The impact of radioactive particles in dose assessments

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1 Introduction

Radioactive particles in the environment pose a novel exposure pathway for members of the public. As the probability of encounter tends to be less than unity standard dose assessments are often inappropriate as they can result in significant over (or under) estimation of the potential risk. This tends to mean that specific assessments need to be undertaken to determine the risk that radioactive particles may pose to health.

2 Background

Typical prospective and retrospective assessments of the potential impact of radioactivity on health are focused on the effects of radioactivity on the human body assuming that the exposure occurs and that the activity is in a form which is homogenous and can be well characterised. Such assessments are only possible following extensive and continuing research into the effects of exposures on the human body, organs and organelles. This work has permitted the development of specific dose coefficients for given radionuclides and tissue weighting factors for human populations. Consensus on these values through the ICRP has allowed consistent assessments to be undertaken on an international level. This information, together with empirical data from appropriately calibrated instrumentation, has allowed robust assessments to be made and the public to have confidence in the outcome of such assessments for homogenous contamination.

For heterogeneous radioactive contamination (particles) the probability of encounter tends to be difficult to ascertain. Although an assessment of the potential effects of such particulate contamination can be undertaken in the same manner as that used for homogenous contamination, a number of assumptions may need to be made including the probability of contact and the hazard posed by the particle. Although this approach can be useful in determining if there is a possible serious risk to health, such assessments are generally invalid as the form of the contamination is poorly characterised and as a consequence can often result in an over or under-estimation of the potential risk.

Assessments of the risk posed by particulate contamination need to consider the two principal factors which are the probability of occurrence and the hazard posed by a particle. Both factors can be assessed separately and, if appropriate, brought together in an overall assessment of risk.

3 Legislative Framework

ICRP guidance applicable to situations where potential exposures could occur, such as radioactive particles, is specifically addressed in Publication 82. Although the advice is restricted to situations where areas are ‘sparsely distributed’ with radioactive particles, ICRP Publication 64 provides a conceptual framework for protection from potential exposure. This publication details individual risk limitation and recommends:

> *In order to establish requirements to constrain exposure to individuals from a particular source, the Commission recommends the use of constraints such that the sum of the risks from all relevant sources does not exceed the individual limit. For the treatment of potential exposure, the Commission recommends that limits of risk be the same order of magnitude as the health risk implied by the dose limits for normal exposures. However, the dose limits themselves are not applicable to potential exposure situations.*

Section 46 of ICRP 64 provides information on the individual risk limitation in relation to the optimisation procedure associated with a justified practice. This principle recommends that the optimisation procedure be *constrained by restrictions on the risks to individuals so as to limit the inequity which may result from the inherent economic and social judgements.*

In terms of the probability of an event occurring, Publication 64 provides a series of constraints (Table 1) which may be imposed taking into account the benefits derived from the particular practice.

Table 1. Range of probabilities in a year from which constraint may be selected

Sequence of events leading to doses treated as part of normal exposures	10^{-1} to 10^{-2}
Sequence of events leading to stochastic effects only but above dose limits	10^{-2} to 10^{-5}
Sequence of events leading to doses where some radiation effects are deterministic	10^{-5} to 10^{-6}
Sequence of events leading to doses where death is likely to result	$< 10^{-6}$

The publication suggested that at effective doses of less than approximately 0.1 Sv, only stochastic effects are expected to occur and their probability of occurrence (of stochastic effects) is assumed to be directly proportional to the effective dose. For absorbed doses of higher than around 0.5 Gy, some deterministic effects can occur and for acute doses of around 6 Gy, if delivered over a short period of time, almost all individuals will suffer severe health effects as a result of the irradiation. Thus Publication 64 provides some basis for consideration of acceptable probabilities of encounter and acceptable doses.

Specific advice in Publication 82 relating to acceptable doses states that in exposure situations where the annual dose approaches 100 mSv intervention will almost always be justified. However, this value may not be appropriate in a potential exposure situation; this advice is consistent with the approach outlined in Publication 64. However, sources which could deliver a dose of around 100 mSv give a valuable indication of the need to consider a specific assessment for potential exposure situations. This value, coupled with a probability of exposure of 1 in a million for death, provides a framework for consideration of the potential need for intervention to protect health.

On a national level, the UK Government and devolved administrations asked specific advice from the Health Protection Agency - Radiological Protection Division in support of the radioactively contaminated land regulations. The response, including specific advice in relation to the assessment of potential exposures, stated that:

> *if the dose that would be received from 'Hot Particles' or other heterogeneous contamination is less than or equal to 50 mSv, and the equivalent doses to the skin and lens of the eye are below 50mSv/y and 15mSv/y respectively, then it is appropriate to compare the product of the annual dose that could be received (Effective Dose) and the annual probability of the dose being received (Probability) with the dose criterion of 3 mSv/y. These dose levels are selected to essentially avoid the possibility of any deterministic effects.*
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> *If 'Hot Particles' or heterogeneous contamination could result in doses above 50 mSv, or equivalent doses to the lens of the eye or to skin above 15mSv/y and 50mSv/y, respectively, then consideration needs to be given to the possibility of deterministic health effects in addition to the probability of the dose being received. At doses above around 100 mSv consideration also needs to be given to the potential non-linearity of the dose-response relationship.*

The advice from by HPA-RPD and ICRP suggests that at doses greater than 50 or 100 mSv specific assessments are needed. For such a dose level, ICRP suggest that an annual probability of encounter of 10^{-5} may be applicable.

For doses which could result in death, a probability of encounter of 1 in a million is appropriate. This value is consistent with the Health and Safety Executive (HSE) advice of 'no danger' being equivalent to an annual fatal risk of less than 1 in a million (Health and Safety Executive, 1988. Tolerability of risk from nuclear power stations).

The evaluation of the doses and probabilities of encounter to determine the potential risk posed by radioactive particles requires specific information on the hazard and probability of encounter. The Environment Agencies are required to make assessments of doses to 'reference groups' as realistic as possible (Article 45 of the Euratom Basic Safety Standards Directive). Such a requirement will need specific information on the hazard posed by the entire population of particles and the potential exposure pathways to realistically assess the potential risks posed by radioactive particles.

The focus of advice from ICRP and HPA-RPD for assessing radioactive particles has been on either prospective assessment where it is possible to characterise, justify, optimise and then limit any release of radioactive particles as part of a practice, or a retrospective assessment of contamination which is already present in the environment. However, in cases where the contamination is poorly characterised, although retrospective assessments can be undertaken, prospective protection of the public is much more problematic.

4 Radioactive Particles

On an anthropogenic scale, the presence of radioactive particles in the environment can result in either homogenous or heterogeneous contamination dependent on the numbers and population characteristics. However, at a cellular level it can be considered that radioactive-particle contamination, together with all forms of radioactive contamination, is heterogeneous as an atom will either release energy or

not. Similarly on a national scale, all radioactive contamination can be considered as heterogeneous as at a UK population level the probability of encounter is less than certain.

Radioactive particles released into the environment can vary dramatically in number and activity; much of this variation is dependent upon their mode of creation and entry into the environment. For example, the authorised release of particles into the environment may require that the individual activities are sufficiently low such that in a likely frequent encounter the resultant dose would be less than 0.3 mSv. Such particles are also likely to be well characterised with the result that the probable effects of the population are known and the variation in characteristics is small. However, typical considerations of radioactive-particle contamination are particles whose activity is sufficiently high to pose a realistic hazard to health. These particles are also normally those which have not been authorised for release and thus little information is available on their characteristics. These particles are also typically of a size which is granular rather than the colloidal or subatomic sizes often associated with the term 'particle' in physics. Such particles tend to be highly heterogeneous at a population level and are characterised by variations in radionuclide content, activities and solubility. Individually, particles can have highly heterogeneous activity across the particle itself which is often a result of the mode of creation of the radioactive particle or environmental processes which have acted upon it since its creation.

Assessing the dose consequences of radioactive particles requires specific information on the form of the particle and its potential to cause harm. Although typical information such as activity can be obtained through normal analytical procedures such as alpha or beta spectrometry, such data can be inappropriate for assessing dose as internal absorbance can mean that the characterisation provided by such analysis is unrepresentative and thus invalid. Equally, caution is needed for empirical information on gamma analysis; although the effects of internal absorption are much reduced, variability (of unknown extent) in detection geometry can result in significant differences in the reported activity of a particle.

The occurrence of particles within the environment requires careful consideration when assessing the potential risk associated with the particles. Similarly, and in providing acceptable levels of protection to the public, consideration must be given to the significant uncertainties associated with the particles and further caution is needed for particles where no prospective assessment of the potential risk has been undertaken.

5 Hazard, Probability of encounter and Risk

The assessment of risk from a potential exposure situation and the subsequent calculation of doses need to consider the potential hazard and the probability of encounter and then, if appropriate, combine these two factors to provide a single comparative value. However, as outlined in Section 3, depending on the results obtained such a combination of these factors may not be necessary or appropriate. Thus, it is necessary to assess the hazard and probability of encounter for a radioactive dose assessment independently.

5.1 Hazard

Following the initial detection of (higher hazard) radioactive particles in the environment, there is often strong pressure to provide an initial assessment to determine whether immediate actions are needed to protect human heath. If such an

assessment is required once the radionuclides of concern have been identified, consideration can be made of the levels of activity of particular radionuclides which would result in concern. Such an approach can allow monitoring effort to be focused to determine whether such particles exist in areas where a pathway to a receptor exists. However, this approach is not sufficiently comprehensive as it does not consider the potential for large numbers of lower activities existing which in totality could represent a greater hazard to health. Thus, information needs to be gathered on the entire population of particles and the range of hazard that such a population presents to health.

The health hazard posed by radioactive particles can be highly variable; in activity, solubility and the route by which dose can be delivered. The assessment must focus on the radionuclides of concern and it is important that such information is as accurate and precise as practically possible. Once the radionuclides of concern have been assessed, consideration should be given to the potential exposure pathways, for example, skin contact, inhalation or ingestion. Should the particle contain only alpha-emitting radionuclides, it may be that the particles do not pose a hazard via direct skin contact and it can be concluded that the risk from such a pathway is negligible. For ingestion pathways, information will be needed on the total activity of the particle, contact dose rates (for irradiation of the gut wall) and the solubility of the particle (for committed doses). To allow a realistic assessment, information should be gathered by representative in vitro experiments and if necessary limited in-vivo experimentation to confirm the results. Information should also be gathered on the distribution of activity within and across the particle to assess the likely extent of self-absorbance. Information on the particle size will assist consideration of the potential for dissolution and also assessment of the potential that a particle could become permanently lodged in the GI tract.

Accurate information on particle size can allow the assessment of the dose effects of radioactive particles to become much more focused. For example, if the particles are too large to be inhaled or inadvertently ingested, the potential hazard posed by these particles need not be considered further.

In situations where the radioactive particles have been authorised for release, assessment of the hazard posed by the particles should have already been undertaken such that the uncertainties associated with the hazard are limited and due to the use of the dose constraint, unlikely to breach the dose limit unless the potential for encounter is significantly greater than that assessed.

For unauthorised releases of radioactive particles, reliable information is unlikely to be readily available and efforts should be focused to recover a representative sample from the population to allow information to be generated on the potential hazard. This process itself can skew the dose assessment as it is generally easier to recover higher activity particles rather than lower activity particles and as such large populations of low activity particles which could have significantly different properties can be missed. Equally, differing detection sensitivities of monitoring techniques may mean that the particles which present the greatest hazard, via effective dose (typically alpha and beta), may be missed entirely or underrepresented in a resultant assessment.

If recovery of particles from the environment is needed, further skewing of the dose assessment can occur if a positive/negative relationship exists between the particle size and activity. This may mean that the potential for high-magnitude events is greatest/least closest to the source. However, with increasing distance from the source the number of potential receptors can be greater. In such situations there

may be a need for separate assessments to be made close to and distant from the source. If only limited information is available on particle activities, environmental processes of sorting and re-distribution can mean that dose assessments made for greater source-receptor distances may be of limited value. These assessments may only be applicable to retrospective situations and be unreliable for the prospective protection of the public. For example, if physically larger and more active particles move from the point of origin at a slower rate than smaller less active particles, an assessment, made at a location some distance from the source based on those particles already present, may be invalid for protection purposes. Such an assessment may not have taken into account the likelihood that a slower moving particle but with greater dose consequences will reach that location in the near future. Thus, care must be taken to ensure that any assessment of hazard is sensitive to the possible uncertainties.

Regardless of the hazard potentially posed by the presence of radioactive particles in the environment, if the probability of contact/encounter with members of the public is zero there is no risk to health. Thus, any assessment of the risk posed by radioactive particles must include an estimation of the probability of encounter.

5.2 Probability of Encounter

Routine dose assessments typically assume that the probability of encounter is close to or effectively certain. For radioactive particles the range of probabilities of encounter can range from effectively zero to unity which is dependent upon the numbers released, applicable pathways and the dispersion characteristics of the release.

Assessing the probability of encounter requires information to be gathered on the number of particles (and their associated activity) present in a given environment and information on the habits of people in the area.

The number of particles present is the summation of the number of particles detected and the number of particles present but not detected. This latter value is generally assessed through determination of the probability of detection of a given activity of particle. In situations where the occurrence of the contamination is dynamic such as beaches, assumptions may need to be made of the number of particles at any given time. If such an assumption is needed, this should be detailed and when the assessment has been completed, a sensitivity analysis undertaken.

Information on the habits of the public can be obtained through specific habits surveys or generalised habit information such as W31. However, as indicated earlier, this information needs to be carefully collected to ensure that it is appropriate for the assessment of potential exposures, for example, for external hazards information may need to be obtained on the areas of skin potentially exposed together with the frequency that such exposures occur. Thus, habits data obtained for routine assessments of dose may be invalid for the assessment of radioactive particles.

The use of habits data to provide information on the most potentially exposed members of the public is essential in providing any holistic assessment of the potential risks associated with radioactive particles. However, unless this information is complemented with other potential habits which may occur in the future, it is impossible to make a precise assessment of the potential future probability of encounter. Thus the assessment must be specifically focused on the purpose for which it is being undertaken to ensure that the output is appropriate.

5.3 Risk Assessment

Information on the potential hazard posed by particles can be combined into a single value through multiplication of hazard assessment and probability of encounter. Combining these two values' allows a hierarchy to be developed of probabilistic hazards. However, for hazards that pose a realistic chance of causing a deterministic effect (i.e. around 100 mSv effective dose) this product is not appropriate. Work by Bo Lindell (2000) reports that a high-hazard multiplied by a low-probability event is not the same as the product of a low-hazard high-probability event, even if the numbers are numerically the same. This is reflected in the advice from HPA-RPD that at "*doses above 50 mSv, or equivalent doses to the lens of the eye or to skin above 15mSv/y and 50mSv/y, respectively, then consideration needs to be given to the possibility of deterministic health effects in addition to the probability of the dose being received".*

Thus, for values where the hazard becomes high, these two values should be kept separate and not combined. In such situations the resultant assessment of risk must consider site-specific issues and the relative benefits of interventions and the associated costs. In the context of public concern regarding any issue which includes wording associated with radioactivity, some form of public information is generally warranted and in light of recent social movements toward litigation for any chance of personal risk, provision of information to individuals who may be exposed to such hazards may be needed.

5.4 Uncertainty

Any assessment of risk, either retrospectively to determine potential historic exposures or prospectively to assess appropriate levels of protection, is subject to significant uncertainty. In more routine assessments uncertainties, such as the effect on the body and probability of encounter, can be well characterised and minimised to make the resultant dose assessment as realistic as possible, as required by Article 45 of the Basic Safety Standards. However, assessing the risk from particles often results in substantially greater uncertainty in the assessment. These uncertainties are further increased if the level of contamination was not assessed prior to the release of the radioactive material.

In any assessment of risk for particles, the assessment must detail and acknowledge all of the uncertainties within the assessment and, if possible, undertake a sensitivity analysis to determine the potential impact of such uncertainties on the overall outcome of the assessment. This will ensure that all relevant information on uncertainties is appropriately included and thus will result in an assessment that is robust and fully comprehensive.

Although not exhaustive, some of the uncertainties which can have a significant impact on a risk assessment for particles and therefore need to be carefully considered are:

- Determination of activity
- Range of activities
- Range of radionuclides
- Decay products
- Assessment of potential energy deposition
- Assessment of bio-availability

- Numbers present in the environment
- Sensitivity of receptors
- Information on habits and novel pathways
- Effectiveness of monitoring
- Exposure pathways
- Probability of exposures
- Individual sensitivities

An understanding of the uncertainties in assessing the potential impact of radioactive particles on health can lead to the conclusion that the range of potential risk is too great to allow any action to be based upon it and thus consideration will be needed on the adoption of the precautionary principle where "*lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation"* (Article 15 of the 1992 UNCED Rio Declaration) and Cm 2426 (sustainable Development – the UK strategy) which states that "*where there is uncertainty and potentially serious risks exist, precautionary action may be necessary*".

6 Prospective and Retrospective Dose Assessment

Radioactive particles have (and continue to be) been released into the environment via authorised releases and inadvertent/accidental releases. If an authorisation to release radioactive particles is to be granted, it may require justification as part of a practice. However, if the release is attributable to a work activity this may not require justification. The requirements of optimisation and limitation are applicable regardless of whether the release is from an authorised practice or otherwise.

The processes of optimisation and limitation of the release of radioactive particles requires that the source-pathway-receptor relationship is well characterised and understood to allow prospective assessment to be made and thus compared to the appropriate dose constraint.

Retrospective assessments of risks posed by radioactive particles can be undertaken for both authorised releases (to test the validity of the prospective assessment) or in cases of inadvertent/accidental releases. For situations where the release of radioactive particles into the environment was not in a controlled or authorised manner and no prospective assessment has been undertaken, assessments are highly likely to have greater uncertainty due to the absence of a well-characterised source term and as a result may need to be more cautious than that undertaken where the release was controlled and authorised.

Dose assessment of homogenous radioactive contamination such as that released in solution can generally be assessed through measurement of activities and determination of the individuals who are most exposed either by consuming the greatest amounts or occupying a given location for the longest period of time. However, for potential exposures to radioactive particles such an assessment of the most exposed group may be invalid. For example, particulate contamination on a beach may pose only a hazard via external direct contact on the skin. For a fisherman who spends the greatest amount of time on the beach but wears large amounts of clothing, the potential for direct contact is low compared to a sun bather who, although using the beach less frequently, has direct skin sand contact. Thus, information on habits needs to be collected and considered carefully when applying it to assessing the effects of particulate contamination.

6.1 Authorised Releases

The hazard posed by authorised releases of radioactive particles can be prospectively assessed using a high-level screening assessment or, if required, a more detailed realistic assessment of the dose consequence can be undertaken. However, both of these approaches allow and information to be gathered and the dose consequence assessed before the public can be exposed to the source.

For an initial screening approach, repeated analysis of a representative sample of the contamination can be performed to provide reliable information on the radionuclide composition. Such analysis may require the destructive analysis for physically large particles if there is a potential for significant internal absorbance of emissions. Work on the potential number of particles, which a critical group could be exposed to, can thus be combined with this cautious assessment either by assuming that the entire particle is soluble and available for absorption resulting in doses to both the GI tract and committed effective doses or, that it is insoluble and the most affected region is that of the wall of the GI tract. Although the result of such an assessment is likely to be cautious, as some of the activity is likely to remain associated with the parent material and move through the entire length of the GI tract, it provides a useful screening tool to determine if further work to assess the hazard is needed.

Should this screening assessment give rise to potential issues of concern such as high variability of hazard or significant doses from the hazard, or that the resultant doses could be close to or breach the 0.3 mSv dose constraint, a further detailed assessment may be needed. Should the assessment indicate that the doses to the critical group are below 20 µSv, no further assessment may be necessary provided that the regulator was satisfied that the operator was using best practicable means to limit discharges (Cm 2919, 1995).

A detailed prospective assessment will involve comprehensive information to better quantify the hazard, and the probability of exposure. All exposure pathways (both existing and future) and the potential for dilution in the environment need to be assessed to provide realistic information on the source-pathway-receptor relationship.

Once the potential dose has been assessed and this has been compared to the dose constraint, the potential dose should be compliant and optimisation of the release can be undertaken to ensure that the doses are as low as reasonably achievable (ALARA). Such measures may include the homogenisation and thorough mixing of the particulate material to ensure that the variability of the hazard is reduced and the potential for over-estimating the hazard of a high-activity particle is minimised. Further stages, such as mixing in a highly energetic environment, can also reduce the potential resultant dose to the critical group.

If releases of particulate material are then authorised, necessary assumptions made in the prospective assessment can be tested in the retrospective assessment. However, given that the dose limit is 1mSv in retrospective assessments, provided that the prospective assessment fully considered all of the uncertainties and the release was optimised and BPM had been applied appropriately, it is highly unlikely that the dose limit would be breached.

6.2 Unauthorised Releases

Assessment of unauthorised or inadvertent releases of radioactive particles into the environment can only be undertaken retrospectively. Assessing the doses from

radioactive particles that have already been released into the environment are far more problematic than in situations where the release was authorised as the source term is generally poorly characterised and the potential for pathways and receptors has not been examined in detail. These problems can be compounded if the release was into a dynamic environment, such as a sea, where constant movement of the particles means that any characterisation of the spatial extent and magnitude of the source term will always have significant uncertainty.

Due to the nature of unauthorised releases, there is often greater public concern than in the case of an authorised release even if the resultant doses to the critical group are comparable. For this reason, such assessments for unauthorised releases need to be robust, well developed and consider the wide range of uncertainties. Public concern can also mean that such assessments need to be undertaken over a shorter timescale than those for prospective assessments and determine if measures are needed immediately to intervene to protect public health. Public concern of unauthorised releases can also mean that the public will expect a retrospective assessment to be applicable to the prospective situation i.e. they will wish to know whether they can continue to use the affected area.

Thus, assessing the doses from particulate contamination can be undertaken on a number of levels which are often driven by time and resource constraints. These levels may be an initial screening level, a more detailed assessment or a more comprehensive and robust assessment. Consideration of whether detailed assessments are needed will depend on the potential risks assessed under the initial screening assessment and the uncertainties factored into such an assessment.

7 Public Confidence

Assessments of radioactive contamination only retain value as long as the public have confidence in the assessment and any resultant actions that may be needed. Thus, although dose assessments are necessarily complex and often tortuous, they must remain robust to future developments and the result must be comprehendible by a range of audiences. In situations where the source term is poorly understood, any assessment must make clear the assumptions used and the impact if such assumptions are latterly proven to be invalid. Regardless of the outcome of a dose assessment in situations where there is already a potential for an exposure to occur, the public must have confidence in the assessment itself and that they are suitably protected.

8 Rapid Assessments

In situations where the radioactive particulate contamination has been newly detected, often rapid assessments are needed to determine whether urgent actions are needed to protect the public. Any assessment undertaken in such situations is likely to contain a large number of uncertainties in terms of particle numbers, activities, potential for exposure and effects. In these circumstances an assessment should be sufficiently cautious to ensure that the public is protected whilst also minimising unnecessary public alarm. In these circumstances contamination, which could result in effective doses of 50 mSv or equivalent doses to the lens of the eye or to skin above 15 mSv and 50 mSv, requires detailed consideration.

9 Actions

The detection of radioactive particles in the environment can often result in significant local interest both by lay people and the scientific community. In order to ensure that public confidence is retained in an assessment, it needs to be robust and appropriate for the nature of the contamination detected. In most situations where particle contamination has been detected in the environment the probability of encounter by any individual is less than unity. However, in order to provide the necessary assurances any resultant actions from the assessment must not only consider the risk to any individual but also the collective risk attributable to the contamination.

There are many difficulties in providing an overall dose assessment for radioactive particles once present in the environment. In situations where the exposure was not planned or authorised there may be a need to set a specific dose value above which actions need to be considered. In light of the HPA-RPD advice given in Section 3, radioactive particles detected in the environment which could give effective doses of around 50-100 mSv should be considered as a reference level whereby consideration should be given to some form of intervention which, at its simplest level, could be the provision of information to potential receptors. At doses lower than this value, actions may need to be considered with consideration of the chance of encounter.

10 Summary

Radioactive particles present significant challenges to dose assessments and the resultant assessment of acceptable levels of risk to the public. Unlike normal assessments of dose, the probability of the dose being received is not certain and the calculation of the dose itself cannot be assumed to be the same as if the contamination were diffuse. As a result the assessment of doses and overall risk to potential receptors is problematic and often complex.

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