and local councils were asked to consult the Minister on certain proposed developments within each of the three zones. The inner and middle zones were based on nominal 1 and 2 mile radii, with the contours adjusted to avoid cutting through centres of population and to follow natural boundaries. The boundary of the outer zone was specified as being 5 miles in radial extent.' They also note at page 6 that '(t)he radial distance bands up to the 8 km (5 mile) limit published in Hansard (1988), have direct correspondence with the nuclear safeguarding zones discussed above.'

3.3.21 Highton and Senior (2008, page 7) go on to argue that '(s)ince large population centres lying in the range $8 \leq r \leq 30$ km from a nuclear site can influence allowable limits for population growth in the immediate vicinity of the site, it is proposed that $1 \leq r \leq 30$ km be considered as the practical range of interest for demographic analysis to evaluate both the generic and site specific site characteristics (or its equivalent range in imperial units $1 \leq r \leq 20$ miles).'

3.3.22 Furthermore, they argue at page 8 that:

- Given the limitations of the Gaussian plume atmospheric dispersion model to real world situations, there is no rigorous justification for making a distinction between site and 30° sector population weighting factors;

- For application to reactor and non-reactor facilities, population weighting factors based on an inverse power law relationship with exponent n = 1.5 should be used for both all around site and 30° sector demographic analyses;

- For the evaluation of generic site demographic characteristics, population weighting factors should be based on the effective dose limits for initiating fault frequencies of < 1×10^{-4} per annum (500 mSv on-site and 100 mSv off-site);[2]

- For evaluation of site-specific demographic characteristics, the population weighting factors should take account of frequency weighted mean weather relative concentrations, based on the latest available meteorological conditions, as this approach is consistent with the best estimate methodology adopted for PSA [Probabilistic Safety Assessment] analyses;

[2] In practice, because of the normalisation involved in the analysis, the frequency and dose values given here are not specifically required in defining the quantitative compliance criteria adopted by the HSE.

- All around site population constraint limits should be based universally on 3 × 30º sector limits for all nuclear facilities;

- Population densities associated with the semi-urban 30º sector population constraint limit (5000 persons per square kilometre) should be retained as an upper bound to define exclusionary criteria; and

- Population densities associated with the remote site 30º sector population constraint limit (1000 persons per square kilometre) should be retained as a lower bound to define inclusionary criteria. In their Appendix A, Highton and Senior (2008) comment that the population weighting factors in Hansard (1988) are based on the original work of Charlesworth and Gronow (1967), and that the over the range of interest ($1 \leq r \leq 30$ km) these weighting factors are well represented by $w = A/r^n$

3.3.23 As noted above, the remote and semi-urban population constraints are applicable only to nuclear power stations and do not directly apply to other types of nuclear installations. Furthermore, even in the context of nuclear power stations they are not absolute constraints, but may be varied depending on local considerations including economic and socio-economic factors.

3.3.24 For site weighting factors Highton and Senior (2008) give $A = 57.882$ and $n = 1.4$, but for 30º sector weighting factors they give $A = 48.235$ and $n = 1.5$. However, as noted above, it is the 30º sector weighting factors that they propose for use in both site- and sector-specific applications.

3.3.25 The units of w are mSv and are defined as the uniform per capita effective dose averaged over the plume front in the case of an accident originating at a fault frequency of less than 1 10^{-4} per annum and delivering the Basic Safety Limit (BSL) of 100 mSv off site. The value of A follows (approximately) from the observation that for a Gaussian plume the ratio of the average concentration over the plume front to its centreline value is 0.56542 for the case where the edge of the plume exhibits a concentration equal to one tenth of its centreline value.

3.3.26 Appendix A of Highton and Senior (2008) also defines the approach to be adopted to take account of frequency weighted mean weather. The weighted mean relative concentration $(\chi/Q)_{mean}$ is given by:

$$(\chi/Q)_{mean} = (1/N)\Sigma f_i(\chi/Q)_i$$

where i signifies an observation and N is the number of observations.

3.3.27 In an illustrative application of this method, Highton and Senior (2008, Appendix A) use hourly observations of atmospheric stability class and wind speed combinations for Wattisham, 46 km WSW of Sizewell and show that the associated values of A are 19.509 for the site and 16.141 for a 30º sector. These values are approximately 0.33 of the values obtained based on Charlesworth and Gronow (1967) and applicable to Category F conditions with a wind speed of 2 m s^{-1}.

3.3.28 It should be noted that the frequency weighted mean weather as defined by Highton and Senior (2008) takes no account of the relative frequency with which the wind blows into different sectors. This is a matter that is discussed below in the context of site-specific interpretation of the siting criteria (see Section 5.6).

3.3.29 An addendum to Highton and Senior (2008) is provided in Highton (2008). This relates to the siting of new-build nuclear facilities in the United Kingdom, but also gives a clear description of the general approach to evaluation adopted. The following gives a concise summary of the proposed approach and is taken from pages 1 to 5 of Highton (2008).

3.3.30 **Radial Distance Bands:** Radial distance bands should be defined in one kilometre intervals over the total range of demographic interest $1 \leq r \leq 30$ kilometres, or its equivalent in imperial units (one mile intervals over the range $1 \leq r \leq 20$ miles). The general form $1 \leq r \leq n$ is used where the choice of either metric or imperial units is at the discretion of the analyst.

3.3.31 **Site Population Factors (SPFs):** It is proposed that SPFs should be determined as a function of radial distance (r) over the range $1 \leq r \leq n$ using the following expression:

$$SPF(r) = \Sigma(w_j \times \Delta P_j)/\Sigma W_j \times \Delta p_j \quad \text{for } \{(j = 1,r), r = 1,n\}$$

where r is an integer that is numerically equal to the outer radius of the annulus located a distance (r) from the site.

3.3.32 The matrix of SPF values has the following dimensions: rows equivalent to twelve 30º sectors plus all around site, and columns equivalent to the number of distance bands.

3.3.33 Note that distinct population weighting factors w_j and W_j apply to the numerator and denominator respectively. Also, ΔP_j is the actual population of the j^{th} annulus for either a 30º sector annulus or all around site annulus, and Δp_j is the population of the j^{th} annulus for a hypothetical population distribution with a uniform population density. The uniform population density is as set out in Table 3.5.

Table 3.5: Population Density Limits

Type of Site	30º sector		All Around Site	
	Persons per square kilometre	Persons per square mile	Persons per square kilometre	Persons per square mile
Remote	1,000	2,590	250	647
Semi-urban	5,000	12,950	1,250	3,237
New build	1,667	4,317	417	1,079

3.3.34 **Viability Condition:** $SPF(r) < 1.0$ for $\{(j = 1,r), r = 1,n\}$

3.3.35 Identification of the most densely populated 30º sector should be determined by sector rotation of the zero degree datum in either one degree or five degree increments contingent on the required degree of rigour and population densities around the site. For most applications Highton (2008) anticipated that five degree increments would suffice.

3.3.36 **Generic Evaluation:** For a generic evaluation of site demographic characteristics, no distinction is made between the population weighting factors w_j and W_j. Thus:

$w_j = W_j = 56.542/r_w^{1.5}$ mSv for r_w km

$r_w = \{(r_j^2 + r_{j-1}^2)/2\}^{0.5}$

i.e. r_w is the area-weighted mean radius in each distance band.

3.3.37 The generic evaluation of SPFs sets the benchmark for the level of ALARP justification required on a site-specific basis. For such a site-specific evaluation:

$w_j/W_j \leq k$ with $0 < k \leq 1.0$

3.3.38 The discussion in both Highton and Senior (2008) and Highton (2008) is all in terms of well-defined radial distances *r*. This implies a source at a well-defined location that corresponds to the origin of the co-ordinate system adopted. However, in relation to new build, consideration had to be given to the possibility that the reactors could be built at any location within the proposed site. Thus, the evaluation described above was conducted at a grid of locations across each site to determine whether the siting criteria would be violated for construction across the proposed site as a whole or within more limited areas within the site. The results of these studies are recorded in the Consultation on draft National Policy Statements for Energy Infrastructure (Department of Energy and Climate Change, 2009) through comments such as that at page 72, relating to Dungeness 'The Health and Safety Executive has advised that no area of the site exceeds the semi-urban criterion.'

3.4 APPLICATION OF THE EXISTING SITING GUIDELINES TO AWE ALDERMASTON BY THE HEALTH AND SAFETY EXECUTIVE

3.4.1 Notwithstanding the inapplicability of the existing siting guidelines to AWE Aldermaston, HSE has applied those guidelines in a series of calculations as an approach to evaluating the appropriateness of the proposed development at the Boundary Hall site. Those calculations are summarised below, since they are relevant to the position adopted by the HSE in relation to the proposed development.

3.4.2 The HSE has provided several different evaluations of the radiological significance of the population distribution around the AWE Aldermaston site. These evaluations were mainly based on the approach set out by Highton (2008) and summarised in Section 3.3 above. HSE has emphasised that these various evaluations were illustrative rather than definitive, and discussions with HSE representatives made it clear that the evaluations were examples from a larger number of studies that had been undertaken. The earlier evaluations were provided in spreadsheet format, whereas the most recent evaluation comprised output from a computation made using a Geographic Information System (GIS).

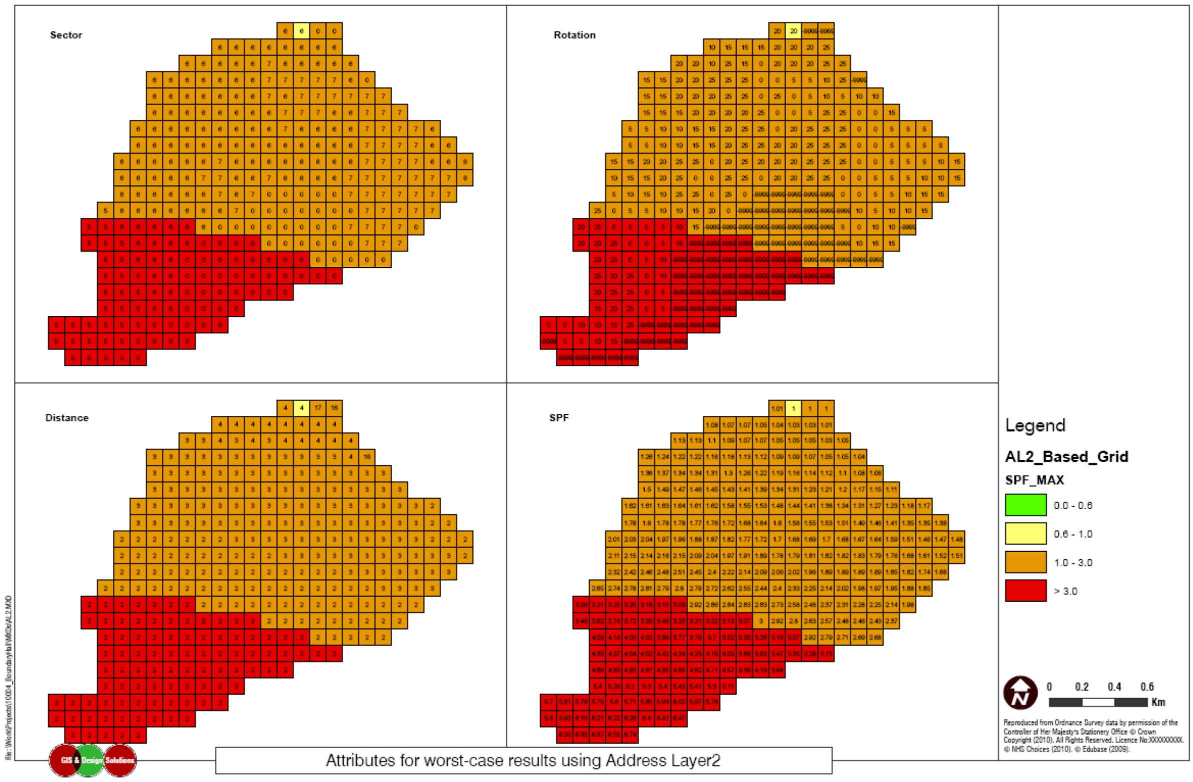
3.4.3 The first spreadsheet (January 2007) treated the AWE Aldermaston site as semi-urban, used twelve 30° sectors, with zero rotation and radial intervals of 1 mile (up to 12 miles). Under these conditions and with the population data provided the maximum SPF value was 0.9445. The second spreadsheet (December 2008) again treated the site as semi-urban, but used twelve 30° sectors, with a 25° rotation and radial intervals of 1 km (up to 30 km). Under these conditions, the maximum SPF for any 30° sector was 0.8649 and the maximum value for any annulus for the site as a whole was 0.763. The third evaluation (February 2009) again treated the site as semi-urban and used twelve 30° sectors, with a 10° rotation. In this case, radial intervals of 1 km (up to 30 km) were used, but the approach went beyond the guidelines in Highton (2008) because the 1 to 2 km band was replaced by 1 to 1.3 km and 1.3 to 2 km bands. This refined approach is unique to the AWE Aldermaston site and appears to have been adopted solely to ensure that the proposed development at the Boundary Hall Site could be entirely included in the 1 to 1.3 km band and therefore associated with a higher population weighting factor than if it had simply been attributed to the standard 1 to 2 km band. In this analysis, the maximum SPF value for any 30° sector was 0.9503. It is important to note that the Proposed Development is located at 1 to 1.3 km from the centre of the AWE Aldermaston site because it constitutes an infill development on an available site broadly consistent with land use in the immediate area, i.e. the population density on the development is similar to the population density in adjacent areas.

3.4.4 It is stressed again that the HSE stated that these spreadsheet analyses were illustrative. They do not provide results for all rotations that should be considered and they are based on population distributions that have been subsequently revised and updated. While, it is interesting to observe that in none of the cases presented was the semi-urban SPF viability criterion exceeded, it is important to re-iterate that there is no basis in policy or precedent for applying this or any other numerical viability criterion to AWE Aldermaston or to developments in its vicinity.

3.4.5 The most recent evaluation (May 2010) adopted a different approach implemented in a GIS, which was identical to that used by the HSE in assessing potential sites for new build nuclear power plants. Rather than adopting a single origin for the assessment, calculations of the same type as undertaken in the spreadsheet calculations were performed on a square grid of edge length 100 m covering the AWE Aldermaston site. For each grid location, SPF values were calculated as a function of radial distance and for rotations of 0, 5, 10, 15, 20 and 25 degrees. The highest SPF value determined for any distance or rotation was assigned to the grid square within the site within which the origin of the calculation was located.

3.4.6 An illustrative set of summary results from this assessment is shown in Figure 3.1. As this figure is rather difficult to read at this scale, it is reproduced in A2 format in a separate document.

Figure 3.1: Results from the New-build Approach to Assessment as Applied by the HSE to AWE Aldermaston



3.4.7 In this case, the SPF values were calculated for a new-build site (since this is the usual application of this methodology). Hence values are a factor of three larger than they would be for a semi-urban location (compare Table 3.5). Results are colour coded by grid square, with red indicating squares for which the maximum SPF value for any distance and rotation was >3.0. The actual maximum SPF values are listed in the lower right quadrant of Figure 3.1 and values of up to 6.74 are recorded (corresponding to 2.25 for a semi-urban site). The other three quadrants give supplementary information. The upper left quadrant gives the sector in which the maximum SPF value is located, the upper right quadrant gives the rotation for which the maximum SPF value was obtained (the significance of the -0000 values has not been determined) and the lower left quadrant gives the upper limit of the distance band (km) in which the maximum SPF value arises.

3.4.8 As would be expected, the largest maximum SPF values arise in the south-west part of the site, as these areas are closest to the highest local densities of population. Furthermore, the maximum SPF values are highest at locations close to the site boundary, because this minimizes the distance to the nearest population. These maximum SPF values are typically found in Sector 6 (175 to 205 degrees) and at 1 to 2 km from the site. This is the sector and distance range within which the Proposed Development at the Boundary Hall site is located.

3.4.9 It is important to emphasise the risk-informed nature of the siting criteria when considering whether the approach adopted in applying those criteria to nuclear new build is also applicable to AWE Aldermaston (bearing in mind that no policy position exists on the siting of nuclear installations other than nuclear power stations). With new build, the key consideration is that the nuclear power station could be constructed at any location within the potential site. Therefore, the siting analysis properly considers each potential location in turn (using a relatively fine grid so that a quasi-continuous spatial evaluation can be provided). Through this analysis, HSE can come to a view as to whether any parts of the potential site are inappropriate for construction. However, if a power station were subsequently constructed at a location deemed suitable, future developments around the site would be assessed using a calculation of SPF values centred on a point representing the actual location of the power station. In the case of AWE Aldermaston, HSE has undertaken the same type of analysis, arguing that the location of sources on the site is unspecified (see below). However, this is not a risk-informed approach, since every off-site location is evaluated by reference to its own worst-case source location. Thus, an off-site location just north of the site will be evaluated as if the entire accident potential of the site was located close to it on the northern boundary, and an off-site location just south of the site will be evaluated as if the entire accident potential of the site was located close to it on the southern boundary. This is excessively penalising to developments and there is nothing in policy statements that requires this approach. Indeed, all the relevant papers cited in Sections 3.2 and 3.3 pre-suppose that a well-defined point origin for the calculations exists.

3.4.10 It is recognised that security considerations may dictate that only limited information on the nature and location of potential accident sources is released into the public domain. However, such information has been made available to HSE and there is no reason why it should not be used to assess developments in the vicinity of the site rather than relying on an approach developed for proposed new-build nuclear power station sites. The AWE Aldermaston site undertakes well defined operations in various specialised facilities. Thus, the determination of possible locations of potential accidents under current and projected operational arrangements should be straightforward, just as is the case at other nuclear licensed sites. If AWE Aldermaston wished in future to substantially modify its operational procedures, the revised procedures would require evaluation at the time to ensure that they did not compromise the safety of populations around the site. If issues arose in this respect, the proposed operational changes could be denied, or subject to any conditions necessary for the maintenance of safety.

3.4.11 On the issue of interpretation, whenever quantitative calculations are undertaken, it is important to bear in mind that they are for the purpose of making comparisons with guidelines. Those guidelines are intended to inform judgements made by the HSE, e.g. in relation to the acceptability of proposed developments in the vicinity of a site. In the context of such developments, local authorities are required to consult with the HSE, but the limiting criteria based upon population distribution are used only for guidance, and the HSE cannot necessarily insist on rigid adherence to demographic constraint limits. Specifically, local considerations may take precedence over the numerical criteria. This was well expressed by Tildsley (1985, page 9) who wrote 'In practice the Inspectorate has not required rigid adherence to them but has been flexible in their application; they have been treated as guidelines to which exceptions may be made in either direction. Some sites may possess compensatory features which allow them to be accepted even though they may not fall strictly within the guidelines, whilst the opposite may be true in other cases.' Just as the Inspectorate has not required rigid adherence to quantitative demographic constraint limits, so it cannot require local authorities to apply such rigid adherence, since those authorities have a responsibility to take into account other unquantifiable factors. Such factors may enhance or diminish the desirability of a particular development.

3.4.12 In view of these considerations, the quantitative analytical tools described above are properly regarded as an instrument designed to help the local authorities, in consultation with the HSE, achieve this objective. They are an aid to decision making, but do not determine the decision, since other, unquantifiable factors may need to be taken into account.

3.5 EVALUATION OF THE APPLICABILITY OF EXISTING SITING CRITERIA

3.5.1 From the historical review set out in Section 3.2, it is clear that siting criteria in the UK were developed solely in the context of the siting of nuclear power reactors. Furthermore, those guidelines were developed primarily to control the **siting** of such installations. Their use to control **developments** in the vicinity of existing installations has been given much less consideration. In particular, there do not appear to have been any policy or technical analyses of their role in achieving the primary policy requirement that once a site has been accepted for a nuclear station, arrangements are made to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. It is not self-evident that the same numerical criteria should be used in an initial siting evaluation as in the control of developments. In particular, it is noted that the burden of compliance in the two cases lies mainly with different stakeholders. In the case of siting, the burden lies mainly with the developer/operator of the proposed installation, whereas in the case of developments in the vicinity of an existing installation the burden lies primarily not with the operator of the installation, but with the proponent of the development. Also, the siting of a new nuclear installation has a potential impact from accidents on the entire population in its vicinity, hence the use of numerical criteria based on the total population in a sector or all around the site weighted for distance from the site as a surrogate for weighting for the radiological impact of accidents on individuals located at different distances. In contrast, with a proposed development in the vicinity of an existing nuclear installation, what is of concern is the increment in potential impact from accidents due to the presence of additional persons associated with the proposed development. This matter is taken up in Section 5, which compares the unweighted and weighted population density in the vicinity of the AWE Aldermaston Site with and without the proposed development to determine whether it constitutes a substantial perturbation to the general characteristics of the site (the term 'site' in this context being necessarily interpreted as the area in the vicinity of the licensed nuclear site and not the licensed nuclear site itself).

3.5.2 AWE Aldermaston came into existence before any formal criteria for the siting of nuclear power reactors had been defined. In developing the criteria, no reference was made to the type of activities undertaken at AWE Aldermaston and the criteria did not give any consideration to the population distribution around AWE Aldermaston.

3.5.3 Current UK international obligations on siting under the Conventions on Nuclear Safety and the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, as expressed through the United Kingdom's Fourth National Report on compliance with Article 17: Siting of the Convention on Nuclear Safety obligations (HSE, 2007), relate entirely to power-generating nuclear reactors. They do not relate to several other types of nuclear installation (e.g. research reactors). Furthermore, the HSE recognises that AWE Aldermaston is not within the scope of the two conventions.

3.5.4 Based on the above, it seems clear that any proposals for developments in the vicinity of AWE Aldermaston can, and should, be decided on their own merits, having regard to the general obligation to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. This does not preclude the use of numerical analyses, but any such analyses should only be used as guidance to inform decision making, which needs to take into account numerous other factors, some of which may be unquantifiable. In particular, those factors include socio-economic considerations.

3.5.5 Nevertheless, there are technical aspects of the existing guidelines that can properly be used to evaluate whether developments in the vicinity of all nuclear licensed sites, including AWE Aldermaston, are appropriate. In particular, extensive technical studies have demonstrated that the radiological impacts on individuals of accidents resulting in off-site releases of radioactive materials typically decrease in inverse proportion to distance to the power 1.5. This means, for example, that the radiological impact on an individual at 10 km downwind of such an accident is a factor of 31.6 ($10^{1.5}$) smaller than the impact on an individual at 1 km downwind. Thus, when evaluating the overall impact of a potential accident, it is appropriate to give consideration to the cumulative weighted population downwind (i.e. the accumulation over distance of the product of the number of people exposed at each distance and a quantity proportional to the radiological impact on people present at that distance). However, the aspect of the current guidelines for nuclear power reactors that cannot be used is the limiting population densities adopted. This is because those densities are conditioned on the types of accidents that could occur at nuclear power reactors and their associated likelihoods of occurrence. These types of accidents are not, in general, relevant at other licensed nuclear sites.

3.5.6 In Section 4, I give consideration to the types of accidents that could occur at AWE Aldermaston in comparison with the types of accidents that could occur at nuclear power reactors. This provides a basis for determining the potential magnitudes of off-site radiological impacts and provides a context for the discussion of the population density and distribution that should be acceptable in the vicinity of AWE Aldermaston. This latter topic is taken up in Section 5, where use is made of those technical components of the existing quantitative analysis method that are relevant in a wider context than nuclear power reactor sites.

4. Impacts of Potential Accidents at AWE Aldermaston compared with Potential Accidents at Nuclear Power Plants

4.1 CONTEXT

4.1.1 As described in Section 3.2, the AWE Aldermaston site was established prior to the development of any siting guidelines for nuclear installations in the United Kingdom. Furthermore, those siting guidelines were developed in relation to the siting of nuclear reactors for power production. Nuclear reactors for research applications, such as the small high neutron flux research reactor (VIPER) and materials test reactor (HERALD) located at Aldermaston (MoD, 2006) were not covered by this policy and such reactors have been located in urban environments within the UK, as discussed in Section 3.3 in connection with the reactor at Queen Mary College.

4.1.2 In view of these considerations, applications for developments around the site at the present day need to be considered on their merits and not in relation to siting criteria developed for nuclear power plants. In making such an evaluation, consideration needs to be given both to the design of the various facilities and also to operational experience in order to provide evidence of the projected frequencies of accidents of different magnitude and their radiological implications. On this point, it is relevant to note that the HSE has set out in Section 2 of its Statement of Case that the AWE Aldermaston site handles radioactive substances such as plutonium, tritium and enriched uranium. Thus, the types of accidents that could occur at AWE Aldermaston would be most likely to involve releases of radioisotopes of these materials. It seems unlikely that these would have off-site consequences of comparable magnitude to those arising from a major release of fission products (notably Iodine-131, Caesium-134 and Caesium-137) and actinides due to a beyond design basis accident at a nuclear power reactor. Thus, the types of accidental release of relevance are very different from those used as a basis for developing the siting criteria for nuclear power reactors (for which a release of Iodine-131 alone was used).

4.1.3 In this section, an evaluation is provided of the radiological impacts of potential accidents that could occur at AWE Aldermaston in comparison with the radiological impacts of potential accidents that could occur at nuclear power reactors and other types of nuclear installations. This analysis provides insights into the degree to which controls on developments around AWE Aldermaston should be less restrictive than controls on developments around nuclear power plants.

4.2 SOURCE TERMS

4.2.1 In evaluating the radiological impact of potential accidents that could result in off-site releases of radioactive materials, consideration needs to be given to the projected frequencies of accidents of different types and the amounts of various radionuclides that could be released in those accidents. The source term for an accident describes the amounts of the various radionuclides that could be released. In the following paragraphs, appropriate source terms for potential accidents at AWE Aldermaston and at nuclear power reactors are discussed in turn. The evaluation of the off-site radiological impacts of such accidents is discussed in Section 4.3.

4.2.1 AWE Aldermaston

4.2.2 As noted in Section 4.1, accidents at AWE Aldermaston would most likely involve tritium, plutonium or highly enriched uranium. However, tritium emits only low-energy beta particles and it is almost impossible to envisage sufficient being released in an accident to give rise to deterministic effects[3] in individuals off site. Thus, the sole concern would be with stochastic effects[4], including the induction of late effects (cancer and serious hereditary disease). For such late effects, the population mainly impacted is not that close in to the site boundary, but those at several kilometres to tens of kilometres distant. In the case of uranium or plutonium, releases would be due to a chemical fire or explosion. In the case of either element, the release would be expected to be as an insoluble to highly insoluble oxide aerosol, and the radiological impact would be primarily due to the inhalation of that aerosol by individuals downwind of the site at the time of the accident. For insoluble, alpha-emitting particulate aerosols, external exposure is a minor consideration, and the low bioavailability of actinides both to plants and from the gastrointestinal tract of domesticated animals and humans, makes exposure due to ingestion of foodstuffs or soil of little significance. Furthermore, such pathways are only of relevance in the longer-term after an accident when they can be mitigated by the institution of controls on consumption of foodstuffs from the contaminated area.

4.2.3 Although requests were made to the HSE for relevant source term information relating to AWE Aldermaston, no such information was provided. Similarly, no such information was provided for use by Electrowatt Engineering (UK) Limited when they undertook a study to investigate the development of possible new guidelines for the siting on nuclear installations in the UK (Electrowatt, 1997). However, the general commentary given at page 43 of the Electrowatt (1997) report is considered to remain valid. The information given there is reproduced in full below.

> ‘The Atomic Weapons Establishment at Aldermaston conceivably holds many kilograms of plutonium. For safety purposes, this can be conveniently classed as ‘new’ plutonium and ‘old’ plutonium, with the latter being more than 30 years old. The new plutonium would give rise to a larger radiological impact for a unit mass release.
>
> There are two possible accident scenarios which must be considered (1) criticality and (2) fire. In the case of criticality, there would be localised damage and a large neutron pulse, but little in the way of fission product formation. If the fissile material were in the form of a solution, e.g. plutonium nitrate, then a criticality accident could give rise to substantial local contamination by plutonium, but only limited off-site release.
>
> A more serious situation occurs with fires, where up to 20% of the plutonium metal could be volatilised and dispersed in the form of aerosol particles in the 1 to 10 μm size range. The associated source term could readily be calculated from the known

[3] Deterministic effects are those due to cell sterilisation and killing, and are characterised by a threshold dose or dose rate for clinical expression.

[4] Stochastic effects comprise cancer in the irradiated individual and hereditary disease in his or her descendents. The probability of such effects occurring is taken to be linearly related to the dose received, i.e. there is no threshold for such effects, though at low doses and dose rates the incidence becomes almost impossible to establish because of the 'natural' incidence of these effects.

isotopic constitution of the plutonium and the amount released. Herein, simple scoping calculations for dispersion of unit mass of ^{239}Pu are presented.'

4.2.4 The Electrowatt (1997) calculations were undertaken for various masses of ^{239}Pu released, but the reference results were reported for 1 kg. It seems extremely unlikely that an amount larger than this would be released. The total amount of plutonium required to make a nuclear weapon is a few kilograms, and substantially smaller quantities would generally be handled in a research and development context, both to avoid the possibility of criticality and because of the desirability of controlling the amounts of fissile material being used on the basis of safety and security considerations.[5] To achieve a 1 kg release would require a fire or explosion involving at least 5 kg of plutonium, volatilisation towards the upper end of the observed range, and only limited deposition of the plutonium prior to its release to the atmosphere, i.e. little effect of the building within which the fire or explosion occurred on the amount of volatilised plutonium released. Therefore, here radiological impact calculations are undertaken for a worst-case release of 1 kg of ^{239}Pu. Radiological impacts can be scaled to other, generally smaller, release sizes, as required.[6]

4.2.5 The radioactivity content of 1 kg of ^{239}Pu is 2.30 10^{12} Bq.

4.2.6 The only other possibility for a large ^{239}Pu release would be due to a fire or explosion within a facility in which plutonium was being stored (rather than being handled). However, the potential for a fire arising in such a facility or affecting the stored material if it did occur is assessed as highly remote. Such facilities would typically be of metallic construction, hold fissile materials in inert form, and would not contain significant amounts of combustible materials.

4.2.2 Nuclear Power Reactors

4.2.7 Reactor accidents could occur at UK Magnox, Advanced Gas Cooled Reactor (AGR) or Pressurised Water Reactor (PWR) sites. All three types of site were addressed in Electrowatt (1997). For the most severe accidents, the fractions of the core inventory released to the atmosphere were typically 0.7 for iodine and 0.5 for caesium (see accident UK1 at page 37 of Electrowatt, 1997). As releases of ^{131}I, ^{134}Cs and ^{137}Cs would be expected to dominate radiological impacts in major reactor accidents, as was the case at Chernobyl, only analyses for these radionuclides are discussed below. The frequency of such accidents was assessed in Electrowatt (1997, page 37) as around 3 10^{-8} per year. Such accidents can be described as worst-case for nuclear power reactors.

4.2.8 From Table 4.2 of Electrowatt (1997), the core inventories of ^{131}I, ^{134}Cs and ^{137}Cs in a PWR are 3.35 10^{19}, 5.18 10^{18} and 3.40 10^{18} Bq, respectively. Therefore, the releases projected to occur in worst-case accidents are 2.35 10^{19}, 2.59 10^{18} and 1.70 10^{18} Bq, respectively.

5 Site licence conditions stipulate that no nuclear matter shall be brought onto site except in accordance with adequate arrangements made by the licensee for that purpose. The HSE has powers to intervene to ensure that, for specific activities, it can assess the adequacy of the licensee's arrangements before nuclear matter is brought on site. The term 'adequate' means that the requirements of the law have been met. It is not to be construed as meaning the achievement of barely acceptable performance.

6 Here and throughout the term 'worst-case' as applied to a release of activity or an accident means close to the largest release or worst accident that can be envisaged. The definition is not precise and the intent is to describe a release or accident that is close to the largest or worst that can be envisaged.

4.3 DISPERSION AND RADIOLOGICAL IMPACT ON INDIVIDUALS

4.3.1 As the aim here is only to determine the relative radiological impact of potential accidents with comparable frequency arising at AWE Aldermaston and sites for nuclear power reactors, the details of the dispersion conditions are of little relevance, provided that the same assumptions are made for the two types of accident. Here, the calculations are undertaken at a point 1 km downwind of a ground-level release occurring under Category F conditions, with a wind speed of 2 m s^{-1}. These conditions were adopted because they have been used previously for reference accidents (see Section 3.2). The distance of 1 km is used because this is comparable to the distance between buildings on the AWE Aldermaston site and the proposed development at Boundary Hall. However, impacts at other distances can readily be obtained by scaling as $1/r^{1.5}$, where r (km) is the distance of interest.

4.3.2 Under the conditions set out in the previous paragraph, Figure 18 of NRPB (1979) can be used to determine that the atmospheric transport factor at the location of interest is approximately 1 10^{-4} s m^{-3}. This means that for a release rate of 1 Bq s^{-1}, the maintained concentration at the location of interest would be 1 10^{-4} Bq m^{-3}.

4.3.3 The typical breathing rate for an adult is 1.2 m^3 h^{-1} (3.33 10^{-4} m^3 s^{-1}) (ICRP, 1994; Smith and Jones, 2003). Thus, for a release rate of 1 Bq s^{-1}, the intake rate at the location of interest would be 3.33 10^{-4}×1 10^{-4} = 3.33 10^{-8} Bq s^{-1}.

4.3.4 The above analysis applies independent of the period of the release. Thus, at the reference location, an adult undertaking light exercise will inhale 3.33 10^{-8} Bq of activity for every 1 Bq released.

4.3.5 The ICRP (1996) has provided values of committed effective dose per unit intake for all the radionuclides of relevance to the comparison presented here. However, in using these values a selection has to be made between whether the material is rapidly soluble in the respiratory system (Type F), moderately soluble (Type M) or insoluble (Type S).

4.3.6 Assuming that the ^{239}Pu released from AWE Aldermaston was released in a fire, the Electrowatt (1997) report considered that it would be sensible to assume that an oxide form was dispersed and to adopt inhalation Type S. In adults, this is associated with an effective dose of 1.6 10^{-5} Sv per Bq inhaled (ICRP, 1996).

4.3.7 For ^{131}I, ^{134}Cs and ^{137}Cs released in an accident at a nuclear power reactor, it is appropriate to use inhalation Type F, as most forms of iodine and caesium are highly soluble and readily absorbed from the respiratory tract. This is the default lung absorption type given in Table 2 of ICRP (1996). For adults, the relevant values of committed effective dose per unit intake are 7.4 10^{-9}, 6.6 10^{-9} and 4.6 10^{-9} Sv per Bq inhaled for ^{131}I, ^{134}Cs and ^{137}Cs, respectively.

4.3.8 Thus, the radiological impacts of potential worst-case accidents at AWE Aldermaston and a nuclear power reactor for the reference conditions set out above are as listed in Table 4.1.

Table 4.1: Radiological Impacts of Potential Worst-Case Accidents

Radionuclide	Release (Bq)	Amount Inhaled (Bq)	Committed Effective Dose per Unit Intake (Sv Bq^{-1})	Committed Effective Dose (Sv)
AWE Aldermaston				
Pu-239	$2.30\ 10^{12}$	$7.66\ 10^{4}$	$1.6\ 10^{-5}$	$1.23\ 10^{0}$
Total				**$1.23\ 10^{0}$**
Nuclear Power Reactor				
I-131	$2.35\ 10^{19}$	$7.83\ 10^{11}$	$7.4\ 10^{-9}$	$5.79\ 10^{3}$
Cs-134	$2.59\ 10^{18}$	$8.82\ 10^{10}$	$6.6\ 10^{-9}$	$5.82\ 10^{2}$
Cs-137	$1.70\ 10^{18}$	$5.66\ 10^{10}$	$4.6\ 10^{-9}$	$2.60\ 10^{2}$
Total				**$6.63\ 10^{3}$**

4.3.9 Thus, in this reference case, the radiological impact of the reference worst-case accident for a nuclear power reactor is a factor of 6630/1.23 = 5390 larger than the radiological impact of the reference worst-case accident for AWE Aldermaston.

4.3.10 Because a worst-case accident at a nuclear power reactor is considered, the radiological impacts are very large at 1 km. An effective dose of only around 50 Sv would be enough to kill a person in one to two days and an effective dose of 10 Sv would be fatal within 30 to 60 days. In contrast, a committed effective dose of 1.23 Sv from inhaled ^{239}Pu would be very unlikely to give rise to deterministic effects, so the principal concern would be the induction of cancer over a period of several decades following the accident.[7]

4.3.11 Another way of looking at this result is by reference to the Basic Safety Limits (BSLs) and Basic Safety Objectives (BSOs) given in the Safety Assessment Principles for Nuclear Facilities (see page 101 of HSE, 2006b). The values of the BSL and BSO for accidents giving different levels of committed effective dose to any person off site are listed in Table 4.2.

[7] In practice, the committed effective dose from such a plutonium release could be substantially reduced by sheltering during the passage of the radioactive plume (as is advised in AWE Aldermaston Emergency Plan), because indoor air concentrations would be substantially less than outdoor concentrations. The comparison made here is between radiological impacts of the different types of accidents assuming no mitigation measures were adopted. In practice, the degree of mitigation is likely to be at least as large in the case of a release of plutonium as in the case of a large reactor accident, for which multiple pathways of exposure, both during and after passage of the plume, would need to be taken into account.

Table 4.2: Basic Safety Limits and Basic Safety Objectives for Accidents at an Individual Facility for Any Person off the Site

Effective Dose (Sv)	Total predicted frequency per annum	
	BSL	BSO
0.0001 to 0.001	1	0.01
0.001 to 0.01	0.1	0.001
0.01 to 0.1	0.01	0.0001
0.1 to 1.0	0.001	0.00001
> 1.0	0.0001	0.000001

4.3.12 Thus, assuming that the nearest individual to the site is located at 1 km and bearing in mind that the atmospheric stability and wind speed conditions assumed imply an unusually low degree of atmospheric dispersion, the committed effective dose from a worst case accident for AWE Aldermaston is only marginally higher than the highest effective dose for which the BSL and BSO are defined. In contrast, the source term for the power reactor accident would have to be more than 6,000 times smaller in order to give rise to a committed effective dose of similar magnitude to the highest effective dose for which a BSL and BSO are defined.

4.3.13 For comparison, the Electrowatt report (Electrowatt, 1997) at page 84 compared the relative magnitudes of the largest types of accidents that could be anticipated at various types of installations, normalised to a large PWR accident. Results were 1.0 for PWR, AGR, Magnox and reprocessing plant accidents, 0.1 for nuclear submarine accidents and 0.001 for research reactor accidents. For comparison, from the analysis presented above, AWE Aldermaston would be assigned a relative magnitude of 1.23/6630 = 0.0002. This strongly indicates that AWE Aldermaston should be considered more closely comparable to a research reactor site than to a power reactor site. For research reactor sites, no specific constraints on local population density have ever been imposed in the UK.

4.3.14 It is recognised that siting considerations do not relate only to the accidents that could have the largest off-site consequences, but to the whole spectrum of accidents with significant off-site consequences. Nevertheless, the accidents with the largest consequences do provide a good indication of the hazards that have to be taken into account. Thus, it is considered that the argument that the radiological risks from AWE Aldermaston on the local population are orders of magnitude less than the radiological risks would be from a nuclear power station sited at the same location applies both to worst-case accidents and to the whole spectrum of accidents that might occur.

4.3.15 In this context, it is of interest to examine the radiological impact of a more plausible off-site release than that postulated in respect of the worst-case accident. From the Electrowatt (1997) report, the fractional release of lanthanides and actinides to the environment in a major nuclear reactor accident (UK1, as used for the ^{131}I, ^{134}Cs and ^{137}Cs release fractions discussed in Section 4.2.2) is 0.004 (see Electrowatt (1997) page 42 and also the footnote to Table 4.10 of that report which defines the elements included in the lanthanum (La) group). For less catastrophic accidents, the release fraction could be orders of magnitude lower.

4.3.16 Assuming that a fire occurred during research and development activities involving 0.1 kg of ^{239}Pu (a reasonable quantity to handle in a laboratory, rather than the 5 kg amount considered in the worst-case) and that a fraction of 0.004 of this was released, the activity released would be $9.20\ 10^{8}$ Bq, i.e. 0.0004 of that released in the worst-case accident discussed in Section 4.2.1. Thus, the committed effective dose at 1 km downwind would be $1.23 \times 0.0004 = 0.000492$ Sv (0.492 mSv). This is less than the limit on annual effective dose for a member of the public of 1 mSv, and is only about one fifth of the annual effective dose incurred from natural background radiation (see, e.g., Thorne, 2003).

5. Comparison of Existing and Projected Future Population Densities in the Vicinity of AWE Aldermaston

5.1 CONTEXT OF THE COMPARISON

5.1.1 In previous sections, it has been made clear the existing guidelines on population densities in the vicinity of nuclear power stations do not apply to AWE Aldermaston. Furthermore, in Section 4 it is demonstrated that the potential off-site radiological consequences from worst-case accidents at AWE Aldermaston are orders of magnitude lower than the consequences from worst-case power reactor accidents and that siting and development considerations for AWE Aldermaston are more akin to those arising in the vicinity of research reactors than those arising in the vicinity of nuclear power stations. These considerations strongly suggest that there is no need to place an upper bound on the population density in the vicinity of AWE Aldermaston. However, if it was determined that such a bound should be employed. that bound should clearly be higher than the bound employed in relation to semi-urban siting of nuclear power stations. In this section, the HSE methodology is used to investigate the distance-weighted population density that exists in the vicinity of AWE Aldermaston and the perturbation to that distance-weighted population density that would be caused by permitting the proposed development at Boundary Hall.

5.2 METHODOLOGICAL BASIS

5.2.1 Because it is not accepted that the existing guidelines on population density are applicable at AWE Aldermaston, it is appropriate to rewrite the approach used by HSE such that the limiting population density does not have to be supplied as an input to the analysis.

5.2.2 It will be recalled that SPF values are calculated using:

$$\mathrm{SPF}(r) = \Sigma(w_j \times \Delta P_j)/\Sigma W_j \times \Delta p_j \quad \text{for } \{(j = 1,r),\ r = 1,n\}$$

5.2.3 However, in agreement with HSE, a generic approach to assessment is used (i.e. ALARP issues are not addressed), so $w_j = W_j$. Furthermore, Δp_j is the population of the jth annulus for a hypothetical population distribution with a uniform population density. Because, as discussed above, there is no *a priori* basis for defining the limiting population density around the site, the limiting uniform population density is not specified numerically. Here it is symbolised as ρ persons per km^2. Thus, the above equation becomes:

$$\mathrm{SPF}(r) = \Sigma(W_j \times \Delta P_j)/\rho\Sigma W_j \times \Delta A_j \qquad \text{for } \{(j = 1,r),\ r = 1,n\}$$

where ΔA_j is the area of the j^{th} annular sector and is equal to $\pi(r_j^2 - r_{j-1}^2)/12$ for a 30º sector.

Also: $W_j = 56.542/r_w^{1.5}$ where $r_w = \{(r_j^2 + r_{j-1}^2)/2\}^{0.5}$

However, since W_j appears in both the numerator and denominator of the equation for SPF, the numerical coefficient cancels and we obtain the overall formula:

$$\mathrm{SPF}(r) = \Sigma(\Delta P_j/r_w^{1.5})/\rho\Sigma\ \pi(r_j^2 - r_{j-1}^2)/12 r_w^{1.5} \quad \text{for } \{(j = 1,r),\ r = 1,n\}$$

5.2.4 Because the value of ρ is not prescribed, it is preferable to rewrite this equation as:

$$\rho \times \mathrm{SPF}(r) = \Sigma(\Delta P_j / r_w^{1.5}) / \Sigma\, \pi(r_j^2 - r_{j-1}^2)/12 r_w^{1.5} \text{ for } \{(j = 1,r),\ r = 1,n\}$$

5.2.5 As SPF(r) < 1.0 for {(j = 1,r), r = 1,n} is the required viability condition, this transforms into:

$$\Sigma(\Delta P_j / r_w^{1.5}) / \Sigma\, \pi(r_j^2 - r_{j-1}^2)/12 r_w^{1.5} < \rho \text{ for } \{(j = 1,r),\ r = 1,n\}$$

where ρ is the maximum acceptable uniform population density.

5.2.6 Thus, the analysis becomes a determination of the minimum value of ρ for which the above inequality is satisfied. This is termed the limiting population density for the site.

5.3 POPULATION DATA USED

5.3.1 The data used in this analysis are the residential night-time population taken from Address Layer 2 of the population census data. This has been agreed as an appropriate basis with the HSE. Because, in the present context, the interest is in populations and population changes close to the site, only the data out to 5 km are listed in Table 5.1, though in comprehensive calculations evaluations would be made out to 30 km. Note that the sectors are rotated by twenty five degrees relative to the standard compass directions. This was found to be the worst case using 5 degree increments of rotation. A point origin located in the centre of the AWE Aldermaston site was adopted.

Table 5.1: Illustrative Population Data

Sector Angular Range (Degrees)	Population 0-1 km	Population 1-2 km	Population 2-3 km	Population 3-4 km	Population 4-5 km
25 to 55	0	27	46	25	18
55 to 85	0	156	38	164	648
85 to 115	0	29	117	148	24
115 to 145	51	1004	1046	717	100
145 to 175	21	1218	3121	199	498
175 to 205	106	2824	2281	43	78
205 to 235	0	2239	1506	81	75
235 to 265	5	148	725	170	278
265 to 295	0	0	31	161	248
295 to 325	11	5	24	239	285
325 to 355	0	246	28	85	320
355 to 25	0	2	7	779	135

5.3.2 The value for the sector between 175 and 205 degrees in the distance range 1 to 2 km is the existing population of 2824. If the Proposed Development were to go ahead, it would be augmented by 268 (Developer's estimate).

5.4 CALCULATIONS OF LIMITING POPULATION DENSITY

5.4.1 Using the data given in Table 5.1, values of $\Sigma(\Delta P_j/r_w^{1.5})/\ \Sigma\ \pi(r_j^2 - r_{j-1}^2)/12r_w^{1.5}$ are as shown in Table 5.2. Note that this is for the existing population unmodified by the new development.

Table 5.2: Values of $\Sigma(\Delta P_j/r_w^{1.5})/\ \Sigma\ \pi(r_j^2 - r_{j-1}^2)/12r_w^{1.5}$

Sector Angular Range (Degrees)	Out to 1 km	Out to 2 km	Out to 3 km	Out to 4 km	Out to 5 km
25 to 55	0.00	16.26	21.51	19.99	18.19
55 to 85	0.00	93.93	75.89	78.51	107.17
85 to 115	0.00	17.46	37.45	45.79	40.59
115 to 145	194.81	707.22	732.75	667.04	575.95
145 to 175	80.21	775.67	1222.78	1008.38	892.15
175 to 205	404.89	1913.82	1866.22	1511.62	1296.01
205 to 235	0.00	1348.17	1293.22	1052.87	903.98
235 to 265	19.10	99.18	225.56	200.01	188.04
265 to 295	0.00	0.00	6.58	22.22	34.33
295 to 325	42.02	25.16	23.26	43.88	55.12
325 to 355	0.00	148.12	112.90	100.10	105.31
355 to 25	0.00	1.20	2.36	83.70	79.85

5.4.2 This demonstrates that, with the existing population, the limiting population density is approximately 1,914 persons per km^2, i.e. the site would satisfy the numerical siting criteria for any criterion population density greater than 1,914 persons per km^2.

5.4.3 The analysis shown in Table 5.2 does not impose an exclusion zone of zero population density, as there is no requirement in policy so to do, but it does extrapolate the existing weighting factors into the distance range below 1 km, which is beyond their stated range of applicability (though the degree of extrapolation is very limited, since the relevant population group is located at 0.8 to 1.0 km from the origin adopted). However, it might be considered desirable that the number of persons present very close to the site should be small. Therefore, a variant calculation was undertaken in which the first term in the denominator summation $\Sigma\ \pi(r_j^2 - r_{j-1}^2)/12r_w^{1.5}$ was set to zero. This effectively imposes a requirement for zero population density out to 1 km. Of course, this calculation cannot be applied over the sector annulus from 0.0 to 1.0 km, as there is a non-zero population present. However, it can be applied beyond 1.0 km. Results are shown in Table 5.3.

Table 5.3: Values of $\Sigma(\Delta P_j/r_w^{1.5})/ \Sigma\ \pi(r_j^2 - r_{j-1}^2)/12\ r_w^{1.5}$, but requiring Zero Population Density from 0.0 to 1.0 km

Sector Angular Range (Degrees)	Out to 1 km	Out to 2 km	Out to 3 km	Out to 4 km	Out to 5 km
25 to 55	-	34.38	34.72	28.86	24.67
55 to 85	-	198.63	122.52	113.35	145.32
85 to 115	-	36.92	60.46	66.10	55.05
115 to 145	-	1495.46	1182.98	963.02	780.99
145 to 175	-	1640.21	1974.09	1455.82	1209.74
175 to 205	-	4046.91	3012.88	2182.37	1757.38
205 to 235	-	2850.79	2087.82	1520.06	1225.78
235 to 265	-	209.73	364.15	288.75	254.99
265 to 295	-	0.00	10.63	32.08	46.55
295 to 325	-	53.20	37.55	63.35	74.74
325 to 355	-	313.22	182.27	144.52	142.79
355 to 25	-	2.55	3.80	120.84	108.28

5.4.4 As the numerator in the calculations is unchanged, but the denominator is decreased, the limiting population density is also increased to approximately 4,047 persons per km^2.

5.4.5 These analyses were then repeated with the number of persons in the sector between 175 and 205 degrees and the distance range 1 to 2 km augmented by 268 to represent the occupancy of the Proposed Development. Results without an exclusion zone are shown in Table 5.4 and results with a zero population density exclusion zone to 1 km are shown in Table 5.5.

Table 5.4: Values of $\Sigma(\Delta P_j/r_w^{1.5})/ \Sigma\ \pi(r_j^2 - r_{j-1}^2)/12\ r_w^{1.5}$ including the Population of the Proposed Development

Sector Angular Range (Degrees)	Out to 1 km	Out to 2 km	Out to 3 km	Out to 4 km	Out to 5 km
25 to 55	0.00	16.26	21.51	19.99	18.19
55 to 85	0.00	93.93	75.89	78.51	107.17
85 to 115	0.00	17.46	37.45	45.79	40.59
115 to 145	194.81	707.22	732.75	667.04	575.95
145 to 175	80.21	775.67	1222.78	1008.38	892.15
175 to 205	404.89	2075.19	1982.74	1605.71	1376.39
205 to 235	0.00	1348.17	1293.22	1052.87	903.98
235 to 265	19.10	99.18	225.56	200.01	188.04
265 to 295	0.00	0.00	6.58	22.22	34.33
295 to 325	42.02	25.16	23.26	43.88	55.12
325 to 355	0.00	148.12	112.90	100.10	105.31
355 to 25	0.00	1.20	2.36	83.70	79.85

5.4.6 The results in Table 5.4 show that the limiting density increases from 1,914 persons per km^2 to 2,075 persons per km^2.

Table 5.5: Values of $\Sigma(\Delta P_j/r_w^{1.5})/\ \Sigma\ \pi(r_j^2 - r_{j-1}^2)/12\ r_w^{1.5}$ including the Population of the Proposed Development but requiring Zero Population Density from 0.0 to 1.0 km

Sector Angular Range (Degrees)	Out to 1 km	Out to 2 km	Out to 3 km	Out to 4 km	Out to 5 km
25 to 55	-	34.38	34.72	28.86	24.67
55 to 85	-	198.63	122.52	113.35	145.32
85 to 115	-	36.92	60.46	66.10	55.05
115 to 145	-	1495.46	1182.98	963.02	780.99
145 to 175	-	1640.21	1974.09	1455.82	1209.74
175 to 205	-	4388.14	3200.99	2318.21	1866.36
205 to 235	-	2850.79	2087.82	1520.06	1225.78
235 to 265	-	209.73	364.15	288.75	254.99
265 to 295	-	0.00	10.63	32.08	46.55
295 to 325	-	53.20	37.55	63.35	74.74
325 to 355	-	313.22	182.27	144.52	142.79
355 to 25	-	2.55	3.80	120.84	108.28

5.4.7 With the imposition of an exclusion zone to 1 km, the critical population density increases from approximately 4,047 persons per km^2 to approximately 4,388 persons per km^2. This is because the population of 106 present within 1 km of the site in the 175 to 205 degree sector contributes to the numerator in the calculation and uses up a population allowance that has to be borne by sector annuli further from the site.

5.4.8 This effect can be illustrated by examining the data in a different way. As the population in each sector and annulus is available, the population density in each such sector and annulus can be computed. The results of this calculation for the existing population are shown in Table 5.6.

Table 5.6: Existing Population Density

Sector Angular Range (Degrees)	Population Density 0-1 km	Population Density 1-2 km	Population Density 2-3 km	Population Density 3-4 km	Population Density 4-5 km
25 to 55	0.00	34.38	35.14	13.64	7.64
55 to 85	0.00	198.63	29.03	89.49	275.02
85 to 115	0.00	36.92	89.38	80.76	10.19
115 to 145	194.81	1278.33	799.09	391.25	42.44
145 to 175	80.21	1550.81	2384.27	108.59	211.36
175 to 205	404.89	3595.63	1742.56	23.46	33.10
205 to 235	0.00	2850.79	1150.50	44.20	31.83
235 to 265	19.10	188.44	553.86	92.76	117.99
265 to 295	0.00	0.00	23.68	87.85	105.25
295 to 325	42.02	6.37	18.33	130.42	120.96
325 to 355	0.00	313.22	21.39	46.38	135.81
355 to 25	0.00	2.55	5.35	425.08	57.30

5.4.9 The highest existing population density is 3,596 persons per km^2 in the 175 to 205 degree sector at 1 to 2 km. The highest population density within 1 km is much lower at 405 persons per km^2. If the population in the 175 to 205 degree sector at 1 to 2 km is increased by 268 to represent the Proposed Development, the population density increases from 3,596 persons per km^2 to 3,937 persons per km^2.

5.4.10 This example shows that out to 5 km the existing population density around the site is nowhere above the semi-urban population density limit of 5,000 persons per km^2, which is regarded as the lowest population density that could be adopted as a constraint, bearing in mind that the potential radiological impacts from the site are thousands of times lower than from a power reactor site.

5.4.11 The analysis in Table 5.4 shows that if no account is taken of the desirability of maintaining a low population density within 1 km, the development would be acceptable if the limiting population density around the site was 2,075 persons per km^2. If the site is considered acceptable at the present time, Table 5.5 shows that the limiting population density must be at least 1,914 persons per km^2.

5.4.12 If the desirability of a low population density very close to the site is factored in through the extreme approach of imposing an exclusion zone to 1 km, Table 5.3 shows that if the site is considered acceptable at the present time, the limiting population density must be at least 4,047 persons per km^2. For the Proposed Development to be acceptable, the limiting population density would have to be at least 4,388 persons per km^2.

5.4.13 In the above, emphasis has been given to evaluation of the significance of populations in 30 degree sectors. However, some consideration needs to be given also to the total population present around the site in different annular ranges. The total residential overnight populations present in the cumulative ranges 0-1, 0-2, 0-3, 0-4 and 0-5 km including the additional 268 residents from the Proposed Development are 194, 8,360, 17,330, 20,141 and

22,848 people, respectively. The total distance weighted populations to the same distances are 326.27, 4,433.55, 6,637.02, 7,059.86 and 7,340.84, respectively.

5.4.14 Values of $\Sigma\ \pi(r_j^2 - r_{j-1}^2)/r_w^{1.5}$ to the same distances are 5.28, 10.02, 13.88, 17.19 and 20.13, respectively. This leads to limiting population densities (neglecting exclusion in the 0-1 km range) of 326.27/5.28, 4,433.55/10.02, 6,637.02/13.88, 7,059.86/17.19 and 7,340.84/20.13 persons per km^2 calculated over 0-1, 0-2, 0-3, 0-4 and 0-5 km, respectively. These population densities are 61.75, 442.30, 478.08, 410.68 and 364.76 persons per km^2, respectively. For comparison, the population density limit for a semi-urban site is 1,250 persons per km^2. Excluding the population of 268 for the Proposed Development, the limiting population densities are 61.75, 428.85, 468.37, 402.84 and 358.06 persons per km^2. Thus, the Proposed Development has little impact on the limiting population density and the maximum value is only 0.38 of the limiting value for a semi-urban site.

5.5 EVALUATION OF SOCIETAL RISK

5.5.1 It is of some interest to evaluate the societal risk that would arise from the worst-case accident at AWE Aldermaston if the wind was blowing toward the sector in which the proposed development at Boundary Hall is located. As determined in Section 4, the committed effective dose on axis at 1 km downwind is 1.23 Sv. The average committed effective dose across a thirty degree sector at 1 km will be approximately 0.565 of this (paragraph 3.3.25) or 0.695 Sv. As noted in paragraph 4.3.1, committed effective doses at any other distance can be obtained by scaling as $1/r^{1.5}$, where r (km) is the distance of interest. Appropriate distances for each annular segment are calculated using $r = \{(r_j^2 + r_{j-1}^2)/2\}^{0.5}$ (paragraph 5.2.3). Calculations of collective committed effective dose to 5 km are given in Table 5.7.

Table 5.7: Calculations of Collective Committed Effective Dose for the 175 to 205 Degree Sector (effects of proposed development at Boundary Hall given in parentheses)

Distance (km)	r (km)	Committed Effective Dose (Sv)	Population	Collective Effective Dose (person-Sv)
0 – 1	0.707	1.169	106	123.9
1 – 2	1.581	0.350	2824 (3092)	988.4 (1082.2)
2 – 3	2.550	0.171	2281	390.1
3 – 4	3.536	0.105	43	4.5
4 – 5	4.528	0.072	78	5.6
Total				**1512.5 (1606.3)**

5.5.2 Thus, the collective committed effective dose within 5 km conditional on a worst-case accident occurring and the wind blowing into the relevant sector is 1512.5 person-Sv without the proposed development at Boundary Hall and 1606.3 Sv with the proposed development. This is an increase of 6.2%. Taking account of the collective dose incurred at more than 5 km from the site, the percentage increase would be less.

5.5.3 However, these individual and collective impacts do not take into account the likely effectiveness of emergency responses in mitigating the consequences of such an accident. If sheltering were to occur before the plume of plutonium was released or reached the populated area, individuals present indoors would be exposed to much lower air concentrations than those calculated and their radiation exposures would be reduced *pro rata*.

5.6 EFFECTS OF CONSIDERING A REALISTIC WIND ROSE

5.6.1 Figure 5.1 shows the wind rose for the Meteorological Office station at Odiham, which is the closest station to the AWE Aldermaston site, and is based on hourly data for one year (2009). From this it is clear that the wind blows primarily from the South-West, i.e. the Proposed Development and high densities of existing population lie generally upwind of the site. The degree of asymmetry in the wind rose is quantified in Table 5.8.

Figure 5.1: Wind Rose based on Hourly Data for One Year (2009)

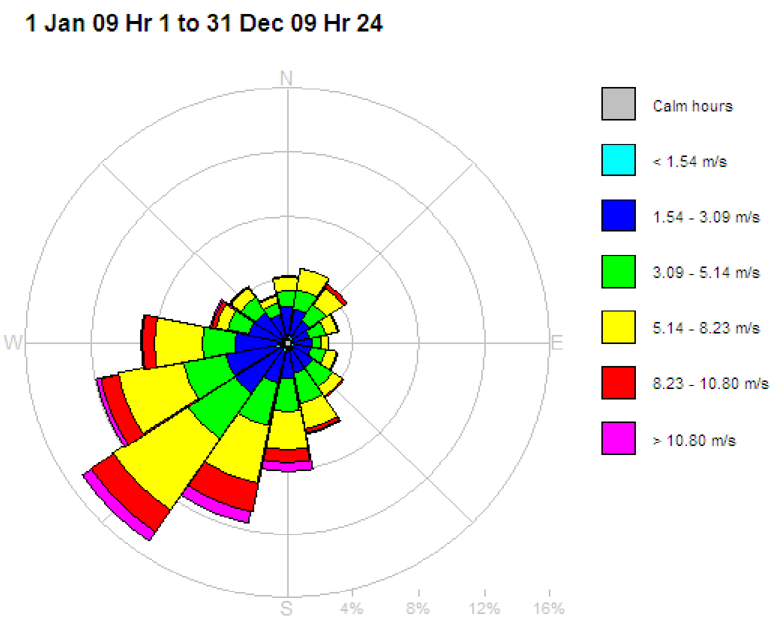


Table 5.8: Analysis of Wind Rose Data

Sector Angular Range (Degrees)	Number of Hours	Fraction	Direction Enhancement Factor	Mean Wind Speed (m s^{-1})
10 to 40	1459	0.167	1.999	5.495
40 to 70	1584	0.181	2.170	5.033
70 to 100	1146	0.131	1.570	4.653
100 to 130	561	0.064	0.768	3.722
130 to 160	433	0.049	0.593	3.502
160 to 190	445	0.051	0.610	3.465
190 to 220	591	0.067	0.810	3.818
220 to 250	413	0.047	0.566	3.929
250 to 280	329	0.038	0.451	3.129
280 to 310	367	0.042	0.503	3.78
310 to 340	563	0.064	0.771	3.956
340 to 10	869	0.099	1.190	5.129

5.6.2 The third column of Table 5.8 gives the fraction of the year for which the wind blows from each sector. For a uniform wind rose, these fractions would all be equal to 0.0833, i.e. 1/12. The fourth column of Table 5.8 is the ratio of the observed fraction to 0.0833. This shows that for the three highly populated sectors (160 to 250 degrees), the average direction enhancement factor is 0.66. Thus, other things being equal, rather higher population densities would be acceptable in this general direction and rather lower population densities would be acceptable in directions with direction enhancement factors of greater than one. The final column of Table 5.8 is included to show that, although there is some variation in mean wind speed with direction, in all directions it is greater than the value of 2 m s^{-1} assumed in the reference case of Category F conditions. As plume dilution increases with increasing wind speed this indicates that there is no requirement to reduce acceptable population densities because of wind speed and atmospheric stability effects.

5.7 OVERALL COMPARISON

5.7.1 There is no justification for using a population density constraint lower than the semi-urban value of 5,000 persons per km^2 for AWE Aldermaston and there are strong arguments, based on the types of accidents that could occur at the site, that a much higher population density constraint should be used.

5.7.2 The existing population density around the site does not violate the semi-urban constraint value, irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. Therefore, there should not be any concern that the existing population density is prejudicial to public safety.

5.7.3 The population density around the site including the additional population associated with the proposed development at Boundary Hall would also not violate the semi-urban constraint value. Therefore, there should not be any concern that the change in population would be prejudicial to public safety.

5.7.4 The increment in population due to the proposed development at Boundary Hall would constitute a small perturbation to the population pattern in the area. It would increase the limiting population density by about 8% irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. This arises because the population density in the 175 to 205 degree sector and distance range 1 to 2 km is increased from 3596 to persons per km^2 to 3,937 persons per km^2. This is an increase of 9.5%.

5.7.5 In the event of a severe accident at AWE Aldermaston with the wind blowing towards Boundary Hall, the proposed development would increase the societal impact of the accident by no more than 6.2%. In fact, the increase would be less than this because the impact beyond 5 km from the site is neglected in this calculation and because no account is taken of the effectiveness of sheltering local to the site.

5.7.6 A consideration of the wind rose for the nearest Meteorological Station to AWE Aldermaston shows that there is no requirement to reduce acceptable population densities because of wind speed and atmospheric stability effects.

6. Conclusions from the Analysis

6.1 INAPPLICABILITY OF THE EXISTING GUIDELINES TO AWE ALDERMASTON

6.1.1 From the historical review set out in Section 3.2, it is clear that siting criteria in the UK were developed solely in the context of the siting of nuclear power reactors. Furthermore, those guidelines were developed primarily to control the **siting** of such installations. Their use to control **developments** in the vicinity of existing installations has been given much less consideration. In particular, there do not appear to have been any policy or technical analyses of their role in achieving the primary policy requirement that once a site has been accepted for a nuclear station, arrangements are made to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. It is not self-evident that the same numerical criteria should be used in an initial siting evaluation as in the control of developments. In particular, it is noted that the burden of compliance in the two cases lies mainly with different stakeholders. In the case of siting, the burden lies mainly with the developer/operator of the proposed installation, whereas in the case of developments in the vicinity of an existing installation the burden lies primarily not with the operator of the installation, but with the proponent of the development. Also, the siting of a new nuclear installation has a potential impact from accidents on the entire population in its vicinity, hence the use of numerical criteria based on the total population in a sector or all around the site weighted for distance from the site as a surrogate for weighting for the radiological impact of accidents on individuals located at different distances. In contrast, with a proposed development in the vicinity of an existing nuclear installation, what is of concern is the increment in potential impact from accidents due to the presence of additional persons associated with the proposed development.

6.1.2 AWE Aldermaston came into existence before any formal criteria for the siting of nuclear power reactors had been defined. In developing the criteria, no reference was made to the type of activities undertaken at AWE Aldermaston and the criteria did not give any consideration to the population distribution around AWE Aldermaston.

6.1.3 Current UK international obligations on siting under the Conventions on Nuclear Safety and the Joint Convention on Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, as expressed through the United Kingdom's Fourth National Report on compliance with Article 17: Siting of the Convention on Nuclear Safety obligations (HSE, 2007), relate entirely to power-generating nuclear reactors. They do not relate to several other types of nuclear installation (e.g. research reactors). Furthermore, the HSE recognises that AWE Aldermaston is not within the scope of the two conventions.

6.1.4 With new build, the key consideration is that the nuclear power station could be constructed at any location within the potential site. Therefore, the siting analysis properly considers each potential location in turn. Through this analysis, HSE can come to a view as to whether any parts of the potential site are inappropriate for construction. However, if a power station were subsequently constructed at a location deemed suitable, future developments around the site would be assessed using a calculation centred on a point representing the actual location of the power station. In the case of AWE Aldermaston, HSE has undertaken the same type of analysis, arguing that the location of sources on the site is unspecified. However, this is not a risk-informed approach, since every off-site location is evaluated by reference to its own worst-case source location. This is excessively penalising to developments and there is nothing in policy that requires this approach.

6.1.5 It is recognised that security considerations may dictate that only limited information on the nature and location of potential accident sources is released into the public domain. However, such information has been made available to HSE and there is no reason why it should not be used to assess developments in the vicinity of the site rather than relying on an approach developed for proposed new-build nuclear power station sites. The AWE Aldermaston site undertakes well defined operations in various specialised facilities. Thus, the determination of possible locations of potential accidents under current and projected operational arrangements should be straightforward, just as is the case at other nuclear licensed sites. If AWE Aldermaston wished in future to substantially modify its operational procedures, the revised procedures would require evaluation at the time to ensure that they did not compromise the safety of populations around the site. If issues arose in this respect, the proposed operational changes could be denied, or subject to any conditions necessary for the maintenance of safety.

6.1.6 Based on the above, it seems clear that any proposals for developments in the vicinity of AWE Aldermaston can, and should, be decided on their own merits, having regard to the general obligation to ensure that residential and industrial developments are so controlled that the general characteristics of the site are preserved. This does not preclude the use of numerical analyses, but any such analyses should only be used as guidance to inform decision making, which needs to take into account numerous other factors, some of which may be unquantifiable. In particular, those factors include socio-economic considerations.

6.1.7 There are technical aspects of the existing guidelines that can properly be used to evaluate whether developments in the vicinity of all nuclear licensed sites, including AWE Aldermaston, are appropriate. In particular, extensive technical studies have demonstrated that the radiological impacts on individuals of accidents resulting in off-site releases of radioactive materials typically decrease in inverse proportion to distance to the power 1.5. Thus, when evaluating the overall impact of a potential accident, it is appropriate to give consideration to the cumulative weighted population downwind (i.e. the accumulation over distance of the product of the number of people exposed at each distance and a quantity proportional to the radiological impact on people present at that distance). However, the aspect of the current guidelines for nuclear power reactors that cannot be used is the limiting population densities adopted. This is because those densities are conditioned on the types of accidents that could occur at nuclear power reactors and their associated likelihoods of occurrence. These types of accidents are not, in general, relevant at other licensed nuclear sites.

6.1.8 Whenever quantitative calculations are undertaken, it is important to bear in mind that those calculations are for the purpose of making comparisons with guidelines. Those guidelines are intended to inform judgements made by the HSE, e.g. in relation to the acceptability of proposed developments in the vicinity of a site. In the context of such developments, local authorities are required to consult with the HSE, but the any criteria based upon population distribution are used only for guidance, and the HSE cannot necessarily insist on rigid adherence to demographic constraint limits. Specifically, local considerations may take precedence over any numerical criteria. Just as the Inspectorate has not in the past required rigid adherence to quantitative demographic constraint limits, so it cannot require local authorities to apply such rigid adherence, since those authorities have a responsibility to take into account other unquantifiable factors. Such factors may enhance or diminish the desirability of a particular development. This situation is similar to that which obtains in respect of non-nuclear safety. As stated at paragraphs 6.103 and 6.104 of the Report to the Secretary of State for Communities and Local Government in relation to proposed developments at the site of the Ram Brewery, Wandsworth (Ball, 2010):

> 'Circular advice makes it clear that the decision maker can grant consent, notwithstanding the view of the HSE, so long as that advice is given the most careful consideration... as the role of the HSE in LUP [Land Use Planning] is not to judge whether a particular risk is unacceptable either in terms of the risk itself or in terms of the overall planning balance... the HSE's role is limited to advising LPAs [Local Planning Authorities] as to the nature and scale of the risk, and as to whether that LPA has valid grounds to resist development based on that risk.'

6.2 COMPARISON OF POTENTIAL ACCIDENTS AT AWE ALDERMASTON WITH THOSE AT NUCLEAR POWER STATIONS AND OTHER LICENSED NUCLEAR SITES

6.2.1 The radiological impact of the reference worst-case accident for a nuclear power reactor is a factor of 5,390 larger than the radiological impact of the reference worst-case accident for AWE Aldermaston.

6.2.2 Overall, AWE Aldermaston should be considered more closely comparable to a research reactor site than to a power reactor site. For research reactor sites, no specific constraints on local population density have ever been imposed in the UK.

6.3 EVALUATION OF EXISTING AND PROJECTED POPULATION DENSITIES IN THE VICINITY OF AWE ALDERMASTON

6.3.1 There is no justification for using a population density constraint lower than the semi-urban value of 5,000 persons per km^2 for AWE Aldermaston and there are strong arguments, based on the types of accidents that could occur at the site, that a much higher population density constraint should be used.

6.3.2 The existing population density around the site does not violate the semi-urban constraint value, irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. Therefore, there should not be any concern that the existing population density is prejudicial to public safety.

6.3.3 The population density around the site including the additional population associated with the proposed development at Boundary Hall would also not violate the semi-urban constraint value. Therefore, there should not be any concern that the change in population would be prejudicial to public safety.

6.3.4 The increment in population due to the proposed development at Boundary Hall would constitute a small perturbation to the population pattern in the area. It would increase the limiting population density by about 8% irrespective of whether or not a 1 km exclusion zone around the centre of the site is represented in the calculation. This arises because the population density in the 175 to 205 degree sector and distance range 1 to 2 km is increased from 3596 to persons per km^2 to 3,937 persons per km^2. This is an increase of 9.5%.

6.3.5 In the event of a severe accident at AWE Aldermaston with the wind blowing towards Boundary Hall, the proposed development would increase the societal impact of the accident by no more than 6.2%. In fact, the increase would be less than this because the impact beyond 5 km from the site is neglected in this calculation and because no account is taken of the effectiveness of sheltering local to the site.

6.3.6 A consideration of the wind rose for the nearest Meteorological Station to AWE Aldermaston shows that the wind blows preferentially away from the proposed development and that there is no requirement to reduce acceptable population densities because of wind speed and atmospheric stability effects.

7. Overall Opinion

7.1 The HSE has not provided a suitably argued basis on public safety grounds, for refusing to permit development of the Boundary Hall site for mixed use including residential. Existing policy on siting relates to nuclear power reactors only and does not apply to AWE Aldermaston for which the magnitudes of potential major accidents are much smaller than those that could occur at nuclear power reactors. Furthermore, the quantitative criteria used in relation to nuclear power reactors only constitute guidance and local factors may take priority. Thus, the proposed development should be evaluated on its own merits. It constitutes an infill development on an available site broadly consistent with land use in the immediate area. Thus, if it were to be implemented, the general characteristics of the site (i.e. the area in the immediate vicinity of AWE Aldermaston) would be preserved. This is the fundamental intent of siting and development policy. The numerical criteria that have been developed by the HSE are intended to inform judgements related to this fundamental principle, but analyses against these criteria have also to be informed by consideration of other unquantifiable factors. Taking these considerations into account, I am of the opinion that there are no issues arising from national siting and development policy that should prevent the proposed development at the Boundary Hall site from being implemented.

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Glossary

Term (Symbol)	Definition
Absorbed dose	Amount of ionising energy deposited per unit mass of material.
ACSNI	Advisory Committee on the Safety of Nuclear Installations.
Address Layer 2	Information on the distribution of the population and on individual premises that can be used to derive high-resolution patterns of population density.
Aerosol	Suspension of liquid or solid particles in air. Small particles can persist indefinitely as aerosols, due to turbulent mixing and diffusion effects. Larger particles are lost by gravitational settling. Other losses occur due to impaction on surfaces.
AGR	Advanced Gas-cooled Reactor that uses uranium dioxide fuel clad in stainless steel. Successors to the Magnox reactors for commercial power production in the UK.
ALARP	As Low As Reasonably Practicable.
AWE Aldermaston	Atomic Weapons Establishment Aldermaston
Atmospheric dispersion	Downwind transport and dilution of contaminants as a result of air movements (including both wind transport and turbulent mixing).
Atmospheric stability	Degree of turbulent mixing in the atmosphere. Typically, quantified by reference to stability categories A to F (or G).
Becquerel (Bq)	Unit of radioactivity. Equal to one transformation per second.
BSL	Basic Safety Limit
BSO	Basic Safety Objective
Collective effective dose	Sum of the effective doses received by individuals in a particular exposed population. This is useful because the risk of stochastic health effects is taken to be directly proportional to the effective dose received, so collective effective dose is a measure of the total radiological impact on the exposed population at low doses and dose rates.
Committed effective dose	Effective dose resulting from an intake of a radionuclide into the body. Refers to the consideration that the individual is committed to receiving that dose as a result of the intake, even though the dose may be delivered over a protracted period (sometimes many years).
Criticality	When a sufficient quantity of a fissile element is brought together, a situation arises in which the neutrons created in each fission event in total induce one or more subsequent fission events. Thus, the rate of fission remains constant or increases with time. In these circumstances, the system is said to have gone critical. Nuclear reactors are maintained in a just critical situation, so that the rate of fission remains constant with time. In contrast, in nuclear accidents and in the explosion of nuclear weapons, the system becomes super-critical and the rate of fission increases very rapidly. Criticality safety assessment involves the analysis of potential configurations of fissile material to ensure that those situations are avoided in which the system would go critical.
Curie (Ci)	Unit of radioactivity corresponding to the activity of 1 g of ^{226}Ra. 1 Ci = 3.7 10^{10} Bq.

Term (Symbol)	Definition
Deterministic effect	Deterministic effects are those due to cell sterilisation and killing, and are characterised by a threshold dose or dose rate for clinical expression.
Effective dose	Weighted sum of equivalent doses to all organs and tissues of the body taking account of their relative sensitivity to the induction of deleterious health effects.
Equivalent dose	Absorbed dose to an organ or tissue multiplied by a radiation weighting factor that expresses the propensity for the radiation to induce deleterious effects relative to a reference radiation.
Fission product	Radionuclide formed by the splitting of an atom of a fissile element (typically uranium or plutonium) due to neutron bombardment.
Gaussian plume	Dispersion such that the concentration of a contaminant across the plume at any distance downwind is represented by a normal distribution. Plumes may be Gaussian in their horizontal profile, in their vertical profile or in both.
GIS	Geographic Information System: Software for storing and manipulating spatially distributed data.
Gray (Gy)	Unit of absorbed dose, equal to 1 Joule per kilogram.
Health detriment	The overall deleterious effect of exposure to ionising radiation or radioactivity on health, including weighting of the various deleterious effects by their impact on quality or length of life.
HERALD	A materials testing research reactor located at AWE Aldermaston.
HSC	Health and Safety Commision
HSE	Health and Safety Executive
LUP	Land Use Planning
Magnox	Gas-cooled nuclear power reactor that uses uranium metal fuel clad in a magnesium alloy. The Magnox reactors were the first generation of nuclear reactors used for commercial power production in the UK.
ND	Nuclear Directorate of the Health and Safety Executive
NII	The Nuclear Installations Inspectorate of the Health and Safety Executive.
NuSAC	Nuclear Safety Advisory Committee
OCNS	Office for Civil Nuclear Security
PWR	Pressurised Water Reactor that uses uranium dioxide fuel clad in a zirconium alloy. One such reactor is in use for commercial power production in the UK and is located at Sizewell, Suffolk.
Radioactivity	The transformation of the nucleus of an atom by the emission of particles of matter or quanta of light. Radioactive decay either transforms an atom of one element to an atom of another or transforms a more energetic state of the nucleus to a less energetic state.

Term (Symbol)	Definition
Radiological impact	The deleterious effect of exposure to ionising radiation or radioactive materials.
Radionuclide	Type of atom that exhibits radioactive decay. Various radionuclides of a particular element are termed radioisotopes of that element. Each radionuclide is characterised by a specific half life (the time over which half the atoms are transformed) and by its emissions, which are typically photons (x rays and gamma rays), electrons (beta particles) and helium nuclei (alpha particles).
REPPIR	Radiation (Emergency Preparedness and Public Information) Regulations
Research Reactor	A nuclear reactor used for research and related activities rather than for power production. The power output of research reactors is typically less than one percent of that of commercial nuclear power reactors.
SAPs	Safety Assessment Principles for Nuclear Facilities: Guidance provided by the NII to its inspectors.
Sievert	Unit of equivalent dose and of effective dose.
Societal risk	Impact of accidents on society as a whole. Typically represented in terms of the frequency distribution of accidents involving different numbers of fatalities.
SPF	Site Population Factor
Stochastic effect	Stochastic effects comprise cancer in the irradiated individual and hereditary disease in his or her descendents. The probability of such effects occurring is taken to be linearly related to the dose received, i.e. there is no threshold for such effects, though at low doses and dose rates the incidence becomes almost impossible to establish because of the 'natural' incidence of these effects.
Tritium	Radioactive isotope of hydrogen. Decays by emission of a low-energy beta particle.
Type F, M, S	Classification of inhaled particles as to whether they are rapidly (F), moderately (M) or slowly (S) solubilised in the respiratory tract.
UKSO	UK Safeguards Office
VIPER	A pulsed research reactor located at AWE Aldermaston.
Wind rose	Representation of the frequency with which the wind blows towards different compass directions and of supplementary quantities such as the mix of atmospheric stability categories for each direction and the distribution of wind speeds.
Worst case	Herein, the term ‘worst-case’ as applied to a release of activity or an accident means close to the largest release or worst accident that can be envisaged. The definition is not precise and the intent is to describe a release or accident that is close to the largest or worst that can be envisaged.

Note on Prefixes and Scientific Notation

Where quantities are defined, these have to be associated with units. Thus, for example, distance is often given in metres (symbol m) and time in seconds (symbol s). Where, a quantity is much larger or smaller than the basic unit, it may be convenient to use a subsidiary unit that is a multiple of the basic unit. Thus, short distances may be given in millimetres (symbol mm) and long distances may be given in kilometres (symbol km). Conventional prefixes are used to indicate the multiplier. Herein, m (for milli, i.e. one one thousandth of the basic unit) and k (for kilo, i.e. one thousand times the basic unit) are used. Thus, 1 mSv = 0.001 Sv and 1 km = 1,000 m.

For very large and very small numbers, it is convenient to use scientific notation in which a number is expressed as a value between 1 and 10 multiplied by a power of 10. Thus, $2.7\ 10^{4} = 2.7\times10\times10\times10\times10 = 27{,}000$. Similarly, $2.7\ 10^{-4} = 2.7/(10\times10\times10\times10) = 0.00027$.

Appendix A: Curriculum Vitae for Dr M C Thorne

MIKE THORNE AND ASSOCIATES LIMITED
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MICHAEL CHARLES THORNE

Qualifications: PhD FSRP FInstP CRadP Year of birth: 1950 Nationality: British

PROFESSIONAL ACTIVITIES AND MEMBERSHIP

Visiting Fellow at the Climatic Research Unit, School of Environmental Sciences, University of East Anglia
Fellow of the Society for Radiological Protection and a Past President of the Society
Member of the Editorial Board of the Journal of Radiological Protection
Member of the National Dose Assessment Working Group (NDAWG) and Chairman of the Habits Subgroup
Member of the Eco-ethics International Union
Consultant to the Institute for Energy and Environmental Research, Washington DC.
Quintessa Associate
Director, Mike Thorne and Associates Limited

ACADEMIC RESPONSIBILITIES

Formal supervision of two PhD students at the University of East Anglia:
P Burgess, Future Climatic and Cryospheric Change on Millennial Timescales: An Assessment using Two-dimensional Climate Modelling Studies, PhD awarded 1998.
M Hoar, Reconstructing Climate Gradients across Europe for the Last Glacial-interglacial Cycle, PhD awarded 2004.
Informal supervision of PhD students at the University of Edinburgh (development and retreat of ice sheets) and at Imperial College of Science, Technology and Medicine (radionuclide transport in vegetated soil columns – experimental studies and modelling interpretations).
Teaching on the MSc course on Environmental Radioactivity at the University of Surrey.
Teaching on the MSc course in Environmental Technology at Imperial College of Science, Technology and Medicine.
Supervision of Post-doctoral research activities at the Universities of East Anglia; University of Newcastle and Imperial College of Science, Technology and Medicine on behalf of various commercial clients.

CAREER HISTORY (Selection of Projects)

Mike Thorne and Associates Limited, 2001 onward

Development of Climate and Landscape Change Scenarios, Biosphere Factors and Characteristics of Potentially Exposed Groups for the LLWR near Drigg, West Cumbria
Client - Nexia Solutions Ltd

Project building on previous work for BNFL relating to the LLWR and for the NDA relating to vulnerabilities of various sites.

Radiological Impact of NORM Discharges to the Marine Environment
Client - Scotoil Services Ltd

Support to an appeal against a SEPA decision to curtail such discharges from North Pier, Aberdeen. Including appearance as a witness at the Public Inquiry into this issue.

Development of Proposals for Setting Radiation Protection Standards based on Consideration of More Sensitive Individuals in a Population
Client – Institute for Energy and Environmental Research, Washington DC

Overall project review and development of techniques for calculating radiation doses to the early embryo from internally incorporated radionuclides.

Review of Impacts of Coastal Erosion at Hunterston
Client – ERM Limited

Evaluation of the potential radiological implications of coastal erosion on the VLLW pits at Hunterston Nuclear Power Station. Similar work on coastal erosion has also been undertaken at Dounreay.

Advice on Dose Reconstruction
Client – S A Cohen & Associates for NIOSH

Advice on dose reconstructions for workers at DOE facilities from 1941 onward.

Advice on Effects of Radionuclides on Organisms other than Man
Client – Nuclear Safety Solutions Limited, Canada

Provision of guidance on dosimetry, reference levels and effects relevant to selected protected species.

Participation in Safety Assessment Studies for the Baita Bihor Repository, Romania
Client – Quintessa/for the European Union

Compilation of inventory data, shielding studies and development of both operational and post-closure safety cases.

Review of the Yucca Mountain Project
Client – State of Nevada

Co-ordination of technical activities involved in a review of the proposed License Application by US DOE for disposal of radioactive wastes at Yucca Mountain.

Co-ordination of biosphere research and participation in BIOCLIM and BIOPROTA
Client – UK Nirex Ltd (NDA/RWMD)

Co-ordination of research on climate change, ice-sheet development, near-surface hydrology and radionuclide transport, as well as participation in an international programme on the implications of climate change for radioactive waste disposal. Also includes development of new models for radionuclide transport in the biosphere and for the gas pathway.

Development of a Handbook on Radionuclide Behaviour in the Environment
Client – Serco Assurance

Development of a handbook for Environment Agency staff outlining the behaviour of a wide variety of radionuclides in terrestrial and aquatic environments.

Development of a Simplified Dose Assessment Model
Client – Serco Assurance

Development of a simplified spreadsheet-based dose assessment tool for use by Environment Agency staff in determining Authorisations.

Provision of Biosphere Advice
Client – Ciemat, Spain

Provision of advice on models and data relevant to geological disposal of radioactive wastes.

Provision of Advice on Safety
Client – NNC Ltd/Defra

Provision of expert advice to the UK Committee on Radioactive Waste Management (CoRWM).

Effects of Radiation on Organisms Other Than Man
Client – AEA Technology/Serco Assurance

Study for ANDRA to identify appropriate indicator organisms and develop appropriate dosimetry and effects models for those organisms.

Member of the Site Investigation Expert Review Group (SIERG)
Client – SKB

Oversight reviews of site investigation activities and the associated research and assessment programmes.

Advice on the Short-, Medium- and Long-term Effects of Climate Change on Nuclear Licensed Sites
Client – BNFL and Nexia Solutions Ltd

Interpretation of results from the international BIOCLIM project in relation to decommissioning and solid radioactive waste management, with particular emphasis on the potential significance of sea-level changes. Review of information on coastal vulnerabilities at NDA sites.

Advice on Submarine Reactor Accidents and the Development of Detailed Emergency Planning Zones
Client – Electrowatt-Ekono

Assistance to MoD in revising emergency planning criteria in the light of recent changes of views on Emergency Reference Levels and other technical developments. Also studies on tritium analyses and migration from transfer tanks.

Review of Continuing Operational Safety Cases
Client – Electrowatt-Ekono

Review of COSRs developed by BNFL for contaminated land.

Development of a New Soil-Plant Model for use in Radiological Assessments
Client – Food Standards Agency/Quintessa

Development of the specification for a new soil-plant model (PRISM) to replace that implemented in the SPADE suite of codes (implementation of the model has been by Quintessa) and extension of that work to new models for ^{3}H and ^{14}C.

Review of Probabilistic Safety Assessment and Criticality Issues relating to a Proposed Surface Storage Facility for Spent Nuclear Fuel
Client – State of Utah

Review of the potential for criticality in breached storage casks and of the probability of breaching by aircraft impacts. Also, supervision of various criticality and radiation shielding calculations.

Development of Models for Radionuclide Transfers to Sewage Sludge and for Evaluating the Radiological Impact of Sludge applied to Agricultural Land
Client – Food Standards Agency

Includes a review of literature and the development and implementation of probabilistic models for such transfers.

Development of Biokinetic Models for Radionuclides in Animals
Client – Serco Assurance

Development of updated biokinetic models for use by the Food Standards Agency in their SPADE and PRISM modelling systems.

Review Studies for the Proposed Australian National Radioactive Waste Repository
Client – RWE NUKEM

Reviews of reports on animal transfer factors and of the potential effects of climate change on the repository plus development of a model for the biokinetics of the ^{226}Ra decay chain in grazing animals.

Development and Application of a Model for Assessing the Radiological Impacts of ^{3}H and ^{14}C in Sewage Sludge
Client – NNC Ltd

Development of a model based on physical, chemical and biochemical principles for the uptake of ^{3}H and ^{14}C into sewage sludge and their subsequent distribution and transport after application of the sludge to agricultural land.

Support for development of the Drigg Post-closure Radiological Safety Assessment
Client - BNFL

Support in the areas of FEP analysis, biosphere characterisation, human intrusion assessment and the effects of natural disruptive events. In addition, provision of advice of future research initiatives that should be pursued by BNFL.

Review of Parameter Values
Client – AEA Technology/Serco Assurance

Review of biosphere parameter values for use in the ANDRA assessment model AQUABIOS.

Development of a Database related to Emergency Planning
Client – AEA Technology (Rail)

Identification of relevant international, overseas and national legislation, regulations and guidance, and production of brief summaries of the documents.

Dose Reconstruction for Workers on a Uranium Plant
Client - McMurry and Talbot

Dose reconstruction for the plaintiffs in a case relating to the Paducah Gaseous Diffusion Plant.

Dose Reconstruction for a Worker Exposed to Pu and Am
Client – Pattinson and Brewer

Dose reconstruction for a worker exposed by a puncture wound in the finger while working at a glove box.

AEA Technology, 1998-2001

Revision of Exemption Orders Made Under the Radioactive Substances Act
Client – DETR

Review of requirements for revision and preparation of a draft text for the purposes of consultation.

Assessment of Remediation Options for Uranium Liabilities in Eastern Europe
Client - European Commission

Studies of remediation requirements relating to mines, waste heaps and hydrometallurgical plant in Bulgaria, Slovakia and Albania.

Evaluation of Unusual Pathways for Radionuclide Transport from Nuclear Installations
Client – Environment Agency

Review of literature and conduct of formal elicitation meetings to determine potential pathways and evaluate their radiological significance.

Support Studies on the Drigg Post-closure Performance Assessment
Client - BNFL

Support in the areas of FEP analysis, biosphere characterisation, human intrusion assessment and the effects of natural disruptive events. In addition, provision of advice of future research initiatives that should be pursued by BNFL.

Development of Models for the Biokinetics of H-3, C-14 and S-35 in Farm Animals
Client - FSA

Review of relevant literature, development of appropriate biokinetic models and implementation in stand-alone software.

Integration of Aerial and Ground-based Monitoring in the Event of a Nuclear Accident
Client - FSA

Desk-based review and simulation study designed to determine optimum monitoring strategies for different types of accidents.

Elicitation of Parameter Values for use in Radiological Impact Assessment Models
Client - FSA

Expert elicitation study to provide distributions of parameter values for use in the suite of assessment models currently used by the FSA for routine and accidental releases.

Biosphere Research Co-ordination and Assessment Studies
Client - United Kingdom Nirex Ltd

Continuation of a programme of work originally undertaken at Electrowatt Engineering (UK) Ltd

Site Investigation and Risk Assessment - Hilsea Lines
Client - Portsmouth City Council

Radiological assessment of a radium-contaminated site.

Electrowatt Engineering (UK) Ltd, 1987-1998

Development of a Siting Policy for Nuclear Installations: Harbinger Project and Follow-up Study
Client - HSE/NSD

Review of existing policy and development of alternatives as a precursor to application to a wide range of installations, not restricted to commercial reactors.

Support to the Rock Characterisation Facility Public Enquiry
Client - UK Nirex Ltd

Preparation of position papers and rebuttals of evidence.

Rongelap Resettlement Project
Client - Marshall Islands Government

Participation in an oversight committee evaluating the radiological safety of Rongelap in the context of resettlement by its evacuated community.

Evaluation of Inhalation Doses from Uranium
Client - Baron & Budd

Provision of expert witness support in a class action relating to environmental exposure from a uranium plant.

Biosphere Studies Relating to Drigg
Client - BNFL

Provision of advice on time-dependent biosphere modelling for the Drigg low-level radioactive waste disposal facility.

Radiation Doses to an Individual as a Consequence of Working on the San Onofre Nuclear Power Plant
Client - Howarth & Smith

Interpretation of personal and area monitoring data for legal purposes.

Interpretation of Uranium in Urine Data for the Fernald, Ohio Feed Materials Processing Center
Client - Institute for Energy and Environmental Research

Interpretation of urinalysis and lung counting data, and appearance as an expert witness in the associated trial.

Determination of Failure Probabilities for use in PRA
Client - Nuclear Installations Inspectorate

Development of new approaches to the use of Bayes Theorem in defining component failure probabilities for use in PRA when statistics on actual failures are limited.

Review of Inventory Information
Client - UK Nirex Ltd

Review of uncertainties in inventories of individual radionuclides.

ALARP Study of Options for the Treatment, Packaging, Transport and Disposal of Plutonium Contaminated Material
Client - UK Nirex Ltd

Use of multi-attribute utility analysis to establish which option is preferred.

Expert Judgement Estimation of Intrusion Model Parameters
Client - British Nuclear Fuels plc

Project Manager of a study assessing the risks of human intrusion into Drigg radioactive disposal site using expert judgement techniques.

Brainstorming Study of Risks Associated with Building Structures
Client - Building Research Establishment

Participation in a classification study of the health risks associated with buildings including both injuries and disease.

Radiological Consequences of Deferred Decommissioning of Hunterston A
Client - Scottish Nuclear Ltd

Project Manager of a study of the radiological impacts of groundwater transport of radionuclides, releases to atmosphere and intrusion.

Reviews of Safety Documentation
Client - UK Nirex Ltd

Review of safety related documentation for Packaging and Transport Branch.

The Sheltering Effectiveness of Buildings in Hong Kong
Client - Ove Arup & Partners

Project Manager of a study evaluating the shielding effectiveness of all types of building in Hong Kong for volume sources of photons in air and surface deposition sources.

Assessment of the Radiological Impact of Releases of Radionuclides from Premises other than Licensed Nuclear Sites
Client - Ministry of Agriculture, Fisheries and Food

Project Manager of a study to identify representative premises, obtain data on their releases of radionuclides and assess radiological impacts using a new methodology developed for the project.

Assessment of the Radiological Implications of Uranium and its Radioactive Daughters in Foodstuffs
Client - Ministry of Agriculture, Fisheries and Food

Project Manager of a review study of concentrations of uranium and its daughters in foodstuffs, taking local and regional variations in uranium concentrations in soils, sediments and waters into account.

Radionuclides in Sewage
Client - Her Majesty's Inspectorate of Pollution

Project Manager of a study including a desk review on alternative methods of disposal of sewage sludges, interpretation of monitoring data relating to radionuclide discharges from Amersham International to the public sewer system, development of a model for radionuclide transport in sewers, and collection and analysis of effluent, foul water, sediment, sludge and other samples suitable for use in model validation studies.

Accident Consequence Calculations
Client - Nuclear Installations Inspectorate

Project Manager of a study to assess the radiological consequences of various atmospheric releases using the MARC code.

Definition of Threshold Recording Levels for Drums of ILW
Client - UK Nirex Ltd

Project Manager of a study of the implications of post-closure radiological impacts of radioactive waste disposal in defining Threshold Recording Levels for radionuclides in individual waste drums.

Definition of Expert Judgment Exercises Relating to Nuclear Safety
Client - Commission of the European Communities

Project Manager for a study defining expert judgment exercises relating to conceptualisation, representation and input data specification. Included a comprehensive review of available formal expert judgment procedures, and mathematical and behavioural aggregation techniques.

Definition of Research Requirements Relating to the Use of Expert Judgment in Parameter Value Elicitation for Reactor Safety Studies in a UK Context
Client - Nuclear Safety Research Management Unit, HSE

Development of proposals for using combined behavioural and mathematical aggregation procedures in formal elicitations of expert judgment.

Development Priorities for the Drigg Technical Development Programme
Client - British Nuclear Fuels plc

Provision of detailed advice to BNFL on future design options, and research and development priorities, in relation to radioactive waste disposal at Drigg.

Channel Tunnel Safety Studies
Client - Channel Tunnel Safety Authority

Provision of advice and guidance on safety criteria appropriate to the Fixed Link, on the classes of Dangerous Goods that may properly be carried and on the overall characteristics of the proposed Safety Case.

Development of Societal Risk Criteria
Client - Marathon Oil

Interpretation of F-N curves in the context of the offshore oil/gas industry, taking risk aversion into account.

Impacts of Salt Dispersal on Plant Communities
Client - Sir William Halcrow

Evaluation of salt dispersal from a major road in winter in relation to adjacent Sites of Special Scientific Interest.

Offsite Consequence Assessments
Client - Nuclear Electric

Studies of the offsite radiological impacts of atmospheric and liquid releases of radioactive materials from Magnox stations.

Dry Run 3
Client - Her Majesty's Inspectorate of Pollution

Uncertainty and bias studies involving formal expert judgment procedures to develop a conceptual model of those factors and interrelationships which are of significance in determining the post-closure radiological impact of a deep geological repository for radioactive wastes. This project also included advice on data and models to be used for post-closure radiological assessments.

Radiological Assessments of Drigg
Client - British Nuclear Fuels plc

Project Manager for post-closure radiological impact assessments of the Drigg LLW disposal site. Also included specification and development of computer codes relating to the radiological impact of fires, releases of radioactive gases produced by microbial action and metal corrosion, and human intrusion.

Biosphere Co-ordination
Client - UK Nirex Ltd

Co-ordination of the UK Nirex Ltd Biosphere Research Programme from its inception, including requirements definition, technical management of all projects and QA surveillance as the Client's Representative.

Biosphere Support for the Nirex Disposal Safety Assessment Team
Client - AEA Technology

Development of approaches for assessing the radiological impact of releases of radionuclides to the biosphere, plus advice on radiological protection criteria, definition of individual risk, implications of conventionally toxic chemicals in wastes and a variety of other matters.

Evaluation and Radiological Assessment of Liquid Effluent Releases from Various Premises
Client - Her Majesty's Inspectorate of Pollution

Reviews of monitoring data and evaluations of radiological impact, primarily related to Harwell, Aldermaston, Capenhurst and Amersham International.

Evaluation of the Radiological Impact of Overseas Nuclear Accidents
Client - Her Majesty's Inspectorate of Pollution

Studies of the impact of potential overseas nuclear accidents on the UK, with emphasis on survey and monitoring requirements, and the selection of appropriate radiation detection equipment for monitoring.

Bilsthorpe Power Station
Client - British Coal/East Midlands Electricity

Preparation of an Environmental Statement with emphasis on atmospheric dispersion of SO_2 and NO_x.

Gas Generation in Radioactive Waste Disposal Facilities
Client - AEA Technology

Development of a coupled microbial degradation and corrosion model for gas generation in repositories for LLW and ILW.

Effects of Chernobyl on Drinking Water Supplies
Client - Her Majesty's Inspectorate of Pollution

Evaluation of the radiological implications of enhanced concentrations of radionuclides in water supplies in England and Wales subsequent to the Chernobyl accident.

Sea Disposal of Radioactive Wastes
Client - UK Nirex Ltd

Participation in an Environmental Impact Assessment of the proposed resumption of sea-dumping of radioactive wastes.

UK Research Related to Radioactive Waste Management
Client - Her Majesty's Inspectorate of Pollution

Identification of gaps in the UK national research effort related to radioactive waste management.

Research Requirements for Repository Design and Site Investigations
Client - UK Nirex Ltd

Review of research requirements for repository design and site investigations in relation to LLW and ILW disposal in near-surface and deep repositories.

International Commission on Radiological Protection, Sutton, Surrey, England, 1985-1986

Scientific Secretary responsible for arranging and minuting meetings, administrative arrangements, technical review of reports, editing of the Commission's journal, liaison with other international organisations and public relations.

ANS Consultants Ltd, Epsom, Surrey, England, 1979-1985

Reviews of data on the distribution at transport of radionuclides in terrestrial and aquatic ecosystems (see publications list).

Development of a dynamic model for radionuclide transport in agricultural ecosystems and implementation of the model on various microcomputer systems.

Photon and neutron shielding studies of radiochemical plant, together with area classification and ALARA studies.

A review of UK use of the criticality code MONK and other approaches to criticality safety assessment.

Radiological and conventional safety aspects of Magnox reactor decommissioning.

Development of metabolic models for inclusion in ICRP Publication 30.

Development of pharmacodynamic models for toxic chemicals.

Review of neutron activation analysis in studies of radionuclide transport in soils and plants.

Experimental studies on radionuclide transport in soils and plants using various photon-emitting radionuclides.

Support for DoE work on probabilistic risk assessment of LLW and ILW disposal.

Review of UK research requirements for HLW disposal.

Post-closure radiological impact assessment of the proposed LLW and ILW facility at Elstow, Bedfordshire.

Development of a generalised biosphere model for use in probabilistic risk assessments of solid radioactive waste disposal.

Initial development of a mathematical model for use in assessing the radiological impact of contaminated groundwater.

Development, computer implementation and comprehensive documentation of a model to calculate the radiological impact of intrusion into radioactive waste repositories.

Development of a general-purpose computer code for solving first-order differential equations using a hybrid Predictor-Corrector/Runge-Kutta method.

Studies on the potential radiological consequences of Magnox reactor accidents.

Medical Research Council Radiobiology Unit, Chilton, Didcot, Oxon, England, 1974-1979

Development of dosimetric and metabolic models for use in ICRP Publication 30.

Studies on the metabolism of plutonium in bone and relationships to blood flow.

Theoretical studies on radionuclide metabolism and dosimetry.

Development of techniques in neutron-induced autoradiography and alpha imaging.

Image analysis studies of plutonium in bone, uranium in lungs, lysosomal inclusions in cells and heterochromatin.

Studies on the clearance of inhaled UO_2.

Alpha spectroscopy in support of toxicity studies with Ra-224.

Data analysis in connection with experimental animal studies on the potential efficacy of neutron therapy using 42 MeV neutrons.

University of Sheffield, 1971-1974

Experimental studies on the reaction $\gamma + p \rightarrow \pi^o + p$ at photon energies between 1 and 3 GeV, using a linearly polarised photon beam.

SELECTION OF PUBLICATIONS

A measurement of the beam asymmetry parameter for neutral pion photoproduction in the energy range 1.2 - 2.8 GeV. P.J.Bussey, C. Raine, J.G. Rutherglen, P.S.L. Booth, L. Carroll, G.R. Court, A.W. Edwards, R. Gamet, C.J. Hardwick, P.J. Hayman, J.R. Holt, J.N. Jackson, J. Norem, W.H. Range, F.H. Combley, W. Galbraith, V.H. Rajaratnam, C. Sutton and M.C. Thorne. London Conference (1974) Abstract 997.

The measurement of the polarisation parameters S, P and T for positive pion photoproduction between 500 and 1700 MeV. P.J. Bussey, C. Raine, J.G. Rutherglen, P.S.L. Booth, L.J. Carroll, P.R. Daniel, C.J. Hardwick, J.R. Holt, J.N. Jackson, J.H. Norem, W.H. Range, F.H. Combley, W. Galbraith, V.H. Rajaratnam, C. Sutton, M.C. Thorne and P. Waller. Nuclear Physics, B104, (1976) 253-276.

The polarised beam asymmetry in photoproduction of eta mesons from protons 2.5 GeV and 3.0 GeV. P.J. Bussey, C. Raine, J.G. Rutherglen, P.S.L. Booth, L.J. Carroll, P.R. Daniel, A.W. Edwards, C.J. Hardwick, J.R. Holt, J.N. Jackson, J. Norem, W.H. Range, W. Galbraith, V.H. Rajaratnam, C. Sutton, M.C. Thorne and P. Waller. Physics Letters, 61B, (1976) 479-482.

Aspects of the dosimetry of plutonium in bone. M.C. Thorne. Nature, 259, (1976) 539-541.

The toxicity of Sr-90, Ra-226 and Pu-239. M.C. Thorne and J. Vennart. Nature 263, (1976) 555-558.

Radiation dose to mouse testes from Pu-239. D. Green, G.R. Howells, E.H. Humphreys and J. Vennart with Appendix by M.C. Thorne. Published in "The Health Effects of Plutonium and Radium", Ed. W.S.S. Jee, (J.W. Press, Salt Lake City, Utah, 1976).

The distribution and clearance of inhaled uranium dioxide particles in the repository tract of the rat. Donna J. Gore and M.C. Thorne. In "Inhaled particles IV", Ed. W.H. Walton, (Pergamon Press, Oxford, 1977) pp. 275-284.

Theoretical aspects of the distribution and retention of radionuclides in biological systems. M.C. Thorne. J. Theor. Biol., 65, (1977) 743-754.

Aspects of the dosimetry of emitting radionuclides in bone with particular emphasis on Ra-226 and Pu-239. M.C. Thorne. Phys. Med. Biol., 22, (1977) 36-46.

A new method for the accurate localisation of Pu-239 in bone. D. Green, G. Howells and M.C. Thorne. Phys. Med. Biol., 22, (1977) 284-297.

The measurement of blood flow in mouse femur and its correlation with Pu-239 deposition. E.R. Humphreys, G. Fisher and M.C. Thorne. Calcif. Tiss. Res., 23, (1977) 141-145.

The distribution of plutonium-239 in the skeleton of the mouse. D. Green, G.R. Howells, M.C. Thorne and J. Vennart. In "Proceedings of the IVth International Congress of the International Radiation Protection Association Vol. 2 (Paris 1977).

The visualisation of fissionable radionuclides in rat lung using neutron induced autoradiography. D.J. Gore, M.C. Thorne and R.H. Watts. Phys. Med. Biol., 23 (1978) 149-153.

Lymphoid tumours and leukaemia induced in mice by bone-seeking radionuclides. J.F. Loutit and T.E.F. Carr with an appendix by M.C. Thorne. Int. J. Radiat. Biol., 33, (1978) 245-263.

Plutonium-239 deposition in the skeleton of the mouse. D. Green, G.R. Howells and M.C. Thorne. Int. J. Radiat. Biol., 34, (1978) 27-36.

Imaging of tissue sections on Lexan by alpha-particles and thermal neutrons; an aid in fissionable radionuclide distribution studies. D. Green, G.R. Howells, M.C. Thorne and R.H. Watts. Int. J. Appl. Radiat. Isotopes, 29, 285-295 (1978).

Analytical techniques for the analysis of multi-compartment systems. M.C. Thorne. Phys. Med. Biol., 24, 815-817 (1979).

The initial deposition and redistribution of Pu-239 in the mouse skeleton: implications for rodent studies in Pu-239 toxicology. D. Green, G.R. Howells and M.C. Thorne. Br. J. Radiol., 52, 426-427 (1979).

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Quantitative microscopic studies of the distribution and retention of Pu-239 in the ilium of the female CBA mouse. D. Green, G.R. Howells and M.C. Thorne. Int. J. Radiat. Biol., 36, 499-511 (1979).

Techniques for studying the distribution of alpha emitting and fissionable radionuclides in histological lung sections. T. Jenner and M.C. Thorne. Phys. Med. Biol., 25, 357-364 (1980).

Morphometric studies of mouse bone using a computer-based image analysis system. D. Green, G.R. Howells and M.C. Thorne. J. Microscopy, 122, 49-58 (1981).

A semi-automated technique for assessing the microdistribution of ^{239}Pu deposited in bone. D. Green, G.R. Howells and M.C. Thorne. Phys. Med. Biol., 26, 379-387 (1981).

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Dynamic models for radionuclide transport in soils, plants and domestic animals. M. C. Thorne and P. J. Coughtrey. In: Ecological Aspects of Radionuclide Release (Ed. P. J. Coughtrey). British Ecological Society Special Publication No. 3, Blackwell, Oxford, 1983.

Studies on the mobility of radioisotopes of Ce, Te, Ru, Sr and Cs in soils and plants. P.J. Coughtrey, M.C. Thorne, D. Jackson and G.F. Meekings. In: CEC Symposium on the Transfer of Radioactive Materials in the Terrestial Environment Subsequent to an Accidental Release to Atmosphere. Dublin, April 1983.

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Pharmacodynamic models of selected toxic chemicals in man. Vol. 2. Routes of intake and implementation of pharmacodynamic models. A.D. Smith and M.C. Thorne. MTP Press. Lancaster 1986.

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