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Guidance on the selection of remedial actions for land contaminated with radioactivity

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Guidance on the selection of remedial actions for land contaminated with radioactivity

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Abstract

There is currently no published guidance to assist in the selection of options for the remediation of contaminated legacy sites in England and Wales. To provide such guidance, this study has applied a decision framework currently used for remediating land contaminated as a result of a nuclear accident. The application of the decision aiding process worked well despite there being significant differences between nuclear accident and legacy contamination with regards to the range of radionuclides considered, their physical and chemical forms, and distribution within the environment. Far fewer remedial actions (17 out of 78) were found to be applicable to contaminated legacy sites than to land contaminated as a result of a nuclear accident, as there is no requirement for precautionary measures or other actions to be taken soon after deposition to remove fresh contamination. Even where remedial actions were applicable to contaminated legacy sites some of these actions required adaptation to manage contamination at depth (e.g. soil removal, ploughing methods).

The decision aiding framework for nuclear accidents has been adapted for contaminated legacy sites and then applied to two scenarios involving historical contamination of land: domestic gardens contaminated by feral pigeon droppings (radionuclides of interest: ^{137}Cs and ^{239}Pu); and a site formerly used to house radium luminising facilities (radionuclides of interest: ^{210}Pb, ^{210}Po and ^{226}Ra). These were chosen to illustrate how a remediation strategy can be developed for: domestic gardens and driveways; agricultural land; recreational areas; and a new housing development requiring a change of land use.

Having established the potential applicability of the decision framework for remediation of legacy sites, several recommendations have been made to further develop the approach.

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Contents

Abstract		**i**
1	**Introduction**	**1**
1.1	**Objectives of the guidance**	**1**
1.2	**Audience and application**	**1**
1.3	**Context**	**2**
1.4	**Scope**	**2**
1.4.1	Sources of contamination	2
1.4.2	Radionuclides of interest	2
1.4.3	Key exposure pathways	3
1.4.4	Surfaces considered for remediation	4
1.4.5	Types of remedial actions	4
1.4.6	Topics not considered	4
1.5	**Structure**	**8**
1.6	**Terminology**	**8**
2	**Radiological protection principles and criteria relevant to remediation**	**9**
3	**Evaluation and selection of remedial actions: the eight-step process**	**10**
3.1	**Key steps in selecting and combining options**	**10**
3.2	**Selection tables**	**11**
3.3	**Applicability of remedial actions according to radionuclide**	**12**
3.4	**Checklist of key constraints for each remedial action**	**17**
3.5	**Effectiveness of remedial actions**	**23**
3.5.1	Inhabited Areas	23
3.5.2	Food production systems	24
3.6	**Types of waste produced from implementation of remedial actions**	**28**
3.6.1	Inhabited areas	28
3.6.2	Food production systems	28
3.7	**Datasheets of remedial actions**	**28**
3.8	**Comparing the remaining remedial actions**	**28**
4	**Worked examples**	**31**
4.1	**Domestic gardens contaminated by feral pigeons**	**31**
4.1.1	Background	31
4.1.2	Decision framework for the remediation strategy	31
4.2	**Site formerly used to house radium luminising facilities**	**35**
4.2.1	Background	35
4.2.2	Decision framework for the remediation strategy	36
5	**Conclusions and recommendations**	**45**
6	**Acknowledgements**	**45**
7	**References**	**45**
Appendix A	**Datasheets of Remedial Actions**	**46**
Appendix B	**Excluded remedial actions**	**83**

1 Introduction

Historical contamination of land by radionuclides from anthropogenic activity has in many cases occurred due to a lack of understanding of the hazards posed by radioactive materials at the time. Industrial activities have involved the use of materials containing radioactive material in a variety of different contexts including: use for their radioactive properties e.g. luminising works; use for their non-radioactive properties where the presence of radioactivity is incidental e.g. gas mantle production; and inadvertent handling and accidental release of radioactive materials e.g. lead mining.

The unregulated disposal of wastes containing enhanced levels of radioactivity from many different types of industry has left an environmental legacy that may require management under today's more rigorous radiological protection regimes. The identification and remediation of land contaminated with radioactivity is managed under Part 2A of the Environmental Protection Act 1990 (UK Government, 1990). Within the radioactive contaminated land regimes in England and Wales, local authorities have a duty to inspect land in their areas to identify sites that represent an unacceptable risk to health due to the presence of radioactivity. Identification of such land will require that remediation is considered. In addition, work undertaken with respect to a change in the use of land, for example the redevelopment of an old industrial site for residential use, may also uncover evidence of radioactive contaminants being present. Where contamination is present that may pose an unacceptable level of risk to the health of future users of the land, remedial action prior to or during development is likely to be required.

There is currently no guidance available to help select options for the remediation of contaminated legacy sites.

1.1 Objectives of the guidance

This guidance has been developed to meet several inter-related objectives:

- **a.** to provide up-to-date information on actions for remediating land contaminated with radioactivity as a result of past practices
- **b.** to illustrate how to select and combine remedial actions and hence form a remediation strategy according to the affected land use
- **c.** to identify any gaps in information and data currently available

1.2 Audience and application

This guidance is specifically targeted at local authorities in England and Wales to support their remediation strategy. However, it may also be used as a reference document to inform central government departments and agencies, experts in radiation protection and other stakeholders who may be affected by/concerned about land which has been contaminated with radioactivity, depending on the situation.

1.3 Context

Whilst the primary focus of this guidance is the protection of members of the public from exposure to radiation, economic, social and environmental aspects can also play a significant role in influencing whether or not remediation is carried out, and in which options are selected. Consequently, some consideration is given to how these non-radiological factors can influence the remediation strategy.

1.4 Scope

1.4.1 Sources of contamination

There are a number of historical land uses that have the potential to result in contamination of land with radioactivity, such that the criteria at which land could be determined as radioactive contaminated land are exceeded; these are summarised in Table 1. Table 2 presents complementary information on historical uses of land which are unlikely to meet these criteria. However, as each site has its own unique characteristics and history, the possibility that those historical land uses given in Table 2 could meet the criteria for being radioactive contaminated land cannot be ruled out completely. For each land use given in Tables 1 and 2, information is given on the potential route of contamination, likely forms of contamination, the key radionuclides likely to be present and main exposure pathways. A more detailed description of historical land uses and their potential to cause contamination is given in report CRCE-RAD-001-2020 (Oatway, 2020a).

1.4.2 Radionuclides of interest

In Table 1 and Table 2, radionuclides of interest have been grouped into five broad categories with the following nomenclature:

a. ‘Any’ indicates that a wide range of radionuclides may be present making identification of key radionuclides impossible (e.g. ^{90}Sr, ^{137}Cs, ^{239}Pu and ^{241}Am);

b. ^{238}U+ includes all members of the radioactive decay chain headed by ^{238}U, principally ^{238}U, ^{234}Th, ^{234m}Pa, ^{226}Ra, ^{222}Rn, ^{214}Pb, ^{214}Bi, ^{210}Pb, ^{210}Po;

c. ^{235}U+ includes all members of the radioactive decay chain headed by ^{235}U, principally ^{235}U, ^{231}Th, ^{231}Pa, ^{227}Ac, ^{227}Th, ^{223}Ra, ^{211}Pb, ^{211}Bi;

d. ^{232}Th+ includes all members of the radioactive decay chain headed by ^{232}Th, principally ^{232}Th, ^{228}Ac, ^{228}Th, ^{224}Ra, ^{212}Pb, ^{212}Bi, ^{208}Tl;

e. ^{226}Ra+ includes all members of the radioactive decay chain headed by ^{226}Ra, principally ^{226}Ra, ^{222}Rn, ^{214}Pb, ^{214}Bi, ^{210}Pb, ^{210}Po.

In the vast majority of land uses discussed in this report, potential contamination of land by radioactivity is likely to involve radionuclides originating from the naturally occurring radioactive decay chains headed by uranium-235 (^{235}U), uranium-238 (^{238}U) and thorium-232 (^{232}Th). An example of this is radium-226 (^{226}Ra) and its radioactive progeny. There are a large number of radionuclides in these radioactive decay chains and hence a mix of alpha particles, beta particles and gamma rays are produced. With respect to the health risk posed by radiation, alpha and beta particles are mainly of concern if they are emitted from inside the body after ingestion or inhalation. However, in some situations, exposure of the skin to alpha and beta particles may also be of concern. Gamma radiation can travel large distances in air and can therefore pose a risk to health even when emitted by radionuclides located outside of, and at some distance from, the body.

1.4.3 Key exposure pathways

When considering the selection of remedial actions for land contaminated with radioactivity, it is important to identify the key exposure pathways for the radionuclides present. When the contaminant is in or on the ground the main exposure pathways are likely to involve the intake of alpha and beta emitting radionuclides or external irradiation from gamma emitting radionuclides located outside of the body. However, the relative importance of each pathway will be determined not only by the radionuclides present but also by the local environment and the habits of potentially exposed individuals. For example, the relative importance of the intake of radionuclides associated with suspended dust may be reduced by the presence of vegetation or hardstanding as these can suppress the suspension of dust. Alternatively, the relative importance of inhaling radionuclides could be enhanced during periods when direct disturbance of the ground occurs, such as when construction work is undertaken, as more suspended dust is created during such activities. Radioactive gases such as radon can also concentrate inside buildings so the dose* received when inside a building can be significantly higher than that received when outside even if the activity concentration in the ground of the source of the radioactivity is the same. It is known that some former MoD sites, such as airfields, have been converted to farmland and the uptake of radioactivity by crops and grazing livestock is possible. However, unless a significant proportion of an individual's diet comes from an area contaminated by radioactivity, the doses from consumption of food will be relatively low compared to other exposure pathways.

Many radionuclides likely to be present in the ground as a result of historical activities, including radium, are relatively immobile in soil. Although these radionuclides will eventually reach groundwater this process is likely to take a considerable period of time and there would be a significant decrease in the activity concentration due to dilution and dispersion. Any water entering the public mains water supply comes from many sources and is regularly checked to make sure that activity concentrations remain low. However, water extracted privately may come from a single source and if that source happens to be close to or in a large area of contamination it may contain elevated activity concentrations.

If discrete items, including radium painted equipment or flakes of radium paint, were disposed of then it is possible that an individual may encounter them when using the land. As these items can contain high levels of radioactivity when compared to other types of contamination, exposure to them could be significant if they come into contact with the skin for several hours or if they are ingested. However, the probability of this occurring is likely to be very low unless the item is visible and possess features that would encourage someone to pick it up.

* *Throughout the remainder of the text the term dose, unless otherwise qualified, is used to signify the effective dose, comprising both external exposure and the committed dose from intakes of radionuclides to age 70 years

1.4.4 Surfaces considered for remediation

Historical activities associated with land may have resulted in the presence of radionuclides in or on a number of different surfaces. This may have occurred either directly, for example through the disposal of wastes into the ground or when material is reused in construction or other projects, or indirectly such as when surfaces become contaminated by suspended dusts. As a result it is possible that any surface, including soils, roads and paved areas, buildings and foundations, furnishings and equipment, and discrete items of various sizes (from small particulate material to spoil rocks used in landscaping) can be contaminated. Contamination of food products may also arise where contaminated soils have been used for agriculture or domestic food production.

Contaminated soil tends to be the most frequently encountered surface requiring some form of remediation, either to reduce external exposure to people living or working in close proximity to the contamination or to reduce internal exposure from the inhalation of suspended dusts, the inadvertent consumption of contaminated soil or from the consumption of food products grown on the contaminated soil. This guidance focuses mainly on large area contamination where the probability of exposure is almost certain. For sites where this is not the case remediation strategies should only be developed following consultation with appropriate experts.

1.4.5 Types of remedial actions

Remedial actions performed on land contaminated with radioactivity needs to be both justified and optimised. Where remedial actions are justified, the aim should be the reduction of both the magnitude of any exposure and the probability that an exposure will occur by:

- **a.** Protecting or removing people from the source of contamination e.g. by restricting public access, by changing land use, or by imposing restrictions on living conditions e.g. stopping domestic food production;
- **b.** Removing contaminated material or reducing the level of contaminants, also known as decontamination;
- **c.** Disrupting the pathway of exposure e.g. by providing shielding, burying contamination or reducing transfer to food.

Within each type of remedial action, there are several options that can be considered. These will be described in more detail in Section 3.

1.4.6 Topics not considered

This guidance is specifically focussed on the process for selecting remediation actions for use on land that is contaminated with radioactivity. The process of remediation itself is broader than this however, and encompasses: site evaluation; dose or risk assessment; remediation planning; implementation of the remediation strategy; and post-remediation management (monitoring, record keeping, lessons learned). Details on the process of remediation are published elsewhere (IAEA, 2007). A complementary publication (Oatway, 2020b) for use by local authorities discusses principles for assessing the radiological impact from land contaminated with radioactivity.

Other topics that are not considered include:

a. Legal framework for dealing with radioactively contaminated land;
b. Roles and responsibilities for remediation;
c. Details of relevant contacts and contractors for remediation;
d. Wider socioeconomic issues of damage, compensation, recovery of business, personal and private losses.

Table 1 Uses of land with the potential to contaminate land with radioactivity to levels where harm is caused

Process	Contamination mechanism	Contamination form	Key radionuclides	Main exposure pathways*	
Uranium mining	Disposal of rock spoil[#]	Spoil rock	^{226}Ra+	External irradiation Food consumption	Inhalation of radon
Rare earth processing	Disposal of inert waste	Soils Furnace slag Pipe scale	^{238}U+, ^{235}U+, ^{232}Th+	External irradiation Food consumption	Inhalation of dust Inhalation of radon
Radium luminising works	Disposal on site of inert waste Disposal of liquid waste to drains Paint spills in buildings	Soils Buildings, foundations Waste drainage systems Discrete items	^{226}Ra+	External irradiation Food consumption Inhalation of radon	Skin contact with items Ingestion of items
Incineration of redundant equipment by MoD	Incineration of inert wastes Burial of clinker[#] Use of clinker in paving[#]	Ash and soils Clinker in paving Discrete items	^{226}Ra+	External irradiation Food consumption Inhalation of radon	Skin contact with items Ingestion of items
MoD maintenance facilities	Disposal on site of inert waste Disposal of liquid waste to drains Paint spills in buildings Use of waste to infill ground[#]	Soils, clinker in paving Buildings, foundations Waste drainage systems Discrete items	^{226}Ra+	External irradiation Food consumption Inhalation of radon	Skin contact with items Ingestion of items
Municipal landfill sites	Disposal of inert waste	Ash and soils Discrete items Miscellaneous items	Any	External irradiation Food consumption Ingestion of items	Inhalation of dust Inhalation of radon Skin contact with items
Gas mantle production	Disposal on site of inert waste	Soils Discrete items	^{232}Th+	External irradiation Food consumption Ingestion of items	Inhalation of dust Skin contact with items
Research establishments	Spills in buildings Disposal of liquid waste to drains Contamination of equipment	Buildings Furnishings and equipment Waste drainage systems	Any	External irradiation Food consumption Ingestion of items	Inhalation of dust Inhalation of radon Skin contact with items
Miscellaneous small users	Disposal on site of inert waste and sealed sources	Soils Sealed sources	Any	External irradiation Food consumption Ingestion of items	Inhalation of dust Inhalation of radon Skin contact with items

* Based on the current use of the land being either agriculture, recreation or residential

\# Some rock spoil and clinker is known to have been used at locations remote from the waste producing site (e.g. in landscaping, rail track ballast or coastal reclamation projects).

Table 2 Uses of land which are unlikely to have the potential to contaminate land with radioactivity to levels where harm is caused

Process	Contamination mechanism	Contamination form	Key radionuclides	Main exposure pathways*	
Metals mining	Disposal of rock spoil#	Spoil rock	^{238}U+, ^{235}U+, ^{232}Th+	External irradiation Food consumption	Inhalation of dust Inhalation of radon
Metals refining	Collection and disposal of ash Disposal on site of inert waste Sediment in settling ponds	Ash and soils Furnace slag	^{238}U+, ^{235}U+, ^{232}Th+	External irradiation Food consumption	Inhalation of dust Inhalation of radon
Depleted uranium munitions manufacture and testing	Manufacturing swarf Fired munitions	Discrete items	^{238}U	External irradiation Ingestion of items	Inhalation of dust Skin contact with items
Oil and gas facilities	Scale from pipes and equipment Discarded equipment	Pipe scale	^{226}Ra+	External irradiation Food consumption	Inhalation of radon
Coal-fired power stations	Collection and disposal of ash and dust	Ash and soils	^{238}U+, ^{235}U+, ^{232}Th+	External irradiation Food consumption	Inhalation of dust Inhalation of radon
Town gas industry	Disposal on site of wastes	Soils	^{238}U	External irradiation	Inhalation of dust
Incinerators	Collection and disposal of ash and dust	Ash and soils	Any	External irradiation Food consumption	Inhalation of dust Inhalation of radon
Scrap recycling	Disposal on site of inert waste	Discrete items	Any	External irradiation Food consumption Ingestion of items	Inhalation of dust Inhalation of radon Skin contact with items
Phosphate industry	Disposal on site of inert waste	Soils	^{226}Ra+	External irradiation Food consumption	Inhalation of radon

* Based on the current use of the land being either agriculture, recreation or residential

Some rock spoil and clinker is known to have been used at locations remote from the waste producing site (e.g. in landscaping, rail track ballast or coastal reclamation projects).

1.5 Structure

Section 2 presents the radiation protection principles and criteria relevant to carrying out remediation activities on radioactive contaminated land. Section 3 describes an eight-step process that has been developed previously in relation to remediation of land after a nuclear accident to help with the evaluation and selection of remedial actions. Section 4 provides two worked examples that illustrate how the 8-step decision aiding process can be applied to different contaminated land scenarios. Section 5 highlights future requirements to address data/information gaps in this guidance. Datasheets for each of the remedial actions considered are presented in Appendix A. Appendix B lists remediation options that have been excluded and the reasons for their exclusion.

1.6 Terminology

Deterministic effect: type of health effect (such as blistering of the skin) which occurs following a dose of radiation above a certain level (a 'threshold' level) with the severity of the health effect dependent on the magnitude and duration of any exposure above this threshold. Deterministic effects are also known as serious direct injury.

Existing Exposure Situation: an exposure situation that already exists when a decision on its control has to be taken.

Remedial measure: the removal of a radiation source or the reduction of its magnitude (in terms of activity or amount) or the interruption of exposure pathways or the reduction of their impact for the purposes of avoiding or reducing doses that might otherwise be received from contaminated land.

Stochastic effect: a radiation-induced health effect (the principal one being radiation-induced cancer) where there is no threshold below which the effect will not occur and where risk of the effect occurring may be assumed to be linearly proportional to the radiation dose.

Land contaminated with radioactivity: Land which has levels of radioactivity above that expected to be present as a result of natural processes due to historical industrial activities or accidents. Land contaminated with radioactivity may be determined to be radioactively contaminated land if it meets the conditions specified in the regulatory statutory guidance.

Radioactively contaminated land: Any land which appears to the relevant authority to be in such a condition that harm is being caused or there is a significant possibility of harm being caused, and where there are no suitable or sufficient risk management arrangements in place to prevent such harm. In the context of existing exposure situations where exposure is certain to occur, harm is defined as lasting exposure to any person where their annual effective dose exceeds 3 mSv or their equivalent annual dose to the lens of the eye or the skin exceeds 15 mSv or 50 mSv respectively[*].

Remediation: Any measures that may be carried out to reduce the radiation exposure due to existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to people.

[*] Other criteria are used to define harm when the probability of exposure occurring is not certain and where exposure is to non-human species (BEIS, 2018)

2 Radiological protection principles and criteria relevant to remediation

Public Health England recommends three principles of radiological protection when considering the management of land contaminated with radioactivity. These principles take into account recommendations from the International Commission on Radiological Protection (ICRP, 2007). In the context of contaminated land, these principles are interpreted as follows:

- All remediation strategies should aim to do more good than harm (*justification*);
- Remediation strategies should aim to avoid the occurrence of serious direct injury (*avoid serious direct injury*);
- Remediation strategies for exposures below the thresholds for serious direct injury should aim to maximise the benefit achieved (*optimisation).*

The first principle of justification applies to all remediation strategies and for all levels of potential exposure. In determining whether a strategy is justified, account should be taken of all the expected consequences, both beneficial and undesirable, including: radiation health risks; wider health risks such as mental health; economic consequences, both direct and indirect; and social factors including disruption and public anxiety. Significantly higher weight should be afforded to the prevention of serious direct injury than to other consequences when determining whether a strategy is justified.

The second principle is to plan for avoidance of serious direct injury (deterministic effects). PHE recommends that priority should always be given to consideration of remediation strategies to avoid exposures that could lead to serious direct injury.

The third principle of optimisation applies to protection from exposures that are expected to be below the thresholds for serious direct injury. Optimisation should only be applied to strategies that have been justified. For low exposures it is generally assumed that, for the purposes of radiological protection, the increase in radiation health risk is directly proportional to the increase in dose, and that there is no threshold dose below which there is no risk (ICRP, 2007). This means that there is no safe/unsafe boundary of dose on which to base protection decisions. Optimisation ensures that the likelihood of incurring exposures, the number of people exposed, and the magnitude of their individual doses should all be kept as low as reasonably achievable, taking into account economic and societal factors. This means that the standard of protection should be the highest possible under the prevailing circumstances, maximising the margin of benefit over harm. In order to avoid severely inequitable outcomes of this optimisation procedure, there should be restrictions on the doses or risks to individuals from a particular source through the application of reference levels.

A reference level is the level of effective or equivalent dose above which it is judged inappropriate to allow exposures to occur. The reference level can be seen as an indicator of the level of exposure considered as tolerable, given the prevailing circumstances. Reference levels are different from dose limits, which are also restrictions on individual doses but only for planned exposure situations. With respect to the radioactive contaminated land regime, whilst the range of reference levels for existing exposure situations (i.e. 1 – 20 mSv y^{-1}) can be used as part of a remediation strategy, the overall aim of any remediation strategy should be to reduce exposure to a level where the land no longer meets the criteria of being radioactive contaminated land. Although remediating to a level that meets this aim is possible at most sites, it is recognised that some sites possess characteristics that prevents this aim being practical or reasonable. Under the radioactive contaminated land regime it is therefore possible for the responsible authority to set a reference level above the threshold for harm in exceptional circumstances.

3 Evaluation and selection of remedial actions: the eight-step process

For land that has been, or which could be determined to be radioactive contaminated land, it will be necessary to develop a remediation strategy that may result in some form of remedial action being taken. As there are number of historical land uses that have the potential to contaminate land with radioactivity and also a range of radionuclides that might be present, it is not possible to devise a generic remediation strategy.

The UK Recovery Handbooks for Radiation Incidents (PHE, 2015) have been developed to assist in the remediation of contaminated inhabited areas, food production systems and drinking water supplies following a nuclear accident. The handbooks are user-friendly guidance documents, specifically designed to aid the decision-making process for developing and implementing a remediation strategy. Whilst the source of contamination and the surfaces impacted by deposition after accidents are different to those from historical land uses, some of the remedial actions described in the handbooks are still likely to be applicable to a greater or lesser extent. Furthermore, the 8-step process for evaluating and selecting various options comprising the remediation strategy is also relevant and useful.

The following section provides a series of tables to guide decision makers to the most appropriate subset of remedial actions that could be applied to various contaminated surfaces and food production systems, by eliminating inappropriate options. Some remedial actions may need to be applied concurrently, while others may be applied sequentially. Two worked examples are given in Section 4 to illustrate how the 8-step process can be used to develop a remediation strategy for land contaminated (a) from feral pigeon droppings and (b) from radium luminising activities.

3.1 Key steps in selecting and combining options

There are 8 key steps involved in selecting and combining remedial actions.

Step 1: Identify the inhabited surfaces and/or types of food production systems that are contaminated. These may be soils and vegetation; buildings; roads and paved areas; crops and grassland; livestock and animal products; domestic production and wild foods.

Step 2: Refer to selection tables listing potential remedial actions for specific surfaces or food production types; some of the actions may be generally applicable whilst others may have limited applicability, according to the radionuclide of interest and the prevailing circumstances (Table 3.1 – Table 3.6).

Step 3: Refer to look-up Table 3.7 (inhabited surfaces) and Table 3.8 (food production) showing applicability of remedial actions for each radionuclide being considered. This step allows various options listed in the selection tables to be eliminated if they are not suitable based, for example, on the radiological hazard, biological and chemical behaviour of the radionuclide.

Step 4: Refer to look-up Table 3.9 (inhabited surfaces) – Table 3.10 (food production) showing checklists of major and moderate constraints for each remedial action. These are constraints that would make implementation of an option very difficult or impossible. Table 3.11 (inhabited surfaces) and Table 3.12 (food production) provide greyscale summaries of the constraints for each remedial action.

Step 5: Refer to look-up Table 3.13 (inhabited surfaces) and Table 3.14 (food production) showing the effectiveness of each remedial action.

Step 6: Refer to look-up Table 3.15 (inhabited surfaces) and Table 3.16 (food production) showing whether remedial actions generate waste and the type of waste produced. This information will not necessarily eliminate options but serves to warn the decision makers that selection of a particular option may have implications for waste disposal that requires further assessment.

Step 7: Refer to individual datasheets (Appendix A) for all remedial actions remaining in the selection table. Further options may be eliminated as a result of additional constraints due to site specific conditions.

Step 8: Based on steps 1-7, select and combine options for remediating the surfaces and food production systems affected by contamination.

3.2 Selection tables

Selection tables of remedial actions are presented for the following inhabited surfaces and food types:

- Soils and vegetation (Table 3.1);
- Buildings: (Table 3.2 - internal surfaces);
- Roads and paved areas (Table 3.3);
- Domestic production and wild foods (Table 3.4);
- Crops and grassland (Table 3.5);
- Livestock and animal products (Table 3.6).

The number and range of remedial actions listed in these selection tables are much more limited than those presented in the UK Recovery Handbooks for Radiation Incidents (PHE, 2015) which addresses land contaminated as a result of a nuclear accident. Specific reasons for excluding remedial actions are provided in Appendix B. In general terms, remedial actions have been excluded because they are:

- Precautionary measures applied when there is a threat of a release (e.g. sheltering of livestock);

- Measures to be applied rapidly after aerial deposition (e.g. grass cutting and collection);
- Measures aimed at short-lived radionuclides not relevant to historical contamination (e.g. natural attenuation with monitoring for ^{131}I);
- Measures to be applied when contamination levels are very high (slaughtering of livestock).

3.3 Applicability of remedial actions according to radionuclide

Most of the practical information that is available on remedial actions relates to radioactive isotopes of caesium following the Chernobyl and Fukushima Daiichi Nuclear power plant accidents in 1986 and 2011 respectively, and from other experimental work undertaken for radionuclides of potential significance following accidents at nuclear facilities, for example, strontium and plutonium. For many of the other radionuclides of significance for historical contamination, there are limited data to indicate whether a particular action is effective or not. Nevertheless, these radionuclides have certain characteristics in terms of their chemical properties and types of hazard posed to indicate whether an option should be considered. Dominant exposure pathways vary according to radionuclide of interest and habits of those using the land (see Table 3.7 and Table 3.8).

In Table 3.7 (inhabited areas) and Table 3.8 (food production systems), a remedial action is considered to be applicable if:

- There is direct evidence that it would be effective for a radionuclide (*known applicability*);
- The mechanism of action is such that it would be highly likely to be effective for a radionuclide (*probable applicability*).

The category of not applicable is attributed to an option if:

- There is direct evidence that it would not be effective for a radionuclide;
- The chemical behaviour of the radionuclide is such that the option would not be expected to have any effect;
- The hazard posed by the radionuclide would not be reduced by the remedial action (e.g. tie-down options for high energy gamma emitters).

Table 3.1 Remedial actions for soil and vegetation

Remedial action	Applicability G - general L - limited	Comment
Cover grass/soil with clean soil/asphalt	G	Burial of contamination is a common practice, depth required is site specific
Ploughing methods	L	Only applicable where contamination is near the surface
Removal of soil (and replacement with clean soil)	G	Soil removal is a common practice
Restrict public access	G	Useful where short-term remedial work is being carried out
Temporary relocation from residential areas	G	Useful where short-term remedial work is being carried out
Tie-down	G	Useful during remedial work

Table 3.2 Remedial actions for Buildings (internal)

Remedial action	Applicability G - general L - limited	Comment
Dismantle and dispose of contaminated material	G	Disposal of contaminated material is a common practice
Fix and strip coatings	L	Only relevant where contamination is recent
Reactive liquids	L	Relevant for a few radionuclides
Restrict public access	G	Useful where short-term remedial work is being carried out
Surface removal (indoor)	G	Useful during remedial work
Temporary relocation from residential areas	G	Useful where short-term remedial work is being carried out
Tie-down	G	Useful during remedial work

Table 3.3 Remedial actions for roads and paved areas

Remedial action	Applicability G - general L - limited	Comment
Restrict public access	G	Useful where short-term remedial work is being carried out
Surface or total removal and replacement (roads)	L	More appropriate for surface contamination
Temporary relocation from residential areas	G	Useful where short-term remedial work is being carried out
Tie-down	L	Useful during remedial work

Table 3.4 Remedial actions for domestic and wild foods

Remedial action	Applicability G - general L - limited	Comment
Dietary advice (domestic)	G	
Removal of soil (and replacement with clean soil)	G	Common practice
Restrictions on foraging (gathering wild foods)	L	Useful for a limited number of food:nuclide combinations

Table 3.5 Remedial actions for crops and grassland

Remedial action	Applicability G - general L - limited	Comment
Ploughing methods	L	Only applicable where contamination is near the surface
Removal of soil	G	Soil removal is a common practice
Restrict entry into food chain (including FEPA orders)	L	Activity concentrations unlikely to exceed MPLs
Select alternative land use	L	Must be a market for alternative products

Table 3.6 Remedial actions for livestock and animal products

Remedial action	Applicability G - general L - limited	Comment
Live monitoring	L	Only applicable for gamma emitting radionuclides
Restrict entry into food chain (including FEPA orders)	L	Activity concentrations unlikely to exceed MPLs
Select alternative land use	L	Must be a market for alternative products
Selective grazing	L	Animals need to be moved to uncontaminated pasture

Table 3.7 Applicability of remedial actions (inhabited areas) for radionuclides likely to be of found on contaminated land*

Remedial actions	Radionuclide										
	^{90}Sr	^{137}Cs	^{210}Pb	^{210}Po	^{226}Ra	^{227}Ac	^{232}Th	^{235}U	^{238}U	^{239}Pu	^{241}Am
Radionuclide half-life (y unless specified)	29.1	30.0	22.3	138.4d	$1.6\ 10^{3}$	21.78	$1.4\ 10^{10}$	$7.04\ 10^{6}$	$4.47\ 10^{9}$	$2.44\ 10^{4}$	432.2
Principal pathway(s)# (includes progeny)	Ing(f). Ext.	Ext.	Ing(f). Ing(s). Inh.	Ing(f). Ing(s). Inh.	Ext.	Inh.	Inh.	Ext. Inh.	Ext. Inh.	Inh.	Inh.
Cover grass/soil with clean soil/asphalt	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dismantle and dispose of contaminated material	✓	✓	a	a	✓	✓	a	✓	✓	a	a
Fix and strip coatings	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ploughing methods	✓	✓	✓	✓	✓	✓	b	b	b	✓	✓
Reactive liquids	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Removal of soil (and replacement with clean soil)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Restrict public access	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Surface removal (indoor)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Surface or total removal and replacement (roads)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Temporary relocation from residential areas	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Tie-down	c	c	✓	✓	c	✓	✓	c	c	✓	✓

Key:

* Information in this table is related to the indicated radionuclide only; depending on the situation account may need to be made of the presence of multiple radionuclides, including those present as a result of radioactive decay

Ext = external; Ing(f) = ingestion (food) ; Ing(s) = ingestion (soil); Inh = inhalation

✓: Selected as target radionuclide (i.e. known or probable applicability, see Section 3.3)

a This remedial action reduces doses from external irradiation which is not an important pathway for this radionuclide (alpha hazard)

b Remediation option enhances availability/mobility of radionuclide in soil

c This remedial action reduces doses from inhalation of resuspended material which is not an important pathway for this radionuclide (beta/gamma hazard)

Table 3.8 Applicability of remedial actions (food production) for radionuclides likely to be of found on contaminated land*

Remedial actions	Radionuclide										
	^{90}Sr	^{137}Cs	^{210}Pb	^{210}Po	^{226}Ra	^{227}Ac	^{232}Th	^{235}U	^{238}U	^{239}Pu	^{241}Am
Radionuclide half-life (y unless specified)	29.1	30.0	22.3	138.4d	$1.6\ 10^{3}$	21.78	$1.4\ 10^{10}$	$7.04\ 10^{6}$	$4.47\ 10^{9}$	$2.44\ 10^{4}$	432.2
Principal pathway(s)# (includes progeny)	Ing(f).	Ing(f). Ext.	Ing(f).	Ing(f).	Ing(f). Ext.	Ing(f). Inh.	Ing(f). Inh.	Ing(f). Ext. Inh.	Ing(f). Ext. Inh.	Ing(f). Inh.	Ing(f). Inh.
Dietary advice (domestic)	✓	✓	✓	✓	✓	a	✓	✓	✓	a	a
Live monitoring	b	✓	b	b	✓	b	b	b	b	b	b
Ploughing options	✓	✓	✓	✓	✓	✓	c	c	c	✓	✓
Removal of soil (and replacement with clean soil)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Restrict entry into the food chain (including FEPA orders)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Restrictions on foraging (gathering wild foods)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Select alternative land use	✓	✓	d	d	✓	d, e	d, e	d, e	d, e	d, e	d, e
Selective grazing	✓	✓	e	e	e	e	e	e	e	e	e

Key:

* Information in this table is related to the indicated radionuclide only; depending on the situation account may need to be made of the presence of multiple radionuclides, including those present as a result of radioactive decay

Ext = external; Ing(f) = ingestion (food) ; Ing(s) = ingestion (soil); Inh = inhalation

✓ Selected as target radionuclide (i.e. known or probable applicability, see Section 3.3)

a Ingestion not an important pathway for this radionuclide

b No/low photon energy of radionuclide makes detection difficult

c Remediation option enhances availability in soil

d Radionuclide has low feed-to-meat or milk transfer, making radical remediation options unnecessary

e Low soil-to-plant transfer makes radical remediation option unnecessary

3.4 Checklist of key constraints for each remedial action

Remedial actions invariably have constraints associated with their implementation. A description of these constraints is presented in Table 3.9 (inhabited areas) and Table 3.10 (food production), taking into account factors such as waste, societal needs, technical aspects and costs. To assist in eliminating unsuitable options major and moderate constraints for each option are summarised in colour-coded grey-scale Table 3.11 (inhabited areas) and Table 3.12 (food production), based on an evaluation of the evidence database and stakeholder feedback. The colour coding gives an indication of whether options have ‘none or minor’, ‘moderate’ or ‘major’ constraints associated with their implementation. The classification used is a generic guide and not radionuclide specific.

Table 3.9 Major and moderate constraints for remedial actions in inhabited areas

Remediation actions	Major (key) considerations	Moderate considerations
Restrict access		
Cover grass/soil with clean soil/asphalt Including burial	<u>Social</u>: • Acceptability in gardens likely to be low. <u>Technical</u>: • Complicates further options involving removal of contaminated soil. • This technique cannot be carried out in severe cold weather (frost and snow). • Can only be implemented on a small scale and even then very large quantities of soils are required.	<u>Social</u>: • May be negatively perceived by the public as the contamination remains in-situ. • Fears are likely to arise concerning potential future exposure • May cause adverse aesthetic effects including the loss of plants and shrubs. • An effective communication strategy is essential <u>Technical</u>: • Use in conservation areas/historic sites may be restricted • Not appropriate for stony soils or where there are steep slopes • May need a mechanism to prevent digging up of buried material (e.g. geomembrane)
Dismantle and dispose of contaminated material	<u>Social</u>: • Dismantling of street furnishing, workbenches or removal of personal items will be disruptive <u>Waste</u>: • May generate large amounts of contaminated material which will require disposal and/or storage under a waste transfer licence	<u>Technical</u>: • May be restrictions on use on listed and historic buildings
Fix and strip coatings	<u>Technical</u>: • This technique may be affected by severe cold weather and wet weather	<u>Social</u>: • Residents of the contaminated area may be sceptical of the contamination remaining in-situ. • Fears are likely to arise concerning potential future exposure. • An effective communication strategy is essential <u>Technical</u>: • Fixative coatings can be applied over a large area but strippable coatings are more suitable for smaller areas. • Fixatives can complicate further options involving removal of surface. • May be restrictions on use on listed and historic buildings.
Ploughing methods	<u>Technical</u>: • Cannot be carried out in severe cold weather (frost and snow). • Can only be implemented in large areas. • A soil depth > 0.3 m is required for normal shallow ploughing or > 0.5 m for deep ploughing. • Where deep ploughing is considered, it must be implemented before normal ploughing has been undertaken.	<u>Technical</u>: • Use in conservation areas/historic sites may be restricted • Complicates further options involving removal of contaminated soil. • The contamination may be moved closer to the groundwater. • Tie-down may be needed to suppress resuspension of contamination in dust. • Ploughing may result in soil erosion. <u>Social:</u> • May be negatively perceived by the public as the contamination remains in-

Table 3.9 Major and moderate constraints for remedial actions in inhabited areas

Remediation actions	Major (key) considerations	Moderate considerations
		situ, • May also cause adverse aesthetic effects including the loss of plants and shrubs. • An effective communication strategy is essential.
Reactive liquids	None	Waste: • Waste products in various forms, dependent on the liquid used, can be generated which may require disposal and/ or storage under a waste transfer licence. Technical: • Surfaces must be resistant to the reactive liquid. • Use on listed and historic building may be restricted.
Removal of soil (and replacement with clean soil)	Waste: • Large quantities of contaminated soil/vegetation will be produced. Although the bulk of this material may be contaminated to low levels, some may require disposal and/or storage under a waste transfer licence. Technical: • Technique is not appropriate for stony soils. • Technique can only be implemented on a small scale. • The technique cannot be carried out in severe cold weather (frost and snow). • Slow work rate if carried out manually. • Soil may require screening which will be time consuming. Cost: • May be high although total will depend on; equipment; personnel; size of the affected area and volume of topsoil requiring disposal.	Technical: • Some form of tie-down may be needed to suppress resuspension of contaminated dust. • Use in conservation areas/historic sites may be restricted. Social: • May cause damage to habitats and biodiversity. • May also cause soil erosion. • Will require good communications to demonstrate that what has been left behind is clean.
Restrict public access	Technical: • Enforcement may require more than a tape barrier • Should be implemented as soon as a contaminated area is identified with cordons and signage to prevent access. • Measures will need to be in place until the doses have been assessed and management of the area agreed.	Social: • Possible disruption and access to an area may not be well received by members of the public with pressure to reopen the area • Effective communication is required to inform the public about the restriction and the potential health risks posed by the contaminant with the aim of ensuring compliance. • Possible difficulties with application on private land.
Surface removal (indoor)	None	Technical: • Use on listed and historic building may be restricted.

Table 3.9 Major and moderate constraints for remedial actions in inhabited areas

Remediation actions	Major (key) considerations	Moderate considerations
		Social: • Potential issues regarding ownership and access to private property.
Surface or total removal and replacement (roads, driveways and paved areas)	Waste: • Large quantities of contaminated tarmac/concrete will be produced and this may require disposal and/or storage under a waste transfer licence.	Technical: • Uneven surface and road camber can make surface removal difficult. • Some form of tie-down may be needed to suppress resuspension of contaminated dust. Social: • There may be disruptions to access routes due to damage to roads or pavements. • This method may also cause aesthetic issues.
Temporary relocation from residential areas	Social: • Temporary relocation can cause disruption to the community and have a large impact on businesses. Technical: • Availability of alternative accommodation (hotels, bed and breakfast, self-catering, hostels etc.) • Availability of transport to aid the relocation process, especially if the affected area has an elderly population or people with disabilities (population profile).	Technical: • Effective communication is required to inform the public. To minimise the social disruptions caused by relocation, certain measures should be taken to assist the process, for example leaflets consisting of important information for people being relocated need to be distributed. • An effective monitoring strategy needs to be implemented to determine the risk of adverse health effects to occupants upon return to the area. Cost: • Cost is influenced by the length of time residents will be temporarily relocated for, and the quality of the temporary housing offered (hotels vs. hostels). This measure can prove to be expensive for local authorities responsible for relocating residents from an affected area.
Tie-down	Technical: • Technique may be affected by severe cold weather and wet weather.	

Table 3.10 Major and moderate constraints for remediation actions directed at food production

Remediation action	Major (key) constraints for selected remedial actions	Moderate constraints for selected remedial actions
Clean feeding	Technical: • Availability of suitable housing with water, power supply, straw for bedding and ventilation. • Availability of alternative clean feed.	Waste**:** • Slurry or manure produced while livestock are fenced in or housed. Cost: • May be high with the total being affected by; number of affected animals; consumables (ie clean feed).
Dietary advice (domestic)	None	Social: • Routes for dialogue and dissemination of information to affected populations.
Live monitoring	None	Technical: • Availability of NaI detectors and trained personnel.
Ploughing options	*Deep ploughing* Technical: • A soil depth of > 0.5m is required • Must be implemented before significant disturbance of the ground (e.g. historic building works, previous shallow ploughing, digging of allotments) has been undertaken • Not applicable if crop is present or if soil is very wet, sandy, frozen or stony *Shallow ploughing* Technical: • Not applicable if crop is present or if soil is very wet, sandy, frozen or stony.	*Deep ploughing* Technical: • Restrictions may be imposed by environmental protection schemes. • Complicates further options involving removal of contaminated soil in some cases. • The contamination may be moved closer to the ground water. • Tie-down may be needed to suppress resuspension of contamination in dust. Social: • May be negatively perceived by the public as the contamination remains in-situ. • An effective communication strategy is essential. *Shallow ploughing* Technical: • Complicates further options involving removal of contaminated soil in some cases, • The contamination may be moved closer to the ground water. • Tie-down may be needed to suppress resuspension of contamination in dust Social: • May be negatively perceived by the public as the contamination remains in-situ. • An effective communication strategy is essential.
Restrict entry into the food chain (including FEPA orders)	Waste: • There may be significant amounts of contaminated food products (i.e. milk, meat, eggs and crops) that will require a suitable disposal route. • Long term restrictions (e.g. FEPA order) may also lead to culling and disposal of livestock.	Technical: • Requirement to establish a monitoring and surveillance programme. Social: • Economic loss occurring as a result of restrictions being imposed.

Table 3.10 Major and moderate constraints for remediation actions directed at food production

Remediation action	Major (key) constraints for selected remedial actions	Moderate constraints for selected remedial actions
Removal of soil (and replacement with clean soil)	Technical: • Slow work rate if carried out manually • Can only be implemented on a small scale • Cannot be carried out in severe cold weather (frost and snow). • Not appropriate for stony soils • Soil may require screening which will be time consuming Waste: • Large quantities of contaminated soil/vegetation will be produced. Although the bulk of this material may be contaminated to low levels, some may require disposal and/or storage under a waste transfer licence. Cost: • May be high depending on; equipment; personnel; size of the affected area and volume of topsoil requiring disposal.	Technical: • Some form of tie-down may be needed to suppress resuspension of contaminated dust. • Use in conservation areas/historic sites may be restricted. Social: • May cause damage to habitats and biodiversity. • May cause soil erosion. • Will require good communications to demonstrate that what has been left behind is clean.
Restrictions on foraging (gathering wild foods)	Social: • Difficulties with enforceability and policing.	Social: • Need to establish appropriate lines of communication to reach the various groups affected (e.g. mushroom and berry collectors).
Select alternative land use	Social: • Market for alternative products and know-how.	Technical: • Restrictions imposed by environmental protection schemes. • Depends on what the site can/will be used for (i.e. for non-food crops or amenities such as golf course or parkland). • The change in land use will result in the land being managed as a planned exposure situation according to more stringent dose criteria (i.e. constraints), which could cause additional restrictions.
Selective grazing	Technical: • Availability of monitoring data identifying less contaminated pastures. • Availability of less contaminated land in the area.	Social: • Willingness of farmers elsewhere to allow livestock from contaminated areas to graze on their land.

Table 3.11 Overview of key constraints for remedial actions in inhabited areas

Remedial action	Waste	Social	Technical	Cost
Cover grass/soil with clean soil/asphalt /burial				
Dismantle and dispose of contaminated material				
Fix and strip coatings				
Ploughing methods				
Reactive liquids				
Removal of soil (and replacement with clean soil)				
Restrict public access				
Surface removal (indoor)				
Surface or total removal and replacement (roads)				
Temporary relocation from residential areas				
Tie-down				
Key to considerations/ constraints	None or minor	Moderate	Major	

Table 3.12 Overview of key constraints for remedial actions in food production systems

Remedial action	Waste	Social	Technical	Cost
Dietary advice (domestic)				
Live monitoring				
Ploughing methods				
Removal of soil (and replacement with clean soil)				
Restrict entry into the food chain				
Restrictions on foraging (gathering wild foods)				
Select alternative land use				
Selective grazing				
Key to considerations/ constraints	None or minor	Moderate	Major	

3.5 Effectiveness of remedial actions

3.5.1 Inhabited Areas

The primary aim of remedial actions in inhabited areas is to reduce doses from external irradiation from deposited radionuclides and inhalation from resuspension of contaminated material.

Remedial actions are directed at shielding people from contamination, fixing the contamination so that it cannot be resuspended and inhaled, or removing the contamination so that exposure is reduced, providing waste is disposed of properly. Effectiveness of remedial actions, in terms of the reduction in exposure to contamination, is expressed in different ways according to the purpose for which it is implemented:

- the effectiveness of shielding is expressed as the percentage reduction in external dose rate from a surface following implementation of the option;
- the effectiveness of fixing contamination is expressed as the percentage reduction in inhalation dose rate from a surface following implementation of the option;
- the effectiveness of removal is expressed as a decontamination factor (DF), which is the ratio of the amount of contamination initially present on a specific surface to that following implementation of the option.

The overall impact of the remedial action on the doses received by an individual living in an inhabited area depends on the contributions from contamination on each surface and the time people spend close to these surfaces.

Table 3.13 summarises the effectiveness of each remedial action considered in the handbook. The dose reductions presented in the table are illustrative and should only be used to scope the level of reduction that is likely to be achieved. The dose reductions achieved will be dependent on the specific situation, habits of the population and the effectiveness of the remedial action. Further details can be found in the datasheets (Appendix A).

3.5.2 Food production systems

Experimental work and field based studies in the regions affected by the accidents at Chernobyl and Fukushima Daiichi have enabled the effectiveness of various remedial actions to be measured under field conditions. Information on effectiveness is provided in the datasheets. It is generally expressed as percentage reduction in activity concentration in the target medium (food product) following implementation of a remedial action.

This section provides a look-up table (Table 3.14) on typical effectiveness (expressed as a percentage value) of remedial actions for a range of radionuclides and food products.

Table 3.13 Effectiveness of remedial actions in reducing doses in inhabited areas

Remedial action	Mode of action	Principal exposure pathway	Effectiveness	Comments
Cover grass/soil with clean soil/asphalt	Shielding	External gamma External beta Resuspension	External gamma dose rates above the surface will be reduced by: • 30-80% reductions in external gamma dose rate above the surface. If buried deep enough then 100% is possible. • 100% for external beta dose rates above the surface. Resuspended concentrations in air above the surface will be reduced by up to 100%.	• Reduction in external gamma dose rate and beta dose rate above the surface is dependent on the energy of the gamma rays and beta particles emitted and the depth of covering layer used. • Likely to only be used for small areas.
Dismantle and dispose of contaminated material (including demolition)	Removal	External gamma External beta	100% contamination removed if all debris is removed and contamination is not spread during demolition.	Removal of contaminated furnishings allows current building to be used.
Fix and strip coatings	Removal, fixing	External gamma External beta Resuspension	Testing of several commercially available films on steel and lead bricks removed between 75 and 95% of contamination (DF of 4-20.) While the peelable coating is in place, resuspended activity in air will be reduced by almost 100%.	This option is likely to be most effective when used on smooth surfaces. DF likely to be lower on some materials, particularly on porous building materials such as bricks and tiles.
Ploughing methods	Shielding	External gamma External beta Resuspension	External gamma dose rates above the surface will be reduced by: • 50-80% for shallow ploughing • 80-90% for deep ploughing for medium to high energy gamma emitters. Resuspended concentrations in air above the surface will be reduced by 90 - 95%.	• The reductions in external gamma dose rate will depend on the radionuclides involved, the ploughing depth and the soil contamination profile with depth at the time of implementation. • Beta dose rate reduction is likely to be significantly higher than the values given for gamma dose rates if the technique is implemented. • By effectively burying most of the contamination, resuspended activity in air above the surface will be reduced by a factor significantly larger than the external gamma dose rate reduction.
Reactive liquids	Removal	External gamma External beta	• For metal surfaces: DF 2-10 (soft techniques) and DF >10 for hard techniques. • Effectiveness is lower on non-metal surfaces.	The effectiveness depends on the reactive liquid used, the radionuclide and the surface that is being decontaminated.

Table 3.13 Effectiveness of remedial actions in reducing doses in inhabited areas

Remedial action	Mode of action	Principal exposure pathway	Effectiveness	Comments
Removal of soil (and replacement with clean soil)	Removal	External gamma External beta Resuspension	90-97% of contamination can be removed (DF of 10 – 30) if implemented within a few years of deposition. Experience in Japan following the Fukushima accident showed 50-80% could be removed (DF = 2 – 20), with indications that the effectiveness could potentially be much higher if soil is replaced.	The removal depth needs to be chosen to ensure maximum removal of contamination in order to achieve maximum effectiveness.
Restrict public access	Shielding	External gamma External beta Resuspension	Up to 100% reduction in dose (all pathways) from areas where access is prohibited.	Effectiveness depends on individuals complying.
Surface removal (indoor)	Removal	External gamma External beta Resuspension	If carried out carefully, virtually all the contamination on the surface may be removed.	The process of removing paper, paint or plaster may result in the spread of contamination on to other surfaces via dust, reducing the effectiveness.
Surface or total removal and replacement (roads)	Removal	External gamma External beta Resuspension	• Decontamination work in Japan stripping the surface or shot blasting asphalt pavements and roads removed 50-95% (DF= 2 – 20) of contamination. • If paving stones are removed then decontamination can be 100%	Repeated application is unlikely to provide any significant increase in DF.
Temporary relocation from residential areas	Shielding	External gamma External beta Resuspension	Up to 100% reduction in dose (all pathways) while individual is away from affected area	If people comply, this option is fully effective at reducing doses during the period of relocation.
Tie-down	Fixing, shielding (low energy beta emitters)	Resuspension External beta	• Up to 100% reduction in resuspension dose from surface while integrity of covering is maintained. • Reductions in external beta dose rates above roads and paved surfaces: 90% for sand, 70% for bitumen and 45% for water. • Small reductions in external beta dose rates above soil surfaces could be expected.	• This option may be effective at reducing external beta dose rates above the surface (for low energy beta emissions) while the tie-down remains intact. • Sand (2 mm) would be the most effective at reducing beta dose rates, typical thicknesses of bitumen (1 mm) and water (1 mm) will give less protection. • Applying water to soil surfaces will aid the bonding of activity to soil particles and can wash contamination below the surface, both of which will reduce resuspension.

Table 3.14 Effectiveness of remedial actions in reducing doses in food production systems

Remedial option	Mode of action	Effectiveness %	Comments
Dietary advice (domestic)	Advice to consumers about restricted intake of home-grown food and free foods from the wild that might be contaminated.	Up to 100	Effectiveness affected by compliance.
Live monitoring	This option does not remove the radionuclide but can be highly effective at excluding meat above the MPL from food chain.	Up to 100	
Ploughing options	Deep ploughing Buries surface contamination at depth, outside the rooting zone of grassland and crops.	50 - 90	Observed data are for Cs and Sr. It would be reasonable to expect similar effectiveness for other radionuclides.
	Shallow ploughing Mixes contamination thereby diluting activity concentrations in rooting depth.	50	For surface deposition only.
Removal of soil (and replacement with clean soil)	Removes contaminated soil from food production system.	95	Observed data are for Cs and Sr. It would be reasonable to expect similar effectiveness for other radionuclides.
Restrict entry into the food chain	Removes contaminated food products from the food chain.	Up to 100	
Restrictions on foraging (collection of wild foods)		Up to 100	Effectiveness affected by compliance.
Select alternative land use	Land previously used for food production is used for alternative enterprises.	Up to 100	
Selective grazing	Livestock are moved to uncontaminated or less contaminated pasture.	Up to 100	

3.6 Types of waste produced from implementation of remedial actions

3.6.1 Inhabited areas

One important criterion to consider when assessing the practicability of a remedial action is whether it generates waste. Shielding options have an advantage in that they do not usually produce any waste because the contamination is left in situ. Removal options will generate contaminated waste material (liquid and/or solid) which will require management (e.g. storage or disposal). Waste hierarchy principles (prevent waste generation, reuse or recycle waste materials where possible, otherwise dispose of waste materials) should be applied if this does not stand in the way of the remediation strategy. Table 3.15 presents information on the types of waste produced for the remedial actions considered for inhabited surfaces.

3.6.2 Food production systems

Table 3.16 presents information on the types of waste produced for the remedial actions considered for various food production systems.

3.7 Datasheets of remedial actions

The UK Recovery Handbook for Radiation Incidents v4 (PHE, 2015) contains a wealth of information on remedial actions. The information is presented in a series of datasheets, designed to systematically record information in a standardised format, taking into account the most important criteria decision makers might wish to consider when evaluating different options. Datasheets relevant to the remedial actions considered in this report have been taken from the UK Recovery Handbook and adapted for their application to contaminated land. The datasheets are presented in Appendix A. An index to the datasheets is provided in Table 3.17.

3.8 Comparing the remaining remedial actions

Once options have been eliminated from the selection tables, the remaining remedial actions need to be evaluated on a site-specific basis using detailed information provided in the datasheets (Appendix 1).

Table 3.15 Type of waste produced by remedial actions for inhabited areas

Remedial action	Type of waste material produced
Restrict public access	None
Temporary relocation from residential areas	None
Cover grass/soil with clean soil/asphalt	None
Dismantle and dispose	Rubble
	Equipment
	Fixtures
Fix and strip coatings	Rubber-like material
Ploughing methods	None (assuming uncultivated)
Reactive liquids	Liquid waste
Removal of soil (and replacement with clean soil)	Soil and turf
Surface removal (indoors)	Carpet
	Plaster
	Paint, wallpaper
	Linoleum
	Wood floor
Surface or total removal and replacement (roads)	Asphalt
	Paving slabs, concrete
Tie-down	Water and dust
	Sand and dust
	Bitumen (permanent)
	Paint

Table 3.16 Type of waste produced by remedial actions for food production systems

Remedial action	Type of waste
Dietary advice	None
Live monitoring	None
Ploughing methods	None (assuming uncultivated)
Removal of soil (and replacement with clean soil)	Soil and turf
Restrict entry into the food chain	Milk, meat, crops, fruits, vegetables
Restrictions on foraging (collection of wild foods)	None
Select alternative land use	None
Selective grazing	None

Table 3.17 Alphabetical index of remedial actions

Datasheet No	Remedial action – Inhabited area surfaces	Page Number
1	Cover grass/soil with clean soil/asphalt	47
2	Dismantle and dispose of contaminated material	50
3	Fix and strip coatings	53
4	Ploughing methods	55
5	Reactive liquids	57
6	Removal of soil (and replacement with clean soil)	60
7	Restrict public access	62
8	Surface removal (indoor)	63
9	Surface or total removal and replacement (roads)	65
10	Temporary relocation from residential areas	67
11	Tie down	68
	Remedial action – food production	
12	Dietary advice (domestic)	71
13	Live monitoring	73
4	Ploughing methods	55
6	Removal of soil (and replacement with clean soil)	60
14	Restrict entry into the food chain (including FEPA orders)	76
15	Restrictions on foraging (gathering wild foods)	78
16	Select alternative land use	80
17	Selective grazing	82

4 Worked examples

Two worked examples have been developed to illustrate how the decision aiding framework described in Section 3 can be implemented for land containing historical contamination. The examples are based on real situations but have been adapted so that the contamination affects inhabited areas and food production systems.

4.1 Domestic gardens contaminated by feral pigeons

4.1.1 Background

A private property in Seascale, West Cumbria was visited by a large number of feral pigeons over a period in excess of twenty years (COMARE and RWMAC, 1999). It was found that the pigeons had become contaminated through contact with radioactive material from historical practices on the Sellafield nuclear site, which is close to Seascale. Surveys found that the pigeons had spread contamination from Sellafield to the property in Seascale and the immediately adjacent areas. The garden of the property was found to be contaminated with man-made radionuclides ^{137}Cs and ^{239}Pu at levels around 800 times higher than the typical concentrations in soils for the region. The owners used grass cuttings to make compost for the vegetable patch. Both the soil from the vegetable patch and the vegetables grown were found to have activity concentrations between five and ten times higher than samples from nearby control sites. Surface dusts on hardstanding around neighbouring properties showed elevated levels of radionuclides although these levels were considerably lower than at the main property.

The total effective dose from the contaminants to residents of the property was about 0.6 mSv y^{-1}, 90% of which was due to external gamma irradiation. This estimated dose is below the threshold for harm specified in the radioactive contaminated land regime and as such the land would not meet the criteria for being determined as radioactive contaminated land. As the land did not meet the legal definition of being radioactive contaminated land there was no urgent need for remediation to be carried out on radiological protection grounds. However, the residents and their neighbours did express a desire to have the contamination removed for reassurance purposes.

4.1.2 Decision framework for the remediation strategy

The development of the remediation strategy for the contaminated domestic garden of one property and hardstanding of neighbouring properties is illustrated in Table 4.1, based on the generic eight step process (Section 3.1).

Table 4.1 Developing a remediation strategy for a contaminated domestic garden

Step	Action
1	**Identify surfaces and/or food products that are likely to be/have been contaminated** From the scenario described, external exposure of the residents is the main exposure pathway and remediation effort should be focused on ‘roads (driveways) and paved areas’ and ‘soils and grass’
2	**Consider all applicable remedial actions for the surfaces selected** Table 4.2 presents a list of options for roads and paved areas, and soils and grass Roads (driveways) and paved areas Of the four potential remedial actions, restricting public access is only applicable in non-residential areas. As inhalation of resuspended soil is not considered an important pathway, tie down need not be considered. Temporary relocation of the residents is not required on radiological protection grounds and can also be eliminated (note: it could be considered as an optional supporting measure while remediation of the properties is being carried out). Only one remedial action remains: • Surface or total removal and replacement Soils and grass Of the six potential remedial actions, ploughing cannot be done in domestic gardens due to the small area involved, and restricting public access is only applicable in non-residential areas. As inhalation of resuspended soil is not considered an important pathway, tie down need not be considered. Temporary relocation of the residents is not required on radiological protection grounds and can also be eliminated (note: it could be considered as an optional supporting measure while remediation of the properties is being carried out). Two remedial actions remain: • Cover grass/soil with clean soil/asphalt • Removal of soil (and replacement with clean soil)
3	**Consider the applicability of remedial actions for each radionuclide being considered** Table 4.3 summarises the relevant data for ^{137}Cs and ^{239}Pu for the remaining set of remedial actions. All of these remedial actions are applicable for both ^{137}Cs and ^{239}Pu contamination. No options can be eliminated at this step.
4	**Consider key constraints for each remedial action** Table 4.4 presents the key constraints relevant to the remaining remedial actions. Roads (driveways) and paved areas No major constraints exist that would eliminate any further remedial actions. Only one remedial action remains: • Surface or total removal and replacement Soils and grass Covering of contaminated soil/grass with clean soil has serious social constraints when implemented in domestic gardens as the contamination remains in place and future uses of the garden could bring contamination back to the surface. Covering of contaminated soil/grass with asphalt would prevent cultivation of domestic produce in the garden. Overall, leaving the contamination in situ would be unacceptable to the residents. Only one remedial action remains: • Removal of soil (and replacement with clean soil)
5	**Consider the effectiveness of each remedial action** Table 4.5.presents data on the effectiveness of the two remaining options. Both are highly effective at reducing external doses from ^{137}Cs and inhalation doses from ^{239}Pu. No options can be eliminated at this step.
6	**Consider the types of waste produced from implementing remedial actions** Table 4.6 indicates the types of waste produced from implementing the two remaining options. As this scenario only involves remediation of a few properties, any waste generated should be manageable with existing disposal routes. No options can be eliminated at this step.
7	**Refer to individual datasheets for all options remaining** This step involves a detailed analysis of all the remaining options by careful consideration of the datasheets. It must be done on a site-specific basis and in close consultation with stakeholders and local residents. In this scenario, there were no further factors that influenced the remediation strategy.

8	**Based on the outputs from Steps 1-7, select and combine options that should be considered as part of the remediation strategy** The low doses (less than 1 mSv y^{-1}) mean that remediation is not required on radiological protection grounds. However, in view of the residents request for remediation and the small scale/extent of the contamination, the removal options that were identified should be considered. <u>Roads (driveways) and paved areas</u> Three remedial actions to be considered • Surface or total removal and replacement <u>Soils and grass</u> Three remedial actions to be considered • Removal of soil (and replacement with clean soil) Whilst remediating both these types of surfaces, consideration should be given to temporarily relocating residents while the contaminated driveways, paved areas and contaminated soils are removed and replaced. The depth of soil removed from the garden would be based on measurements taken at the site.

Table 4.2 Selection table of remedial actions

Surface/production system	Remedial action	Comment
Roads and paved areas	Surface or total removal and replacement	To be considered
	Restrict public access	N/A to residential areas
	Temporary relocation from residential areas	N/A on radiological protection grounds
	Tie down	N/A as inhalation pathway not important in this scenario
Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	To be considered
	Ploughing methods	N/A as area too small
	Removal of soil (and replacement with clean soil)	To be considered
	Restrict public access	N/A to residential areas
	Temporary relocation from residential areas	N/A on radiological protection grounds
	Tie down	N/A as inhalation pathway not important in this scenario

Table 4.3 Applicability of remedial actions to ^{137}Cs and ^{239}Pu

Surface/production system	Remedial action	^{137}Cs	^{239}Pu
Roads and paved areas	Surface or total removal and replacement	✓	✓
Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	✓	✓
	Removal of soil (and replacement with clean soil)	✓	✓

Table 4.4 Checklist of major constraints

Surface/production system	Remedial action	Major constraints
Roads and paved areas	Surface or total removal and replacement	Waste: • Potential for large quantities of contaminated tarmac/concrete to be produced, requiring disposal
Soils and vegetation (grass)	Cover grass/soil with clean soil	Social: • Acceptability in gardens likely to be low Technical: • Complicates further options for removal of contaminated soil • Can only be implemented on a small scale - large quantities of soil are required
	Removal of soil (and replacement with clean soil)	Cost: • may be high – depends on equipment, personnel, size of the affected area and volume of topsoil requiring disposal Waste: • Potential for large quantities of contaminated soil/vegetation to be produced, requiring disposal

Table 4.5 Effectiveness of remedial actions

Surface/production system	Remedial action	Effectiveness
Roads and paved areas	Surface or total removal and replacement	Decontamination work in Japan stripping the surface or shot blasting asphalt pavements and roads removed 50-95% (DF= 2 – 20) of contamination.
Soils and vegetation (grass)	Removal of soil (and replacement with clean soil)	Experience in Japan following the Fukushima accident showed 50-80% could be removed (DF = 2 – 20), with indications that the effectiveness could potentially be much higher if soil is replaced with clean soil.

Table 4.5 Waste generation by remedial actions

Surface/production system	Remedial action	Type of waste
Roads and paved areas	Surface or total removal and replacement	Asphalt, concrete, paving slabs
Soils and vegetation (grass)	Removal of soil (and replacement with clean soil)	Soil and grass

4.2 Site formerly used to house radium luminising facilities

4.2.1 Background

A site was formerly operated by the Royal Navy as a major airfield between 1917 and 1958. Aircraft refurbishment took place in maintenance buildings in the 1940s. These buildings included radium luminising facilities where radium paint was stripped off old equipment and new paint applied. Disposal of luminising equipment and paint was often undertaken with no regard for their radiochemical properties and hence it was assumed that disposal of such material at the airfield was achieved via the common practice of burning and burial. The precise location of the buildings and waste pits associated with luminising are not known, although it was suspected that they were grouped together in a single location within the airfield boundary.

Monitoring of the site found an area of about 200 m^2 with elevated levels of radioactivity. Analysis of soil from this area showed that ^{226}Ra and its radioactive progeny, including ^{210}Pb and ^{210}Po, were present at above background levels in the top 30 cm of soil. While other members of the ^{226}Ra decay chain will be present, ^{226}Ra, ^{210}Pb and ^{210}Po are the main contributors to any doses received. These are therefore the radionuclides of interest.

The areas of elevated activity were found in land that is currently used to grow arable crops (fruit) and for recreational purposes such as dog walking. There is also a possibility that the land may be developed in the future for the construction of residential buildings. The agricultural and recreational scenarios are considered as existing exposure situations as the exposure situation already existed when a decision on its control had to be taken. The relevant criterion to compare the estimated effective dose to is the 3 mSv y^{-1} harm threshold specified in the radioactive contaminated land regime. Housing development involves a change in land use resulting in new exposures from the source; this has to be managed as a planned exposure situation where the appropriate criterion is an effective dose constraint of 0.3 mSv y^{-1}.

The principal pathway of concern in the agricultural scenario is ingestion of fruit by the farmers' family (maximum estimated dose of around 4 mSv y^{-1} from exposure to ^{210}Pb and ^{210}Po). As this estimated dose exceeds the harm threshold specified in the radioactive contaminated land regime, urgent remediation should be undertaken on this site. Activity concentrations of ^{210}Po in the fruit also exceed Maximum Permissible Levels (MPLs) in foodstuffs which would result in restrictions on entry of the fruit into the food chain. For recreational use of the land, the principal pathway of concern is external irradiation by gamma emitting radionuclides. For this land use the dose, mainly from exposure to ^{226}Ra, was estimated to be about 0.3 mSv y^{-1}. As this level of dose is below the threshold for harm given in the radioactive contaminated land regime, the land will not require remediation from a radiological protection perspective. Should the land be redeveloped for housing, the principal pathway of concern for construction workers would be external irradiation by gamma emitting radionuclides (doses of around 0.3 mSv $y^{-1}$from ^{226}Ra). This estimated dose is equal to the dose constraint and as such some form of remediation would be needed to protect that workforce. Future residents could potentially receive doses of around 3 mSv y^{-1} (comprising of 2 mSv y^{-1} from the ingestion of ^{210}Pb and ^{210}Po in domestically produced fruit and vegetables and 1.0 mSv y^{-1} from external irradiation from ^{226}Ra); as these levels are in excess of the 0.3 mSv y^{-1} dose constraint, planning permission would unlikely be granted until the land is remediated.

4.2.2 Decision framework for the remediation strategy

Development of remediation strategies for the three scenarios, based on the generic eight step process (Section 3.1), is presented in Table 4.6. This shows how different remedial actions may be applied according to land use.

Table 4.6 Developing a remediation strategy for a former luminising site

Step	Actions		
	Agricultural scenario	**Recreational scenario**	**Housing development**
1	**Identify surfaces and/or food products that are likely to be/have been contaminated**		
	From the scenario described, ingestion of contaminated fruit by the farmer and family is the main pathway of exposure. Consequently, the focus of remediation should be on option for 'crops and grassland'.	From the scenario described, external exposure of recreational users of the land is the main pathway of exposure, although it should be stressed that the doses from recreational use of the land are not high enough that the land requires remediation on radiological protection grounds. If remediation is considered for other reasons then the focus should be on soils and vegetation as soil is the surface that is the source of the exposure. Consequently, the focus of remediation should be on options for 'soils and vegetation'.	From the scenario described, there are several important pathways of exposure. For the construction workers, external exposure is important with the focus of remediation on 'soils and vegetation'. For families living on the proposed new housing development, ingestion of domestic fruit and vegetables as well as external exposure from the ground, are important contributors to dose. The focus of remediation should be on options for 'crops and grassland' and 'soils and vegetation'.
2	**Consider all applicable remedial actions for the surfaces selected**		
	Table 4.7 presents a list of options for each of the main surfaces or food products affected in each scenario.		
	<u>Crops and grassland</u> Of the four potential remedial actions, ploughing methods are unlikely to be appropriate, as contamination is already mixed at depth due to regular ploughing of the land as part of its present use; further ploughing will not reduce uptake of ^{210}Pb and ^{210}Po to fruit. Three options remain: • Removal of soil (and replacement with clean soil) • Restrict entry into food chain • Select alternative land use	<u>Soils and vegetation</u> Of the six potential remedial actions, temporary relocation from residential areas is not applicable as there is no residential area considered in this scenario. As inhalation of resuspended soil is not considered an important pathway, tie down need not be considered. Restricting public access would not be required as the doses from recreational use of the land do not require remediation on radiological protection grounds. Therefore, this option can be eliminated. Three options remain: • Cover grass/soil with clean soil/asphalt • Ploughing methods • Removal of soil (and replacement with clean soil)	<u>Soils and vegetation</u> Of the six potential remedial actions, temporary relocation from residential areas is not applicable as this is a construction site. As inhalation of resuspended soil is not considered an important pathway, tie down need not be considered. Four options remain: • Cover grass/soil with clean soil/asphalt • Ploughing methods • Removal of soil (and replacement with clean soil) • Restrict public access (construction site only) <u>Domestic food production</u> Of the three potential remedial actions, restriction on foraging is not applicable as this only applies to wild foods not domestic production. Two options remain: • Dietary advice • Removal of soil (and replacement with clean soil)
3	**Consider the applicability of remedial actions for each radionuclide being considered**		
	Table 4.8 summarises the applicability data for ^{226}Ra, ^{210}Pb and ^{210}Po for the remaining set of remedial actions. All options are applicable so no options are eliminated at this stage.		

<table>
<tr><th rowspan="2">Step</th><th colspan="3">Actions</th></tr>
<tr><th>Agricultural scenario</th><th>Recreational scenario</th><th>Housing development</th></tr>
<tr><td rowspan="2">4</td><td colspan="3">Consider key constraints for each remedial action
Table 4.9 presents the key constraints relevant to the remaining remedial actions.</td></tr>
<tr><td><u>Crops and grassland</u>
No major constraints exist that would eliminate any further remedial actions.
Three options remain:
• Removal of soil (and replacement with clean soil)
• Restrict entry into food chain
• Select alternative land use</td><td><u>Soils and vegetation</u>
Removal of soil to at least 30 cm would generate large volumes of waste that would not be justified for such low doses. It would also require large volumes of clean soil to be brought in which would be very expensive. Similarly, covering the area with clean soil (asphalt would be environmentally unacceptable) would also be very expensive. These two options can be eliminated.
One option remains:
• Ploughing methods</td><td><u>Soils and vegetation</u>
This scenario involves the construction of new houses. Ploughing methods and the covering the contaminated land with clean soil/asphalt would seriously complicate removal of the contamination in the future. These two options leave contamination in situ which is likely to be socially unacceptable; residents of new homes would expect the site to be clean.
Two options remain:
• Removal of soil (and replacement with clean soil)
• Restrict public access (construction site only)

<u>Domestic food production</u>
The provision of dietary advice to residents of new homes that they cannot consume fruit and vegetables grown in their gardens/allotments is likely to be socially unacceptable; residents of new homes would expect the site to be clean.
One option remains:
• Removal of soil (and replacement with clean soil)</td></tr>
</table>

Step	Actions		
	Agricultural scenario	**Recreational scenario**	**Housing development**
5	**Consider the effectiveness of each remedial action** Table 4.11 presents the data on effectiveness for the remaining remedial actions.		
	Crops and grassland The three remaining options are all effective at reducing ingestion doses by (i) reducing transfer of ^{210}Po and ^{210}Pb into fruit and vegetables by removing the contaminated soil and replacing with clean soil; (ii) restricting entry of contaminated fruit into the food chain; or by using the land for non-food production. No options can be eliminated. Three options remain: • Removal of soil (and replacement with clean soil) • Restrict entry into food chain • Select alternative land use	Soils and vegetation For contamination that has reached 30 cm depth, of the ploughing methods available only deep ploughing would be effective as this inverts the soil profile and buries the contamination at depth. One option remains: • Ploughing methods	Soils and vegetation Removal of soil and replacement with clean soil is highly effective at reducing external doses to those involved in constructing new homes. Restricting public access to the construction site is highly effective at preventing exposure of members of the public to the contamination. Two options remain: • Removal of soil (and replacement with clean soil) • Restrict public access (construction site only) Domestic food production Removal of soil and replacement with clean soil is effective at reducing transfer of ^{210}Po and ^{210}Pb into fruit and vegetables. One option remains: • Removal of soil (and replacement with clean soil)
6	**Consider the types of waste produced from implementing remedial actions** Table 4.12 presents information on waste generation by the remaining actions.		
	Crops and grassland Removal of soil will generate large volumes of waste soil that will require disposal. Restricted entry of fruit and vegetables into the food chain will only generate waste in the year of production. Subsequent management of the land (i.e. removal of soil or selection of alternative land use) will not result in additional produce requiring disposal. Selecting an alternative land use will not generate waste. No options can be eliminated. Three options remain: • Removal of soil (and replacement with clean soil) • Restrict entry into food chain. • Select alternative land use	Soils and vegetation Ploughing does not generate any wastes. One option remains: • Ploughing methods	Soils and vegetation Removal of soil will generate large volumes of waste soil that will require disposal. Restricting public access does not generate any waste. Two options remain: • Removal of soil (and replacement with clean soil) • Restrict public access (construction site only) Domestic food production Removal of soil will generate large volumes of waste soil that will require disposal. One option remains: • Removal of soil (and replacement with clean soil)

Step	Actions		
	Agricultural scenario	**Recreational scenario**	**Housing development**
7	**Refer to individual datasheets for all options remaining** This step involves a detailed analysis of all the remaining options by careful consideration of the datasheets. It must be done on a site specific basis and in close consultation with stakeholders and local residents.		
8	**Based on the outputs from Steps 1-7, select and combine options that should be considered as part of the remediation strategy**		
	Three options remain: • Removal of soil (and replacement with clean soil) • Restrict entry into food chain • Select alternative land use The estimated dose to the farmer and family exceeds the 3mSv y^{-1} criterion for designating the land as contaminated. It is likely that some remediation will be required in this scenario to reduce doses from ingestion of contaminated fruit. As the activity concentration of ^{210}Po in fruit exceeds the MPL, restrictions will be placed on entry of this fruit into the food chain. The farmer will need to decide whether to select an alternative (non-food, e.g. coppicing) use for the contaminated land or to have the contaminated soil removed and replaced with clean soil so that he can continue food production.	One option remains: • Ploughing methods The estimated dose to recreational users of the land of around 0.3 mSv y^{-1} is well below the criterion for designating the land as contaminated. Therefore no remedial action is required on radiological grounds. If the community expresses a desire for something to be done then deep ploughing could be applied to reduce external doses. If the contamination is left in situ, there will need to be a good communication plan in place for recreational users of the land.	Two options remain: • Removal of soil (and replacement with clean soil) • Restrict public access (construction site only) The estimated dose to construction workers is equal to the 0.3 mSv y^{-1} dose constraint for planned exposure situations, suggesting that some form of remediation may be required. However, when considered in conjunction with the estimated doses of around 3 mSv y^{-1} to residents of the new homes, there is strong case for remediation to be carried out. The favoured option would be removal of the contaminated soil and replacement with clean soil. Restricting public access would be important during remediation of the construction site.

Table 4.7 Selection table of possible remedial actions according to land use scenarios

Scenario	Surface/ production system	Remedial actions	Comment
Agricultural	Crops and grassland (fruit production)	Ploughing methods	N/A contamination is already well mixed.
		Removal of soil (and replacement with clean soil	To be considered
		Restrict entry into food chain (including FEPA orders)	To be considered
		Select alternative land use	To be considered
Recreational	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	To be considered
		Ploughing methods	To be considered
		Removal of soil (and replacement with clean soil)	To be considered
		Restrict public access	N/A on radiological protection grounds
		Temporary relocation from residential area	N/A not a residential area
		Tie down	N/A inhalation of resuspended material not a significant pathway
Housing development	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	To be considered
		Ploughing methods	To be considered
		Removal of soil (and replacement with clean soil)	To be considered
		Restrict public access	To be considered
		Temporary relocation from residential area	N/A not a residential area
		Tie down	N/A inhalation of resuspended material not a significant pathway
	Domestic vegetable production	Dietary advice (domestic)	To be considered
		Removal of soil (and replacement with clean soil)	To be considered
		Restrictions on foraging (gathering of wild foods)	N/A gardens and allotments only, not foods from the wild

Table 4.8 Applicability of remedial actions to ^{226}Ra, ^{210}Pb and ^{210}Po

Scenario	Surface/ production system	Remedial actions	Radionuclide		
			^{226}Ra	^{210}Pb	^{210}Po
Agricultural	Crops and grassland (fruit production)	Removal of soil (and replacement with clean soil)	✓	✓	✓
		Restrict entry into food chain (including FEPA orders)	✓	✓	✓
		Select alternative land use	✓	✓	✓*
Recreational	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	✓	✓	✓
		Ploughing methods	✓	✓	✓
		Removal of soil (and replacement with clean soil)	✓	✓	✓
Housing development	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	✓	✓	✓
		Ploughing methods	✓	✓	✓
		Removal of soil (and replacement with clean soil)	✓	✓	✓
		Restrict public access	✓	✓	✓
	Domestic fruit and vegetable production	Dietary advice (domestic)	✓	✓	✓
		Removal of soil (and replacement with clean soil)	✓	✓	✓

Key:

✓: Selected as target radionuclide (i.e. known or probable applicability, see Section 3.3)

* The short half-life of ^{210} Po would normally preclude radical remedial actions such as 'select alternative land use'. However, the presence of ^{226}Ra maintains levels of progeny such as ^{210}Po and ^{210}Pb in soils.

Table 4.9 Checklist of key constraints

Scenario	Surface/ production system	Remedial actions	Major constraints
Agricultural	Crops and grassland (fruit production)	Removal of soil (and replacement with clean soil)	Cost: • May be high – depends on equipment, personnel, size of the affected area and volume of topsoil requiring disposal. Waste: • Potential for large quantities of contaminated soil/vegetation to be produced, requiring disposal.
		Restrict entry into food chain (including FEPA orders)	Waste: • There may be significant amounts of contaminated food products that will require a suitable disposal route.
		Select alternative land use	Social: • Market for alternative products and know-how.
Recreational	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	Technical: • Complicates further options involving removal of contaminated soil. • Can only be implemented on a small scale and even then very large quantities of soils are required. Social: • Acceptability in domestic gardens likely to be low.
		Ploughing methods	Technical: • A soil depth > 0.3 m is required for normal shallow ploughing or > 0.5 m for deep ploughing. • Deep ploughing must be implemented before shallow ploughing is undertaken.
		Removal of soil (and replacement with clean soil)	As above
Housing development	Soils and vegetation (grass)	Cover grass/soil with clean soil/asphalt	As above
		Ploughing methods	As above
		Removal of soil (and replacement with clean soil)	As above
		Restrict public access	None
	Domestic fruit and vegetable production	Dietary advice (domestic)	None
		Removal of soil (and replacement with clean soil)	As above

Table 4.10 Effectiveness of remedial actions

Scenario	Surface/ production system	Remedial actions	Effectiveness
Agricultural	Crops and grassland (fruit production)	Removal of soil (and replacement with clean soil)	~ 95%
		Restrict entry into food chain (including FEPA orders)	Up to 100%
		Select alternative land use	Up to 100%
Recreational	Soils and vegetation (grass)	Ploughing methods	External gamma dose rates above the surface will be reduced by: < 10% shallow ploughing ~ 70% deep ploughing
Housing development	Soils and vegetation (grass)	Removal of soil (and replacement with clean soil)	~ 95%
		Restrict public access	Up to 100%
	Domestic fruit and vegetable production	Removal of soil (and replacement with clean soil)	~ 95%

Table 4.11 Type of waste generated by remedial actions

Scenario	Surface/ production system	Remedial actions	Type of waste
Agricultural	Crops and grassland (fruit production)	Removal of soil (and replacement with clean soil)	Soil and vegetation
		Restrict entry into food chain (including FEPA orders)	Fruit and/or other crops
		Select alternative land use	None
Recreational	Soils and vegetation (grass)	Ploughing methods	None
Housing development	Soils and vegetation (grass)	Removal of soil (and replacement with clean soil)	Soil and vegetation
		Restrict public access	None
	Domestic fruit and vegetable production	Removal of soil (and replacement with clean soil)	Soil and vegetation

5 Conclusions and recommendations

There is currently no published guidance to assist in the selection of options for the remediation of contaminated legacy sites. To provide such guidance, this study has applied a decision framework currently used for remediating land contaminated as a result of a nuclear accident. The decision aiding process worked well despite there being significant differences between nuclear accident and legacy contamination with regards to the range of radionuclides considered, their physical and chemical forms, and distribution within the environment. Far fewer remedial actions (17 in total) were found to be applicable to contaminated legacy sites than to land contaminated as a result of a nuclear accident as there is no requirement for precautionary measures or actions to be taken to remove fresh contamination. Even where remedial actions were applicable to contaminated legacy sites some required adaptation to manage contamination at depth (e.g. soil removal, ploughing methods).

Having established the potential applicability of the decision framework for remediation of legacy sites, there are several recommendations to further develop the approach:

a. Conduct a review of past remediation activities to identify additional remedial actions not covered by this guidance;

b. Conduct a review of the applicability and effectiveness of remedial actions for the range of radionuclides typically found at contaminated legacy sites as current information is focused on radionuclides released as a result of nuclear accidents;

c. Continue to test the decision aiding framework for a wider range of scenarios.

6 Acknowledgements

Samantha Watson (PHE) is acknowledged for her contribution to the second worked example.

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Appendix A Datasheets of Remedial Actions

1 Cover grass/soil with clean soil/asphalt	
Objective	To reduce inhalation and external doses from contamination on areas of grass or soil within inhabited areas.
Other benefits	The spread of contamination will be limited. Shielding of contamination with soil effectively ties-down the underlying contamination that could otherwise be resuspended. This is therefore an effective tie-down option. If asphalt is used as the covering material, or if geomembranes and/or clay are incorporated into a covering soil layer, water infiltration will be restricted. This will reduce leaching of radioactive material into drinking water sources. The geomembrane also restricts the potential for inadvertent disturbance of the contamination.
Remedial action description	A layer of soil or a hard surface such as asphalt may be used to cover contaminated grass or soil to provide shielding from contamination on the ground area. May also be applied to reduce the external dose rate from residual contamination on a soil surface after removal of the soil (see Datasheet 6). Can also be used for tie-down of contaminated soil to reduce the resuspension hazard to members of the public (See Datasheet 11 for more information on tie-down options). This option severely complicates subsequent removal of the contamination and restricts future development of the area. Soil: A 5 - 10 cm layer of radiologically clean soil can be applied in areas where people spend time. Use of sprays to dampen soil would help reduce resuspension and help with bedding in until plants are growing through the new soil layer to anchor it. A multi-layered cap may be constructed using compacted filler underneath a geomembrane, a layer of compacted clay, another geomembrane and a layer of topsoil. Asphalt: A layer of asphalt (or alternatives, e.g. concrete or paving stones) can be applied over small areas adjacent to buildings. Generally, the procedure would involve applying a layer of stabilising gravel, then asphalt (using shovels and other hand-tools) and finally to use a roller to consolidate. Resurfacing using asphalt may also be carried out by applying a thick layer of gravel onto which a thin sealing asphalt emulsion layer is sprayed and finishing with a thin layer of gravel. A geomembrane can also be used under the asphalt to warn about inadvertent penetration, if future work is done. Dust creation during implementation is unlikely to be a problem hence remedial actions to reduce resuspension hazard to workers will not be necessary (unless the resuspension hazard in the area is deemed significant).
Target	Grass/soil surfaces in inhabited areas. Typically coverage with clean soil will be targeted at gardens, parks, playing fields and other open spaces, while use of asphalt will be targeted at small to medium sized open areas, often around residential buildings, schools etc. where people generally spend much of their time while outdoors.
Targeted radionuclides	All long-lived radionuclides. Tie-down usage targets alpha emitting radionuclides that give rise to inhalation doses from resuspended material.
Scale of application	Covering with soil: Best suited to smaller areas, though larger areas may be possible. Covering with asphalt: Small - medium sized areas with boundaries around buildings.
Time of application	Any time
Constraints	
Legal constraints	Liabilities for possible damage to property. Ownership and access to property. Cultural heritage protection, e.g. use on listed and other historically important sites and in conservation areas.
Environmental constraints	Cold weather (temperature must be > 5 °C). In extreme cases, the slope of the area may be a concern. There may be issues with the acceptability of smothering flora and fauna, if covering with asphalt. The condition of the underlying area may affect the ability to cover, e.g. mud cannot easily be covered with asphalt or soil.
Effectiveness	
Reduction in contamination on the surface	The decontamination factor (DF) for this option is 1, as no contamination is removed. Subsequent disturbance of the clean layer, by whatever means, will reduce the effectiveness of the option.
Reduction in surface dose rates	Soil: A reduction in gamma dose rate above the clean soil of 30-80% could be expected depending on the energy of the gamma rays emitted by the radionuclide. This option will be

1 Cover grass/soil with clean soil/asphalt

	100% effective in reducing external beta dose rates. Asphalt: While the asphalt remains undisturbed, the external gamma dose rate above the surface will be reduced by a factor which is dependent on the energy of the gamma rays emitted and the depth of the asphalt layer used. This option will effectively reduce external beta dose rates above the surface by 100%, also alpha emitters.
Reduction in resuspension	Resuspended activity in air above the soil (or grass) surface will be effectively reduced to 100%.
Technical factors influencing effectiveness	Design of the cover - this may need to be adjusted to the specific features of a site e.g. amount of rainfall. Thickness of layer used. Density of material used - compaction may be required depending on the density of the material. Availability of required quantities of material - this may be an issue with soil. Evenness of ground surface. Number of plants, shrubs and trees left in area.
Social factors influencing effectiveness	If soil is used as the covering medium, there may be restrictions on digging the soil that has been used to cover contamination.
Feasibility	
Equipment	Soil: Spades. Bobcat mini-bulldozer. Rake. Plywood for surface compaction Sprinkling equipment Transport vehicles for equipment and soil. Asphalt: Small asphalt roller. Shovels. Special rakes for plaining gravel / asphalt layers. Trucks for transport of roller, asphalt and stabilising gravel.
Utilities and infrastructure	Roads for transport of equipment and materials.
Consumables	Soil and possibly geomembrane/clay material, or asphalt and stabilising gravel. Fuel and parts for equipment and vehicles.
Skills	On a small scale, using spades, covering with soil can be implemented by unskilled workers. Requires hard physical work, which not all persons would be capable of. If covering a larger area with soil, or if covering with asphalt, skilled workers will be required to operate equipment.
Safety precautions	All workers may require respiratory protection, particularly in dry and dusty conditions.
Waste	
Amount and type	None
Intervention costs	
Operator time	Depends on access and openness of area and equipment used. Soil, small areas: 20 m^2 h^{-1} $team^{-1}$ (team size: 1 person). Soil, larger areas: 400 m^2 h^{-1} $team^{-1}$ (team size: 2 people). Asphalt: 15 m^2 h^{-1} $team^{-1}$ (team size: 4 people).
Factors influencing costs	Type of equipment and covering medium used. Thickness of covering layer used. Quality of the asphalt or soil type and condition. Operator skill. Amount of vegetation to be removed. Evenness of surface. Weather. Topography. Size of area. Access. Use of personal protective equipment (PPE). Need to take into account drainage/sewerage pipes etc.
Side effects	
Environmental impact	Possible adverse impact on biodiversity. In particular, use of asphalt will result in total loss of biodiversity in the treated area.

1 Cover grass/soil with clean soil/asphalt	
	Possible impact on fertility. In particular, use of asphalt will result in total loss of fertility in the treated area. Aesthetic consequences of landscape changes, particularly from soil to asphalt. Possible soil erosion risk due to increased soil depth, although reseeding of grass or replanting would reduce the risk of soil erosion. As contamination is not removed over time some radionuclides may leach deeper into the soil.
Social impact	Acceptability of leaving some contamination in-situ. Future development of the site may be limited in order not to re-exposure contamination. Possibility of radionuclides leaching deeper into the soil may preclude use of land for food production. Access to public areas may need to be restricted temporarily before clean surface is applied.
Practical experience	The method has been widely applied in the former Soviet Union after the Chernobyl accident.

2 Dismantle and dispose of contaminated material

Objective	To remove contamination, including hotspots or more widespread material, associated with internal building surfaces and other contaminated indoor objects, personal items, furnishing and fixtures.
Other benefits	To reduce inhalation and external doses arising from contamination.
Remedial action description	Depending on the level of contamination on surfaces/objects, and the ease of decontamination, it may be decided to dismantle or remove objects and dispose of them, rather than carrying out decontamination. A variety of equipment will be required, together with regular vehicular access to remove items and rubble. Consideration should be given to monitoring of equipment and vehicles to prevent the spread of contamination. Dismantling may generate large volumes of wastes. It is important to apply best practise techniques for minimising the waste produced, with efficient and effective management of waste through a planned waste management strategy being essential to ensuring the success of the remediation process. It will therefore be important to: Establish clearance levels to help manage the volume of waste being disposed of as radioactive material. Cleared material should be considered for recycling where possible; Establish appropriate disposal routes for each of the waste types generated - some negotiation with the facility owners (operators of landfill sites or incinerators) and regulators may be necessary; Bag waste items where possible to contain contamination and segregate material collected, using a suitable area for sorting, based on its radioactivity content. Consider size reduction, if possible; Establish an inventory of materials to keep track of the activity and amounts generated. Dismantling refers to the physical removal of selected items, objects, fixtures and fittings. Dismantling could be the sole activity of the remediation strategy or involve removal of substructures prior to other clean-up techniques, or to expose inaccessible areas of contamination. Disposal refers to the complete destruction and/or disposal of equipment, parts of equipment or any other parts of the infrastructure by an appropriate disposal route. Significant preparation activities may be required, for example all surfaces may need to be washed down to minimise dust. Internal objects, fixtures and furnishings in buildings can be removed, or it may be possible to remove and replace part of an object. Contamination should be fixed to the surface prior to removal if there is a risk of dust further spreading contamination during the removal process. For upholstery, unfixed carpets and linen, a spray fixative of 10% glycerol in water can be used; wax polish can be sprayed on to smooth finished furniture to prevent dust spreading during removal.
Target	Highly contaminated items, within areas where exposure concentrations are too high for people to live or work.
Targeted radionuclides	All long-lived radionuclides, especially on material that is otherwise difficult to decontaminate.
Scale of application	Any.
Time of application	Short – long term. Dismantling can cause significant resuspension of radioactive material. Therefore, if other decontamination options are also being implemented, it is important to consider the sequencing of techniques to avoid recontamination of previously treated areas.
Constraints	
Legal constraints	Ownership and access to property. Liabilities for possible damage to property. Use on listed and other historically important buildings and on precious objects. Solid waste treatment and disposal legislation.
Environmental constraints	The dismantling process can result in release of contaminated dust and other debris into the environment. Control of dust is required, and the use of fix and strip coatings should be considered to limit this. The disposal or storage of waste arising from the implementation of this option may have an environmental impact. However, this should be minimised through the control of any disposal route and relevant authorisations.
Effectiveness	

2 Dismantle and dispose of contaminated material	
Reduction in contamination on the surface	Option will be virtually 100% effective in removing contamination on surfaces if all debris is removed and contamination is not spread during demolition process. The amount of contamination re-distributed will depend on the extent to which contamination is contained prior to the removal.
Reduction in surface dose rates	Dose rates from contamination on surfaces will be eliminated.
Reduction in resuspension	Up to 100% as contaminated material is removed.
Technical factors influencing effectiveness	The materials and radionuclides involved. The techniques used. Type and condition of surface as this will affect the amount of dust that is likely to be produced and hence spreading of contamination - though dust suppression technologies can be used where necessary. The amount of contamination (including dust and particulate matter) released into the environment, and the level of control of such contamination. Amount of dust on indoor surfaces. Whether any cleaning has already been undertaken. Collection of all removed surface material.
Social factors influencing effectiveness	There may be issues with regard to public acceptability of the measure itself and of waste treatment and storage routes.
Feasibility	
Equipment	Specific equipment may vary depending on the technique and surface involved, but the following may be required: Monitoring equipment. Tools for dismantling/disposing of contaminated material e.g. pneumatic chisels, machine (long reach scaler) to remove tiles stuck to concrete floors, saws etc. Equipment for control of dust and particulate matter. Appropriate containers for temporary storage of waste products. Transport vehicles for equipment and waste.
Utilities and infrastructure	Roads for transport of equipment, materials and waste. Access and sufficient operational space is required for equipment. Power and water supply. Infrastructure for management of large volumes of generated material. Storage for waste.
Consumables	Water. Fixative coatings such as acrylic paint (to prevent dust). Bags for containing items and wastes. Fuel and parts for equipment and vehicles.
Skills	Depending on the techniques used skilled personnel may be required.
Safety precautions	Employers have a duty of care to protect employees from hazards and risks in the workplace and to ensure that safety procedures and processes are in place. Structural engineering reports may be required to assess safety of work. Additionally, a risk assessment would need to be undertaken to determine safety measures required for the radionuclide involved. Remediation workers must use appropriate PPE (hat, boots, goggles, gloves, overalls; respiratory protection if dust and particulate matter would be generated or if asbestos is present; additional safety equipment if working at height) and follow Standard Operating Procedures (SOPs).
Waste	
Amount and type	Likely to generate large amounts of contaminated solid waste such as furniture, soft furnishings, electrical goods, fixtures and objects from inside a building. Materials should be segregated by type (wood, concrete, metal etc.) and ideally by activity. Removal of furniture, soft furnishings, and objects from inside a building can be expected to generate 20 - 30 kg m^{-2} floor area, while removal of fixtures may generate 50 kg m^{-2} floor area.
Intervention costs	

2 Dismantle and dispose of contaminated material	
Operator time	Costs for operator time will vary depending on size and scale of the remediation programme. The work rate to remove contaminated objects for a team of 2 people is estimated at 20 - 30 m^2 h^{-1} $team^{-1}$.
Factors influencing costs	Costs and equipment required will vary according to the scale of contamination and size and construction of structure or objects that requires dismantling or disposal. Other factors influencing costs include: Property type and use (i.e. residential or commercial). Compensation for damage to building/property or loss of items. Weather. Size of structure that requires disposal. Type of equipment used. Access. Use of personal protective equipment (PPE). Use of scaffolding. The costs associated with demolition/dismantling could vary considerably depending on the situation and would need to be carefully balanced with the costs of decontamination.
Side effects	
Environmental impact	The disposal or storage of waste arising from the implementation of this option may have an environmental impact. However, this should be minimised through the control of any disposal route and relevant authorisations.
Social impact	Acceptability of production and disposal of large amounts of waste. Disposal of contaminated material may lead to the opportunity for redevelopment. There may a positive benefit of cleaning houses.
Practical experience	Tested on selected houses in the former Soviet Union (e.g., in Gomel, Belarus) after the Chernobyl accident. Used following the polonium poisoning incident in London. Used following the incident in Goiania, including the demolition of seven residences and the replacement of two roofs. Used in Japan following the Fukushima accident.

3 Fix and strip coatings	
Objective	To reduce inhalation and external doses from contamination on internal building surfaces, and roads/paved areas.
Other benefits	While they are in place, peelable coatings will also provide a tie-down effect and reduce exposure to remediation workers.
Remedial action description	The application of peelable coatings to a surface can fix contamination to the coating such that when the coating is peeled off the contamination is stripped away from the surface. As well as contamination adhering to the coating, there may also be chelating agent properties in the coating that bind organic chemicals to a metal ion, bringing them into solution and increasing removal from the surface. Peelable coatings have the additional benefit of providing a tie-down effect, but this only temporary while the coating is in place (though subsequent applications may be applied to extend the tie-down effect for a longer duration) and the primary use is to remove contamination from the surface. Detex and Pelableau are examples of peelable coatings though other materials, including polymer pastes, may be appropriate (e.g. PVA). A sharp knife can be used to score a surface into large sections to facilitate peeling of cured coatings. The coating can be rolled as it is removed for ease of handling and to further entrap any contamination on the surface of the coating. Removed coatings should be incinerated where possible. Coatings can be reapplied to a surface in order to sandwich in layers of contamination. Detex: On buildings, Detex is applied by brush because it is difficult to use in a spray gun. Brushing will also force the liquid into surface areas and crevices, which is better for decontamination. On flat surfaces, it can be poured manually and spread using metal rakes. After curing (typically up to 2 hours, though will depend on factors such as application, temperature and humidity) the rubber film is removed with a knife or by peeling. The contamination adheres to the peeled film, which is then disposed of as solid active waste. Pelableau: Pelableau is sprayed on to the surface using an airless pump. After curing it is peeled off. It is not widely available and not suitable for use on roofs, thereby reducing its usefulness. Polymer pastes: based on PVA, these can be used for the removal of contamination from metal surfaces. In particular they can be used for machinery and ventilation systems. The detachable coatings are liquids or gels. When the dry intact film has formed on the surface, the coating is peeled off by hand, removing any loose contamination. The technique can be applied easily and quickly and requires minimum equipment and personnel.
Target	Any robust hard surface.
Targeted radionuclides	All long-lived radionuclides. As a tie-down option: alpha emitting radionuclides that give rise to inhalation doses from resuspended material.
Scale of application	Small scale.
Time of application	Short term is preferable as this is when contamination is at the surface. The peelable coating will be effective in stopping resuspension over the period that it remains intact.
Constraints	
Legal constraints	Liabilities for possible damage to property. Use on listed buildings, historically important sites and conservation areas. Solid waste disposal legislation. Ownership and access to property.
Environmental constraints	Severe cold weather. Cannot be applied in wet weather.
Effectiveness	
Reduction in contamination on the surface	This option is likely to be most effective when used on smooth surfaces and not long after the contaminating event (DF of around 5). Later application is likely to give a lower DF as the contamination becomes more fixed to the surface, particularly on porous building materials such as bricks and tiles.

3 Fix and strip coatings	
Reduction in surface dose rates	External gamma and beta dose rates dose rates from external walls and roofs will be reduced by approximately the value of the DF.
Reduction in resuspension	While the peelable coating is in place, resuspended activity in air will be reduced by almost 100%.
Technical factors influencing effectiveness	Weather conditions and temperature: temperature will affect curing time and on outdoor surfaces curing may not be possible in bad weather conditions. Type, evenness and condition of surface. With increasing surface roughness/complexity, strippable coatings become more difficult to remove easily leading to reduced effectiveness. If metal surfaces are rusty or peeling, decontamination is reduced. Time of operation: the longer the time between deposition and implementation of the option the less effective it will be due to fixing of the contamination to the surface. Care of operation - careful removal (by hand) is required to be effective. Consistent application of peelable coating over the contaminated area.
Social factors influencing effectiveness	Public acceptability of waste treatment and storage routes.
Feasibility	
Equipment	Brushes. Paint rollers and telescopic poles. Metal rake. Airless spray pump and compressor. Transport vehicles for equipment and waste.
Utilities and infrastructure	Roads for transport of equipment, materials and waste.
Consumables	Proprietary strippable coatings are recommended, or otherwise a paste made from PVA, EDTA, sodium carbonate and glycerine. Fuel and parts for equipment and transport vehicles.
Skills	Skilled personnel essential to apply (and remove) coating. Industrial cleaning companies will have the required skills.
Safety precautions	Protective clothing, including respiratory protection.
Waste	
Amount and type	Around 1 kg m^{-2} (range 0.2 - 1.8 kg m^{-2}) solid, rubber like material.
Intervention costs	
Operator time	10^1 m^2 h^{-1} $team^{-1}$ (with a team of 2 people), with slower speeds (2 - 6 m^2 h^{-1} $team^{-1}$) possible when working with polymer pastes. Japanese experience estimated decontamination speeds of 10 m^2 day^{-1} from application of stripping agent to roofs of residential houses. Assuming a 7 hour working day, this suggest around 1.5 m^2 h^{-1} $team^{-1}$.
Factors influencing costs	Weather. Access. Evenness of surface. Size of area to be treated. Cost of specialist labour. Cost of chemicals.
Side effects	
Environmental impact	The disposal or storage of waste arising from the implementation of this option may have an environmental impact. However, this should be minimised through the control of any disposal route and relevant authorisations.
Social impact	Acceptability of disposal of contaminated waste. Reassurance of employees and users and maintaining continuity of work. Use of peelable coatings may have the potential to damage surfaces. Application is slow so may impact upon business continuity and lead to financial losses.

4 Ploughing methods	
Objective	Inhabited areas: To reduce inhalation and external doses from contamination in outdoor areas covered in grass or soil Food production: To reduce radionuclide uptake by crops including pasture
Other benefits	Does not generate waste
Remedial action description	Ploughing can be carried out at a range of depths depending on the equipment used. A standard single-furrow mouldboard plough can be used to a depth of 25 – 30 cm, or to a deeper depth of 45 cm. Deep ploughing inverts the top 45 cm of the soil profile. Much of the contamination at the surface will be buried deep in the vertical profile which (i) will reduce radionuclide uptake by plant roots depending on their specific rooting behaviour and (ii) reduce external exposure from the contaminants. Removal of plants, shrubs and trees may be necessary before ploughing. Afterwards, replanting may be required. The mixing of contamination by ploughing is irreversible and will severely complicate subsequent removal of contamination. This option is likely to give rise to dust, so application of water to dampen the surface or the use of a tie-down material is recommended prior to implementation.
Target	Inhabited areas: Grass and soil surfaces in large, parks, playing fields and other open spaces. Food production systems: Pasture or fallow arable land.
Targeted radionuclides	Known applicability: ^{90}Sr, ^{134}Cs, ^{137}Cs. Probable applicability: ^{226}Ra, ^{239}Pu, ^{241}Am. Not applicable: This remedial action may increase the mobility of U.
Scale of application	Large scale, where ploughing is possible.
Time of application	Medium to long term.
Constraints	
Legal constraints	Inhabited areas: Ownership and access to property. Use on listed and historic sites or in conservation areas. Food production systems: Ploughing may be restricted at farms participating in environmental stewardship schemes. Restrictions will also apply in areas designated within Nitrate Vulnerable Zones (NVZs). The Codes of Good Agricultural Practice should also be followed. A consent will be required if ploughing is to be carried out in an area designated a Site of Special Scientific Interest (SSSIs). There may also be constraints in archaeological areas and ancient monuments.
Environmental constraints	Severe cold weather. Soil texture (must not be too loose/sandy or stony). Use of machinery difficult on land with >16^{o} slope. Soil depth < 0.3 m for shallow ploughing and < 0.5 m for deep ploughing. High ground water level may be a constraint on deep ploughing.
Effectiveness	
Reduction in contamination on the surface	This option has a decontamination factor (DF) of 1 because it removes no contamination.

4 Ploughing methods	
Reduction in surface dose rates	Reductions in external gamma dose rate above the surface depend on: radionuclides involved, i.e. their gamma energies ploughing depth - an external gamma dose rate reduction factor of between 2 and 7 can be expected for shallow ploughing and between 5 and 10 for deep ploughing contamination profile with depth at the time of implementation Beta dose rate reduction is likely to be significantly higher, effectively stopping beta emitters, if the technique is implemented effectively.
Reduction in resuspension	By effectively burying most of the contamination, resuspended activity in air above the surface will be reduced by a factor significantly larger than the external gamma dose rate reduction.
Reduction in plant uptake	Plant uptake reduced by up to 90% (factor of 10), averaging 50% (typically a factor of 2). While observed data are limited to Sr and Cs, it is reasonable to expect similar reduction factors for the other targeted radionuclides as ploughing results in mechanical redistribution of contamination within the soil profile.
Factors influencing effectiveness of procedure	Ploughing depth. Contamination profile in soil. Efficiency of inversion of upper layer. Radionuclide distribution within soil profile after inversion. Rooting depths of different crops.
Feasibility	
Required specific equipment	Plough (with minimum furrow width of 0.75 m). Only depths of up to 45 cm can be ploughed by normal agricultural machinery.
Required ancillary equipment	Tractor (Deep ploughing requires powerful tractors e.g. 76-90 kW, which may need to be hired).
Required utilities and infrastructure	Roads and general access for equipment.
Required consumables	Fuel around 15 litres hectare^{-1} for ploughing.
Required skills	Farmers or agricultural workers are likely to possess the necessary skills but must be instructed carefully about the objectives.
Required safety precautions	Very dusty conditions: respiratory protection and protective clothes may be recommended to reduce the hazard from resuspended activity.
Other limitations	High ground water level.
Waste	
Amount and type	Some vegetation may be present,
Intervention costs	
Operator time	1 operator per plough: 0.2 man-days hectare^{-1}, i.e. 1.5 h hectare^{-1}
Factors influencing costs	Work rates vary depending on soil type and conditions, size and shape of the area, topography and operator experience.
Side effects	
Environmental impact	The procedure imposes environmental risk i.e. brings contamination closer to the ground water which may lead to transfer of radionuclides to other areas and affect other populations. Severely complicates subsequent removal of the contamination. Biodiversity could be affected, particularly for soil dwelling organisms. Long term changes in physical characteristics and structure of the surface horizon e.g. enhanced mineralisation of organic matter, change of nutrient loading and soil erosion. Field drainage systems destroyed (deep ploughing). Soil fertility markedly reduced - fertilisation may be required (deep ploughing).
Social impact	Contamination of soil at depth may restrict subsequent uses
Practical experience	Used widely in former Soviet Union following the Chernobyl accident. Tested on a limited scale in Denmark. Used in Japan following the Fukushima accident, where typically a ploughing depth of 30 cm was used.

5 Reactive liquids	
Objective	To reduce external doses from contamination on a variety of internal surfaces
Other benefits	May reduce resuspension doses in dusty environments.
Remedial action description	A number of reactive liquids are available. Depending on the chemicals applied, procedures are termed soft (non-corrosive reagents such as detergents (including household cleaners), chelating agents, diluted acids or alkalis, can be used when the object has to be treated without attacking the base material) or hard (concentrated strong acids or alkalis and other corrosive reagents). The choice of agent will depend on the surface being treated. For example, a plastic surface may need a soft procedure using a mild detergent or chemical, while metals surfaces may withstand more aggressive, hard treatment. Procedures can be static (without flow) or dynamic (with flow). The dynamic method is useful for removing radionuclides from both internal and otherwise inaccessible surfaces. Otherwise spray bottles, wipes, paper towels or tack cloths may be used. Repeated applications may be necessary to decontaminate the affected surface. Chemical decontamination is usually carried out by circulating the selected reagents through a filter system. The chemical solution is contained in a tank in which a spraying system, placed near to or below the surface being cleaned, circulates the solution. Decontamination can also be carried out by immersion of the contaminated item (hand tools, special parts of machinery) in a bath. Chelating (complexing) agents: Chelation (also known as complexation or sequestration) binds an organic chemical, the chelating agent, to a metal ion so as to bring it into solution and hence remove it from the surface. Chelation is normally used against fixed contamination. Common chelating agents are organic acids which also cause decontamination by an oxidation-reduction mechanism as well. Acids are also more effective chelators for radioactive contamination. Chelation can be carried out as a stand-alone technique, but is often part of a more complex process. Strong mineral acids: These release bound contaminants by dissolving metal oxide films that contain contamination. Acids used are hydrochloric acid (HCl), nitric acid (HNO_3), sulphuric acid (H_2SO_4) and phosphoric acid (H_2PO_4), which can be used on all metal surfaces except more reactive metals such as zinc. Oxidising and Reducing agents: Oxidising and Reducing (redox) reactions can be used to aid decontamination by increasing the solubility of metal ions, or the degree to which a metal ion will bond with a chelating agent. Agents may be used stand-alone, though they have limited effectiveness on their own, or in more complex processes with chelating agents or acids. Bleach, nitric acid and alkaline-permanganate solutions are the most commonly used oxidising agents. Chemical foams and gels: These are commonly used as carrier agents for other reactive agents such as chelators or acids. Foam is produced using water, detergent and the decontamination agent(s) using and industrial foam generator, which is cheap, simple and reliable. Foams have little decontamination ability on their own, although the detergent part may have some minor decontamination effect. Foams allow increased contact time compared with aqueous solutions, although repeated applications may be necessary as the amount of agent in contact with the surface is small compared to with the aqueous solution. Foams and gels are good for complex shapes.
Target	Indoor surfaces and objects.
Targeted radionuclides	All radionuclides.
Scale of application	Small scale.
Time of application	Short – long term. Maximum benefit if carried out soon after contamination.
Constraints	
Legal constraints	Liability issues regarding possible damage to property. Issues with ownership and access to property or affected site. Cultural heritage protection of listed and other historically important buildings. Possible regulations on use of chemicals.
Environmental constraints	Chemical incompatibility. For example, if the system to be decontaminated previously contained special chemicals, this material can produce some explosive gases when put together with the decontamination chemical. Depending on the reactive liquid used and the type of contaminant(s) involved, the toxicity of waste products would need to be considered.
Effectiveness	

5 Reactive liquids	
Reduction in contamination on the surface	This depends on the exact technique and agents used. Soft techniques: typically 50 - 90% reduction. Hard techniques: typically > 90% (up to 100%) reduction. Effectiveness may be lower on non-metallic surfaces.
Reduction in surface dose rates Reduction in resuspension	If the surface is decontaminated effectively, there should be a significant reduction in both dose rates and resuspension, similar to the reduction in contamination on the surface, and hence in potential exposure.
Technical factors influencing effectiveness	Time between contamination and clean up. Surface type (less effective on porous surfaces or if contamination has penetrated into inaccessible surfaces (ie under a screw). Contact time. Treatment temperature
Social factors influencing effectiveness	Potential damage to items.
Feasibility	
Equipment	High pressure water washer. Spray machines. Other hand tools (sponge, brush, cloths). Liquid tanks.
Utilities and infrastructure	Water and power supplies. Pressurised air supply.
Consumables	Depends on the target surfaces and hence the chemical agents used i.e. soft or hard treatment. Soft (mild) chemical decontamination will typically require: Step 1 attack & dissolve metal oxide films: potassium permanganate ($KMnO_4$) (one of the best for Cs) or potassium hydroxide (KOH) or sodium hydroxide (NaOH) or trisodium phosphate (Na_3PO_4). Step 2 bind and remove the radionuclides: detergent - any hydrophobic materials e.g. dodecyl benzene sulphuric acid - and chelating (complexing) agent such as EDTA (one of the best for Cs) or oxalic acid ($C_2H_2O_4$) or citric acid ($C_6H_8O_6$) (one of the best for Cs). Step 3 passivation: nitric acid (HNO_3) or phosphoric acid (H_3PO_4) or sulphuric acid (H_2SO_4) or hydrogen peroxide (H_2O_2). Hard (strong) chemical decontamination will typically require: Step 1: as for soft decontamination, but at higher concentration. Step 2: detergent - any hydrophobic materials e.g. dodecyl benzene sulphuric acid and chelating (complexing) agent such as sodium bisulphate ($NaHSO_4$) or sodium sulphate (Na_2SO_4) or ammonium oxalate ($NH_4C_2O_4$) or ammonium citrate [$(NH_4)_2HC_6H_5O_7$] or EDTA. Step 3: as for soft decontamination, but at higher concentration.
Skills	Skilled personnel required. Knowledge and experience in corrosion technology, waste generation/removal techniques and chemical cleaning is needed. Industrial cleaning companies will have the required skills.
Safety precautions	PPE and safety equipment should consider the hazards arising from the use of chemicals (corrosive, toxic or oxidising materials, gases, fires and explosion hazards) as well as radiological protection. Safety helmets and lifelines. Water proof safety clothing. Respiratory protection. Proper ventilation (because the tanks are usually open to the air).
Waste	
Amount and Type	30 litres m^{-2} liquid waste (applying a recycling system). Efficient recycling of reactive chemicals will help to keep waste levels low. There may be limitations on disposal routes available based on the agents used.

5 Reactive liquids	
Intervention costs	
Operator time	2 - 6 m^2 h^{-1} $team^{-1}$. Depending on the PPE used individuals may need to work restricted shifts. Variable time for setting up scaffolds/transport.
Factors influencing costs	Different types of treatment of surfaces and waste chemicals. Cost of specialist labour. Cost of chemicals.
Side effects	
Environmental impact	If strong chemicals are used they may lead to corrosive and toxic reagents being produced which will need to be handled and disposed of.
Social impact	Removal of the corrosion products from the surface
Practical experience	Chemical decontamination is very effective at NPPs in normal practice and is used in decommissioning. Acidic and caustic solutions are used in industry for decontamination. Decon 75 and Decon 90 are commonly used in industry, though there are limitations to their use e.g. Decon 90 is alkaline and therefore not suitable for use on non-ferrous metals or on polycarbonate. Tested in a number of industrial buildings in the former Soviet Union and Europe after the Chernobyl accident.

6 Removal of soil	
Objective	Inhabited areas: to reduce inhalation and external beta and gamma doses from contamination on outdoor grassed and soil areas by removing the soil and turf. Food production systems: to reduce radionuclide uptake by crops, pasture, allotment and kitchen garden produce.
Other benefits	None.
Remedial action description	Decontamination can be achieved by removal of soil and turf to the required depth. They can be removed together either manually using a spade, or by bobcat mini-bulldozers, back-hoes or mechanical digger. The scale of equipment used will depend on the size of the area, with small areas needing equipment which is easy to manoeuvre. A surface cutter or hammer knife mower is an effective method for covering vast areas. Any plants and shrubs may need to be removed first. On arable land any crops/plants that are present need to be removed first. The soil can be replaced with clean soil and reseeded or re-turfed depending on the size of the area. See Datasheet 1 for information on covering with grass or clean topsoil. This option is likely to give rise to dust and can be implemented in conjunction with tie down to limit resuspension hazard. This may be done by application of water to dampen the surface or the use of a tie-down material (see Datasheet 11).
Target	Inhabited areas: grass surfaces in gardens, parks, playing fields and other small open spaces. Food production systems: pasture or fallow arable land, areas used for domestic production and allotments.
Targeted radionuclides	All long-lived radionuclides.
Scale of application	Small – large, although disposal of large volumes of contaminated soil can present a challenge when large areas are subject to soil removal.
Time of application	Early – long term.
Constraints	
Legal constraints	Ownership and access to property. Waste disposal of collected waste, especially as there is a risk of generating very large volumes of waste materials. Use on listed or historically important sites and conservation areas. Farms participating in environmental stewardship schemes. Farms in SSSIs.
Environmental constraints	Soils which are shallow and stony. Severe cold weather. Soil texture: soil removal can be impractical on land that is uneven or that contains roots. In extreme cases, the slope of the area may be a constraint.
Effectiveness	
Reduction in contamination	Effectiveness depends on distribution of contamination within soil profile. Manual removal of soil can achieve a decontamination factor (DF) of 10, while mechanical removal may achieve a higher DF of between 10 and 30. DF could potentially be higher if soil is replaced.
Reduction in surface dose rates	External gamma and beta dose rates above the soil or grass surface will be reduced by up to the value of the DF.
Reduction in resuspension	Resuspended activity in air above the surface will be reduced by the value of the DF.
Technical factors influencing effectiveness	Depth of removal relative to depth of contamination. Soil texture: dry, crumbly soils will be more difficult to remove completely. Stones will affect the ability to implement the option effectively. If mechanical removal is to be used, soil must be compact enough to bear the equipment.
Social factors influencing effectiveness	None.
Feasibility	
Required specific equipment	Depends on the technique used and the size of the area being treated. Manual soil removal: Spade and wheel barrow Mechanical soil removal: Bobcat mini bulldozer, backhoe or mechanical digger.
Utilities and infrastructure	Roads for transport of equipment, materials and waste.
Consumables	Fuel and parts for vehicles and equipment.

6 Removal of soil			
Skills	Can be carried out by already skilled operators such as municipal workers. Care must be taken to remove soil to the optimal depth. This option requires hard physical work, especially for manual removal of soil.		
Safety precautions	Under very dusty conditions respiratory protection and protective clothes/gloves may be recommended to reduce the hazard from resuspended activity.		
Waste			
Amount and type	This option has the potential to generate large volumes of waste. Disposal will be subject to conditions depending on the activity levels and other properties of the waste. It may be possible to use removed soil in construction (e.g. of banks or roads		
Intervention costs			
Operator time	Manual soil removal:	10 m^2 h^{-1} $team^{-1}$	Team size: 1 to remove soil and turf.
	Mechanical soil removal:	100 - 400 m^2 h^{-1} $team^{-1}$	Team size: 2 people for soil and turf removal.
Factors influencing costs	Size of area. Soil type, condition and depth removed. Topography. Type of equipment used.		
Side effects			
Environmental impact	Soil erosion risk. Possible loss of soil fertility, nutrient and water retention. Changes in landscape.		
Social impact	Access to public areas may need to be restricted temporarily before soil removal is implemented and afterwards while grass grows/turf settles. Disruption to farming and other related activities (e.g. tourism) Waste disposal may not be acceptable. Loss of public amenities. Loss of sentimental features in private gardens (e.g. pet graves)		
Practical experience	Topsoil removal has been tested on semi-large scale (~ 400 m^2 manual removal, ~ 2000 m^2 mechanical removal) on several occasions in the former Soviet Union. Manual topsoil removal has also been carried out on a large scale by the Russian authorities after the Chernobyl accident, but not optimised with respect to contaminant distribution. Replacement of garden lawn and topsoil was carried out at a private residence in Cumbria, to remove activity deposited by feral pigeons that were contaminated with radioactive material at the Sellafield site. Topsoil removal was tested on playground and residential areas following the Fukushima accident.		

7 Restrict public access

Objective	To reduce external gamma and beta doses from material deposited on surfaces and inhalation dose from material resuspended from surfaces within contaminated non-residential areas.
Other benefits	Any necessary remedial actions will be implemented more easily whilst the population are absent from the area. Restricted public access will limit the spread of contamination.
Remedial action description	For non-residential areas accessed by the public (e.g. parks, recreational areas), only a total prohibition on access will be enforceable. Public land would be controlled with notices and barriers on main access routes (if practicable). Access restrictions can be in place while planning a remediation strategy (not just implementing it).
Target	People living in and visiting contaminated areas.
Targeted radionuclides	All radionuclides.
Scale of application	Any scale.
Time of application	Can be applied at any time and for any duration of time. May be implemented while other remedial actions are being planned and/or implemented.
Constraints	
Legal constraints	May require legislation to restrict access to land, depending on ownership.
Environmental / technical constraints	Ability to erect barriers (uneven ground).
Effectiveness	
Reduction in contamination on the surface	If people comply, this option is fully effective at reducing doses from the areas where access is prohibited. This option will not reduce contamination levels in the area subject to access restrictions although it may restrict the spread of contamination.
Reduction in surface dose rates	
Reduction in resuspension	
Technical factors influencing effectiveness	Effective exclusion of people from an area may be difficult to demonstrate. Success of barriers and fences (if used).
Social factors influencing effectiveness	Compliance: an effective public information strategy will be essential.
Feasibility	
Equipment	Barriers.
Utilities and infrastructure	None.
Consumables	Notices, signs, etc.
Skills	None.
Safety precautions	None.
Waste	
Amount and type	None.
Intervention costs	
Operator time	Labour for implementing option.
Factors influencing costs	Size of areas(s) where access is restricted. Type of area(s) where access is restricted - the costs of restricting access to a highly populated area will be different to restricting access to a rural area or recreational land. Possible need to regulate access prohibition in some areas.
Side effects	
Environmental impact	None
Social impact	Loss of public amenities. Changed perception of the countryside / other recreational areas. Living adjacent to areas that are known to be contaminated, even if access is restricted, can have a negative psychological impact.
Practical experience	In the former Soviet Union after the Chernobyl incident. In Japan after the Fukushima accident. In the UK as a consequence of foot and mouth disease.

8 Surface removal (indoor)	
Objective	To reduce inhalation and external doses arising from contamination on indoor surfaces of buildings (primarily floors, walls and ceilings) within inhabited areas.
Other benefits	Will remove contamination from indoor surfaces in buildings.
Remedial action description	If water-based cleaning is not suitable, some form of surface removal may be required on indoor surfaces. Although some internal floors and walls with large area hard surfaces may be robust enough to withstand more aggressive techniques, in general internal surfaces will require gentler treatments, such as those described below. Measures to prevent the generation of dusts or liquid wastes should be used as there may be difficulty in arranging ventilation/liquid run-off collection in indoor environments. Wooden or metal surfaces: can be treated using sandpaper, power sanders, or steam cleaners. Paint: can be removed using paint strippers or hot air guns. Alternatively, commercial sanders can be used though this is likely to produce a lot of dust. Plaster: can be removed using long-reach pneumatic chisels. Wallpaper: can be removed by manual scraping or using steam strippers. Linoleum and carpet: if not stuck to floors can be manually removed relatively easily. Linoleum tiles stuck to concrete floors may require machinery to remove. For tiles stuck to hardboard, removal involves removing both the hardboard and tiles together by removing the pins and pulling the hardboard away from the floor. Wooden floors: are removed by prising the floorboards from the cross joints which are then themselves removed using saws. Concrete: A number of techniques can be used on concrete.
Target	Indoor surfaces of buildings.
Targeted radionuclides	All radionuclides.
Scale of application	Small areas of indoor surfaces in all types of building.
Time of application	Short – long term. Maximum benefit if carried out soon after contamination.
Constraints	
Legal constraints	Liabilities for possible damage to property. Ownership and access to property. Use in listed or other historic buildings and on precious objects.
Environmental constraints	None.
Effectiveness	
Reduction in contamination on the surface	If carried out carefully, these removal processes can remove virtually all the contamination on the surface. However, the process of removing paper, paint or plaster may result in the spread of contamination on to other surfaces via dust.
Reduction in surface dose rates	External dose rate can be significantly reduced but depends on how much activity is removed?
Reduction in resuspension	No estimates made, but likely to be minimal as the contamination is embedded in surfaces.
Technical factors influencing effectiveness	Type and condition of surface. Timing of operation. In general, the longer the time between contamination and implementation, the less effective it will be). However, there are cases where contamination has only penetrated a few mm over decades. Whether any cleaning has already been undertaken.
Social factors influencing effectiveness	Negative impact of walls without paint and wallpaper and possible damage to walls and floors.
Feasibility	
Equipment	Scrapers. Sandpaper, power sanders with suitable extract and filter. Steam strippers. Pneumatic chisels. Removing lino tiles from concrete: machine (long reach scaler) to remove tiles stuck to concrete floors. Saws for removing wooden floors. Brooms and dustpans for collecting debris. Bags or containers for waste. Transport vehicles for equipment and waste.

8 Surface removal (indoor)

Utilities and infrastructure	Mains electricity supply. Water supply.
Consumables	Water and detergent.
Skills	Only a little instruction is likely to be required.
Safety precautions	Gloves and overalls. Waterproof clothing may be required. Personal protective equipment (PPE) may be required under dusty conditions to reduce the hazard from resuspension.

Waste

Amount and type

Surface removed	Amount (kg m^{-2} solid waste)	Type
Wallpaper	1.0	Wallpaper
Paint	1.0	Paint and plaster dust
Plaster	$1\ 10^{1}$	Plaster
Carpet	$4\ 10^{-1}$	Carpet
Linoleum/linoleum tiles (laid on concrete)	4	Tiles and hardboard
Wood floor	7	Wood

Any water resulting from steam stripping will not be collected and so floor surfaces will need to be covered and covering disposed of.

Disposal will be subject to conditions depending on the activity levels and other properties of the waste.

Intervention costs

Operator time

Surface removed	Work rate ($m^2\ h^{-1}$ $team^{-1}$)
Wallpaper	60 (scraping) 230 (scraping and peeling) 400 (peeling)
Paint	5 (walls); 4 (ceilings)
Plaster	25 (walls and ceilings)
Carpet	100
Linoleum	80
Linoleum tiles (laid on concrete)	20
Linoleum tiles (laid on wood)	200
Wood floor	3

Factors influencing costs	Type of equipment used. Thickness of surface covering/layers of wallpaper and/or paint.

Side effects

Environmental impact	None as long as proper disposal routes are used.
Social impact	Possible damage to building surfaces. Positive benefit of cleaning houses.
Practical experience	Paint stripping carried out as part of decontamination following the incident in Goiania.

9 Surface or total removal and replacement (roads)		
Objective	To reduce inhalation and external doses from contamination on roads, paved and other outdoor areas with hard surfaces within inhabited areas. Removal of contamination from roads and paved areas.	
Other benefits		
Remedial action description	The most common forms of hard outdoor surfaces will be tarmac or concrete slabs. Standard machinery to remove asphalt surfaces is available in different sizes. They have a rotating drum with cutting teeth which conveys planed material (about 40 mm thick) to the middle of drum where it is pushed on to a conveyor belt and from there to a flatbed truck. If the machines do not have brushes for debris collection these must be added, or manual sweeping carried out. Water is sprayed continuously on to the drum to suppress dust. Typical highway maintenance machinery can remove a width of about 2 m per pass. A small excavator/bobcat can be used to remove concrete slabs. Concrete slabs are replaced by hand. Replacing/resurfacing asphalt and concrete roads can be undertaken using standard equipment. For replacement in small areas, manual methods are likely to be used, ie tarmac is deposited in several places and spread by shovel and rake, then tamped. The need to resurface asphalt and concrete surfaces will depend on the depth removed and other factors, such as acceptability. The area can be repaved with hot rolled asphalt or concrete paving machine to relay concrete. This option is likely to give rise to dust, so application of water to dampen the surface or the use of a tie-down material is recommended prior to implementation to limit resuspension.	
Target	Hard outdoor surfaces (roads, pavements, paths, playgrounds etc.)	
Targeted radionuclides	All long-lived radionuclides.	
Scale of application	Theoretically any sized road or paved area. However, use of large equipment may not be appropriate if treating small areas.	
Time of application	Short – long term. Maximum benefit if carried out soon after contamination.	
Constraints		
Legal constraints	Liabilities for possible damage to property. Ownership and access to property. Use in conservation areas or at listed sites – restricted access will be required during remediation.	
Environmental constraints	If the surface of the road is cambered the removal depth will not be uniform.	
Effectiveness		
Reduction in contamination on the surface	A decontamination factor (DF) of up to 50 can be achieved. Decontamination work in Japan stripping the surface or shot blasting asphalt pavements and roads gave DFs of 2 - 20. If paving is removed then all activity associated with it also removed (100% effective).	
Reduction in surface dose rates	External gamma and beta dose rates above a ‘paved’ surface will be reduced by the value of the DF.	
Reduction in resuspension	Resuspended activity in air above the surface will be reduced by the value of the DF. If contamination is part of the paving material and not a surface deposit, there will not be a resuspension hazard.	
Technical factors influencing effectiveness	Evenness and condition of roads. Depth of surface removed. Ineffective removal of contamination around drains and in gutters.	
Social factors influencing effectiveness	Public acceptability of waste treatment and storage routes.	
Requirements		
Equipment	The equipment used for surface removal and replacement will depend on the size of the area being treated.	
	Small areas	Large areas
	Small scale planer; Shovel; Tamper; Wheelbarrow; Lorry.	Planer with conveyor; Paving machine; Road sweeper; Roller; JCB; Lorry
Utilities and infrastructure	Roads (transport of equipment, materials and waste).	
Consumables	Tarmac, concrete, or concrete paving slabs. Tungsten carbide teeth. Fuel and parts for equipment, generators and vehicles.	

9 Surface or total removal and replacement (roads)		
Skills	Skilled personnel essential to operate equipment.	
Safety precautions	Gloves. Safety goggles. Safety helmets. Respiratory protective equipment (RPE).	
Waste		
Amount	Asphalt: about 15 kg m^{-2} per cm depth removed. Paving slabs (concrete): about 30 kg m^{-2} per cm depth removed. Waste depends on thickness removed and density of material. Disposal will be subject to conditions depending on the activity levels and other properties of the waste.	
Type	Paving slabs, concrete and asphalt.	
Intervention costs		
Operator time	Work rate (m^2 h^{-1} $team^{-1}$)	Depending on the PPE used individuals may need to work restricted shifts. Asphalt: 4 10^2 - 1 10^3. Paving slabs (concrete): 4 – 30.
	Team size (people)	Asphalt: 2 – 4. paving slabs (concrete): 2. Team of 14 needed if road surface replaced. Team of 4 needed for paving slab replacement.
Factors influencing costs	Weather. Evenness and condition of surface (affects grinding depth). Size of area to be treated. Type of equipment used / planer size / sweeping equipment. Access. Use of personal protective equipment (PPE).	
Side effects		
Environmental impact	Road and pavement condition may be improved.	
Social impact	Disruption of access if people remain in the area. May improve road conditions.	
Practical experience	Tested on a small scale in the former Soviet Union, pre-Chernobyl tests in the USA. Following the Fukushima accident, parking lots, roads and paved surfaces were treated with high pressure water in combination with surface removal.	

10 Temporary relocation from residential areas	
Objective	To reduce external gamma and beta doses from contaminated material on surfaces and to reduce inhalation doses from material resuspended from these surfaces.
Other benefits	Remedial actions will be more easily implemented whilst the population are absent.
Remedial action description	The temporary removal of individuals from a contaminated area to reduce doses and to facilitate remediation activities. People would be moved to an uncontaminated area nearby to reduce disruption.
Target	People living in contaminated areas.
Targeted radionuclides	All radionuclides.
Scale of application	Easier to implement on a small scale.
Time of application	Short – long term.
Constraints	
Legal constraints	Access to private properties Provision of security for empty buildings.
Environmental constraints	None
Effectiveness	
Reduction in contamination on the surface	This option will not reduce contamination in the affected area. However, if people comply, this option is 100% effective at preventing all doses during the period of relocation.
Reduction in surface dose rates	
Reduction in resuspension	
Technical factors influencing effectiveness	Clear communication of need to relocate and related instructions.
Social factors influencing effectiveness	Ability to prevent subsequent unauthorised access (theft from properties). Ability to maintain normal lifestyle (work, shopping recreation). Good communications for reassuring people it is safe to return home.
Feasibility	
Equipment	Transport for moving people and possessions.
Utilities and infrastructure	Alternative accommodation / housing. Infrastructure to support relocated populations: schools, doctors, social services etc. Security services for area that has been relocated.
Consumables	Fuel and parts for vehicles and other transport.
Skills	Drivers.
Safety precautions	None.
Waste	
Amount and type	No waste produced.
Intervention costs	
Operator time	
Factors influencing costs	Number of people being relocated. Type of temporary accommodation.
Side effects	
Environmental impact	None.
Social impact	Disruption in the affected communities. Additional burden on schools, medical and recreational services, in the receiving community. When temporary relocation orders are lifted, residents may have mixed feelings of relief and worry about whether radiation levels have been lowered.
Practical experience	Relocation after flooding. Relocation after the accidents at Chernobyl and Fukushima.

11 Tie-down

Objective	To reduce inhalation doses from material resuspended from internal building surfaces, roads, paved areas, and soil/grass areas within inhabited areas in the short or long term. Also used to prevent enhanced resuspension during implementation of remedial actions that create dust.
Other benefits	May also reduce external beta doses.
Remedial action description	A number of treatments can be used, with the choice of treatment depending on the surface, the aim (long or short term protection, noting that some of the treatments listed below are temporary while others are permanent) and the size of area to be treated. Depending on the objective (long or short term tie-down) and the tie-down material used, repeated application may be necessary to maintain the integrity of the covering. Acrylic paint (e.g. Vinacryl) can be used to treat soil/grass areas. It is sprayed using a fine-mist spray gun with an airless pump to give with droplets 100 μm in diameter to ensure that radioactive particles adhere to the paint rather than being knocked off the surface. For large areas of soil/grass, the paint is applied by tractor-towed spray boom. Water can be used as a temporary tie-down measure on hard outdoor surfaces such as roads/paved areas. Spraying water on to the surface, from a sprinkler boom mounted on a vehicle, forms a meniscus between the radioactive particles and the paved surface, preventing resuspension. Water can also be used on soil/grass areas. If treating small areas of grass/soil, the area is sprayed with water using a hose connected to a hydrant. For large areas, large hose reels rotated by a water turbine are used. As the reel winds in, a spraying boom is pulled towards the reel, propelling itself over the area. When one area is complete, it is towed by tractor to the next area. Sand can be used as a temporary tie-down measure on hard outdoor surfaces such as roads/paved areas. For small areas, sand is shovelled by hand from a lorry on to the paved surface. For large areas, about 1mm of sand is sprinkled on to the paved surface using a lorry fitted with a rotary motorised sprinkler. Bitumen can be used to give permanent tie-down on hard outdoor surfaces such as roads/paved areas. For small areas, bitumen is sprayed on to the surface. A tank with a capacity of about 2000 - 3000 litres is required which can be moved by a four-wheel drive vehicle. The coating is permanent. For large areas, bitumen is sprayed on to the surface via a bulk surface-dressing machine. In both cases, if the surface is damp, a bitumen emulsion should be applied. When spraying bitumen, account should be taken of ironworks (e.g. drain covers) etc. within the surface being covered. Clean soil can be used to tie down contaminated soil in order to prevent against resuspension hazard.
Target	All surfaces.
Targeted radionuclides	Alpha emitting radionuclides. May be used for other radionuclides if conditions mean that inhalation doses from resuspended material are likely to be of concern.
Scale of application	Small – medium; there may be difficulties with treating large areas.
Time of application	Short –long term. Tie-down is effective for the period over which the integrity of the covering is maintained.
Constraints	
Legal constraints	Liabilities for possible damage to property. Ownership and access to property. Use on listed and other historic buildings and in conservation areas.
Environmental constraints	Severe cold weather, especially for tie-down with water.
Effectiveness	
Reduction in contamination on the surface	This option is not applied to decontaminate a surface. It is assumed that the decontamination factor (DF) is 1. In practice, some contamination may be removed along with the tie-down material (if it is removed). If treatment gives long-term tie-down on hard outdoor surfaces, account should be taken of the need for surface repair and access to underlying services (e.g. gas/water pipes, cables).
Reduction in surface dose rates	While the tie-down material is in place, external beta dose rates adjacent to the surface will be reduced by a factor depending on the tie-down material, its thickness and the energy of the beta emissions. This option will be more effective at reducing dose rates associated with low energy beta emissions. It is not effective at reducing external gamma dose rates adjacent to the surface.
Reduction in resuspension	While the tie-down material is in place, resuspended activity in air adjacent to the surface will be reduced by close to 100%.

11 Tie-down

Technical factors influencing effectiveness	Weather conditions. Type, evenness and condition of surface. Time of implementation: weathering will reduce contamination over time so quick implementation will improve effectiveness. Length of time tie-down material is in place. Amount of paved surface. Length of grass (for lignin and paint): shorter grass is preferable to facilitate bonding.
Social factors influencing effectiveness	None.
Feasibility	
Equipment	The equipment required depends on the surface, tie-down material, and size of area being treated. In all cases, transport vehicles for equipment are required. For external building surfaces, using acrylic paint: Airless spray pump and compressor. Access by scaffolding or fire-tender with hydraulic platform. For roads/paved areas: Water: a motorised street washer is required. Sand: a lorry, sprinkler attachment and JCB loader are required. Bitumen: a hot bitumen sprayer or cold emulsion sprayer are required. For soil/grass areas: Water: on small surface areas, a hydrant and hose are used. For large areas, a winding hose reel, pump and tractor with boom are used. Paint: on small surface areas, an airless spray pump and air compressor are used. For large areas, a tractor and boom are used.
Utilities and infrastructure	Roads for transport of equipment, materials and waste. Water supply may be required.
Consumables	Acrylic paint (e.g. Vinacryl), water, sand, hot bitumen or bitumen emulsion, or lignin may be required.
Skills	Skilled personnel essential to operate equipment. Personnel applying coatings will need to understand how the coatings will react with the application surface and also how the coatings will stand up to wear and tear and weathering.
Safety precautions	Gloves and overalls. Additional protective clothing may be required when applying paint, including respiratory protective equipment (RPE) to protect against paint spray. Water-resistant clothing recommended when using water. Gloves and overalls for applying bitumen.
Waste	
Amount and type	The amount of waste depends on the treatment used. Removed material used for temporary tie-down may be contaminated. Disposal will be subject to conditions depending on the activity levels and other properties of the waste. Monitoring would be required to determine if normal disposal routes can be used. For internal building surfaces using acrylic paint: If paint is subsequently removed: amount - 4 10^{-1} kg m^{-2}; type - paint. For roads/paved areas: Water: 3 10^{-1} litres m^{-2} water and dust Sand: 1 - 2 kg m^{-2} sand and dust Bitumen: no waste because this is a permanent tie-down option
Intervention costs	

Operator time	Surface/tie-down material	Work rate (m^2 h^{-1} $team^{-1}$)	Team size (people)
	External building surfaces/acrylic paint	1.5 10^2 - 2 10^2 (excludes setting up of scaffolding)	3 - 6 (depends on size of area, equipment used and access to surfaces)

11 Tie-down

	Roads/water	$3\ 10^4$	1
	Roads/sand	Small areas $5\ 10^2$ Large areas $1\ 10^4$	2
	Roads/bitumen	$5\ 10^2$ - $1\ 10^3$	2
	Soil or grass/ paint or water	$2\ 10^2$ - $3\ 10^3$ (depending on tie-down material and equipment used)	2
Factors influencing costs	Size of area. Type of area (affects techniques used). Topography. Type of equipment used.		
Side effects			
Environmental impact	The use of water may wash some of the contamination on to other surfaces. Chemical contamination from acrylic paint (Vinamul) migrating into soil may be an issue. Bitumen spraying on to roads may provide positive impact if road surfaces are poor.		
Social impact	Acceptability of contamination remaining in-situ. Perception of contamination of the environment with chemicals.		
Practical experience	Use of lignin on soil has been tested on a small scale (only a few m^2) in Denmark in conjunction with removal. Full scale tests on the use of lignin for dust suppression have been carried out in the USA and Sweden, where it is routinely used.		

12 Dietary advice (domestic)	
Objective	To reduce ingestion dose to consumers of domestic produce and free food by providing food safety advice on contamination levels in the produce and information on the risks
Other Benefits	Help people maintain their way of life. Enables informed choice.
Remedial action description	Provision of advice and information to allotment holders, kitchen garden producers and wild or free food gatherers on the risks associated with the consumption of contaminated produce and ways to restrict their dietary intake of radionuclides. This would include: The provision of information on activity concentrations in a range of domestically grown products and free foods The issuing of guidance on which foodstuffs can be eaten without restrictions, those which should only be consumed occasionally, and those which should be avoided completely. The provision of advice on additional remedial actions that can be carried out to either reduce contamination levels in produce or provide reassurance that produce is safe to eat.
Target	Consumers of domestic produce and gatherers of free foods.
Targeted radionuclides	All radionuclides.
Scale of application	Generally applicable to all population groups although may be most appropriate to people with a high rate of wild food or homegrown vegetable consumption.
Time of application	Short – long term.
Constraints	
Legal constraints	None
Social constraints	None
Environmental constraints	N/A
Effectiveness	
Remedial action effectiveness	Compliance with the recommendation of avoidance of certain foodstuffs would be 100% effective. Washing has been shown to remove between 10% and 90% of a range of radionuclides (including Ru, I, Sr, Cs, Am, Pu) from vegetables and fruits. Strawberries are an exception. Peeling is a very effective way of reducing the activity levels of insoluble radionuclides such as plutonium and americium (removing between 10 and 100% of the activity) in root vegetables and is also effective for radiocaesium (up to 80% but as little as 2%) and radiostrontium (50-90%).
Factors influencing effectiveness of procedure	Foodstuffs and methods of preparation. Willingness of affected population to accept this type of intervention, and the extent to which advice is used (possible language and literacy issues). This may depend on the extent to which the food has a cultural and economic significance in the population.
Feasibility	
Required specific equipment	Normal cooking utensils.
Required ancillary equipment	None
Required utilities and infrastructure	Appropriate lines of communication lines.
Required consumables	Dependent on communication method.
Required skills	Communication skills.
Required safety precautions	N/A
Other limitations	N/A
Waste	
Amount and type	There would be waste arising in situations where the advice given was to avoid eating a foodstuff.
Possible transport, treatment and storage routes	N/A
Factors influencing waste issues	N/A
Intervention costs	
Equipment	N/A
Consumables	Dependent on communication method, e.g. printing and distributing leaflets.

12 Dietary advice (domestic)	
Operator time	The time used for providing information, advice and guidance will depend on the communication method (press releases, television interviews, public meetings, face to face meetings, magazine articles, letters, leaflets, internet and social media, telephone).
Factors influencing costs	Scale of contamination.
Waste costs	N/A
Assumptions	None.
Communication needs	Dialogue and dissemination of information about the remedial action (its rationale and possible alternatives) within affected communities.
Side effect evaluation	
Environmental impact	None
Agricultural impact	None.
Social impact	Changed perception of natural resources because of feeling that they are damaged or polluted. Potential loss of home produce may have the most negative impact on poorer population groups.
Other side effects	Improves personal control and ability to make informed choices.
Practical experience	Used in Western Europe (especially Scandinavia) and the former Soviet Union after the Chernobyl accident. Proven to be a cheap and effective remedial action, if people are willing to follow the advice.

13 Live monitoring	
Objective	To determine whether activity concentration in animals are below Maximum Permitted Levels (MPLs).
Other benefits	Reassurance.
Remedial action description	Live monitoring can establish the contamination level of gamma-emitters in animals before slaughtering and can be used to confirm that MPLs are not exceeded in livestock destined for the food chain. Live monitoring of animals may be carried out on the farm and also at slaughterhouses. A rapid, simple, inexpensive and effective method of monitoring contamination for gamma-emitting radionuclides is to use a portable, preferably lead-shielded, NaI detector, linked to (or with integral) single or multi-channel analysers. If the activity concentration is above the MPL for animals on the farm, other remedial actions such as selective grazing can then be used to lower the activity concentration before slaughter. The practice of live monitoring will thus reduce the need for meat condemnation.
Target	Meat-producing livestock (e.g. cattle, sheep, goats)
Targeted radionuclides	Known applicability: ^{134}Cs, ^{137}Cs Probable applicability: ^{226}Ra, Not applicable: Radionuclides with no effective photon emissions (ie beta and alpha emitters) and radionuclides with low photon energies (e.g. ^{235}U, ^{238}Pu, ^{239}Pu and ^{241}Am).
Scale of application	Large scale when monitors are available.
Contamination pathway	N/A
Time of application	Early to long term. At times when livestock are being moved from a contaminated area, just before slaughter or to design remedial action strategies.
Constraints	
Legal constraints	Meat intended for human consumption is subject to Maximum Permitted Levels.
Social constraints	Resistance by farmer or herder.
Environmental constraints	None.
Effectiveness	
Remedial action effectiveness	Can be highly effective (near 100%) at excluding meat above MPL from food chain.
Factors influencing effectiveness of procedure	Accuracy of monitoring result will be influenced by the equipment and techniques being used. Effectiveness can be maintained by including an uncertainty margin into the estimated radionuclide concentration at which animals are rejected for entry into the food chain (see radiocaesium below). Radiocaesium Accuracy of calibration and detector type; uncertainty on measurement may mean that a rejection level much below the intervention limit is used (e.g. in the UK where the post Chernobyl intervention level for radiocaesium is 1000 Bq kg^{-1} sheep with a lower estimated activity concentration, based on the type and age of the monitor used (for example 645 Bq ^{137}Cs kg^{-1}) were not allowed to enter the human food chain as a consequence of detector uncertainty). Adequate shielding of monitors is preferable to avoid impractically high background counts in highly contaminated areas or areas with high natural background. Consideration of the monitoring environment (for example, proximity of stone walls). Duration of counting time. Weather conditions - equipment needs to be weatherproof (ie resistant to low temperatures (potentially to -20ºC), snow etc. under field conditions); rapid temperature shocks to the detector should be avoided. Other radionuclides. While in theory live monitoring may be possible for all gamma-emitting radionuclides with energy sufficiently high to detect there is little field experience of trying to determine levels in meat for radionuclides other than Cs. The following may be problematic or need consideration: Mixed deposits would present problems if using NaI detectors (especially single channel analysers). Variation in the size of animals monitored due to the age and breed. Difficulty in keeping animals still during monitoring can lead to erroneous readings.

13 Live monitoring

Feasibility	
Required specific equipment	Portable, preferably lead-shielded, NaI detector linked to single- or multi-channel analyser with battery supply - calibrated for animals being monitored. Detector and analyser should preferably be as weatherproof as possible.
Required ancillary equipment	Restraints for livestock (e.g. cattle crush) will be required while monitoring some animals.
Required utilities and infrastructure	Suitable penned area to contain livestock before monitoring. Good administrative support.
Required consumables	Paint and ear tags to mark failed animals, or alternative identification method.
Required skills	Monitoring would be carried out by trained personnel. Animal handling experience or training would also be preferred. Ideally, the team would consist of two people with the farmer providing assistance (catching animals etc.). More people may be required if the animals are large (e.g.cattle).
Required safety precautions	General precautions for animal handling.
Other limitations	Availability of NaI detectors may be limited. Similarly, there may be a shortage of trained personnel. Consider time required to carry out training. These limitations mean that this measure is largely a mid to long term measure.
Waste	
Amount and type	None.
Possible transport, treatment and storage routes	N/A.
Factors influencing waste issues	N/A.
Intervention costs	
Equipment	Portable, preferably lead-shielded and weatherproof, NaI detector linked to single- or multi-channel analysers.
Consumables	Fuel for monitoring vehicles. Running costs for repairs and maintenance of detectors. Appropriate animals to calibrate detector.
Operator time	Work rates should take into account: travel time to or from an area and between farms. Time required to set up equipment, including taking background readings. Time required to monitor livestock. Number of staff per team.
Factors influencing costs	Margin of uncertainty associated with the live monitor estimate. Distances to farms or herds. Numbers of animals. Duration of the restrictions.
Compensation costs	Farmers: For assisting during monitoring and for unmarketable livestock because activity concentrations in the meat are in excess of the Maximum Permissible Levels.
Waste costs	None.
Assumptions	None.
Communication needs	Dialogue with farmer or herders. Farmer or herder and buyers of animals need to be aware of the implications of the measurement data, particularly for those animals exceeding MPLs. Possible requirement for labelling products that have been subject to live monitoring.
Side effect evaluation	
Environmental impact	None.
Agricultural impact	No direct impact other than a disruption to normal practice. However, a monitoring result in excess of the MPL (with any associated uncertainty) may result in slaughter or sale times being delayed until activity concentrations fall below the MPL. This represents a loss of flexibility in marketing practice and may also result in the production of overfat animals.
Social impact	Depending upon results, the remedial action could be either reassuring or concerning for the farmer or herder.

13 Live monitoring	
	May impact on public confidence e.g.: Increased confidence that the problem of contamination is being effectively managed; Loss of confidence that farm produce and derivative products from affected areas is 'safe' (may result in loss of employment in local industries or growth of a black market).
Other side effects	Information on activity levels in livestock and how this changes between years.
Practical experience	Used in Norway (from 1987 until present, 2014) and the UK (from 1986 until 2012) for monitoring sheep from Chernobyl in restricted areas. Soon after the Chernobyl accident also used for monitoring cattle and goats in Norway. Used in Norway (from 1987) and Sweden (from 1988) until present (2014) to monitor reindeer from Chernobyl restricted areas. Used in Ireland and Sweden to monitor carcasses at slaughterhouses, following Chernobyl accident. Used in Spain after the incident at Palomares, involving a collision with an American B-52 carrying four thermonuclear bombs.

14 Restrict entry into the food chain

Objective	To remove food containing radionuclides in excess of Maximum Permitted Levels (MPLs), from the food chain, thereby reducing ingestion doses
Other benefits	Maintenance of confidence in food products.
Remedial action description	Milk, meat, and crops, and processed products made from them, with activity concentrations in excess of the MPL may be withheld or withdrawn from sale. This removes contaminated food from the market but can leave large quantities of waste needing disposal.
Target	Predominantly milk, meat and crops (cereals, fruit and vegetables) but may also be applicable to eggs, honey, freshwater or marine fish. Also derived products from processing of these foodstuffs.
Targeted radionuclides	All radionuclides.
Scale of application	Large scale.
Time of application	Early to long term. This option should be considered as soon as a risk is recognised.
Constraints	
Legal constraints	MPLs are legally binding for marketed foodstuffs.
Social constraints	None
Environmental constraints	The fate of unfit foodstuffs must be considered when food restrictions are introduced.
Effectiveness	
	Highly effective (up to 100%) at removing commercially produced food that is contaminated above the MPL from food chain. Food contaminated below the MPL still enters the food chain.
Factors influencing effectiveness of procedure	Compliance. Timing and mode of implementation of the restriction
Feasibility	
Required specific equipment	The equipment required would depend upon the radionuclide. Food restrictions, which could be applied on any food where contamination is suspected, would be accompanied by measurement of radionuclide contamination in consignments of foodstuffs produced for commercial distribution. The measurement programme would also demonstrate that the restrictions are working.
Required ancillary equipment	None.
Required utilities and infrastructure	Extensive monitoring and surveillance programme.
Required consumables	None.
Required skills	Personnel will be required to enforce the restrictions.
Required safety precautions	None.
Other limitations	None.
Waste	
Amount and type	Foodstuffs e.g. milk, meat, eggs and crops.
Factors influencing waste issues	Area under restrictions and duration of restrictions. Acceptability of, and compliance with, waste disposal practice. Local availability of suitable disposal routes.
Intervention costs	
Equipment	Appropriate monitoring equipment to determine multiple radionuclides. Vehicles and equipment for collecting contaminated foodstuffs
Consumables	Fuel and parts for vehicles.
Operator time	That associated with enforcement.
Factors influencing costs	Time and distances involved in travelling to areas under restrictions for monitoring purposes.
Compensation costs	Farmer: for restricted products (unless landowner is liable for the contamination).
Waste cost	Dependent on subsequent disposal route selected for unfit foodstuffs and quantities of waste produced.
Assumptions	None.
Communication needs	Stakeholder dialogue will be essential. Good communication with members of public is essential to prevent alarm within communities.

14 Restrict entry into the food chain	
Side effect evaluation	
Environmental impact	None, although likely to be indirect environmental impacts depending on disposal route chosen for unfit foodstuffs.
Agricultural impact	If there are delays in re-stocking land, under-grazing of pasture could be a problem when animals return.
Social impact	Policing the remedial action and averting growth of a black market. Stigma associated with areas where restrictions have been applied. Perceived contamination of all food products (and loss of confidence in crops, dairy, and meat).
Other side effects	None.
Practical experience	Following the Fukushima accident, the Japanese government stopped the distribution and sale of contaminated food from Fukushima prefecture and surrounding areas.

15 Restrictions on foraging (gathering wild foods)	
Objective	To reduce consumption of contaminated self-gathered wild or free foods
Other benefits	Reduce the time people spend in contaminated area
Remedial action description	Restrictions on gathering of wild or free food products such as game, nuts, mushrooms, honey, fruits and berries will reduce dose to those consuming these foodstuffs. The major foodstuffs contributing to dose will be those which have the highest concentrations of the radionuclides and/or which are eaten in large quantities. For example, although consumed in relatively small quantities, wild mushrooms and berries are known to most readily concentrate radioactivity (particularly ^{137}Cs). Certain groups may be exposed to higher doses than others due to their dietary, social and other habits.
Target	People who gather and/or consume wild foods. Foodstuffs such as fruits, berries, herbs, edible flowers, aquatic plants, nuts, mushrooms and game.
Targeted radionuclides	All.
Scale of application	Large scale.
Time of application	Early to long term.
Constraints	
Legal constraints	None.
Social constraints	Likely to be met with strong resistance from local populations for whom collection of wild food has a cultural and economic significance.
Environmental constraints	N/A
Effectiveness	
Remedial action effectiveness	Effectiveness will be 100% if restrictions are complied with. Most effective if gatherers and locations of wild or free foods are known in community.
Factors influencing effectiveness of procedure	Success of communicating the restrictions to gatherers. Availability of other sources of free foods. Individual willingness to submit to restrictions, particularly over long time periods.
Feasibility	
Required specific equipment	Signage, information boards, leaflets.
Required ancillary equipment	Monitoring equipment for authorities to regularly check level of contamination in wild or free foods.
Required utilities and infrastructure	Communication lines to inform those about restriction and 'policing' to ensure compliance.
Required consumables	Dependent on communication method (e.g. leaflets and signage).
Required skills	Communication skills.
Required safety precautions	N/A
Other limitations	None.
Waste	
Amount and type	N/A
Possible transport, treatment and storage routes	N/A
Factors influencing waste issues	N/A
Intervention costs	
Equipment	Signage, information boards, leaflets. Monitoring equipment.
Consumables	Production of leaflets circulated to gatherers via local groups. Production and erection of signs in areas known to be used by gatherers (similar to Foot and Mouth Disease procedures). Information and advice distributed via specialist associations or societies i.e. ramblers.
Operator time	Time associated with policing the restrictions. Time associated with the erection of signs in areas known to be used by gatherers. Time associated with distribution of leaflets circulated to gatherers.
Factors influencing costs	Degree of policing and monitoring required.
Compensation costs	There may be commercial enterprises affected by the restrictions - collection of some wild foodstuffs is conducted at a commercial scale.

15 Restrictions on foraging (gathering wild foods)	
Waste costs	N/A
Assumptions	None.
Communication needs	Public and stakeholder dialogue and dissemination of information about the restrictions (their rationale and possible alternatives) within affected communities, as part of a wider communication and information strategy. Need for update of information as data becomes available.
Side effect evaluation	
Environmental impact	Possible positive ecological effects e.g. increase in game population if hunting or fishing declines, or greater numbers or diversity if cessation of large-scale fungi or berry collections, conservation of habitats and increased nutrient availability resulting from increased decomposition. Possible negative ecological effects and animal welfare issues include change in ecological equilibrium, lack of animal foodstuffs due to increased competition for game.
Agricultural impact	Possible increased utilisation of agricultural grasslands or crops by ‘uncontrolled’ game species.
Social impact	Stigma associated with restricted area. Disruption to people’s image of countryside as ‘natural’. Negative social and psychological impacts caused by, for example, the loss of traditional activities and loss of cheap food sources. The willingness of affected populations to observe restrictions will change over long time periods. Experience has shown that restrictions such as harvesting of wild foods can result in significant negative social consequences and consequently advice from the authorities to the general public may be ignored.
Other side effects	Replacement foods may be required.
Practical experience	Restrictions enforced in Belarus following the Chernobyl accident. Restricted harvesting of food by the public in forest areas was successfully implemented in Japan following the Fukushima accident.

16 Select alternative land use

Objective	To allow agricultural land to be used for productive activities by selecting crops or animals for the production of non-edible products.
Other benefits	Keeps land in production and provides income to farmer.
Remedial action description	Contaminated land may be used for non-food production, such as flax for fibre; rapeseed for bio-diesel; sugar beet for bio-ethanol; perennial grasses or coppice for biofuel. Agricultural land may also be used for the production of leather and wool. In extreme situations land may be used for forestry or given over to recreational use (e.g. golf courses).
Target	Farmland used for crops (e.g. cereals, fruit and vegetables) and livestock (milk, meat and egg production).
Targeted radionuclides	Known applicability: ^{134}Cs, ^{137}Cs Probable applicability: ^{90}Sr, ^{226}Ra Not applicable: Low soil-to-plant or feed-to-meat/milk transfer makes radical remedial actions unnecessary (i.e not applicable to radionuclides that do not concentrate in foods).
Scale of application	Large.
Contamination pathway	Soil to plant. Plant to animal.
Exposure pathway pre-intervention	Ingestion of contaminated crops, meat or milk.
Time of application	Long-term.
Constraints	
Legal constraints	Change in land use may not be allowed at farms participating in Environmental Stewardship Schemes. Change of land use may require planning permit with additional restrictions.
Social constraints	Farmers, food industry or consumers resistance to remedial action. Perception that land remains contaminated.
Environmental constraints	The agricultural limitations of the affected land - this will determine the crops and practices that the land can support.
Effectiveness	
Remedial action effectiveness	This remedial action does not remove contamination but the ingestion pathway is no longer relevant since inedible crops have replaced crops grown for the food chain. The remedial action is therefore 100% effective at reducing ingestion doses, but there is still likely to be dose from external exposure from the radionuclides still present in the soil.
Factors influencing effectiveness of procedure	Expertise in growing alternative crops and supporting different livestock. Acceptability of alternative crops or livestock to farmers. Ease of substitution of non-edible crops for farmer and associated industries. Acceptability to processors and public of using contaminated crops or animal products to make non-food products. Proof for profitability of suggested production in advance of investments. Access to other food-sources.
Feasibility	
Required specific equipment	Sowing or harvesting equipment for alternative crop type.
Required ancillary equipment	None.
Required utilities and infrastructure	Processing facilities for chosen crop or animal product.
Required consumables	Seed stock of alternative crop (availability may be limited). Stock of alternative livestock. Animal feed.
Required skills	Expertise in cultivation of alternative crop or livestock.
Required safety precautions	
Other limitations	There must be a market for the new products.
Waste	
Amount and type	Depends on the non-food crop selected and production process. Contaminated by-products from for example the refining of rapeseed and sugar beet to

16 Select alternative land use	
	bio-diesel and bio-ethanol may be generated in processing plants. In the case of change to leather production, meat will need to be disposed of.
Factors influencing waste issues	Alternative crop chosen and processing required.
Intervention costs	
Equipment	Sowing or harvesting equipment for alternative crop type may not be available on farm and have to be hired.
Consumables	Seed. Livestock.
Operator time	Sowing or harvesting of alternative crop. Looking after new livestock. Transportation of crop or livestock to processing plant.
Factors influencing costs	Crop type. Livestock type. If new equipment is required. Training.
Compensation costs	Farmer (assuming the farmer isn't deemed liable for the contaminated land): For changes in land use on the farm. Requirements for additional manpower. Training and equipment. Potential less economic use of land. Processing plants: For accepting contaminated produce. Possible decontamination of equipment.
Side effect evaluation	
Environmental impact	Change in ecosystem.
Social impact	Stigma or disruption to peoples' image or perception of 'countryside'. Possible loss of confidence in products. Disruption or adjustment of farming and related industrial activities or maintenance of farming and associated communities. Alternative practices may not be as economically viable (e.g. wool and leather production versus normal animal production regimes). May impact on public confidence *e.g.*: Loss of confidence that farm produce and derivative products (e.g. cheese) from affected areas are 'safe' (may result in loss of employment in local 'cottage' industries or growth of a black market); Increased confidence that contamination is being effectively managed.
Other side effects	Markets may be limited for alternative crop or animal products. Maintains income to the farmer. In communities affected by overproduction, diversification may be advantageous.
Practical experience	Existing commercial processes.

17 Selective grazing	
Objective	To reduce activity concentrations of radionuclides in meat, milk and eggs to below Maximum Permissible Levels (MPLs).
Other benefits	Reduction in quantities of contaminated animal produce that will need to be disposed of.
Remedial action description	Livestock can be physically excluded by erection of temporary fences. It is also possible to move livestock to uncontaminated pasture (particularly those almost ready for slaughter, or dairy animals) to allow contamination levels in meat and milk to fall below MPLs at slaughter.
Target	Meat, milk and egg producing animals.
Targeted radionuclides	Known applicability: ^{137}Cs Probable applicability: ^{90}Sr Not applicable: - Low feed to meat transfer of the following radionuclides makes implementation of this remedial action unnecessary: ^{235}U, ^{238}Pu, ^{239}Pu, ^{241}Am
Scale of application	Large.
Time of application	Medium to long term.
Constraints	
Legal constraints	Depends on land status Grazing may be restricted at farms participating Environmental Stewardship Schemes.
Social constraints	Willingness of farmer to participate.
Environmental constraints	There may be restrictions on where temporary fences can be erected.
Effectiveness	
Remedial action effectiveness	Can be highly effective (up to 100%).
Factors influencing effectiveness of procedure	Initial activity concentration in animals and biological half-life of radionuclide. Availability of uncontaminated pasture nearby.
Feasibility	
Required specific equipment	Monitoring equipment to assess contamination status of land. Machinery to aid construction of fences to temporarily restrict access of animals to contaminated land.
Required ancillary equipment	Transportation of livestock to less contaminated areas.
Required utilities and infrastructure	None.
Required consumables	Fuel for transportation and construction machinery.
Required skills	Farmer should have necessary skills.
Required safety precautions	None.
Other limitations	
Waste	
Amount and type	None.
Possible transport, treatment and storage routes	None.
Factors influencing waste issues	N/A.
Intervention costs	
Equipment	Fencing.
Consumables	Fuel.
Operator time	Time to erect fencing. Time to herd animals and transport them to uncontaminated areas.
Factors influencing costs	Size of contaminated area to be fenced off. Location of uncontaminated land with respect to the contaminated farm.
Waste costs	None.
Side effects	
Environmental impact	Change in biodiversity of fenced area.
Social impact	Stigma associated to affected areas. Disruption to farming and other related activities (e.g. tourism).
Practical experience	Used widely in the former Soviet Union and also employed in Norway. Used in the uplands of UK, in combination with live monitoring to produce lamb with activity concentrations of ^{137}Cs < MPL.

Appendix B Excluded remedial actions

Table B1 Summary of the reasons remedial actions were excluded with respect to land contaminated with radioactivity

Remedial action	Reason for exclusion
Inhabited areas	
Collection of leaves	Only relevant for early phase of accidents
Control workforce access	Only relevant to urban areas (retail, offices, infrastructure)
Grass cutting and removal	Only relevant for early phase of accidents
Impose restrictions on transport	Only relevant for early phase of accidents
Manual and mechanical digging	Only relevant for surface deposits
Modify operation/cleaning of ventilation systems	Only applicable to atmospheric releases
Natural attenuation (with monitoring)	Not relevant to long lived contamination
Permanent relocation from residential areas	Doses not high enough
Pressure and fire hosing	Only relevant for early phase of accidents, before deposition becomes fixed
Roof cleaning including gutters and downpipes	Only relevant for atmospheric deposition following accidents
Snow/ice removal	Only relevant for early phase of accidents
Storage, covering, gentle cleaning of precious objects	Only relevant for early phase of accidents
Surface removal (buildings)	Deposition onto buildings not relevant
Treatment of walls with ammonium nitrate	
Treatment of waste water	Used in conjunction with pressure and firehosing – early phase
Tree and shrub pruning and removal	Only relevant for early phase of accidents
Vacuum cleaning	Only relevant for early phase of accidents
Water based cleaning	Only relevant for early phase of accidents
Food production	
Addition of AFCF to concentrate ration	Only applicable for large scale contamination with Cs
Addition of calcium to concentrate ration	Only applicable for large scale contamination with Sr. Not tested for Ra.
Addition of clay minerals to feed	Only applicable for large scale contamination with Cs
Adminster AFCF boil to ruminants	Only applicable for large scale contamination with Cs
Application of lime to soils	Only applicable for large scale contamination with Sr. Not tested for Ra.
Application of potassium fertilisers to soils	Only applicable for large scale contamination with Cs. UK soils tend to have high potassium status, so this option would not be effective
Clean feeding	Not relevant to long lived contamination
Close air intake systems at food processing plant	Only applicable pre-deposition following an accident
Clean feeding (domestic livestock)	Domestic livestock unlikely to be affected by contamination
Land improvement	Only applicable to poor quality upland pastures
Manipulation of slaughter times	Complicated to manage. Livestock products unlikely to be significantly affected by historical contamination
Natural attenuation (with monitoring)	Not applicable for long lived radionuclides
Prevent contamination of greenhouse crops	Only applicable pre-deposition following an accident
Product recall	Activity concentrations unlikely to exceed MPLs. Contamination unlikely to get into the food chain on a large scale
Protect harvested crops from contamination	Only applicable pre-deposition following an accident
Processing or storage of domestic food products	Only applicable to short-lived radionuclides
Provision of monitoring equipment (domestic produce)	Domestic products unlikely to be affected on a large scale.
Restrictions during hunting and fishing	Fish and wild animals likely to become contaminated
Skim and burial ploughing	These types of ploughs are not available in the UK
Short-term sheltering of animals	Only applicable pre-deposition following an accident

Slaughtering (culling) of livestock	Radical option. Livestock products unlikely to be significantly affected by historical contamination.
Suppression of lactation before slaughter	Carried out in conjunction with slaughtering of livestock