

NuSAC Paper		NuSAC(2008)P12	
Date:	3 July 2008	Open Gov. Status:	Open
Type of Paper:	DISCUSSION	File Ref:	TRIM 1.14.2.9/
Exemptions:	None		

NUCLEAR SAFETY ADVISORY COMMITTEE

THE SITING OF NUCLEAR INSTALLATIONS IN THE UNITED KINGDOM

by

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SUMMARY

This paper explores the background to the Hansard demographic siting criteria in current usage in the United Kingdom, and offers proposals for revised demographic siting criteria for application to both reactor and non-reactor nuclear facilities. The revised proposals are based on developments of previously published considerations on the topic of demographic siting criteria, provide consistency with decisions made for existing sites and have been updated to reflect HSE's Safety Assessment Principles (2006) which provide a framework for making consistent regulatory judgements on nuclear safety cases. Opportunity has also been taken to provide some comparison with International practise in this area and the detailed analytical methodology has been peer reviewed by appropriate specialists.

INTRODUCTION

Siting policy takes advantage of the contribution which the selection of sites can make to the safety of the public from the operation of nuclear facilities. The site characteristics of interest include the population distribution in the vicinity of the site, the meteorological, topographical, and geological and land usage in the region surrounding the site, and the ability to provide an adequate infrastructure for emergency preparedness.

The improvement in safety which can be achieved solely by a choice of nuclear sites is limited however, and needs to be considered against the social, economic and amenity advantages that may arise. In this sense the selection of sites for nuclear power plants in the United Kingdom involves some judgement of the balance between safety, economics and amenity.

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.¹

The regulatory assessment of siting which are relevant to various circumstances - new facilities or sites or modifications to them, is described in HSE's Safety Assessment Principles (2006). Of particular note for the purpose of this paper, are the targets for effective dose received by any person off-site arising from a design basis fault sequence.²

Site Evaluation

The assessment of risks arising from nuclear facilities needs to consider both normal operation and fault conditions. Conservative design, good operational practise and adequate maintenance and testing, should minimise the likelihood of faults. Nevertheless, faults may still occur and so a facility must be capable of tolerating them. This is known as the design basis.

The design basis analysis (DBA) is about a demonstration of the fault tolerance of the facility and the effectiveness of engineered safeguards. In respect of ensuring that the risks arising from a nuclear facility are tolerable, an important safety measure is the siting of the facility and the characteristics of the area surrounding the site involving population demographics.

In siting a nuclear facility, there are two main objectives: (i) ensuring the technical and economic feasibility of the plant; and (ii) minimising potential adverse impacts on the community and environment. Site evaluation therefore will involve a consideration of a number of factors which include:

- proximity to appropriate electricity transmission infrastructure,
- proximity to large centres of demand,
- proximity to transport infrastructure,
- access to large quantities of cooling water,
- population density, and the distribution of population around the site,
- geophysical, geological, hydrological, meteorological and seismotectonic issues,
- security risk,
- aesthetics, and sensitive ecological and heritage areas,
- geomorphological issues and the effects of landscape change,
- external hazards both natural and man-made, and the proximity of the site to other hazardous facilities, and military installations,
- economic and socio-economic factors.

A formal consideration of the above factors will invariably require input from a multi-attribute value analysis as an integral part of the overall site selection process.

¹ Department for Business Enterprise and Regulatory Reform, September 2007.
<http://www.berr.gov.uk/files/file41297.pdf>

² Dose Targets for Design Basis Fault Sequences, Safety Assessment Principles for Nuclear Facilities (2006), Revision 1.

Where unfavorable physical characteristics of the site exist, the proposed site may nevertheless be judged to be acceptable if the design of the facility includes appropriate and adequate compensating engineering safeguards.

Demographics

While it remains the case that the major contribution to public safety lies in the standards achieved in the design, construction and operation of the nuclear plant, there are further benefits in reducing societal risk through control of the population in the immediate locality of the installation.

Although a consideration of demographics is sometimes considered of secondary importance in relation to technical and economic factors because of the limited reduction in risk that can be achieved by site selection alone, it is nevertheless the only effective non-engineered means of controlling the exposure of the population in the event of an incident leading to a release of radioactive material into the environment. There is a need therefore, to consider the demographic make up around sites from the dual perspectives of limiting doses to individuals and groups, and ensuring that prompt evacuation can be undertaken should the need arise in the event of a nuclear emergency. The ability to implement prompt evacuation provides additional conservatism from a defence-in-depth perspective, and represents the final level of protection for members of the public.

Scope of the Paper

The principal aim of this paper is to inform members of NuSAC of proposals for revised demographic siting criteria for nuclear installations in the United Kingdom and to invite comment on the proposals presented herein.

The paper:

- (i) examines the background to the Hansard (1988) demographic siting criteria in current usage,
- (ii) explores how, and to what extent the Hansard criteria can be adapted and extended for application to new build nuclear power plants,
- (iii) presents proposals for demographic siting criteria in the United Kingdom for application to (a) new build nuclear power plants, (b) existing licensed nuclear power plants, and (c) existing licensed non-reactor nuclear facilities .

For immediate reference, a list of previous papers on the development of siting policy for nuclear power plants in the United Kingdom presented to the Advisory Committee on the Safety of Nuclear Installations (ACSNI) is provided in Table 1.

This paper follows on from, and is based in part on a paper recently submitted to the Management Board of the Nuclear Division of the HSE in March 2008 and will eventually feed into the Strategic Siting Assessment process for new build power reactor sites.

BACKGROUND TO THE HANSARD (1988) DEMOGRAPHIC CRITERIA

The Hansard demographic siting criteria in current usage is in essence a population density criteria and provides for both all around site and 30° sector criteria, which are written in terms of (i) population weighting factors, and (ii) weighted population constraint limits for remote (Magnox) and semi-urban (AGR) sites, Table 2. Although readily available and in common usage within NII for demographic analysis, the entries in the cells shown shaded in Table 2 for the 8-15 kilometre and 15-30 kilometre distance bands, were not made available for open publication in Hansard.

For the purpose of comparison with the current Hansard criteria, a classification schema for remote, semi-urban, and hypothetical city sites according to Beattie (1969, 1975) is provided in Table 3. The extent of the reduction in risk that can be achieved from a consideration of site selection alone, is clearly illustrated in the Figure shown inset in Table 3.

Population Weighting Factors

The population weighting factors, which are based on the original work of Charlesworth and Gronow (1967), are derived from a consideration of the dispersion characteristics of the generalized Gaussian Plume Model for a prolonged release of radioactive material. The population weighting factors represent the variation in the per capita thyroid dose (mrem), averaged over the total width of the plume front, to a standard man from a unit Curie (Ci) release of ^{131}I as a function of downwind distance from the site.

Weighted Population Constraint Limits

The weighted population constraint limits in Hansard represent the cumulative collective thyroid dose (man-rem) following an accidental release of 1000 Ci (37 TBq) of ^{131}I as a function of downwind radial distance.³

The semi-urban 30° sector constraint limits in Hansard, can be derived on the basis of: (i) an exclusion zone with zero population for $r \leq \frac{2}{3}$ mile, and (ii) a uniform population density of 20 people per acre (5,000 people per square kilometre) for $\frac{2}{3} \leq r \leq 20$ miles.⁴ The all around site constraint limits are $3 \times 30^\circ$ sector limits, which is equivalent to a uniform all around site population density of 1,250 people per square kilometre for $\frac{2}{3} \leq r \leq 20$ miles. The semi-urban constraints were derived originally on the basis that the Heysham and Hartlepool AGR sites represented the benchmark for an acceptable upper bound limit for population densities with an allowance for future developments to account for natural growth needs (excess births over deaths).

³ Griffiths (1978): For the earlier steel pressure vessel Magnox reactors, the reference maximum credible accident leading to a bounding accidental release was based on a sudden loss of coolant pressure following a bottom inlet duct failure with air ingress in conjunction with a single channel melt in the most highly rated fuel channel.

⁴ 20 people per acre = 12,800 people per square mile = 4942 people per square kilometre \approx 5000 people per square kilometre.

The remote site population constraint limits were not based on a uniform population density but were drawn as a bounding envelope around existing Magnox sites. The most densely populated 30° sector for these sites occurred at Sizewell where beyond the emergency planning zone of 1½ miles the population rapidly increased to nearly 6000 people within a radius of 3 miles. The remote site limits correspond to a density of about 1000 persons per square kilometre in the most densely populated 30° sector and about 130 persons per square kilometre all around the site.

In broad terms therefore, the remote site constraints are at most, one order of magnitude lower in terms of the reduction in the overall societal risk, than the semi-urban constraint limits in Hansard, Figure 1. This observation follows from a straightforward consideration of the all around site relative population densities.

Nuclear Safeguarding Zones

Current custom and practise 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.

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.

*R.D. Anthony, Chief Inspector Nuclear Installations
Sizewell 'B' Public Inquiry, Daily Transcripts Days 56-60*

The 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.

The basis for the 1, 2 and 5 mile zones and the population increments associated with them, was the need to ensure the Government's reactor siting policy was not invalidated by increases in the population around the site. It was considered at the time that the control given by the above safeguarding zones would be sufficient to ensure that creep in population growth around the sites would not take place without the knowledge of the regulators.

The 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.

Sizewell 'B' and Hinkley Point 'C' Public Inquiries

At this juncture, it is worthwhile recalling the statements by NII on Government siting policy presented to the Sizewell 'B' and Hinkley Point 'C' Public Inquiries.

.... if a reactor system new to commercial operation in the UK such as a PWR, is put forward for licensing, it is Government policy that initially it would be located only on a remote site until appropriate experience had been gained.

*R.D. Anthony, Chief Inspector Nuclear Installations
Sizewell 'B' Public Inquiry, Daily Transcripts Days 56-60*

... to require PWR stations, which are new to this country, to be sited in remote areas, at least until satisfactory operating experience is obtained.

*E.A. Ryder, , Chief Inspector Nuclear Installations
Hinkley Point 'C' Public Inquiry, Transcripts 2 February 1989.*

Following the Sizewell B public inquiry, more relaxed siting criteria were proposed and presented to ACSNI for later PWRs, based on a population density of 900-1800 persons per square kilometre in the most populated 30° sector, with an all around site limit given by 3×30° sector limit, ACSNI(88)P5. These proposed limits for later PWRs fall between the remote site criteria and about one third of the semi-urban criteria in Figure 1.

The equivalent all around site population density limits proposed in ACSNI(88)P5 for later PWRs lies in the range 225-450 persons per square kilometre (583-1165 persons per square mile). These populations density limits have correspondence with the guideline population density limits published in NRC Regulatory Guide 4.7 Rev.1 (1975) for initial nuclear power plant operation (500 persons per square mile) averaged over any radial distance out to 30 miles and for the projected population density over the lifetime of the facility (1000 persons per square mile) averaged over any radial distance out to 30 miles.

NRC Regulatory Guide 4.7 Rev.2 (1998) provides some relaxation in the above constraints and only refers to the population density limit at the time of initial site approval and within about 5 years thereafter, the population density, including weighted transient population, averaged over any radial distance out to 20 miles (cumulative population at a distance divided by the circular area at that distance), does not exceed 500 persons per square mile. It further states that:

If the population density of the proposed site exceeds, but is not well in excess of the above preferred value (500 persons per square mile), consideration will be given to other factors such as safety, environmental, or economic considerations, which may result in the site with the higher population density being found acceptable.

Regulatory Guide 4.7 Rev.2 (1998; p.12)

PROPOSALS FOR REVISED DEMOGRAPHIC SITING CRITERIA

Individual Risk Dose Targets

In respect of protecting the public and society from the hazards of nuclear installations, HSE's Safety Assessment Principles (2006) prescribe targets for effective dose received by any person off-site arising from a design basis fault sequence. For initiating fault frequencies less than 1×10^{-4} per annum, Target 4 prescribes a Basic Safety Limit (BSL) of 100 mSv for any person off-site. It is assumed that:

- (i) the person remains at the point of greatest dose for the maximum duration, although for extended faults a more realistic occupancy may be assumed after a suitable interval;
- (ii) the conditions under which the fault is analysed has characteristics which produce the highest dose to that person; and
- (iii) no emergency countermeasures are implemented, other than those whose implementation is shown to be highly likely.

The Target 4 effective dose limit of 100 mSv for a limiting design basis fault sequence, forms the basis for revised population weighting factors as described in Appendix A.

Region of Interest for Demographic Analysis

Since 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).

Experience has shown that the potential for interaction is very limited beyond 30 kilometres (20 miles), and that large population centres will have negligible influence on estimates for allowable increments in population growth in the immediate vicinity

of the site. It should be noted that over this range, the per capita whole body effective dose attenuates by over two orders of magnitude.

Atmospheric Dispersion

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

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

Population Factors Generic Site Evaluation

For the evaluation of generic site demographic characteristics, it is proposed that population weighting factors should be based on the Target 4 effective dose limits for initiating fault frequencies less than 1×10^{-4} per annum, Eqs. (4a) and (4b) in Appendix A.

Population Factors Site Specific Evaluation

For the evaluation of site specific demographic characteristics, it is proposed that population weighting factors should be based on the most limiting design basis off-site release consistent with Target 4, Appendix A: Table (i) and Eq.A.3.

The coefficient (A) evaluated at the assumed boundary of the exclusion zone ($r = 1$ km) for a ground level, limiting design basis accidental release, reflects the overall risk spectrum for the site specific evaluation of demographic characteristics.

Frequency weighted mean weather relative concentrations, based on the latest available meteorological conditions, should be used to determine the site specific population weighting factors. This approach is consistent with the best estimate methodology adopted for PSA analyses.

Cumulative Collective Dose - Population Constraint Limits

Only 30° sectors population constraint limits are considered here. It is proposed that all around site population constraint limits should be based universally on $3 \times 30^\circ$ sector limits for all nuclear facilities.

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

Population densities associated with the remote site 30° sector population constraint limit (1000 persons per square kilometre) should be retained as a lower bound to define inclusionary criteria.

Population densities associated with the 30° sector population constraint limit for new build nuclear sites should be based on one-third the semi-urban population constraint limit (1667 persons per square kilometre) as presented previously in ACSNI(88)P5. This population constraint limit is designed to reflect the ability of these facilities to meet more stringent demographic siting criteria.

Site Population Factors

Site characteristics should then be determined in a manner analogous to the derivation of Site Population Factors described by Openshaw (1986: 208), Appendix B.

CONCLUSIONS

The proposed siting criteria discussed within this paper are now presented on a generic basis to cover both reactor and non-reactor nuclear facilities.

The revised demographic criteria are consistent with decisions made on the siting characteristics of existing nuclear facilities in the United Kingdom and have been reviewed to inform decisions for new developments.

Opportunity has been taken to make some comparison with International practise on the siting of nuclear installations and the methodology proposed has been subject to peer review.

REFERENCES

Beattie J.R. (1963), An Assessment of Environmental Hazards from Fission Product Releases, UK Atomic Energy Authority Health and Safety Branch and Systems Reliability Service, UKAEA Report No. AHSB(S) R64.

Beattie J.R. (1969), Paper 1: A Review of Hazards and Some Thoughts on Safety and Siting, Proceedings of Symposium on Safety and Siting, London, British Nuclear Energy Society, The Institute of Civil Engineers, pp.1-6.

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Pasquill F. (1961), The Estimation of the Dispersion of Windborne Material, The Meteorological Magazine, v90 n1063, February 1961, pp.33-49.

Pasquill F. and Smith F.B. (1983), Atmospheric Diffusion, 3rd edition (June 1983), Ellis Horwood Series in Environmental Science, Ellis Horwood Ltd.

Till J.E. and Meyer H.R. (eds.) (1983), Radiological assessment - A Textbook on Environmental Dose Analysis, NUREG/CR-3332; ORNL-5968.

Table 1

Advisory Committee on the Safety of Nuclear Installations (ACSNI)

The following ACSNI papers provide additional background to the development of siting policy for nuclear power plants in the United Kingdom:

ACSNI(78)P4: W.S. Gronow, The Development of Siting Policy for Nuclear Power Stations in the United Kingdom, October 1978.

ACSNI(81)P3: R.D. Anthony, Siting Policy for Nuclear Power Plants in the UK, September 1981.

ACSNI(85)P8: F.C.J. Tildsley, Siting Policy and Emergency Arrangements for UK Nuclear Power Stations, June 1985.

ACSNI(87)P9: Anon., Siting and Safety Requirements for PWR's after Sizewell 'B', May 1987.

ACSNI(88)P1: F.E. Taylor, The Siting of Nuclear Installations in the UK, February 1988.

ACSNI(88)P5: P.B. Woods, The Siting of Nuclear Installations in the UK: Development of the Proposals, June 1988.

Table 2
Hansard (1988) Demographic Siting Criteria

The Secretary of State for Energy on 11 March 1988 tabled the demographic criteria for assessing potential sites, for both Magnox reactors and AGRs. Magnox reactors in concrete pressure vessels would be allowed some relaxation of the general Magnox criteria if necessary. The following appeared in Hansard for 11 March 1988:

“Energy: Nuclear Power Stations

“Mr Beith: To ask the Secretary of State for Energy what statistical and demographic criteria, for each type of nuclear reactor, are used in Her Majesty’s Nuclear Installations Inspectorate’s assessment of the safety of sites for nuclear power stations; if he will publish a list showing for each existing nuclear station (a) the relevant limiting criteria compared with (b) the actual population figures in each case; and if he will make a statement.

“Mr Michael Spicer: I am advised by the HSE’s Nuclear Installations Inspectorate that the current demographic criteria for assessing potential AGR sites were developed in the late 1960s. These, and more restrictive criteria of a similar type, are used as guidelines for controlling development in the vicinity of existing AGR and Magnox stations respectively. 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.

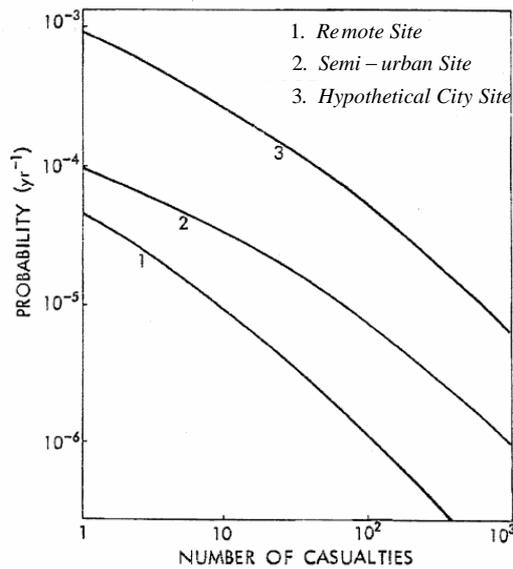
The limiting criteria are in the form of cumulative weighted population out to various distances all around the site and in any 30 degree sector. To assess a site against the criteria at a certain distance, the population for a given band distance is multiplied by the appropriate weighting factor and the values up to the distance being evaluated are added together. The weighting factors and limiting criteria for Magnox and AGR sites are:

Distance Band (km)	Weighting Factors (w)	CuSum Weighted Population Limiting Constraint	
		Magnox	AGR
Population in a 30° Sector			
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
Population All Around Site			
0-2	32.0	45,000	290,000
2-3	15.0	69,000	520,000
3-5	7.7	120,000	870,000
5-8	4.0	180,000	1,300,000
8-15	1.9	340,000	2,100,000
15-30	0.8	650,000	3,400,000

Entries in the cells shown shaded above, have been extracted from References (1) and (2) given in the footnote below.¹ Although readily available within NII, data for the 8-15 km and 15-30 km bands was not made available for open publication in Hansard.

¹ References:

- (1) Davison S. and Griffiths M.P. (1995), Proposed Improvements to Strategy for Assessing Populations Close to Licensed Nuclear Sites, WS Atkins Technical Note No. AM2910-TN1, August 1995, Woodcote Grove, Epsom, Surrey. File Ref: NUC 56/154/04A.
- (2) Electrowatt Engineering (1997), Development of Updated Siting Guidelines for Nuclear Installations, Report No. EWE-17360.6/2, May 1997, Electrowatt Engineering (UK) Ltd, Horsham, West Sussex. File Ref: NUC 56/107/7.



Source: Beattie (1975: Figure 2, p.237)

Remote site. This has some villages totalling 10,000 people or so at 4 to 5 miles, and a few larger towns totalling 50,000 people or so at 9 to 10 miles. There is a city of 200,000 people at 40 miles. There is a background population of 150 people per square mile in the populated rural areas inland of this coastal site.

Semi-urban site. This is a coastal site on the fringe of a highly populated county. The nearby population includes a city of 200,000 people at 3 to 5 miles, and there is a conurbation of ~ 1,000,000 people at 20 to 30 miles. There are subgroups of 10,000 to 50,000 people in the range 5 to 20 miles, and the background population is 300 people per square mile.

Hypothetical city site. There is assumed to be an exclusion zone of ½-mile radius around the reactor and a uniform population density of 12,800 people per square mile (5000 /km²) in all directions from ½ to 10 miles. This

Curve 1 is typical of a fairly remote site having:

- some villages totalling 10,000 or so at 4 to 5 miles.
- larger towns totalling 50,000 or so at 9 to 10 miles.
- a large town of 200,000 at 40 miles.
- a background of 150 people per square mile in other populated areas.

Curve 2 is typical of a site on the fringe of a highly populated county:

- a town of 200,000 people at 3 to 5 miles.
- a background 300 people per square mile in the range 5 to 20 miles, including sub-groups of 10,000 to 50,000.
- a conurbation of towns of 1,000,000 people at 20 to 30 miles.

Curve 3 represents a uniformly dense population of 12,800 people per square mile from ⅓ rds of a mile to 12 miles.

population density is typical of wide suburban areas around large cities in the United Kingdom (the central zone of such a city would have up to 10 times this population density however).

Source: Beattie (1975: 237)

Source: Beattie (1969: Table IV, p.5)

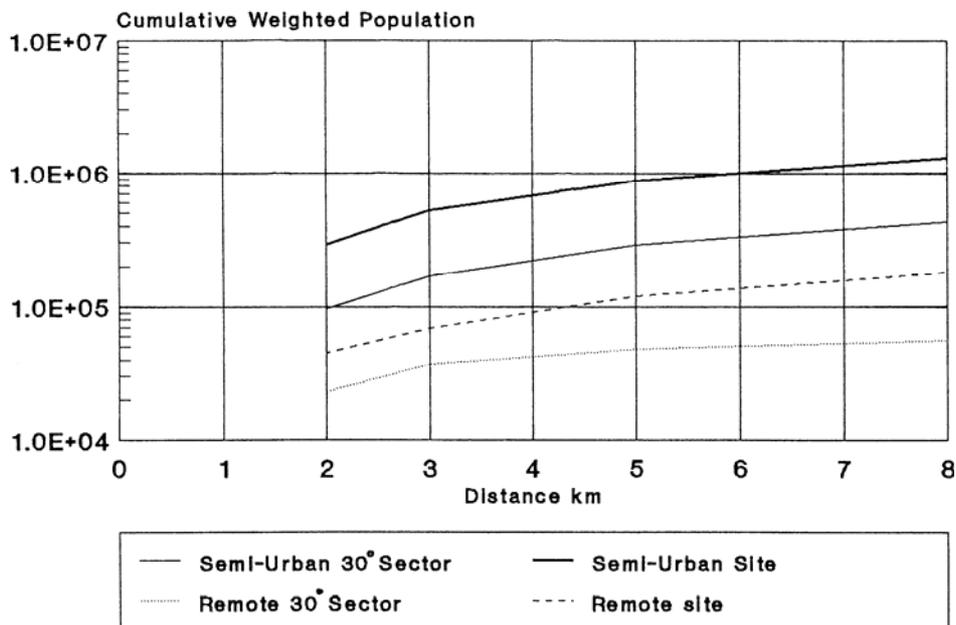
Table 3: Site Classification According to Beattie (1969, 1975).

In the region of most concern, events causing thyroid cancers in the range $10^2 - 10^3$, there is a factor of ~ 10 between each of the curves.

The choice of semi-urban rather than remote sites thus increases the frequency of given consequences by a factor of ~ 10 , and a further factor of ~ 10 is lost if city-centre siting is chosen.

Farmer (1977: 66)

Limiting Curves for Remote and Semi-Urban Sites



Source: ACSNI(88)P1: Figure 1

Figure 1

APPENDIX A

DEMOGRAPHIC SITING CRITERIA

A.1 Population Weighting Factors

The population weighting factors in Hansard (1988), which are based on the original work of Charlesworth and Gronow (1967), were derived from a consideration of the dispersion characteristics of the generalized Gaussian Plume Model for a prolonged, accidental ground level release of radioactive material.^{5, 6}

The population weighting factors describe the variation in the relative concentration $\frac{\chi}{Q}$ with downwind distance, expressed as a uniform concentration over the width of the plume front.⁷

The boundaries of the plume front are assumed to correspond to the point at which the concentration has reduced to one-tenth of its peak centreline value, Figure A.1. Defining χ_p as the peak concentration value on the plume centreline, and χ_a as the average concentration over the plume front, then for a Gaussian distribution it follows that:

$$\frac{\chi_a}{\chi_p} = 0.56542 \quad (\text{A.1})$$

Over the range of interest for demographic analysis $1 \leq r \leq 30$ km, it can be shown that the population weighting factors derived by Charlesworth and Gronow, are well represented by the following power law fit as illustrated in Figure A.2:

$$w = \frac{A}{r^n} \quad (\text{A.2})$$

where:

	A	n
Site	57.882	1.4
30° Sector	48.235	1.5

Table (i)

These power law relationships which are governed solely by meteorological factors such as atmospheric stability classification and mean wind speed, were derived assuming Pasquill atmospheric stability class F conditions with a constant mean wind speed of 2 m/sec. At the time, these meteorological conditions were judged by Charlesworth and Gronow (1967) to

⁵ Pasquill F. and Smith F.B. (1983) Atmospheric Diffusion, 3rd edition (June 1983), Ellis Horwood Series in Environmental Science, Ellis Horwood Ltd.

⁶ Till and Meyer (1983: Section 14.2.2) state that at a nuclear reactor site, a release is considered to be elevated if the point of release is more than 2½ times the height of any structure close enough to affect the dispersion of the plume. If the point of release is lower, it is categorized as a ground level release. NUREG/CR-3332.

⁷ Note that unless otherwise stated, in the context of a release of radioactive material, the term relative concentration usually refers to the time-integrated relative concentration $\int \frac{\chi}{Q} \cdot dt$, see Beattie (1963: p.18, Eq.5).

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provide conservative estimates for population weighting factors and collective dose population constraint limits.

It follows therefore, that the classical Gaussian Plume Model underpinning the Hansard (1988) demographic siting criteria remains equally applicable to all nuclear reactor and non-reactor facilities with population weighting factors $w(r)$ written in the more general form:

$$w \propto \frac{1}{r^n} \quad (\text{A.3})$$

where the coefficient of proportionality (A) implied in Eq.A.3 now represents the site and/or fault specific per capita whole body effective dose for all radionuclides, expressed as a uniform average value over the width of the plume front.

The coefficient (A) is evaluated at $r = 1$ km, the assumed boundary of the exclusion zone, and should be based on the most limiting within design basis release category or its equivalent for non-reactor nuclear facilities consistent with Target 4 of the Safety Assessment Principles for Nuclear Facilities (2006) given in Table (i) below:

Target 4: Design Basis Fault Sequences - Any Person
<p>The targets for the effective dose received by any person arising from a design basis fault sequence are:</p> <p>On-site</p> <p>BSL: 20 mSv for initiating fault frequencies exceeding 1×10^{-3} pa 200 mSv for initiating fault frequencies between 1×10^{-3} and 1×10^{-4} pa 500 mSv for initiating fault frequencies less than 1×10^{-4} pa</p> <p>BSO: 0.1 mSv</p> <p>Off-site</p> <p>BSL: 1 mSv for initiating fault frequencies exceeding 1×10^{-3} pa 10 mSv for initiating fault frequencies between 1×10^{-3} and 1×10^{-4} pa 100 mSv for initiating fault frequencies less than 1×10^{-4} pa.</p> <p>BSO: 0.01 mSv</p> <p>Source: Safety Assessment Principles for Nuclear Facilities (2006)</p>

Table (i)

Given the well documented limitations of the Gaussian plume model to real world situations, Pasquill and Smith (1983), there is no rigorous justification for making the distinction between site and 30° sector population weighting factors in the Hansard (1988) demographic criteria. Henceforth, for application to both reactor and non-reactor facilities, it is proposed that $n=1.5$ should be used in Eq.A.3 for both all around site and 30° sector demographic analyses.

An inverse power law fit with exponent $n=1.5$ is governed solely by the dispersion coefficient in the vertical plane and assumes that meander of the plume in the horizontal plane for a prolonged accidental release, is constrained within a constant $\theta = 30^\circ$ sector for all values of r , consistent with the observed behaviour of the release from the Windscale

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accident in 1957 reported by Beattie (1963), see Table (ii) below.⁸

Pasquill Stability Class F

Downwind distance x (km)	0.1	1	10	100
Lateral Plume Spread θ (deg) ¹	10	-	-	5
Lateral Plume Spread θ (deg) ²	30	25	20	15
Vertical Plume Spread h (m)	5	30	100	200

¹ Short release, Pasquill (1961) ² Prolonged release, Beattie (1963)

Pasquill (1961) specifies values of θ for 0.1 km and 100 km and recommends linear interpolation for intermediate values at 1 km and 10 km.

Implicit in this assumption is the constraint that the total angular width of the plume is identical to a constant $\theta = 30^\circ$ for all r and that it is independent of the Pasquill atmospheric stability classification.

For the purpose of estimating societal risk in terms of cumulative collective dose (man-Sv) and noting Eq.A.1, the 100 mSv BSL for initiating fault frequencies less than 1×10^{-4} in Table (i), translates to 56.542 mSv when expressed as a uniform per capita effective dose averaged over the plume front.

It is proposed therefore that weighting factors used to determine weighted population constraint limits for generic site characterisation, should be based on a coefficient of proportionality (A) equal to 56.542 mSv effective dose such that:

$$w(r) = \frac{56.542}{r^{1.5}} \text{ mSv for } r \text{ (km)} \quad (\text{A.4a})$$

$$w(r) = \frac{27.695}{r^{1.5}} \text{ mSv for } r \text{ (miles)} \quad (\text{A.4b})$$

Over the range $1 \leq r \leq 30$ km, it follows from Eqs.A.4 that the relative concentration from an accidental release of radioactive material in Table (i) attenuates by over two orders of magnitude.

A.2 Weighted Mean Weather

The concept of a weighted mean weather provides a convenient means of evaluating the relative risks to populations in the vicinity of alternative power reactor sites, Bryant (1964: 6), Beattie and Bryant (1970: 9).^{9, 10}

⁸ Beattie J.R. (1963) An Assessment of Environmental Hazards from Fission Product Releases, UK Atomic Energy Authority Health and Safety Branch and Systems Reliability Service, UKAEA Report No. AHSB(S) R64.

⁹ Bryant P.M. (1964) Methods of Estimation of the Dispersion of Windborne Material and Data to Assist in their Application, UK Atomic Energy Authority Health and Safety Branch, Radiological Protection Division, UKAEA Report No. AHSB(RP) R42.

¹⁰ Beattie J.R. and Bryant P.M. (1970) Assessment of Environmental Hazards from Reactor Fission Product Releases, UKAEA Report No. AHSB(S) R135.

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Given the frequencies f_i of the Pasquill stability class and wind speed combinations for a specific site or region, a weighted mean weather relative concentration may be calculated from:

$$\frac{\chi}{Q}_{mean} = \frac{1}{N} \cdot \sum f_i \cdot \left(\frac{\chi}{Q} \right)_i \quad (\text{A.5})$$

where N is the total number of observations.

The relative concentration $\left(\frac{\chi}{Q} \right)_i$ can be evaluated on the basis of a 30° sector with a constant averaged concentration along the plume front. Population weighting factors then follow knowing the variation of $\left(\frac{\chi}{Q} \right)_{mean}$ with downwind distance.

Frequencies for atmospheric stability class and wind speed combinations comprising hourly observations spanning a 10 year period (1997-2006), for a typical weather observation station located at Wattisham, 46 km WSW of the Sizewell site are given below:

Beaufort Scale (B) - Wind Speed					
B	≤ 1	2	3	4	> 4
knots	0-3 kt	4-6 kt	7-10 kt	11-16 kt	17-98 kt
m/sec	0.84	2.36	4.34	6.69	18.92
A	11	110	49	1	0
B	654	210	16	6	0
C	509	3230	3239	50	0
D	1643	7470	22624	22836	6982
E	376	5690	4329	30	0
F	2971	3997	153	5	0

N = 87,189 observations

Table (iii)

The Meteorological Office provides the following correlation for representative wind speed (m/sec) as a function of Beaufort scale (B):

$$\text{Wind Speed (m/s)} = 0.8360 \times B^{1.5} \quad (\text{A.6})$$

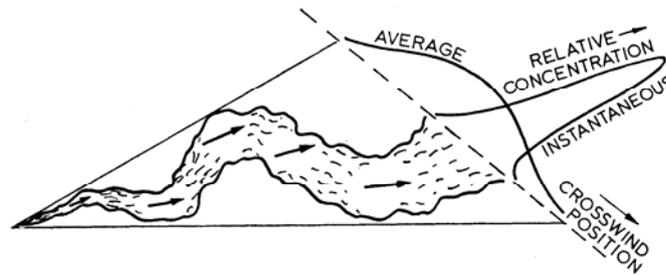
Repeating the analysis of Charlesworth and Gronow (1967) for the Wattisham meteorological dataset in Table (iii) produces the results for population weighting factors presented in Figure A.1. It can be seen that the exponent (n) associated with the inverse power law relationship governing the variation in population weighting factor $w(r)$ with downwind distance, remains relatively unchanged from that given in Table (i) above, derived assuming atmospheric stability class F conditions with a constant mean wind speed of 2 m/sec.

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The main influence of using a weighted mean weather approach in this particular application, has been to reduce the population weighting factor $w(r)$ to approximately one-third of its previous value at the assumed boundary of the exclusion zone at $r = 1$ km.

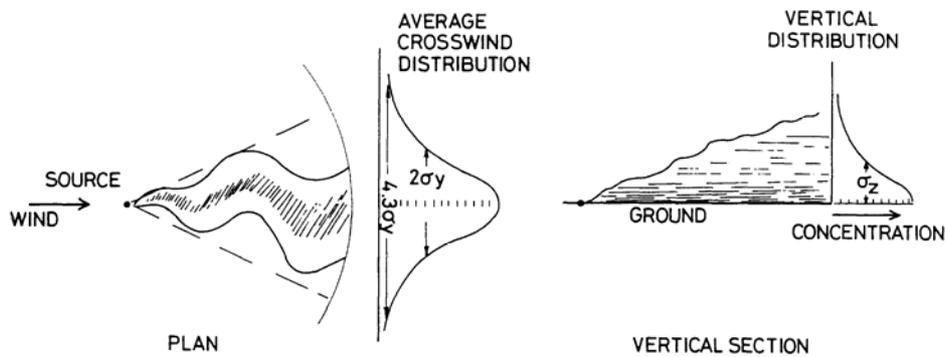
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Instantaneous and average aspects of the crosswind plume spread.



Source: Pasquill and Smith (1983: 311)

σ_y and σ_z are the statistical measures of crosswind and vertical plume dimensions. The $4.3\sigma_y$ is the width corresponding to a concentration one-tenth of the central value, when the distribution is of Gaussian form. The corresponding height of the plume is $2.15\sigma_z$.



Source: Pasquill and Smith (1983: 320)

Let the boundary of the plume be defined by $\pm y_b$ and concentration $\chi_b = 0.1\chi_p$ where χ_p is the peak concentration value on the plume centreline. For a Gaussian distribution it follows that:

$$\frac{\chi_b}{\chi_p} = \exp\left(-\frac{y_b^2}{2}\right) = 0.1$$

and solving for y_b gives:

$$y_b = 2.14597 \approx 2.15$$

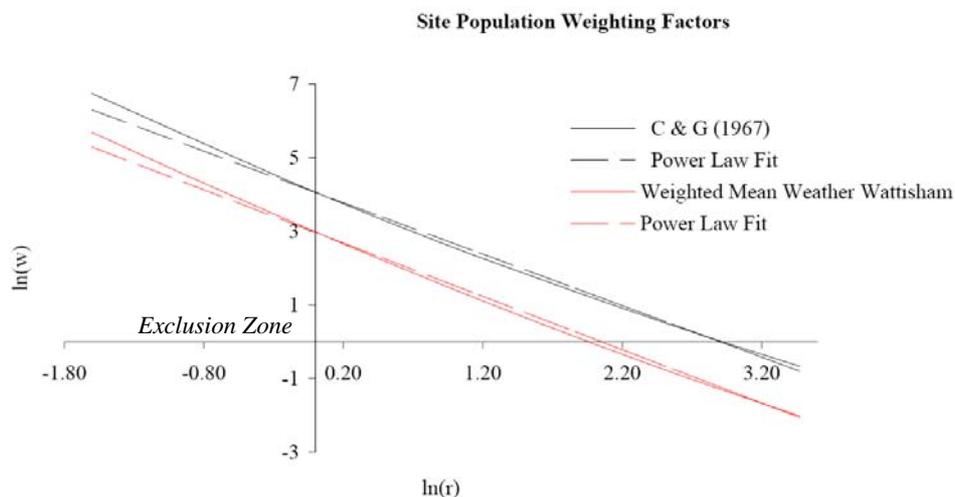
Let χ_a define the average concentration over the total width of the plume front. The ratio of average to peak concentration $\frac{\chi_a}{\chi_p}$ can be determined by integration of the Gaussian integral between the limits $\pm y_b$ to give:

$$\frac{\chi_a}{\chi_p} = \sqrt{\frac{\pi}{2}} \cdot \frac{\text{erf}(t)}{y_b} = 0.56542 \approx 0.565$$

$$\text{where } t = \frac{y_b}{\sqrt{2}}$$

Figure A.1: Schematic representation of time-mean distribution and spread for a continuous plume from a ground release point source.

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Power Law Fits

$$w = \frac{A}{r^n}$$

	Site		30° Sector	
	A	n	A	n
Charlesworth and Gronow (1967)	57.882	1.400	48.235	1.500
Wattisham Weighted Mean Weather	19.509	1.450	16.141	1.555

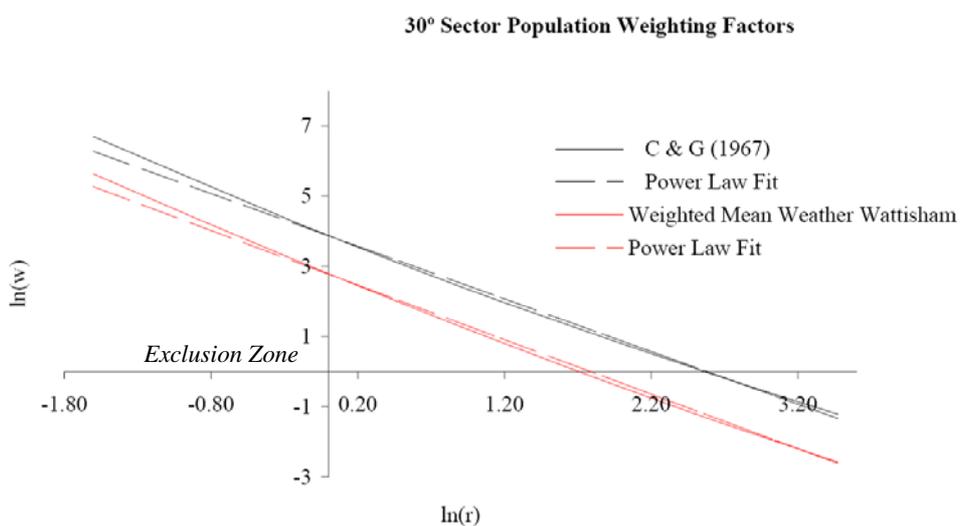


Figure Population Weighting Factors - Wattisham Mean A.2: Weather Dataset.

APPENDIX B**Extract from Openshaw (1986: 207-209)**

SITING REACTORS IN THE US

times that of Indian Point was rejected. Indian Point seems to have been taken as the limiting case until improved safety measures could be devised that would allow full metropolitan siting. In 1967 a site on Newbold Island within 5 miles of Trenton was also rejected; this is the period when equivalent UK sites at Hartlepool and Heysham were being proposed and later accepted. An application in 1967 for a site at Bailly within 10 miles of Gary was accepted as was an application for a site at Perryman which is 16 miles from Baltimore, although both were subsequently cancelled. So it would appear that in the UK reactors were being allowed on metropolitan sites with neither the benefits of geographical isolation nor secondary containment systems, and with complete reliance on engineered safeguards – something which was considered premature in the US.

The 1975 revisions

By the 1970s there was growing concern about the siting of reactors in densely populated areas, something which was not prohibited by the 1962 guidelines. This was reflected in the revised siting guidelines published in 1975 (NRC, 1975). It was also an attempt to develop generic guidelines based on a consolidation and standardisation of current practice as it was emerging from the results of various decisions. The situation was complicated by the large order rush and the wide range of different reactor types.

Regulatory Guide 4.7 (NRC, 1975) notes that based on past experience, the Nuclear Regulatory Commission (NRC) have found that a maximum exclusion boundary of 0.4 miles usually provides assurances that engineered safety measures can bring the calculated doses to within the 10CFR100 guidelines, even with unfavourable atmospheric patterns. Also based on past experience a low population zone (LPZ) of 3 miles is usually found to be adequate. These seem to be median values. Bunch *et al.* (1979) note that about 40 per cent of the current sites had distances of less than these recommended values and would have required compensatory design modifications.

There was also concern about the need to balance significant environmental, economic, and other aspects of alternative sites, including population. The 1962 guidelines did not properly include population density. There was a growing view that new sites should not be as densely populated as Indian Point unless there were other over-riding justifications. Although there is no specific regulation concerning population density in the vicinity of a power reactor site – other than that implicit in the EZ, LPZ,

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and population centre distances – the criteria published in Regulatory Guide 4.7 state that

Areas of low population density are preferred for nuclear power station sites. . . . If the population density at the proposed site is not acceptably low, then the applicant will be required to give special attention to alternative sites with a lower population density (p. 16).

It was indicated that if the population density averaged over any radial distance out to 30 miles (i.e. cumulative population at a distance divided by the area at that distance) exceeds 500 persons per square mile at the projected time of initial operation or will exceed 1,000 persons per square mile during the lifetime (40 years) of the plant, then special attention should be given to the consideration of alternative sites with lower population densities. The idea was that these population densities would trigger an additional review of alternative sites, if none were found a site may still be acceptable (NRC, 1979). Bunch *et al.* (1979) observe that less than 10 per cent of the existing sites exceed the 500 persons per square mile density limitation and 2 exceed the lifetime limit; all were approved prior to the 1975 guidelines.

The recommended method for comparing the population distributions around sites is by computing site population factors (SPF). The SPF for any site is defined as

$$SPF_i(n) = \frac{\sum_j^n W_j P_j}{\sum_j^n W_j P_j^*}$$

where

n is the outer radius of the largest annulus located n miles from site i , W_j is the weighting factor for the j^{th} 1 mile distance annulus (i.e. a radial distance band with an outer radius of j miles from the site), the weight is defined as a function of distance

$$W_j = r_j^{-1.5}$$

where r_j is the distance of the j^{th} 1 mile distance band from the site (i.e. $r_j = j$), the W_j term is supposed to represent the approximate distance dependency of the short-term atmospheric diffusion factor;

P_j is the population of the j^{th} annulus; and

P_j^* is the population of the j^{th} annulus for a hypothetical population distribution with a density of 1000 persons per square mile, it is defined as

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$$P^*_j = 1000 \times 3.14159 \times (r_j^2 - r_{j-1}^2).$$

The basic reference for the SPF is Kohler *et al.* (1974).

The SPF for a given bounding radius is different from the ratio of cumulative population densities within the same bounding radius, because of the distance weighting term. A densely populated area close to a reactor will have an effect on the SPF for all greater values of the bounding radii. However, with a simple density measure its effects will be progressively diluted. The SPF is intuitively sensible in that the influence of 100,000 people located close to a reactor yields a higher SPF than if it were located further away. The SPF also has a particularly simple interpretation. For instance, an SPF of 0.5 for a bounding radius of 30 miles is numerically equivalent to that for an area having a uniformly distributed population density of 500 persons per square mile out to a distance of 30 miles. It is designed to allow a population distribution that is skewed in the radial direction to be compared with a uniformly distributed one.

The critical SPF (30) values of 0.5 and 1.0 may be taken as indicative of the population density criteria intended in Regulatory Guide 4.7.

The 1979 report of the Siting Policy Task Force

Despite the stop-gap measures provided by the 1975 revisions it was clear that the fluidity of the licensing policy made it difficult for utilities to forecast the acceptability of sites for nuclear plant. There was no absolute set of siting criteria but a whole range of site related pronouncements. To remedy these problems the NRC set up the Siting Policy Task Force (SPTF) with the objective of providing a single statement on siting policy and practice. Their recommendations were published in 1979 (NRC, 1979).

The SPTF make a number of recommendations concerning the development of siting criteria to be applied to new nuclear plants. It is particularly interesting that an attempt is made to re-establish demographic criteria as a reactor independent safety measure at a time when there is no real prospect of any new sites being developed. The SPTF establish *three goals* for siting policy: (1) Attempts should be made to strengthen siting as a factor in defence-in-depth by establishing requirements for site approval that are independent of plant design considerations. This is a reflection of the fact that current and previous siting policies have permitted plant design features to compensate for unfavourable site characteristics by improvements in design. This has had the

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