INVESTIGATIONS INTO UNUSUAL PATHWAYS OF TRANSFER OF RADIOACTIVITY TO THE ENVIRONMENT FROM NUCLEAR SITES

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NOTE

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EXECUTIVE SUMMARY

In early 1998 feral pigeons contaminated with radioactive material were discovered in the village of Seascale, 3km south of the Sellafield nuclear site. A study into levels and consequential doses to individuals was subsequently undertaken.

The study found that feral pigeons had become contaminated through contact with radioactive materials in buildings at the Sellafield site. These birds then congregated at a nearby private property used as a small bird sanctuary. The overall dose to residents at the property in the year prior to remediation was estimated as 0.57 mSv. This is significant when compared to the statutory individual annual dose limit of 1 mSv to the public, and exceeded estimated doses via established pathways from the site.

Following this study, specific recommendations were made to nuclear site operators to review their operations (past and present) and the characteristics of their sites in order to identify any unusual pathways for the transfer of contamination to the environment.

The Environment Agency responded to this recommendation by contracting AEA Technology to undertake a further study with the aim of identifying other potential, hitherto unaccounted human and environmental exposure routes, assessing their potential radiological significance relative to conventional exposure routes, and considering how they might be monitored. This would then be used to provide guidance for operators of nuclear licensed sites on how to identify and assess the existence of unusual human exposure pathways.

These objectives have been met through a major elicitation exercise identifying as far as possible all potential "unconventional" pathways from nuclear sites. These pathways have then been assessed for their radiological significance and procedural approaches have been developed for monitoring their actual existence. A large number of source, pathway and receptor combinations that might conceivably exist at nuclear sites has been identified and presented. A qualitative assessment followed considering both exposures of members of critical groups and exposures of larger population groups. A method of attribute analysis has been used to rank potential pathways in order of importance. The most highly ranked pathways were then assessed quantitatively, by developing feasible but hypothetical scenario to illustrate the potential radiological impacts that could arise from these releases, should they actually exist. This work demonstrated that some pathways could give rise to potentially significant dose uptakes to some critical groups. The prioritised generic pathways for further consideration are identified as:

1. External exposure to contaminated biotic material;
2. External exposure to radioactive sources in the environment;
3. External exposure to contaminated artefacts/sources of contamination;
4. Inhalation/ingestion of contaminated biotic material;
5. External exposure to contaminated minerals.

These pathways do not necessarily exist at any nuclear site in the UK, but serve as examples to illustrate the methodology developed in this work and assist in their actual identification and mitigation at the site level. Such site-specific assessments may identify potential unconventional pathways that will need to be verified. Therefore this study has identified the issues to be addressed for these generic source-pathway-receptor combinations in order that

specific monitoring requirements can be determined. These structured approaches can be used and adapted by the Agency and licensed nuclear site operators to identify, quantitatively assess and validate the existence of unconventional pathways.

These assessments highlight the *potential* significance of unusual pathways, and place them in the context of regulatory limits and current "conventional" pathways. The identification and assessment of *actual* instances of unusual pathways needs to be made site operators. The methodologies developed during this work should assist operators and regulators with such site-specific assessments and monitoring for the licensed nuclear sites. It is intended that this sort of approach will form the basis for assessing whether any unconventional pathways do exist at nuclear licensed sites in the UK.

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INTRODUCTION

1. In early 1998 feral pigeons contaminated with radioactive material were discovered in the village of Seascale, 3km south of the Sellafield nuclear site. A special study [1] into levels and consequential doses to affected groups of individuals was subsequently undertaken by a working group comprising Copeland Borough Council, the Department of Health, the Environment Agency (the Agency), the Health & Safety Executive (HSE), the Ministry of Agriculture, Fisheries and Food (MAFF), and the National Radiological Protection Board (NRPB).

2. The study found that the feral pigeons had become contaminated through contact with radioactive materials in non-operational buildings and possibly, in some cases, in operational buildings at the Sellafield site. These birds congregated in large numbers at a private property with a small bird sanctuary. The overall dose from man-made radionuclides to residents of the bird sanctuary in the year prior to remediation was estimated as 0.57 mSv. The dose from this newly identified pathway is significant when compared to the statutory individual annual dose limit of 1 mSv from anthropogenic sources, and exceeded estimated doses via established pathways from the site [2].

3. In response to the findings and recommendations of the working group, the Agency commissioned AEA Technology to undertake a further study to:

   - identify other potential, hitherto unaccounted for human exposure routes (for the purposes of this study, such pathways are termed “unusual”, though it should be noted that pathways that may be considered to be “conventional” for certain nuclear sites, could be presently unaccounted for and hence be “unusual” pathways at other nuclear sites);
   - assess the potential significance of the identified unusual pathways relative to conventional exposure routes; and
   - provide guidance to operators of nuclear licensed sites on how to identify the existence of unusual human exposure pathways.

4. The project was restricted to the identification and assessment of unusual exposure pathways relating to licensed nuclear sites. Such exposures may need to be evaluated as a requirement for disposal authorisations, and subject to monitoring and dose reduction measures, as appropriate, under the terms of European Radiological Protection Directives put into force in the UK [3].

5. This document provides a summary overview of the approach adopted in the project and the key findings from the study. A more detailed account of the project is presented in the Contractor Technical Document [4].

APPROACH

6. The overall aim of the project was to provide a basis for the Agency to seek assurance from the operators of nuclear sites that the existence and significance of the human exposure pathways has been comprehensively addressed. It is not feasible for all potential unusual pathway at all nuclear licensed sites to be identified and assessed within a single, one-off study, due to reasons of resource and practicality. Rather, the objective of this study was to identify potentially significant unusual elements of human exposure routes in generic terms, and illustrate them with specific examples. Through this approach, a framework is provided so that each nuclear site operator can use it to assess in detail the characteristics of their specific sites for unusual exposure routes. Identification of potentially significant unusual elements of human exposure routes has been achieved through a staged process as follows:

   - identification of potential unusual pathways;
   - assessment of the potential radiological significance of the identified pathways;
   - development of monitoring requirements.

7. Each of these stages is now described in the following sub-sections.

Pathway Identification

8. The objective of this stage was to identify potential unusual pathways of transfer of contaminated material to the environment from nuclear sites, including any concentration processes. The identification of such pathways was achieved through an initial literature review and a major elicitation exercise, comprising:

   - the development and issue of a questionnaire to interested parties in England and Wales and overseas, and analysis of the replies received;
   - structured “creative thinking” workshops involving selected individuals in order to identify and assess potential unusual pathways.

9. The questionnaires were developed to elicit information on unusual pathways from a wide audience. Questionnaires were sent out to over 200 individuals who represented a broad cross-section of interested parties. Specifically, the audience for the questionnaire included representatives of:

   - nuclear industry companies (including the management of every nuclear licensed site in England and Wales) and industry bodies;
   - relevant UK Government bodies including national agencies, regional officials and local government;
   - relevant Non-Government Organisations, including national and regional environmental pressure groups, local stakeholders and nuclear site liaison committees;
   - international experts; and
   - other interested parties

10. A full list of recipients of the questionnaires is provided in [4]. Given the differing backgrounds, interests and specialist knowledge of the recipients, three different

questionnaires were developed, each aimed at best eliciting information from recipients. The three questionnaires were developed for the recipients in the following groups:

- **Site Operators/Site Inspectors Questionnaire**
  This questionnaire was designed to elicit both site-specific and generic information, and assumed a detailed knowledge of a least one specific nuclear licensed site. The questionnaire was sent to site management, site inspectors, local pressure groups and stakeholders.
- **NGO/Expert Questionnaire**
  This questionnaire was aimed at individuals with expert knowledge of the nuclear industry, but focused on the generic elicitation of exposure routes rather than on specific nuclear sites
- **Local Stakeholder Questionnaire**
  This questionnaire was aimed at individuals with a specific interest in a local nuclear site, but who would not necessarily have detailed knowledge of the nuclear industry (many recipients of this questionnaire also received the Site Operators/Inspectors questionnaire).

11. The questionnaires were structured in such a way that the recipient was asked to consider the known "conventional" exposure pathways, the types of storage and release mechanisms at nuclear sites and any relevant assessment studies. The reader was then invited to identify alternative, unusual elements of the human exposure pathways through consideration of both unconventional release mechanisms for radioactively contaminated material and unusual habits, habitats or activities that may lead to human exposures other than those normally taken into account.

12. Over 200 questionnaires were sent out and 50 completed questionnaires were received. Analysis of the questionnaire returns identified a number of exposure pathway areas of potential interest:

- consumption of Flora/fauna (e.g. novel foods);
- exposure to contaminated flora/fauna (other than ingestion, e.g. pets gaining access to contaminated areas);
- human habits and behaviour (e.g. exploitation of contaminated minerals, novel farming practices);
- process operations (e.g. bulk processing of contaminated water);
- environmental pathways/concentrating mechanisms (e.g. re-release of activity from forest fires).

13. These elements were taken forward to the "creative thinking" elicitation meetings (see below) and provided the basis for a facilitator prompt sheet at these meetings. Review of the questionnaire returns also helped identify prospective participants in the creative thinking workshops. Two workshops were held to which limited numbers of individuals, representing a wide variety of interests and backgrounds, were invited. These meeting were held as follows:

- Environment Agency Office at Penrith, 11th November 2000
- The Hilton Hotel at Bristol, 22nd November 2000.

14. The format and objectives of both meetings were broadly the same, although a different geographic focus was placed on each meeting. The Penrith meeting focused on licensed nuclear facilities in Northern England (*e.g.* Sellafield), whereas the Bristol meeting considered a wider variety of licensed nuclear establishments in southern England and Wales.

15. The overall aim of each meeting was to bring together individuals representing different viewpoints in order to identify unusual pathways that may exist and set priorities for their further investigation. The identification of pathways requires expansive thinking, but within a structured approach to help ensure comprehensiveness of the analysis. In order to facilitate this, the meetings utilised standard techniques of Decision Conferencing (see [5] for details on the Decision Conferencing technique).

16. The approach taken in the meetings was to structure the elicitation process through consideration of the potential sources of radioactive material, the pathways by which they may be transported through the environment and the modes by which human exposure may result. The division between sources, pathways and modes of exposure of human receptors was then further broken down for the purposes of comprehensive analysis. The break down of the source, pathway and receptor elements was presented diagrammatically at the workshops using in-house AEA Technology software.

17. The elicitation process was broken down into ordered stages as follows:

    Stage 1 – Identification and characterisation of known and potential sources of release from the types of installation of interest.

    Stage 2 – Identification and characterisation of known and potential pathways of radionuclide transport from the installations of interest through to the surrounding environment.

    Stage 3 – Matching of the source and pathways analyses.

    Stage 4 – Identification of known and potential exposure groups in the vicinity of the installations of interest and characterisation of their potential modes of exposure.

    Stage 5 – Matching of the modes of exposure with the pathways of transport.

18. By the end of the meetings, sources, pathways and receptors had been identified (see Table 1) and source-pathway, and pathway-receptor linkages had been established. The connection of these linkages developed a set of continuous narratives of how a release from a source could be transported through the environment and impact on a receptor.

Assessment of Radiological Significance

19. Following the identification of potential unusual exposure pathways, the pathways were assessed in order to both prioritise the identified exposure routes and to assess their likely radiological significance in absolute terms. This was achieved through:

- a qualitative assessment of the relative importance of the identified generic pathways in order to build a prioritised set of potential unusual pathways; and
- a quantitative assessment of some specific instances relating to the higher priority generic pathways in order to assess the radiological significance of the pathway and to place these pathways in the context of the currently accounted for (or "conventional") exposure pathways.

20. In order to assess the potential significance of the identified generic source-pathway-receptor exposure routes, a qualitative analysis was developed to help identify those generic elements of the exposure routes that may be most significant. In order to achieve this, the assessment was made through consideration of source-pathway and pathway-receptor combinations, *i.e.*:

- how contaminated material may be removed from different types of sources by various environmental transport media (the source-pathway combinations); and
- how individuals may become exposed to contaminated environmental media (the pathway-receptor combinations)

21. A protocol was then required to undertake a qualitative ranking/assessment of these sources, pathways and receptors in order to identify those pathway linkages that may be potentially of most significance and thus merit further and more detailed assessment. For the source-pathway combinations, a scoring system was developed to rank the identified source-pathway combinations through consideration of the following criteria:

- accessibility of the environmental transport medium to the source?
- removability of the source to the environmental transport media?
- level of contamination of the source?

22. Similarly, the relative importance of pathway-receptor combinations was then assessed by consideration of the following criteria:

- How much of the medium is affected?
- What is the degree of dilution (within the immediate pathway)?
- What is the level of human accessibility to the contaminated medium?
- What is the level of human utilisation of the contaminated media?

23. When assessing each source-pathway and pathway-receptor combination against the above criteria, assessments were made of potential doses to representative members of critical groups of individuals, and of potential doses to larger population groups. The distinction between these two types of assessment was that different weights were applied to the assessment criteria.

24. On this basis a prioritised list of source - pathway – receptor linkages was made. From this qualitative assessment of unusual exposure pathways it was possible to identify a number of generic pathways, which could then be assessed for their potential radiological significance. The highest ranked generic source-pathway-receptor linkage combinations are described in Table 2.

25. In relation to each of these generic pathways, a number of specific practical examples were conceived to illustrate subsequent quantitative assessments (see [4] for more detail). The aim of the quantitative assessments was to assess the radiological significance of those specific generic linkages, and to place them in the context of existing conventionally assessed exposure routes from nuclear licensed sites.

26. The first stage of the quantitative assessment was a detailed literature search to identify examples of contamination pathways in the past and experimental/field studies that may be used as a basis for illustrative assessment models. The main sources of the literature were the International Atomic Energy Authority (IAEA) International Nuclear Information System (INIS) database [6] and the World Wide Web (with particular focus on the web sites of nuclear organisations such as the IAEA, the NRPB, the Agency, the US Environmental Protection Agency (USEPA) and the Food Standards Agency). The search keywords were developed from the generic pathways and the specific identified instances. Generally, the INIS database proved the most fruitful data source. Example assessments for specific instances in each of generic pathways identified above were then performed.

Development of Monitoring Requirements

27. Following the identification and prioritisation of the unusual elements of the potential exposure pathways, an approach to determining monitoring requirements at a specific site was developed. The approach described here could be used by operators on nuclear licensed sites to assist in identification and assessment of unusual pathways that may exist at their sites.

FINDINGS OF THE ELICITATION AND ASSESSMENT EXERCISE

28. During the elicitation exercise a number of Feature, Events and Processes (FEPs) were identified that might give rise to an unusual release from a nuclear site. Table 1 summarises a wide range of potential sources, pathways and receptors specific to these FEPs. A qualitative assessment of this information was undertaken and considered for both exposures of members of potential critical groups and larger populations. Table 2 describes the highest ranked (generic) source – pathway – receptor linkages arising from the assessment. For the assessment of critical group exposure routes, the most important generic pathways and specific examples were identified as:

Ingestion of agricultural flora and fauna	- Unusual/novel commercial foods - Unusual/specific farming practices
External exposure to contaminated biotic material	- Domestic/wild animals after gaining access to on-site sources
Ingestion of wild fauna and flora	- Unusual/novel foods
External exposure to sources (direct)	- Human breach of source containment e.g. under historic or legacy circumstances such as finds on ex-MoD sites, old pipes etc.
External exposure to contaminated artefacts	- Tools etc. removed from controlled areas, or contaminated fishing gear
Inhalation of contaminated biotic material	- Aerosolised droppings from congregating animals, such as birds and bats, after access to on-site sources

29. Of these, the ingestion pathways may be considered to be essentially conventional exposure routes. However, consideration needs to be given to unusual (and potentially changing) farming practices and the collection of high-accumulating unusual wild foods or wild animals that may have access to on-site sources. Within these generic categories the study found the following unusual potential exposure routes to be of relatively more importance and were therefore be given priority for further study:

1. External exposure to contaminated biotic material;
2. External exposure to radioactive sources in the environment;
3. External exposure to contaminated artefacts/sources of contamination;
4. Inhalation/ingestion of contaminated biotic material;
5. External exposure to contaminated minerals.

30. For the assessment of population group exposures, two routes were identified as dominant:

- Ingestion of agricultural flora; and
- Ingestion of agricultural fauna.

31. As noted above, these represent essentially "conventional" pathways. Furthermore, in contrast to the critical group assessment, all the medium-ranked pathway-receptor combinations highlighted in the population group assessment may also be considered as largely "conventional" exposure routes. This is as expected, since it is to be hoped that pathways that may lead to exposure of large populations, even at low dose levels, have already been identified and are already monitored around nuclear facilities. As such, the detailed assessment of unusual exposure routes to be undertaken in the latter stages of the project largely focused on the assessment of critical group exposures, as it was concluded that the more important unusual pathways are more likely affect such groups rather than larger populations.

32. In the quantitative assessment, a number of specific instances within each of the high priority generic pathway types identified above were assessed more quantitatively through consideration of reported historical incidents, the findings of experimental/field data and the development of hypothetical exposure scenarios. Through such assessments, the potential for significant radiological impacts from specific examples of exposure routes has been demonstrated. This study looked at particularly interesting scenario for exposure from contaminated biota and biotic materials, radioactive sources/contaminated artefacts, and contaminated minerals, and further detailed information on these illustrative examples and how they were assessed is provided in [4]. A short summary is provided here.

33. Many forms of biota and animals that have been considered previously might give rise to a means of transporting contamination from a nuclear site. While the levels of radioactivity are considered to be relatively small as compared to authorised emissions, significant amounts of radioactivity could be estimated to be potentially removable by some forms of wildlife. Birds in particular have been shown to be able to transfer materials from either accessible buildings or open ponds on nuclear sites (e.g. pigeons, seagulls, ducks etc). However, the radiological significance of such removal depends not just on the amount of activity removed, but also on the size of the animal, and therefore the range over which it is moved, the level of dilution (or indeed concentration) prior to human exposure and the type of human exposure (*e.g.* external, inhalation or ingestion).

34. Animals that may enter nuclear sites and potentially gain access to contaminated areas include domestic pets such as dogs and cats. In [4] the scenario of a contaminated cat was considered based on US research and radiation levels associated with the Sellafield feral pigeon incident. If the animal then spends considerable time in close proximity with its owner substantial dose uptakes could be postulated. Realistically domestic cats are less likely to range the necessary distances and gain access to contaminated materials on nuclear sites, unlike feral cats. On the other hand feral cats are less likely to gain the same contact with human beings. Nevertheless it is clear that a combination of these factors and the existence of certain human behaviour in the locality of a nuclear site could easily give rise to a significant dose uptake by a member of the public if this pathway was found to exist.

35. The quantitative study [4] also considered specific scenario based on similar examples in other countries involving various forms of biota such as floral, vegetable and resource material (e.g. wood) plants. Consideration was given to the release of spores and seeds from plants growing near effluent pipeline and ventilation outlets and from operations that process biota in large volumes (such as wood processing). Generally the radiological significance of these potential pathways was found to be small.

36. Assessment of the source – pathway – receptor combinations involving exposure to sources or contaminated artefacts a scenario was considered where contract workers such as landscape gardeners unearth historic contamination or artefacts. There have been examples of contaminated land being found on or near to nuclear sites that hitherto was considered to be uncontaminated (e.g. based on walk over surveys). These examples were used to extrapolate the potential dose uptake to a person in that area. It is conceivable that if the contamination gives rise to radiation levels up to $10\mu Sv.hr^{-1}$, workers, such as landscape gardeners may begin to receive significant doses. These dose uptakes could become comparable to the "conventional" critical group doses currently estimated for authorised releases from many UK licensed sites, if their occupation of the area exceeds more than a few hours per year. Additionally, longer exposure periods may occur due to subsequent use of gardening tools, equipment and clothing contaminated at the site and removed.

37. Potential exposures through contamination of minerals (e.g. gravels, sands etc) led to the consideration of releases to groundwater on nuclear sites. If leaks from nuclear plant to ground reached preferential transport routes and certain geological features (e.g. a perched aquifer) it was considered possible for concentrating mechanisms to enhance activity levels within the strata material. From this several possible exposure routes might occur. Firstly it was postulated that if crops are grown at where the strata outcrops consumption of that food could conceivably lead to dose uptake approaching 1mSv. Although this is highly pessimistic it serves to indicate the potential of unknown geological conditions under and local to nuclear sites. Equally quarrying or other exploitation and use of the minerals in such contaminated geological features could potentially give rise to a significant dose uptake to individuals if their residence time is long enough.

38. This assessment of these possible unusual pathways does not mean that the example exposure routes will exist in relation to UK nuclear licensed sites, and they are certainly unlikely to be prevalent at all such sites. Furthermore, the dose estimates presented in [4] can only be illustrative and even if a particular unusual pathway does exist at a site, its radiological significance is not necessarily the same as the illustrative assessment made here. The aim of the illustrative assessment presented is to highlight the *potential hypothetical* significance of the identified unusual pathways and to place them in the context of regulatory limits and the presently considered "conventional" pathways. The identification and assessment of *actual* instances of unusual pathways needs to be made at a site level. This generic work should also assist in directing any potential environmental monitoring arrangements that may ensue subsequently. To help facilitate such site-specific assessments monitoring requirements for licensed nuclear site operators have been developed (see next section). A summary of all sources, pathways and receptors identified is given in Table 1 and the assessed high priority source – pathway – receptor links are given generically in Table 2.

MONITORING REQUIREMENTS

39. Monitoring at and around a nuclear facility can occur at the point of release, at any point along the pathways of transport, or at the point of exposure. These three modes are conveniently referred to as source, pathway and receptor monitoring. For control of releases, source monitoring is preferred, as there can be direct feedback to the process generating the source. Conversely, for evaluating radiological impact, receptor monitoring is preferred. However, receptor monitoring cannot always readily be interpreted in relation to a particular source, because changes in exposure may be due to changes in the pathway characteristics, and there may be contributions from several anthropogenic sources, as well as natural background.

40. Receptor monitoring is not generally feasible for extended periods, as it involves direct investigations of exposed individuals. Thus, if humans are the identified receptor, such monitoring could involve procedures such as whole body counting and the analysis of urine samples. Duplicate diet surveys[1] are also included under the general heading of receptor monitoring. Such studies are useful in confirming the adequacy of more indirect approaches but are too resource intensive for routine application. There are also risks of raising undue alarm unless there is good cause for concern.

41. Receptor monitoring is also of no use in identifying potential exposure routes that have not yet been expressed, e.g. because the receptors are not currently making use of the contaminated materials or because the relevant pathway does not currently exist.

42. Source monitoring is a standard procedure at nuclear installations, so it is not discussed in detail here. However, it is noted that releases to groundwater received a high significance ranking in the qualitative analysis. Unlike atmospheric and liquid effluent discharges, which are controlled and subject to detailed monitoring, groundwater releases have the potential to be uncontrolled and unmonitored. Therefore, there is a need to determine whether such releases could be of significance. In general terms, the questions that should be addressed are:

- Are there or have there been spills or disposals of waste present on the site that could contaminate groundwater (e.g. leakage from ponds)?
- Is radioactive contamination present in groundwater on site (is sampling undertaken from boreholes on and around the site)?
- If radioactive contamination is present in on-site groundwater, are groundwater flow paths such that off-site contamination could arise?
- Is radioactive contamination attributable to the site present in off-site groundwater?

43. The sequence of the above questions is in the order in which investigations of this route should be undertaken. Depending on the circumstances surrounding the responses to these questions, this should lead to appropriate mitigation being introduced to protect the groundwater and subsequent receptors.

[1] In duplicate diet surveys, consumers purchase duplicate amounts of all foodstuffs, half for their own consumption and the other half is used for analysis of radioniuclide content. By recording the amounts of each food type actual consumed and combining this with the analysis data, the radionuclide intake can be estimated.

44. Pathways monitoring can be considered as a surrogate for receptor monitoring. It is used in conjunction with habit surveys to define the degree of exposure of representative members of critical groups. The habit surveys define occupancies and consumption rates that are used together with concentrations in environmental media to estimate radiation exposures. In general, the media monitored are the materials occupied or consumed. This approach works well for the standard pathways considered in assessments (*e.g.* ingestion of agricultural flora and fauna, external exposures from soils and sediments). It is likely to work less well for other more discrete pathways. For example, in the case of ingestion of wild flora and fauna, monitoring of a wide variety of seasonal items that might be consumed could entail an excessive and unbalanced use of resources when consumption of specific items is in relatively small quantities. In this case, it may be more effective to monitor soils, grass or surface water (including water from local wells or boreholes) generally in the area of the wild flora and fauna. This information could then be used to estimate potential exposures using standard, cautious models. Check sampling might be used if the specific flora and fauna becomes readily available to corroborate assumptions. Only if the estimated exposures were substantial relative to exposures from more conventional pathways would it be appropriate to investigate further.

45. From the analysis of source-pathway combinations, the potential importance of biota and materials they may come into contact with as a transport medium is clear. This requires that the biota have access to sources of radionuclides. Specific examples identified in the elicitation sessions were:

- Site access by:
  - flying fauna (*e.g.* birds, insects, bats)
  - burrowing and digging fauna (*e.g.* rabbits, dogs)
  - climbing fauna (*e.g.* squirrels)
  - access by small fauna (*e.g.* insects, rodents, reptiles, cats)
- Boundary damage (e.g. by ferrets, deer)
- Fungal growth on/around sources (e.g. rotting wood, sugar based-fixatives)
- Microbial growth on/around sources and outlets (e.g. lichen on cooling towers, corals around discharge pipes)
- Floral growth on/around sources and outlets (e.g. moss on stacks or vents, seaweed around discharge pipes)
- Faunal growth on/around sources and outlets (e.g. mollusc growth around discharge pipes)

46. In this context, it is emphasised that the identification of requirements for monitoring should consider not only what pathways exist at the moment, but also what pathways could develop in the future. Thus, accessibility of large areas of loose surface contamination may give rise to the potential for removal of that material by birds, even if this is not currently occurring.

47. In this case, the relevant questions are:

- What flora and fauna have been observed on site?
- By what mechanisms will they have crossed site boundaries?

- Could other organisms cross the site boundaries by these mechanisms?
- Are there other mechanisms by which organisms could cross the boundaries of the site?
- Have any of the flora and fauna been observed on site, or been observed to have access to active materials or sealed sources?
- Could other organisms also have access to these active materials or sealed sources?
- Is the active material removable or transferable by these organisms?
- Have flora and fauna that has access active material been monitored for their radionuclide content?
- How are organisms that could carry radioactive material off site likely to interact with humans?

48. In the above, reference to the 'site' is defined broadly to mean everything within the nuclear site boundary, and includes routes for controlled discharges that penetrate beyond the site boundary (e.g. pipelines).

49. Again depending on the answers to these questions, this should lead to appropriate monitoring and mitigation being introduced to either prevent access or break the pathway leading to protection of the general environment.

50. When considering whether organisms can penetrate the site boundaries, it is important to remember that effective barriers for humans are not necessarily effective against animals. This is obvious for flying creatures, but security fences may be leapt, burrowed under or penetrated. Furthermore, burrows and penetrations may provide an entry for others than the original creator. Also, an open gate with a security guard will effectively prevent the entry of humans, but not necessarily that of other creatures, such as foxes, dogs and cats.

51. In considering the potential for site access and egress, it is important to have a sound understanding of the ecology, geology, land use and human practices of the local area; the importance of using local expert knowledge should be emphasised. This is also relevant to identifying potential exposure pathways. For example, development of clover on a contaminated area on site together with the presence of a local apiary could indicate that it would be prudent to investigate the radionuclide content of the clover. If this proved to be significant, honey from the apiary could also be analysed. It should be noted that both wild and domesticated animals could potentially obtain access to a site. The above comments apply to all types of animals and plants, and also to animals and plants operating in conjunction, as in the case of honey production and plants growing in a contaminated area.

DISCUSSION

52. It has already been pointed out that operators should be vigilant and look out for changing practices, both on and off the licensed site. Local changes in land use, customs and practice are not always apparent even to the communities within which it occurs. Nuclear Site licensees review their operations on a regular basis and conventional discharges are included, but unconventional or unusual discharges with the potential for releases of relatively small amounts of radioactivity by unauthorised routes, have hitherto been given less formal attention. This approach to the identification of unusual pathways could be used as a basis for formally reviewing the potential existence of these discharges from nuclear sites. It may even be possible to include such site-specific studies within the Agency's formal four-year review of discharge authorisations. These issues may take on more importance as the characteristics of many nuclear sites change over the next 10 to 20 years, and the pace of decommissioning increases.

53. It is likely that such a site-specific evaluation will identify a substantial number of different source-pathway-receptor combinations that could be of relevance. Priorities must necessarily be set for investigation and subsequent monitoring of those combinations. It is recommended that a staged approach should be adopted to setting these priorities:

- In the first instance, the potential unusual pathways should be identified through a structured elicitation exercise. Consideration should be given to involvement of a range of on site experts and stakeholders with knowledge of local habits and behaviours. This exercise should be followed by a qualitative ranking analysis, similar to that undertaken in this study, to determine which of the source-pathway-receptor combinations are thought to be of low significance.
- For combinations of higher potential significance, a cautious quantitative radiological analysis should be undertaken to assess their potential importance. Those pathway combinations resulting in impacts that are less than a few tens of $\mu Sv.y^{-1}$ to a representative member of the actual, or hypothetically most exposed group, should be considered as lower priority. It should be borne in mind that where impacts are <10μSv they are considered to be of no further regulatory concern, although the principles of ALARP (As Low As Reasonably Practicable) and BPM (Best Practical Means) still apply.
- Where source-pathway-receptor combinations are identified with potentially significant radiological impacts, the monitoring required to determine those impacts should be assessed. For combinations where access to a source of contaminated material is already known to occur, samples of the relevant material or organisms involved in such access should be obtained and analysed. Combinations where the current or future potential for such access is identified, monitoring the activity of the material/organisms involved will determine when and if such access does occur. Alternatively, it may be desirable to institute measures to prevent such potential for future access before it occurs. The latter should be preferred where feasible, when the potential for access to, and removal of, solid sources of activity has been identified.

- In cases where a potential for significant radiological impact remains after monitoring has established the level of contamination of the material or biota involved, more detailed investigations should be undertaken to establish actual and potential exposures of members of the public. This will include a more complete or precise characterisation of actual and potential pathways of exposure, including radiochemical assays of environmental media and may include external counting and bioassay of samples from individuals known to be exposed.

54. It is also noted that a review of local ecology, geology, land use and human practices has the potential to identify specific unusual or unique pathways that require further investigation. For example, if unusual crops are grown or animals are reared, it will be important to determine whether these could result in unusually high concentrations of radionuclides in the products. If the literature suggests that this is the case, or is inadequate to resolve the issue, then direct monitoring of those products will be required. Similar remarks apply when plant or animal material is processed in an unusual way that could substantially increase the radionuclide concentration in the product, *e.g.* production of mineral supplements from shellfish.

55. This approach to the identification and monitoring of potential pathways should assist Site Operators in understanding of the characteristics of the site and whether actual or potential unusual pathways for transfer from radioactive sources are present. It will also help direct both the Operator and the Agency in conducting and or adapting their environmental monitoring programmes.

CONCLUSIONS

56. The objective of the project has been to provide a basis for the Agency to seek assurance from the operators of nuclear sites that the existence and significance of human exposure pathways has been comprehensively addressed. This objective has been met through the development of a methodology for identifying existing and or potential "unusual" pathways for radioactivity transfer from nuclear sites, assessment of their potential radiological significance, and monitoring requirements.

57. Through this process the following generic pathway elements has been identified as being of greatest potential significance:

- External exposure to contaminated biotic material;
- External exposure to radioactive sources in the environment;
- External exposure to contaminated artefacts;
- Inhalation of contaminated biotic material;
- External exposure to contaminated minerals.

58. Several specific instances within each of the above generic pathway types have been identified and their radiological significance has been assessed through the development of hypothetical scenarios. Through such assessments, the potential for significant radiological impacts from specific examples of possible exposure routes has been demonstrated. The quantitative assessments have highlighted the *potential hypothetical* significance of the identified unusual pathways such that they can be compared with regulatory limits and the impacts of "conventional" pathways.

59. These pathways do not necessarily exist at any nuclear site in the UK, but serve as examples to illustrate the methodology developed in this work and assist in their actual identification and mitigation at the site level. Such site-specific assessments may identify potential unconventional pathways that will need to be verified. Therefore this study has identified the issues to be addressed for several generic source-pathway-receptor combinations in order that specific monitoring requirements can be determined. These structured approaches can be used and adapted by the Agency and licensed nuclear site operators to identify, quantitatively assess and validate the existence of unconventional pathways.

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Table 1 Specific Instances within Features, Events and Processes (FEP) Elements Identified during the Elicitation Process

Ability to Penetrate Rats, Mice, Voles, Shrews, Stoats, Weasels, Ferrets, Snakes, Insects, Frogs, Squirrels	**Adventitious** Soil and sediment consumption Animal detritus (e.g. animal contaminated on site and human contact with animal) Contaminated paint from the hulls of boats Sea spume, Surface processes, Pens (e.g. sucking the ends), Grooming horses, Bird / rabbit droppings, Handling stolen contaminated plant or equipment, Leisure activities (e.g. bathing, walking, yachting, surfing, water skiing), Activities near discharge points (e.g. mud walking, diving, fishing)
Agricultural Animals Grazing estuaries (both tidally and occasionally inundated pastures), Food additives (e.g. seaweed), Mineral additives to diet, Radionuclides in silage, Growing mushrooms on animal waste products, Animal drinking water supplies (different to human supply), Soil ingestion	**Agricultural Crops** Seaweed as fertiliser, Fishbone meal, Cow or sheep dung, Production of liquid manure from sheep dung, Sewage sludge amendment Composting as a concentration mechanism Importation of contaminated turf, Irrigation, Biofuels, Flowers, Xmas trees, Bloodmeal Paper residues, Leaf mould, Recycled agricultural products (e.g. milk)
Biotic Materials Spores and pollen, Production of herb tobaccoes, Vegetation die back, Forest fires Agricultural burning, Fell fires, Peat burning, Charcoal production, Animal slurry Burning animal carcasses (but not too any great extent), Production of detritus from animal skins, Aromatherapy (e.g. lavender, geranium)	**Burrowing** Rabbits, Foxes, Moles, Badgers, Mink, Hares, Domestic dogs, Cats (feral and domestic), Lugworms, Razor shells
Concentration Mechanisms Tar, Soils acting as exchange resins, Organic waste / flotsam, Drift wood, Concentration of particulates by sewage works, Fishing equipment	**Contaminated Air** Plume, Welding processes, Sewage treatment plants (e.g. methane, CO2), Decommissioning activities producing aerosols (e.g. cutting up structures), Mining and milling (e.g. USA, Canada etc)
Contaminated Biotic Products Building materials (timber, bricks, slates, etc), Plants grown for making clothing, Thatching, Animal products for making clothing, Grain silos, Reeds for matting etc. Moss (e.g. in hanging baskets)	**Contaminated Water** Swimming / bathing, Canoeing, Windsurfing General water and outdoor sports, Fishing Recreation by water, Houseboats, Dog walking by rivers
Deliberate Soil (in particular kids (pica)), Chalk, Biros Sand (e.g. beach), Barbecues (smoke), Smoked fish, Tobacco	**Deliberate Removal** Theft of objects (e.g. tools, paint brushes) Failure to monitor properly waste materials leaving the site, Contamination of transport equipment
Direct Exposure to Contaminated Artefacts Artefacts from fishing, Beach combing (e.g. with metal detectors), Contaminated materials (e.g. packing) blown off site Interactions with the pipeline(s), Stolen equipment, Sewage discharge, Snagged anchors (i.e. boats), Treasure hunts (e.g. from shipwrecks), Retrieval of stolen cars from quarries, Historic waste, Flood damage	**Direct Exposure to Debris** Plastic bottles washed up
Estuarine CROPS Samphire, Seaweed's ANIMALS Various shellfish, Flatfish, Trout, Cod, Skate, Fish pate	**Fires** Forest fires, Ashes (washout into streams), Bonfires, Stubble burning, Peat burning

Table 1 Specific Instances within Features, Events and Processes (FEP) Elements Identified during the Elicitation Process (cont)

Flora Includes lichen, Aquatic flora near discharge points (e.g. kelp, seamice, seaweed's), Products of aquatic flora (e.g. laverbread, composting, food supplements, algenates) Terrestrial, Growbags, Grass, Moss eaten by cows, Pollen, Seeds, Plants used to produce drinks, Lawn cuttings, Dandelions, Burrs (e.g. on animals), Falling leaves	**Food Additives and Supplements** Invertebrates in estuarine environments, Fish oils, Sea salt, Algenates, Health foods, Cow / goat milk, Sunflower oil, Homeopathic medicines, Herbs, Watercress, Mineral waters
Food Supplements and Additives Calcium supplements, Iron haemoglobin supplements, Medical preparations, Colouring and flavouring agents, Fishmeal Natural candles	**Fungi** Rotting wood, Sugar-based fixatives, Off-site accumulation
Gases and Vapours Methane production, Tritiated water, Clouds Mist, Items dissolved in water (e.g. radon, SO_2, CO_2), Krypton (-85), Liquid gases	**Groundwater** Seepage points, Unauthorised discharges, Breaching of barriers with tritiated water, Rainwater mobilising activity from roof (e.g. from congregating seagulls, resuspended dust, electrostatic attraction, mosses in gutters, Cs absorption by roofing materials)
Human Intervention There are two types: • Deliberate intervention (e.g. theft) • Inadvertent actions (e.g. human error)	**Humans** Boots, Shoes, Clothing, Stationery
Jumping Deer, Rabbits	**Liquid Releases** Different forms of liquid: Aqueous, Non-aqueous, Particulate, Dissolved gases, Organic
Liquids Resuspension from Trawsfynydd	**Medical Procedures** Dialysis, Injection of contaminated material
Microbes Sewage (treatment sites), Microbe coverage on flora (e.g. seaweed), Cooling towers, Corals at the end of discharge pipes	**Migration** Flying • Starlings • Ducks • Waders • Geese • Guano • Wild fowl Non-flying • Fish • Otters • Dolphins • Whales • Sharks • Seals • Porpoise • Sprats • Eels • Frogs

Table 1 Specific Instances within Features, Events and Processes (FEP) Elements Identified during the Elicitation Process (cont)

Mineral Solids Mud on clothing, Pottery manufacture, University research (e.g. sieving stream sediment samples), Geotechnics, Routine sampling, Land reclamation (eg. salt marshes), Quarrying, Gravel extraction Dredging operations (off coast, estuaries)	**Present in-situ** Terrestrial environment, Sediments in estuary and on beach, Sediment on dredgers, Lake edge at Trawsfynydd, Edge of streams, rivers and beaches, Landfill sites (e.g. leachates), Disposal of sewage sludges
Range Non-flying • Foxes • Rabbits • Cats • Badgers • Various rodents • Insects • Mink • Snakes • Deer • Newts	**Subject to Processing** Production of aggregate Natural erosion of surfaces to reveal regions of high concentration Cutting of turf (revealing high concentrations in soil) Revealing beds of dry water bodies Use of decommissioning materials for roads, etc.
Surface Water Authorised discharges, Acid rain (C-14 labelled), Surface sewers, Resuspension	**Swarming / Shoaling Behaviour** NON-FLYING • Ants • Humans looking after feral animals • Insects • Shellfish • Lugworm • Lobsters • Spawning grounds (e.g. salmon)

Table 1 Specific Instances within Features, Events and Processes (FEP) Elements Identified during the Elicitation Process (cont)

<table>
<tr>
<td>Swarming Behaviour
FLYING
• Insects
• Bees
• Ants (flying)
• Bats
• Mosquitoes
• Birds (e.g. humans feeding them)
• Pigeons
• Starlings
• Seagulls
NON-FLYING
• Ants
• Humans looking after feral animals
• Insects
• Shellfish
• Lugworm
• Lobsters</td>
<td>Terrestrial
FLORA
• Fungi
• Berries
• Elderberries
• Blueberries
• Rosehips
• Orchard fruit
• Seashore plants
• Home brewing
• Wild Sicily
• Nettles
• Nuts
• Dandelions
• Herbs
• Sorrel
• Wild strawberries
• Distillation
FAUNA
• Pheasant
• Other game
• Wood pigeon
• Ostrich farms
• Emus
• Fish farms
• Rabbits
• Deer
• Duck
• Geese
• Wild fowl
• Game pate</td>
</tr>
<tr>
<td>Treated
Water wells</td>
<td>Untreated
Water butts, Bathing in rainwater, Rainwater for drinking, Water recycling systems</td>
</tr>
<tr>
<td>Uptake through the Skin
Tattoo’s, Mosquitoes, Snake bites, Contaminated liquids (e.g. tritiated water)</td>
<td></td>
</tr>
</table>

Table 2 Highest Ranking Generic Source-Pathway-Receptor Linkages

Receptor	Radio-labelled media	Original transport media	Original source	Rank
Ingestion fauna Agri. Animals	Biota	Biota	Liquid	High
Ingestion fauna Agri. Animals	Biota	Biota	Uncontrolled	High
Ingestion fauna Agri. Animals	Biota	Water	Emplaced Wastes	High
External con. biotic material	Biota	Solids	Con. Ground	High
External con. biotic material	Biota	Solids	Uncontrolled	High
External direct exposure Sources	Solids	Water	Emplaced Wastes	High
External con. biotic material	Biota	Biota	Liquid	High
External con. biotic material	Biota	Solids	Liquid	High
Ingestion fauna Agri. Animals	Biota	Water	Liquid	High
Ingestion fauna Agri. Animals	Biota	Biota	Con. Ground	High
External con. biotic material	Biota	Biota	Uncontrolled	High
External con. biotic material	Biota	Solids	Emplaced Wastes	High
Ingestion fauna Agri. Animals	Biota	Water	Uncontrolled	High
Ingestion Flora Agri. Crops	Biota	Water	Emplaced Wastes	High
Ingestion fauna Agri. Animals	Biota	Solids	Con. Ground	High
Ingestion fauna Agri. Animals	Biota	Water	Con. Ground	High
Inhalation Aerosols biotic	Biota	Water	Emplaced Wastes	High
External con. biotic material	Biota	Water	Emplaced Wastes	High
External direct exposure Sources	Solids	Air	Aerial	High
External direct exposure Sources	Solids	Water	Liquid	High
Ingestion fauna Agri. Animals	Biota	Solids	Uncontrolled	High
External direct exposure Sources	Solids	Water	Uncontrolled	High
Ingestion fauna Agri. Animals	Biota	Solids	Liquid	High
Ingestion fauna Agri. Animals	Biota	Water	Aerial	High
Ingestion fauna Wild animals Terrestrial	Biota	Biota	Liquid	High
Ingestion fauna Wild animals Estuarine	Biota	Biota	Liquid	High
External direct exposure Sources	Solids	Solids	Con. Ground	High
External direct exposure Sources	Solids	Water	Con. Ground	High
External direct exposure Facility	Solids	Solids	Con. Ground	High
Ingestion Flora Agri. Crops	Biota	Water	Liquid	High
Inhalation Aerosols biotic	Biota	Water	Liquid	High
External con. biotic material	Biota	Water	Liquid	High