

08 July 2008

NuSAC(2008)P12 Addendum

**NUCLEAR SAFETY ADVISORY COMMITTEE**  
**THE SITING OF NUCLEAR INSTALLATIONS IN THE UNITED KINGDOM**

**(ADDENDUM)**

by

Dr John Highton

Health and Safety Executive, Nuclear Directorate  
Nuclear Installations Inspectorate

## Site Population Factors

---

### Introduction

It is stated in NuSAC(2008)P12 that site demographic characteristics should be determined in a manner analogous to the derivation of Site Population Factors (SPFs) described by Openshaw (1986: 208), Appendix A.

This Addendum provides more detail on the means by which the expression given by Openshaw should be adapted for application to new build nuclear facilities in the United Kingdom.

Where appropriate, the notation used by Openshaw is retained.

### 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 in the narrative below where the choice of either metric or imperial units is at the discretion of the analyst.

### 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:

$$SPF(r) = \frac{\sum(w_j \times \Delta P_j)}{\sum(W_j \times \Delta \bar{P}_j)} \quad \text{for } \{(j = 1, r), (r = 1, n)\} \quad (1)$$

where ( $r$ ) is the outer radius of the largest annulus located a distance ( $r$ ) from site. SPFs should be evaluated for each distance band in each of the twelve 30° sectors and also for each distance band all around the site.

The matrix of SPFs which results from the application of Eq.1 has the following dimensions: rows equivalent to twelve 30° sectors plus all around site, and columns equivalent to the number of distance bands.

Eq.1 has been adapted from the expression given by Openshaw in Appendix A. At this juncture, it is important to note that distinct population weighting factors  $w_j$  and  $W_j$  apply to the numerator and denominator respectively.

$\Delta P_j$  is the actual population of the  $j^{th}$  annulus, for either a 30° sector annulus or all around site annulus.

$\Delta \bar{P}_j$  is the population of the  $j^{th}$  annulus for a hypothetical population distribution with a uniform population density. They are specified in Table 1 and discussed in more detail below.

## Site Population Factors

---

### Viability Condition

Site selection based on the matrix of SPFs should such judged against the viability condition:

$$SPF(r) < 1.0 \text{ for } \{(j-1, r), r-1, n\} \quad (2)$$

The application of Eq.2 will invariably involve the identification of the most densely populated 30° sector, which 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 it is anticipated that five degree increments would suffice.

### Population Weighting Factors

$(W_j)$  and  $(w_j)$  are population weighting factors associated with the  $j^{th}$  radial distance band with outer radius  $(r_j)$ , and inner radius  $(r_{j-1})$  from site.

For both reactor and non-reactor facilities, population factors  $(W_j, w_j)$  take the general form of an inverse power law relationship with downwind distance:

$$\text{Population weighting factors } w_j \text{ and } W_j \propto \frac{1}{r^{1.5}} \quad (3)$$

It is assumed that this relationship is applicable to all prevailing wind speed, atmospheric stability class combinations in the United Kingdom.

Note that different constants of proportionality apply for  $(w_j)$  and  $(W_j)$  in Eq.3.

### Generic Evaluation of the Site Demographic Characteristics

For a generic evaluation of the site demographic characteristics, no distinction is made between the population weighting factors  $(w_j)$  and  $(W_j)$  in Eq.(1) such that:

$$w_j = W_j \quad (4)$$

For a generic site application, Eq.1 thus reduces to the expression given by Openshaw in Appendix A.

Target 4 of the Safety Assessment Principles for Nuclear Facilities (2006) forms the basis for the evaluation of the population weighting factors  $W_j$ .

For initiating fault frequencies less than  $1 \times 10^{-4}$  per annum, Target 4 prescribes a Basic Safety Limit (BSL) of  $100 \text{ mSv}$  for any person off-site. The  $100 \text{ mSv}$  effective dose target is set at a level

## Site Population Factors

---

such that fault sequences within the Design Basis should not require the implementation of countermeasures which are disruptive to the public.<sup>1, 2</sup>

The 100 mSv effective dose target, translates to 56.542 mSv when expressed as an average per capita effective dose evaluated at the  $r = 1$  kilometre boundary of the assumed exclusion zone.<sup>3</sup>

We have therefore:

$$W_j = \frac{56.542}{r_w^{1.5}} \text{ mSv for } r_w \text{ (km)} \quad (5)$$

$$r_w = \sqrt{\frac{(r_j^2 + r_{j-1}^2)}{2}} \quad (6)$$

Eq.6 defines the area weighted mean radius ( $r_w$ ) in each distance band.

The denominator in Eq.1 is thus representative of the limiting value for cumulative collective dose as a function of downwind distance consistent with Target 4. The numerator in Eq.1 is representative of the site specific cumulative collective dose for the nuclear facility.

The generic evaluation of SPFs sets the benchmark for the level of ALARP justification required on a site specific basis as illustrated schematically below in Figure 1.

### Site Specific Evaluation of the Demographic Site Characteristics

For a site specific evaluation of the demographic site characteristics, population factors  $w_j$  are defined such that:

$$w_j \propto W_j \quad (7)$$

The constant of proportionality in Eq.7 should be determined on ALARP grounds such that:

$$0 < \left( \frac{w_j}{W_j} \right) \leq 1.0 \quad (8)$$

The justification for the value ascribed to the quantity  $\left( \frac{w_j}{W_j} \right)$  in Eq.8 will involve a consideration

---

<sup>1</sup> Design Basis: The range of conditions and events that should be explicitly taken into account in the design of the facility, according to established criteria, such that the facility can withstand them without exceeding authorised limits by the planned operation of safety systems.

<sup>2</sup> Emergency Reference Levels: criteria for limiting doses to the public in the event of accidental exposure to radiation, National Radiological Protection Board, July 1981, ISBN: 0859511596.

<sup>3</sup>  $W_j = \frac{27.695}{r_w^{1.5}} \text{ mSv for } r_w \text{ (miles)}$  conversion factor 1.609344 km = 1 mile

## Site Population Factors

of the actual overall risk spectrum for the site set against the risk targets prescribed in HSE's Safety Assessment Principles for Nuclear Facilities (2006), and will require assessment by NII specialist inspectors.

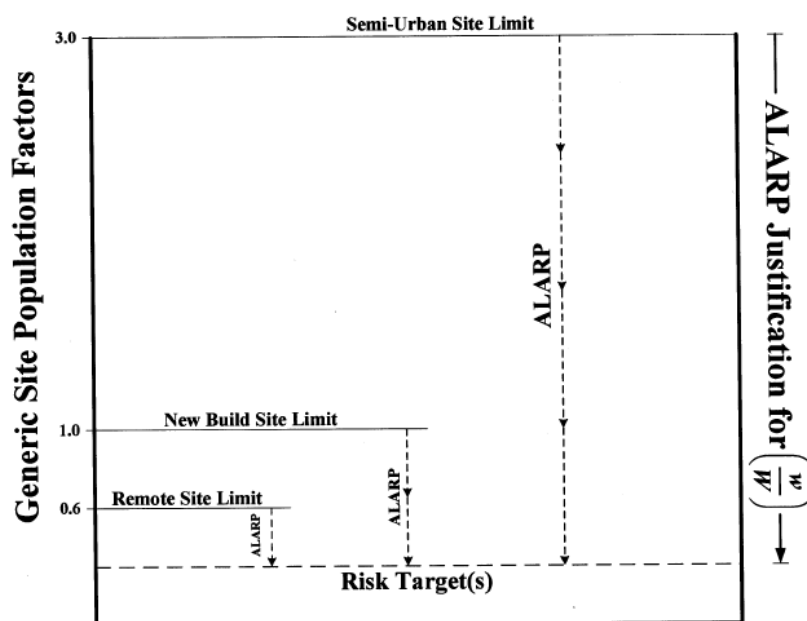


Figure 1

### Population Density Constraint Limits

Population density limits for 30° sector, and all around site constraints for remote, semi-urban and new build nuclear facilities are specified in Table 1.<sup>1</sup>

The entries in Table 1, have been derived on the following basis:

- Population densities associated with the all around site population constraint limits are based universally on 3 × 30° sector limits for all nuclear facilities. This allows one complete quadrant to be fully populated to the limit of its constraint value over the full range of demographic interest.
- Population densities associated with the remote site 30° sector population constraint limit are based on 1000 persons per square kilometre.
- Population densities associated with the semi-urban 30° sector population constraint limit are based on 5000 persons per square kilometre. Population densities in excess of the semi-urban constraint limit define exclusionary criteria.

<sup>1</sup> Table 1: A conversion factor 1.609344 km = 1 mile has been used to derive the cell entries for persons per square mile.

## Site Population Factors

---

- = Population densities associated with the 30° sector population population constraint limit for new build nuclear facilities are based on one-third of the semi-urban population constraint limit, 1667 persons per square kilometre.

	30° Sector Population Density Limits		All Around Site Population Density Limits	
	Persons per square kilometre	Persons per square mile	Persons per square kilometre	Persons per square mile
Remote Site	1,000	2,590	250	647
Semi-Urban Site	5,000	12,950	1,250	3,237
New Build Site	1,667	4,317	417	1,079

**Table 1**

## Site Population Factors

---

**APPENDIX A****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,

## Site Population Factors

## APPENDIX A

## Extract from Openshaw (1986: 207-209)

## SITING REACTORS IN THE US

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  $j^{\text{th}}$  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  $j^{\text{th}}$  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  $j^{\text{th}}$  annulus; and

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

## Site Population Factors

---

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

---

## SITING REACTORS IN THE US

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

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