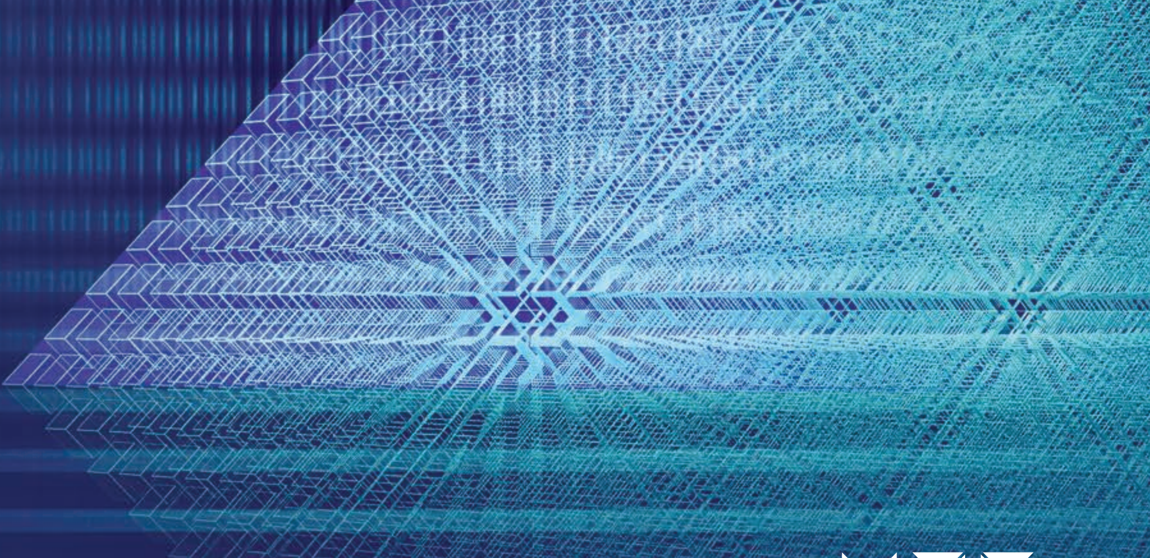


TECHNICAL REPORTS SERIES NO. 475

Guidelines for Remediation Strategies to Reduce the Radiological Consequences of Environmental Contamination

Technical Editors
S. Fesenko, B.J. Howard

IAEA
International Atomic Energy Agency

GUIDELINES FOR REMEDIATION STRATEGIES TO REDUCE THE RADIOLOGICAL CONSEQUENCES OF ENVIRONMENTAL CONTAMINATION

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHRAIN
BANGLADESH
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D’IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GUATEMALA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE’S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
THE FORMER YUGOSLAV REPUBLIC OF MACEDONIA
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VENEZUELA
VIETNAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency’s Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is “to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world’’.

TECHNICAL REPORTS SERIES No. 475

GUIDELINES FOR REMEDIATION STRATEGIES TO REDUCE THE RADIOLOGICAL CONSEQUENCES OF ENVIRONMENTAL CONTAMINATION

Technical Editors
S. FESENKO, B.J. HOWARD

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

COPYRIGHT NOTICE

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
November 2012
STI/DOC/010/475

IAEA Library Cataloguing in Publication Data

Guidelines for remediation strategies to reduce the radiological consequences of environmental contamination. — Vienna : International Atomic Energy Agency, 2012.
p. ; 24 cm. — (Technical reports series, ISSN 0074–1914 ; no. 475)
STI/DOC/010/475
ISBN 978–92–0–134110–5
Includes bibliographical references.

1. Hazardous waste site remediation — Management. 2. Nuclear power plants — Accidents — Environmental aspects. 3. Radioisotopes — Environmental aspects. I. International Atomic Energy Agency. II. Series: Technical reports series (International Atomic Energy Agency) ; 475.

IAEAL 12–00779

FOREWORD

There are many areas around the world contaminated with radioactive substances which may require remediation. The source of contamination with radionuclides varies; the most important sources include nuclear testing, radiation accidents and inadequate waste disposal practices. Contamination at such sites may present a risk to humans and the environment. Therefore, issues related to remediation of such sites are potentially of concern for both the general public and a wide variety of stakeholders.

In response to the needs of its Member States, the IAEA has published many books covering different aspects of remediation of contaminated environments. These books range from safety fundamentals and safety requirements to technical publications describing remedial technologies. Almost all of the publications on environmental remediation are related to uranium mining areas and decommissioning of nuclear facilities. IAEA radiation safety standards on remediation of contaminated environments are largely based on these two types of remediation. The exception is a publication that was a joint undertaking by the IAEA and the Food and Agriculture Organization of the United Nations (FAO) related to accidents entitled Guidelines for Agricultural Countermeasures Following an Accidental Release of Radionuclides, Technical Reports Series No. 363 (1994) (TRS 363). This publication has constituted a major source of information over many years for staff of authorities providing environmental remediation planning after accidents. TRS 363 focused mainly on agricultural management options following an accidental release of radionuclides; remedial actions for other environments and other practices were not considered.

Since the publication of TRS 363, there has been a considerable increase in relevant information. Given the importance of Chernobyl and other accidents, there have been a considerable number of IAEA activities devoted to the remediation of radiation accidents since 1994. Many lessons have been learned from experience in the implementation of remediation strategies in different affected areas, most notably in countries affected by the Chernobyl accident. Both international and national guidance publications have been produced based on this experience. The former include new International Commission on Radiological Protection recommendations, the IAEA Chernobyl Forum Report and IAEA Radiological Assessment Series reports on nuclear test sites, such as the Marshall Islands; Maralinga, Australia; Mururoa and Fangataufa, French Polynesia; and Novaya Zemlya, Russian Federation.

Given the considerable increase in knowledge and available information, the IAEA initiated the development of a new publication, which incorporated the additional information, lessons learned and subsequent changes in the regulatory framework. The book specifically collates, and summarizes recent activities relevant to remediation conducted under the auspices of the IAEA, but also refers to relevant studies conducted elsewhere. The text, thus, capitalizes on the knowledge and expertise gained by the many experts involved. In common with previous IAEA publications on remediation, much of the book is relevant for many other situations which may need to be remediated. Activities related to production of the publication were initiated within the IAEA environment programme and were then further developed with support from the FAO through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

The IAEA is grateful to all contributors and reviewers. The contribution of G. Pröhl of the Division of Radiation, Transport and Waste Safety is acknowledged. The IAEA officers responsible for this publication were S. Fesenko of the IAEA Environment Laboratories, and H. Monken of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

There are a number of sites around the world with large amounts of radionuclides present due to a variety of different events. Some of these sites were impacted by nuclear testing or radiation accidents, while others became contaminated as a result of authorized discharges or inadequate waste management and/or waste disposal practices. For some of these sites, a decision needs to be taken as to whether the site needs to be remediated. After the Chernobyl accident, remediation was carried out for a period of more than two decades. More recently, remediation strategies have had to be prepared and implemented after the accident at the Fukushima Daiichi nuclear power plant. In the past, some nuclear facilities were evaluated based on former criteria for radiation protection that were less strict than they are at present. Therefore, under current regulations, some of these contaminated sites need to be reconsidered as sites which may present a hazard to humans and the environment, and which may, therefore, require remediation. Consequently, some previously contaminated sites, which have been released for unrestricted use, are being reclassified because of recognition of the fact that there was a previous underestimation of radiation risk or an absence of relevant radiation safety regulations at the time when previous decisions were taken. The need for remediation of such contaminated sites may only be recognized after a long time period has elapsed since the use of radioactive materials for a variety of medical, industrial or research purposes.

In 1994, the IAEA published Technical Reports Series No. 363, Guidelines for Agricultural Countermeasures Following an Accidental Release of Radionuclides [1]. The publication summarized experiences on the application of remediation actions gained in the first few years after the Chernobyl accident. Over the years, the publication was used in many countries where remediation of areas contaminated with artificial radionuclides was implemented. However, since that time, many new IAEA and external publications reviewing and assessing different aspects of remediation in different areas have become available.

In recent decades, a wide range of options for remediation have been developed, tested and implemented in contaminated areas. This experience is the main source of data on the effectiveness of different remedial actions (called management options). As a result, a large amount of data on the effectiveness of management options has been generated, together with information on ancillary factors, such as the required resources and costs. The experience gained has been invaluable in quantifying the efficiency of remediation actions. In addition, prominence has been given to identifying many other factors which affect the potential use of various management options, such as environmental conditions, radionuclide properties, land use of the affected areas and response from the local population and stakeholders [2].

Remediation (or remedial action) is normally defined as any measure that may be carried out to reduce radiation exposure from existing contamination through actions applied to the contamination itself (the source) or to the exposure pathways to humans [3]. A time dependent sequence of remedial actions undertaken in an area, region or country identified for a time period where application of remediation is justified can be defined as a remediation strategy. Although the main objective of a management option within a remediation strategy is to reduce or prevent doses to humans, the provision of reassurance to consumers and people living in contaminated areas is also an important objective of remediation as it helps to maintain public confidence.

It should be recognized that both remedial actions and remediation strategies have many facets and, thus, have to be approached in a multidisciplinary way. At the beginning of the new millennium, efforts undertaken to adopt a wider perspective on the selection of countermeasures were being reported [4, 5], with more recent compilations on remediation of contaminated environments [6] and decision aiding handbooks [7] addressing and compiling important features of remediation which were rarely considered in the past.

Environmental remediation is often considered to have the goal of returning a site to the conditions that prevailed before the contamination. In practice, however, this is often not feasible, especially if vast areas are affected.

For a radiation accident, there is no definitive set time period for a transition from an emergency situation to when countermeasures are applied to an existing situation when remediation is applied. The transition is characterized by a change in management. Initial countermeasure strategies are mainly driven by urgency, with potentially high levels of exposures. Nevertheless, these strategies must take into account the long term dimension of the situation, with the possible direct involvement of the exposed individuals in their own protection [2]. In practical terms, countermeasures are applied during the period of significant deposition whereas remediation occurs when aerial concentrations have greatly declined and associated new deposition is low compared with that already present in the environment.

The data presented in the current publication are intended for use in remediation planning in areas affected by radiation accidents, radiological incidents and sites contaminated as a result of former nuclear practices, including testing of nuclear weapons. However, radioactive contamination can also be caused inadvertently by human activities involving processes in which natural radionuclides can become concentrated in areas that are not normally controlled by nuclear regulatory bodies. Such activities can include uranium and conventional mining, processing of ores and production of phosphogypsum [8, 9]. These types of activity are not considered in this report as they are the subject of a separate, planned IAEA publication on lessons learned with environmental remediation programmes. This planned publication will focus on the remediation of uranium mining and milling sites, and similar approaches will be used to describe remedial actions and decision making processes on remediation planning.

1.2. RADIATION SAFETY REQUIREMENTS RELEVANT TO REMEDIATION

For contamination resulting from past activities and accidents, the required level of remediation shall be established on a site specific basis and in accordance with radiation protection principles. For the control of exposures to the public, the IAEA's publication, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (BSS) distinguishes planned, existing and emergency exposure situations [10]. A planned exposure situation arises from the deliberate operation of a source or from the conduct of activities that result in or could result in exposure. Provision for protection and safety can be made before embarking on the activity concerned. An emergency exposure situation can arise as a result of an accident, a malicious act or another unexpected event; it requires prompt action to avoid or to reduce adverse consequences.

An existing exposure situation already exists when decisions for controlling exposures have to be taken. Those situations relate to contamination of areas by residual radioactive material arising from: (i) past activities that were never subject to regulatory control or that were subject to regulatory control but not in accordance with the requirements of currents standards; or (ii) a nuclear or radiation emergency, after an emergency exposure situation has been declared ended.

Remedial actions aiming at the reduction of exposures to the public are subject to the application of the three radiation protection principles, namely, justification, optimization and limitation. Thus, any action has to be justified, so remedial actions should do more good than harm. It has to be ensured that remedial actions are commensurate with risks and that they are expected to yield sufficient benefits to individuals and to society (including the reduction in radiation detriment) that outweigh the cost of such action and any harm or damage caused by the action.

For the control of exposure of the public, the BSS do not give dose limits, but reference levels. All reasonable steps shall be taken to prevent doses remaining above the reference levels. Reference levels are typically expressed as an annual effective dose to the representative person in the range of 1–20 mSv or other equivalent quantity, the actual value depending on the feasibility of controlling the situation and experience in managing similar situations in the past. Even if the expected exposure levels are below the reference level set by the regulatory body, all measures taken are subject to optimization to ensure that all exposures are controlled to levels that are as low as reasonably achievable (ALARA), and that economic, societal and environmental factors have been taken into account. Population groups with the highest exposure are given highest attention, in particular population groups for whom residual doses exceed the reference level. However, the optimization process is intended to provide optimized protection for all individuals subject to exposure [10].

Generally, it can be assumed that for similar ambient activity concentrations, similar mobility in the environment and physical properties (i.e. with similar energies of β particles or γ photons per disintegration), radionuclides with a longer physical half-life will have a greater overall impact on the environment than short lived radionuclides in an existing situation. This is because when the residence time of radionuclides in the environment is long, the total dose to the human population or to other species during their lifespan is greater [11]. However, even substantial releases of some radionuclides to the environment requiring radiation protection of the public do not necessarily result in the need for remedial actions because they are no longer present in substantial amounts after the emergency situation has passed. For example, short lived radioisotopes of elements, such as I, Zr, Ba and La, which may present a threat to both humans and other species in accidental or incidental situations, are only subject to short term management options [12].

1.3. OBJECTIVE

The primary objective of this report is to provide Member States and responsible organizations with information on available management options for remediation of terrestrial and freshwater ecosystems contaminated with radioactive substances. An associated objective is to provide guidelines on the formulation of sustainable remediation strategies based on the experience and lessons learned following previous severe radiation accidents and other existing situations. The report also guides readers to relevant IAEA publications providing detailed information on different aspects of remediation.

1.4. SCOPE

This report addresses the remediation of terrestrial and freshwater ecosystems, including agricultural, forest and aquatic environments contaminated with radionuclides from events such as radiation accidents, radiological incidents and former nuclear activities. Sites contaminated with natural radionuclides (such as uranium mining sites) are not in the scope of the report. The report considers only remediation strategies and management options which are relevant for existing exposure situations. Furthermore, the report focuses on remediation connected with exploitation of ecosystems to provide food entering the human food chain or products used in other parts of the economy. Therefore, management options for pre-deposition and early phases after emergencies (termed countermeasures) are out of scope and will be considered in separate publications. Remedial options for urban areas, marine and coastal environments, and for groundwater are not considered.

This report is intended for individuals and authorities dealing with remediation projects and includes an overview of the current state of knowledge on remediation planning for stakeholders of different levels of decision making. It does not provide detailed information on implementation of management options for remediation.

The report is also intended to facilitate the use of recently published IAEA radiation safety standards related to the remediation of contaminated environments [10, 13–15]. The report can also be used as background information for other relevant activities such as training in radioecology and remediation of contaminated environments.

1.5. STRUCTURE

Section 1 provides an introduction to the subject, including information on radiation safety requirements for remediation and the corresponding regulatory framework. Section 2 discusses the required characterization of the contaminated environment for remediation purposes, monitoring related issues for different stages of remediation planning and implementation of the remediation programme. Section 3 discusses the approach adopted for evaluating remediation management options. The selected management options for remediation are outlined in Section 4 with brief descriptions and evaluation, while Section 5 outlines decision aiding technologies and support to remediation planning, including examples of application of environmental decision support systems (EDSSs). Finally, Section 6 provides descriptions of examples of remediation conducted in areas affected by nuclear accidents (Chernobyl, Ukraine; Kyshtym, Russian Federation)[1] and nuclear testing (e.g. Bikini Atoll, Marshall Islands), summarizing lessons learned from the experience of remediation in each case.

2. CHARACTERIZING THE CONTAMINATED ENVIRONMENT FOR REMEDIATION PURPOSES

S. Fesenko
International Atomic Energy Agency

2.1. GENERAL ISSUES

The IAEA has previously published many books on characterization of contaminated environments and associated environmental monitoring as a tool for underpinning remediation strategies and evaluating the effectiveness of implemented remedial actions. The publications include safety requirements, safety reports and technical information on both environmental monitoring sampling and analytical techniques for determination of radionuclides in environmental samples [16, 17]. Such issues are also specifically addressed in a comprehensive overview of available knowledge and recommendations in a recently published book entitled Remediation of Contaminated Environments [6]. The purpose of this section is to provide a short introduction to this issue, referring to the relevant available literature which can provide more detail where appropriate.

2.1.1. Key stages in characterizing the contaminated environment

Decisions taken to commence remediation need to be based on an accurate assessment of the amount and extent of contamination in relevant environmental compartments and how they vary with time. Therefore, a comprehensive evaluation of the site is an essential first step in application of remediation of

---

[1] In this publication, the Belorussian Soviet Socialist Republic, the Russian Soviet Federative Socialist Republic and the Ukrainian Soviet Socialist Republic (part of the USSR until 1991) are referred to by their present country names, Belarus, the Russian Federation and Ukraine, respectively.

contaminated environments. Initial measurements made during the first detailed site survey should provide adequate information on ambient radionuclide activity concentrations to enable a decision to be made on whether a site should be remediated or not. These initial activities should be sufficient to make a preliminary assessment of the radiation risk associated with the site contamination and should, therefore, include environmental data appropriate for dose assessments. Furthermore, site characterization should also provide the data required to enable optimization of a remediation strategy and be sufficient to identify appropriate management options. A specific monitoring programme should also be developed which would eventually underpin the justification to allow a contaminated site to be used in an appropriate manner [18]. The development of such a programme commences with the determination of previous contamination and comprises a review of the history of site contamination or former nuclear activities, if relevant.

During implementation of the remediation programme, monitoring is also required to support implementation of remedial management options and provide data on their actual efficiency. It is also necessary to demonstrate the impact of different components of the remediation strategy adopted.

Finally, if monitoring indicates that remediation has been effective, a final survey (or compliance monitoring) is required to demonstrate that the overall objectives of remediation were successfully achieved [15]. It should also aim to ensure that: (i) subsequent radionuclide dispersion and migration will not have deleterious effects on the population; and (ii) the environment and the site can be returned to some form of use following remediation if possible. At this stage, compliance of residual activity concentrations of radionuclides in the environment with acceptable levels must be verified. Any areas with contamination remaining must be identified and the nature, quantity and distribution of the radioactivity determined [18].

Justification of the design of a remediation strategy and also the verification of its success, are both based on analytical data collected during site characterization and post-remediation surveys. The data should also include the environmental characteristics of the contaminated site, such as soil type, land use and topography. Data quality is critical since the collected information will influence the extent, effort and methods used for remediation and also, therefore, the related costs. Thus, analytical quality and general quality assurance principles should be an integral part of all steps within site characterization and post-remediation surveys and in the related survey planning processes. General quality assurance requirements applicable for environmental measurements are given in many international standards and guides [8, 16, 19–23].

2.1.2. Evaluating factors governing the need for remediation

The importance of the environment as a source for exposure of the population depends on site specific features of the contamination, highlighting the need for adequate pathway analysis. Specific characteristics of contamination of the environment which may trigger the need for restoration measures include [8]:

- Ambient activity concentrations of radionuclides in environmental compartments;
- Physical and chemical properties of radionuclides which may influence their mobility in the environment;
- Soil, water, plant and animal characteristics;
- Farming practices and land use.

The activity concentrations of radionuclides in environmental compartments are the most important initial criterion to identify a need for different management options on contaminated land in the first few years.

The mobility of radionuclides along both agricultural and extensive food chains, especially initially within the soil, is another important factor determining the consequences of radioactive contamination and the need for remedial actions. The relative importance of quantifying potential radionuclide mobility increases with time. The environmental behaviour and mobility of radioactive contamination, in terms of the predicted dose received by humans, depends on the composition and physicochemical form of the radionuclides present and the characteristics of the ecosystem affected by the contamination and how it is used by humans [5, 24–30].

Therefore, monitoring programmes intended for identification of the need for remediation and selection of the optimum management options should include both measurement of radionuclide activity concentrations and the chemical and physical properties of both radionuclides and soil. The information is combined with knowledge of transfer rates between environmental compartments to quantify predicted radionuclide activity concentrations in food for both humans and livestock for different impacted areas. The outcome feeds into the formulation of an optimized remediation strategy by enabling effort to be effectively targeted.

There are different types of monitoring programmes depending on both the technical approaches used (based on in situ measurements or sample based) and environmental compartments monitored. Whatever the focus of the monitoring scheme adopted (soil, plant, animal feed, etc.), the key element of monitoring for remediation purposes is to be able to reliably quantify, within appropriate models, the spatial and temporal variation in radionuclide mobility and resulting activity concentrations in foodstuffs.

2.2. IN SITU TECHNIQUES

2.2.1. In situ soil measurements

In situ soil measurements allow a large amount of measurement data to be collected rapidly. In the early period, when the situation changes from an emergency situation to an existing situation, in situ techniques enhance the rate of data acquisition, reduce early uncertainty in contamination maps and improve their accuracy in describing the spatial variation in the amount of each radionuclide deposited. If possible, in situ soil measurements should be carried out in a scanning mode with detectors in mobile laboratory vehicles, mounted on tracks or in low flying aircraft, such as helicopters. Scanning data always need to be geo-referenced to the specific location of the measured site which can be achieved by the use of techniques such as the global positioning system, microwave and ultrasonic ranging [17, 31].

The type of detectors used for monitoring depends on the objectives of the remediation and the degree to which high method sensitivity and isotopic selectivity are needed for subsequent decisions. Normally, NaI detectors with a multichannel analyser and high purity germanium gamma spectrometers are used [18]. Most alpha and beta emitters cannot be determined directly due to self-absorption, but their gamma decay products or indicator/surrogate radioisotopes can be measured instead [32].

The minimum detectable concentration of radionuclide activity of a scan survey depends on many different factors. These include: (i) the intrinsic characteristics of the detectors (efficiency, physical probe area, etc.); (ii) scan rate; and (iii) environmental factors, such as the nature of the radionuclides present (type and energy of emission) and their relative distribution in the soil (point versus distributed source, depth of contamination) [17, 32].

The total area coverage obtained using mobile and aerial monitoring can be much greater than other methods of site characterization. The detailed coverage achieved helps to improve confidence in the design of a sampling plan and may also detect unknown or buried contamination sources.

2.2.2. Live monitoring

Animal products contribute significantly to the internal dose in many existing situations and live monitoring of animals is an integral part of many remedial actions. Live monitoring of livestock is largely relevant for gamma emitters, notably radiocaesium, and it was applied extensively after the Chernobyl accident to measure in situ activity concentrations of $^{134/137}$Cs in livestock. These measurements are performed largely before slaughtering to confirm that action levels are not exceeded. If the activity concentration is above the action level, management options, such as decontamination by clean feeding, or administration of Cs binders, which reduce its absorption in the gut, can be used to lower the activity concentration before slaughter. The time period needed to do this can be assessed based on measured radionuclide activity concentrations in muscle and the corresponding radiation safety standard (action level), utilizing knowledge of biological half-lives [33]. Accordingly, the use of live monitoring reduces the need to condemn meat and provides important information on the effectiveness of options which aim to reduce contamination of animals.

Live monitoring of animals may be carried out on farms and also at slaughterhouses. A rapid, simple, inexpensive and effective method of monitoring contamination for gamma emitting radionuclides is to use a robust and portable, preferably lead shielded, NaI detector, linked to (or with integral) single or multichannel analysers [34–37]. In areas of elevated external dose, it may be necessary to ensure adequate shielding to attain sufficiently low minimum detectable levels in the detector.

2.3. SAMPLE BASED TECHNIQUES

2.3.1. Sampling strategies

The intensity of soil and other sampling should be dependent on the extent of heterogeneity of the deposition density, the complexity of the landscape and the purpose for which the data are needed. It will vary depending on the size of area considered. In general, more intensive sampling will create greater statistical confidence. However, the targeting of samples can improve the efficiency. For example, with gamma emitters, pre-screening using external dose measurements can be used to determine the intensity of sampling [17, 38]. The greater the variation, the higher the sampling intensity required. Intensive sampling or field measurements covering the whole area would give comprehensive information about the site, but such an approach is not practicable in most situations. A sampling coverage with the highest practicable and achievable resolution is recommended for sites with high contamination levels and/or a highly heterogeneous distribution of the contamination [32, 38]. However, the disadvantage of this sampling approach is the high number of samples or

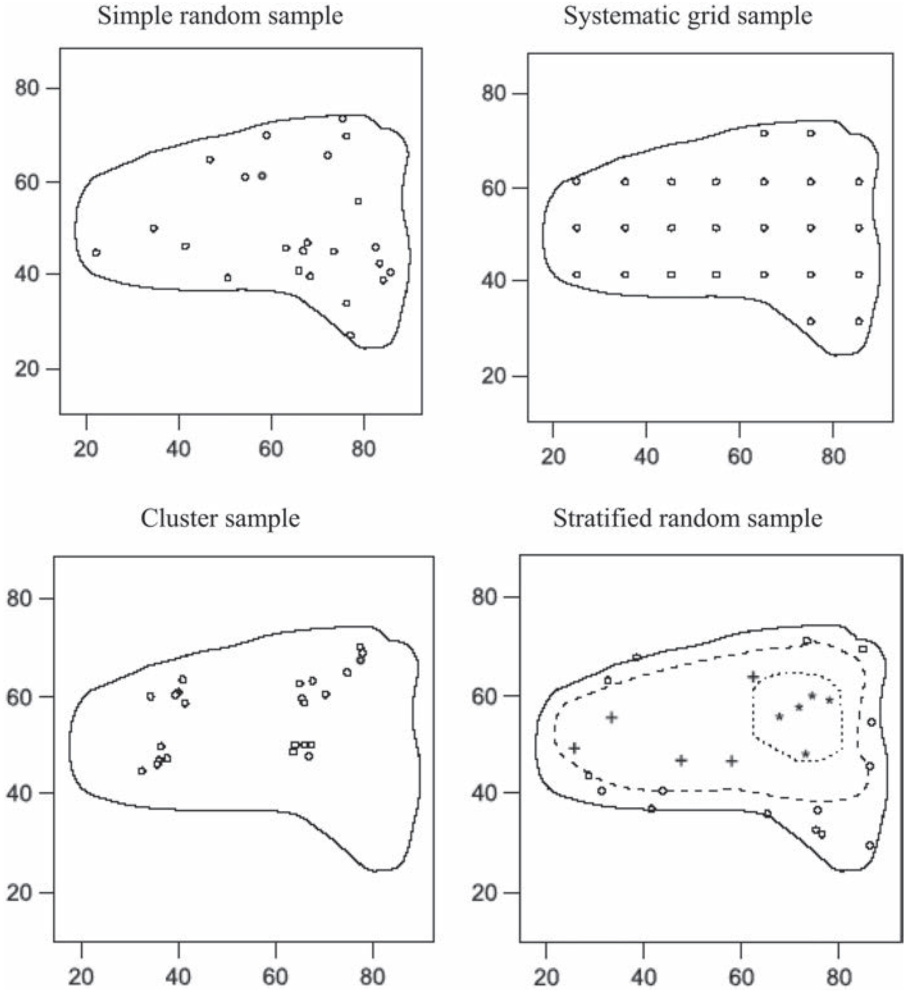


FIG. 1. Examples of possible sampling designs [38].

measurements needed to cover large contaminated areas. It may, therefore, not be feasible.

There are many different sampling strategies. Commonly adopted schemes include: simple random sampling, systematic grid sampling, cluster sampling, stratified random sampling, judgemental sampling, double sampling and two stage sampling [38]. Some of these strategies are outlined in Fig. 1.

Simple random sampling (selecting the sampling locations and distance between samples randomly) bears the risk of not detecting the highest contamination areas unless the sample density is high. It, therefore, needs appropriate statistical considerations to ensure that the required data quality objectives are met for subsequent decisions and actions.

Systematic grid sampling is based on application of a sampling grid or sampling pattern (e.g. square or triangular). This type of sampling reduces the number of samples/measurement points, but may lead to detection errors if hot particles or hot spots are present which are smaller than the defined grid size or if there are cyclical trends of a similar scale to the sampling grid.

Cluster sampling is normally used in situations where the measured determinant occurs in clusters or colonies, resulting in a high inhomogeneity of the measured determinant within a population or area. In this situation, clusters are selected randomly and all individuals within each cluster are selected and measured. The form of cluster sampling is adaptive sampling where decisions on additional sampling are made directly during the survey, when measured characteristics within a cluster are detected unexpectedly.

Stratified random sampling involves dividing areas that need to be sampled into homogeneous subgroups (strata) before sampling. Random or systematic sampling can then be used within each stratum. The use of stratified sampling can reduce sampling error and can be used to derive a weighted mean with less variability than the arithmetic mean derived from a random sampling scheme.

Judgemental sampling involves the use of professional expertise to select the sampling locations. An error in judgement would be critical if the site were highly contaminated; therefore, judgemental sampling is often only proposed for sampling areas with expected low contamination [18, 32].

Double sampling might be of value if multiple characteristics can be derived from the same samples. The technique is useful if one of the characteristics can be measured more efficiently (either easier or cheaper) compared with another characteristic, and the latter may be predicted based on the former using a known relationship. In this way, a large number of analyses can be made to measure the first characteristic and the more difficult and/or expensive analysis can be confined to a few samples. Then, the data obtained based on the more efficient techniques and the corresponding relationship can be used to estimate the distribution of the less intensively measured characteristic in all samples.

Two stage sampling is based on a definition of primary units (areas), some of which are selected randomly for further analysis. Then, samples can be taken randomly from every selected primary unit. The design can be cost effective and useful for components of variation estimation [38].

All sampling methods have advantages and disadvantages that contribute to uncertainty. It is important to be aware of them and to adapt the method used according to the prevailing situation and as more information becomes available. The intensity of sampling may increase or decrease as the specific targets and focus of remediation change with time. In the former USSR after the Chernobyl accident, the deposition density of $^{134/137}Cs$ was initially estimated using a systematic sampling grid of 10 km in 1986 and then of 1 km^2 in 1991. The frequency of the sampling grid for ^{90}Sr and plutonium isotopes was 10- and 100-fold lower, respectively, than that for ^{137}Cs. Experience in agricultural production on contaminated territory showed that detailed maps of contamination for each field were needed rather than averaged data derived from the available large scale maps. Individual field surveys, also mainly based on a systematic grid sampling strategy, were, therefore, initiated in 1987 and continued until 1993 in selected areas [12]. The improved data allowed detailed planning of the application of management options at farm level.

Once collected, the data need to be carefully analysed and presented. Geographic information systems (GISs) are important in this process, not simply for generating mapped output, but also for geostatistical analysis such as kriging. Such analysis will both interpolate sample data collected for interpretation over surrounding non-sampled areas and identify areas where there is low confidence in the estimates, and possibly target additional sample collection. These tools require considerable skill to be applied effectively and experts should be consulted early in the sampling schedule.

2.3.2. Soil

Contamination of the environment resulting in a need for remediation can occur due to sources with widely differing characteristics, and can affect surface areas from a few tens of metres to hundreds of square kilometres. These areas may include agricultural areas (arable land and pastures) or other extensive (unimproved) semi-natural regions (such as forests, uplands).

As soil and sediments are natural sinks for radionuclides, the activity concentrations of radionuclides in these environmental compartments are one of the most important criteria that need to be identified to guide the need for remediation. Although a mixture of radionuclides is often deposited in the acute phase of an emergency situation, in existing situations the radiation impact is mainly driven by a few key, usually long lived, isotopes termed ‘reference’ radionuclides. Decisions on remediation strategies can be based on the radionuclide activity concentrations of such reference radionuclides in different environments.

After the Kyshtym accident, the reference radionuclide, ^{90}Sr, determined the long term impact of contamination [39]. Agricultural land with a ^{90}Sr deposition density above 74 kBq/m^2 was excluded from economic use and different selected management options were implemented for the remaining affected areas (see Section 6.1).

Caesium-137 was, still is and will be the key dose forming radionuclide in the areas contaminated by the Chernobyl nuclear power plant accident (except for the key period during and immediately after the release when short and intermediate lived radionuclides played an important role, especially radioiodine). Strontium-90 is of some importance but only in the 30 km zone around the Chernobyl nuclear power plant, where economic activities had to be discontinued, and in a small area beyond. Therefore, evaluation of the radiological consequences of the accidental releases from the Chernobyl nuclear power plant, as well as planning and implementation of remedial actions, have been based on information on the reference radionuclide, ^{137}Cs, and consider deposition densities in the soil and the associated ecological half-lives in agricultural and semi-natural products [12].

Following the Chernobyl accident, the physical and chemical characteristics of radiocaesium varied spatially [24, 30]. Most ^{137}Cs was deposited in the form of easily soluble finely dispersed aerosols; however, coarsely dispersed particles and radioactive particles were also found in some affected areas near the nuclear power plant. The presence of $^{134/137}$Cs in the form of particles in soils resulted in the competition of two simultaneous, but opposing processes, namely an increase with time of the amount of $^{134/137}$Cs ‘available’ to plants due to the disintegration of fuel particles, and a decrease in its ‘mobility’ due to the fixation of $^{134/137}$Cs in soil. The presence of particles, distinguished by their resistance in the environment, can result in an irregular decrease of ^{137}Cs uptake by plants.

The rate of release of ‘available’ $^{134/137}$Cs from radioactive particles was strongly influenced not only by the type of particle but also by soil properties such as pH, organic matter content and clay particles. Overall, these processes resulted in distinctly longer ecological half-lives for radiocaesium transfer from soil to plant in areas with particles compared with those with aerosol types of deposition (Fig. 2). Such patterns of radionuclide behaviour in soil and the transfer of radionuclides to plants should be considered in the formulation of the remediation strategies.

Appropriate selection of soil based remedial options is always related to a consideration of soil properties as mentioned above. Therefore, the objective of soil monitoring should include a provision of coherent and well linked information on soil properties, activity concentrations and properties of radionuclides of concern. Sampling and analysis of the vertical distribution of contaminants in the ground are also necessary as baseline data for evaluation of management options, such as topsoil removal, deep ploughing, and skim and burial ploughing [12, 37].

Samples need to be taken of agricultural soil as part of a programme to study food chain pathways and evaluate management options to reduce food

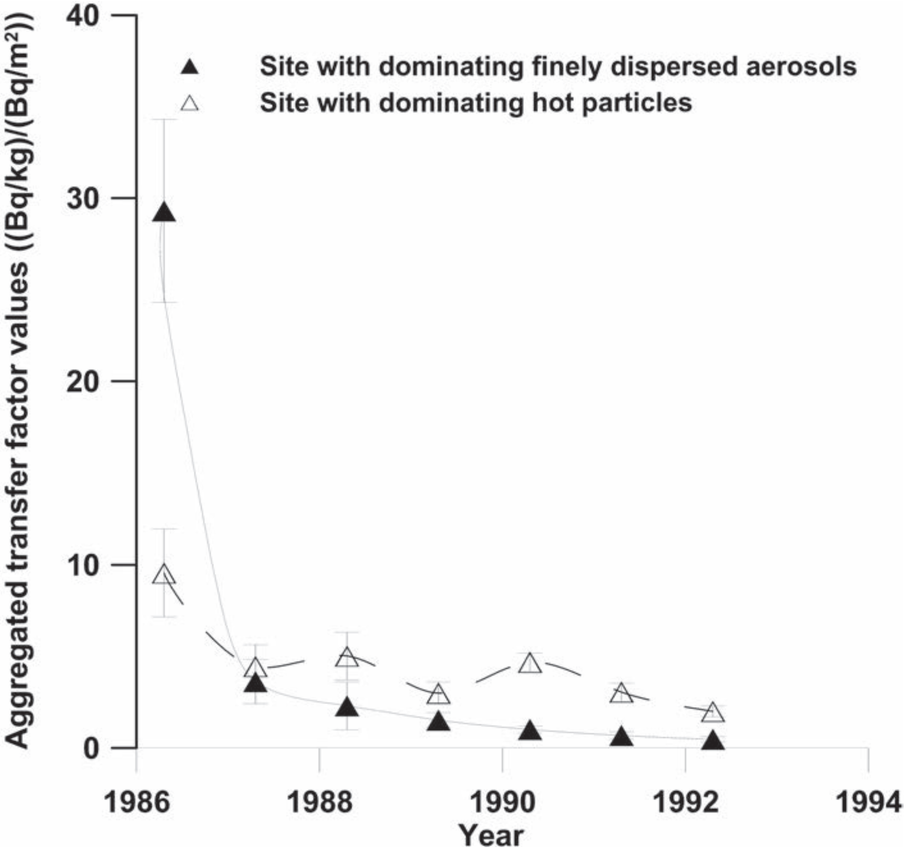


FIG. 2. Variation with time in the dynamics of ^{137}Cs transfer factors to meadow plants for different fractions of hot particles in the fallout in the 30 km zone of the Chernobyl nuclear power plant [25].

contamination. In particular, it is necessary to take samples of all plant types used for animal fodder[2], such as cereals, vegetables or grass, from the same location where soil samples were taken.

Soil sampling should be conducted in a manner which avoids cross-contamination, either between samples or between sampler and sample. Precautions should be taken, when using corers or similar devices, to ensure that surface material is not carried down the core to contaminate lower soil or

---

[2] The term ‘fodder’ here refers to plant material which has been cut and fed to livestock, whereas the term ‘forage’ is used to refer to plant material grazed by livestock.

sediment layers. Similarly, extensive distortion of the core via compression or elongation should be avoided [17].

The sampling of soils can lead to uncertainties in the final quantitative data. Therefore, precautions must be taken to ensure the quality of data generated from such samples. Appropriate information should be recorded during sampling regarding any aspect that may affect the final analytical result. Basic recommendations on procedures for the taking, storing and preparation of soil samples are given in Refs [40–44]. Recommendations on measurements of soil samples are provided in Refs [8, 19–23, 44].

2.3.3. Plants, animals and foodstuffs

The main objective of monitoring plant and animal derived food products is to determine whether radionuclide activity concentrations in food are below the action level[3], thus preventing radionuclides entering the food chain where necessary. Information on actual radionuclide activity concentrations in food, and how these levels change with time, allows priorities to be identified when formulating remediation strategies. Food samples should be collected from areas expected to have received the highest levels of contamination, be typical of the affected areas and be related to determining the exposure of any representative person [17]. The strategy to adopt for a standard method of sampling for most agricultural food products is provided in Ref. [40].

In the acute phase of an accident, above ground parts of plants are primarily contaminated by interception. Therefore, foliar uptake and monitoring of plant and related food products is an important issue during the first days and months after deposition occurs. Root uptake becomes gradually more important in the mid- to long term after deposition has ceased and remediation is then appropriate.

Sampling of plants that are typical of the diet of the representative person or agricultural animals is needed. Sampling should concentrate on the edible part of the plant and should be performed near the harvesting period. The exact location where the plant was grown (sampling in the field) should be documented, when possible in relation to soil sample points (see comment on soil sampling), not where the product was purchased (sampling from markets).

Data from plant monitoring should be directly used for identification of optimal management options because transfer rates from soil to plants can vary within several orders of magnitude, depending on plant (species and variety) and

---

[3] The ‘action level’ is the level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations [3].

soil properties. Indeed, ‘crop based’ management options are based on the selection of plants (varieties) with low accumulation of reference radionuclides. Data on plant contamination are also important to understand variation in contamination levels of animals and food, and to be able to formulate priorities in the selection of management options. Examples of guidelines on the determination of radionuclides in plant samples can be found elsewhere [45].

Sample based monitoring includes sampling of milk and muscle (meat) of animals; the latter can be supplemented by live monitoring to reduce sampling intensity if appropriate. Overall, milk is a good indicator of the extent of ^{137}Cs and ^{90}Sr contamination of animals and animal products. Less frequent sampling or monitoring of meat is required as radionuclide activity concentrations in animal muscle respond more slowly to those in the diet compared with milk.

As is the case for soil and plant samples, animal samples may also be taken as part of a programme to study the ingestion pathway and to evaluate management options to reduce food contamination. In this case, it is necessary to have corresponding information on radionuclide activity concentrations in animal fodder and forage (plants), and contamination of the soil where the feedstuffs were produced. Recommendations on the sampling of milk and milk products can be found in Ref. [46]. Information on the measurement of radionuclides in foodstuffs is given in many publications [32, 45–47].

2.3.4. Characterizing management options based on environmental data

One of the main objectives of environmental monitoring conducted while management options are being implemented is to control the efficiency of their implementation. This is because (i) there are many uncertainties in the measurements (variation in environmental conditions, quality of work carried out, etc.) and (ii) there is a need for reassurance of stakeholders that management options implemented in contaminated areas meet expectations. For most options, such monitoring involves measurements to demonstrate that remediation has reduced radionuclide activity concentrations in crops, animals or food to acceptable limits according to anticipated reduction factors which are specific for every option.

For some soil based management options involving redistribution of radionuclides in the soil profile (such as ploughing), it is necessary to confirm whether the radionuclides have then become homogenously distributed in the soil layer or have been placed at a depth in the soil where they are unavailable for root uptake. The latter would involve soil core sampling and spectrometric measurements in the laboratory of vertical sections of the sampled soil core.

Monitoring data can also be used to demonstrate when it is appropriate to cease the application of management options implemented earlier in the recovery strategy [33, 34, 37].

2.3.5. Assessing long term processes

When relatively long lived radionuclides occur in the release to the environment, the need to assess radionuclide activity concentrations in some environmental compartments (mainly soil, crops, wood, mushrooms, animals, etc.) may persist over long time periods (as occurred after the Kyshtym and Chernobyl accidents). Such demands may persist, independent of contamination levels, to provide reassurance to consumers and people living in contaminated areas [8, 12]. Therefore, long term observations are of importance in many contamination scenarios involving long lived radionuclides. Longer term monitoring is also important because radionuclide uptake to food products may increase over time, depending on the characteristics of the initial release and subsequent mobility of the contaminants in the environment [48, 49]. There could also be a requirement for long term measurement of vertical contamination profiles in soil (e.g. following ploughing procedures) to ensure and demonstrate that the more mobile radionuclides have not reached the groundwater [48].

2.4. CHARACTERIZING LAND USE AND FARMING SYSTEMS

2.4.1. Land use

Similar deposition densities of radionuclides may result in a different impact in different ecosystems depending on the radioecological sensitivity of the ecosystem in question and specific features determining radionuclide transfer in these environments [26, 29]. The radioecological sensitivity can be defined as the response of the environment to radioactive contamination in terms of radiation doses to the population or radionuclide activity concentrations in food consumed by the population or in non-human species.

One example illustrating the influence of land use on radioecological sensitivity (or vulnerability) of a contaminated environment is demonstrated from the Chernobyl affected area in Fig. 3. Some plant species take up more radiocaesium than others [33, 51, 52]. The difference in plant uptake due to variation in both soil and plant characteristics can be as great as a factor of a hundred [33, 51, 52]. Thus, the contamination of agricultural produce, and, hence, the need for remediation, depends on both the soil type and the plant

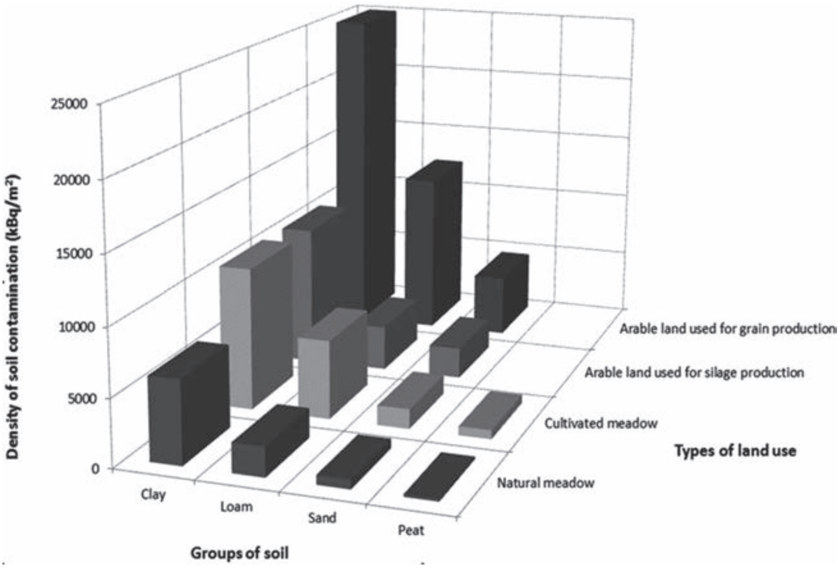


FIG. 3. Densities of soil contamination by ^{137}Cs which would result in exceeding the Chernobyl related temporary permissible levels, also called action levels, for 1994 in various products produced in the Russian Federation with different types of land use and soil groups [50].

species associated with the different types of land use. Such land use related variation needs to be considered when selecting a possible alternative land use for contaminated regions, together with any variation in action levels for different agricultural products.

2.4.2. Farming systems

Differences in rates of radionuclide transfer to plants and animals in farming systems related to both extensive and intensive agricultural systems were well recognized following the Chernobyl accident. In particular, because of the much higher application rates of mineral fertilizers, ^{137}Cs transfer to crops in some agricultural areas of western European countries was 2- to 3-fold lower than that in some former USSR countries where many soils were nutrient deficient [48]. Similarly, high productivity of domestic animals in some European and other countries with intensive agricultural systems may lead to lower ^{90}Sr and ^{137}Cs transfer to animals compared with developing countries where agriculture is less intensively managed. Such differences can result in different demands for remediation even when the deposition densities of agricultural land used for the same purposes are similar.

The feasibility of management options depends on many environmental, social and technical constraints which are specific for every farming system and community. Thus, for example, some restrictions on farms with organic status can limit application of many soil based management options, such as liming or deep ploughing. Other types of restrictions can apply on farms which are registered within some environmental protection schemes [5, 37].

Overall, the Chernobyl accident clearly demonstrated that there needs to be a careful evaluation of farming systems, with respect to several aspects including ability to: (i) justify proper monitoring programmes for remediation purposes; (ii) make a preliminary assessment of the expected effectiveness of potential management options to mitigate consequences of the contamination; and (iii) identify constraints limiting application of some management options.

3. EVALUATING REMEDIAL MANAGEMENT OPTIONS

B.J. Howard
Centre for Ecology and Hydrology
Lancaster, United Kingdom

Management options are largely designed to reduce: (i) ingestion doses from the consumption of contaminated foodstuffs and drinking water; (ii) external doses from surfaces contaminated by deposited radionuclides; and (iii) inhalation doses from resuspended material. Although inhalation of resuspended material is a potential pathway, the doses in many situations arise largely from ingestion and external doses. Therefore, remediation strategies must take account of both internal and external doses. Management options used in a remediation strategy should also be part of a sustainable approach which will allow normal agricultural and other use of contaminated areas, as well as commercial trading and social and cultural activities to continue. Such positive social and economic consequences can act as important additional benefits of remediation, in addition to dose reduction.

Remedial actions aiming at the reduction of exposures to the public are subject to the application of the three radiation protection principles: justification of practice, optimization of protection and limitation of individual doses [10]. One challenge is, therefore, to identify features of different potential management options which allow a remediation strategy to be derived that complies with each of these three criteria.

A large number of management options have been developed and applied, especially since the Chernobyl accident. From 2000, initial efforts were made in the STRATEGY project to synthesize the information on available management options for the mid- to late phases after an accident, and to critically evaluate whether they were generally applicable and useful to areas other than those in which they had been applied [5]. The data sheets developed in STRATEGY were revised during the EURANOS project with more detail provided and the scope widened to provide information representing more diverse conditions, including a wider range of radiological hazards as well as emergency situations [37].

Many factors can influence the implementation, impact and consequence of the use of various management options. Some of the most important factors to consider when selecting suitable management options for a remediation strategy for the long term recovery of contaminated areas are described below, adapted mainly from the outputs of the STRATEGY and EURANOS projects; others are considered in more detail in subsequent sections.

3.1. FACTORS AND PROCESSES AFFECTING MANAGEMENT OPTIONS

3.1.1. Temporal factors

The bioavailability of radionuclides tends to decline with time to varying extents depending on a radionuclide’s physical and chemical form, and its mobility in different soils and sediments. However, there are exceptions, such as the gradual disintegration and release of radionuclides from particles in the 30 km zone at Chernobyl [48]. Management options need to take account of variation in radionuclide activity concentrations with time in different environmental compartments, in food and in feed for animals. Changes with time in these compartments may differ between different types of ecosystem and are particularly affected by soil type for some radionuclides, such as radiocaesium, in the longer term. The effectiveness of different management options in terms of dose reduction is, therefore, dependent on timing relative to deposition. In addition, the time of application of management options will need to take into account the normal seasonal farming cycle. For example, fertilization needs to occur prior to the growing season.

3.1.2. Spatial factors

The size of the affected area, and the spatial variation in the deposition density, soil characteristics and land use type will all influence decisions on which management options will be appropriate. Adjacent, relatively unaffected areas will also need to be monitored in case there is lateral or vertical movement of radionuclides and to maintain public confidence. The rate of transfer of radionuclides between environmental compartments may vary with many factors, especially soil type. This may mean that less heavily contaminated areas with radioecologically sensitive soil types may have higher radionuclide uptake into plants. Therefore, such areas may produce more highly contaminated food products than those areas which received higher deposition [28, 29, 33, 50, 53]. After the Chernobyl accident, relatively highly contaminated food products were produced in some areas with relatively low radiocaesium deposition densities but with soil types which allow high radiocaesium uptake [50]. The development of models which use GISs, incorporating data on radionuclide deposition densities, plant uptake rates associated with soil characteristics or types, and agricultural production data, has allowed radioecologically sensitive areas to be identified [28]. Remediation strategies can, therefore, be adapted to locally varying conditions.

3.2. EVALUATING MANAGEMENT OPTIONS FOR DIFFERENT ECOSYSTEMS

3.2.1. Agricultural ecosystems (both intensive and extensive)

The agricultural food chain supplies the majority of food to most humans. Therefore, the application of management options to intensively and extensively farmed areas is a critical part of many remediation strategies. In contaminated lands used for farming, initial concerns should include external and inhalation doses to agricultural workers from contaminated fields and dust. Subsequently, management options need to be targeted to various media (soil, sediment, water) and contamination pathways from the media to crops, livestock and other animal products. The remediation strategy for agricultural systems should not only be aimed at addressing health concerns, but also a wide range of other issues, such as maintaining the local economy, promoting/upholding consumer trust and ensuring appropriate disposal of wastes [54].

Many agricultural food chain management options focus on: (i) intervention along the soil–crop pathway; (ii) application directly to agricultural animals; or (iii) intervention at the food production, processing and cooking stage. Intervention is largely, but not exclusively, aimed at reducing dose to humans. Some management options apply to both the soil–crop pathway and to agricultural animals; for example, the selection of crop varieties with low radionuclide uptake will reduce contamination in crops and in fodder for animals.

The soil crop pathway includes: (i) arable land used for the production of crops intended for the human food chain (including cereals, vegetables and horticultural crops, and fruit) and for non-food crops for industry (such as flax, bioenergy or biofuel crops); and (ii) grassland[4] used for the production of fodder crops such as hay and silage intended as feed for animal consumption. The various available management options that intervene along the soil–crop pathways can be grouped according to two main aims:

- Removing most of the contamination, usually through topsoil removal; this option also reduces external and potential inhalation doses to workers;
- Reducing soil to plant transfer of radionuclides, through a variety of techniques including various forms of ploughing and soil treatment.

If crops are too highly contaminated for direct human consumption, they can still be fed to non-dairy agricultural animals in the early stages of growth or breeding livestock (see Section 4).

Intervention in animal production systems is largely aimed at reducing the ingestion dose from meat, milk and other dairy products, offal, eggs and other foodstuffs derived from agricultural animals and game [12, 34, 55–60]. It can also be aimed at the production of non-food items such as leather and wool. The options generally involve [55–60]:

- Clean feeding and decontamination, by feeding animals with uncontaminated feed or feed with low levels of radionuclides;
- Reducing ingestion of contaminated feed by selective grazing regimes;
- Reducing gut uptake of radionuclides;
- Manipulating slaughter times to minimize the activity concentrations in animal food products, ensuring that the meat is below action levels.

---

[4] The term ‘grassland’ is used here to refer to both cultivated and uncultivated land used as either pasture for grazing animals or for growing fodder. ‘Pasture’ is used in the report when referring to land used for grazing animals. The term ‘meadow’ is used in the report for case studies in the former USSR and refers to uncultivated grassland used for grazing animals or to grow some fodder crops.

Many of the above management options for agricultural animals can be combined with live monitoring to determine whether their radionuclide activity concentration is below the action levels and/or to optimize application of these management options (see Section 4 for details).

Intervention in the food preparation and processing stage is largely focused on reducing radionuclide activity concentrations in the final product consumed.

3.2.2. Aquatic ecosystems

Aquatic ecosystems include lakes, rivers, groundwater and marine waters, each of which have contrasting hydrological and morphological characteristics, in particular the rate of flow of water into and out of the water body. The need for application of management options for aquatic ecosystems is largely dependent on site specific parameters which often severely constrain what can be done [61, 62]. Management option application in aquatic systems may be expensive, including high engineering costs, making cost–benefit analysis particularly important.

The main dose pathways for the general population from aquatic sources are from their use as drinking water supplies (which is not considered here), for irrigation and as a source of aquatic foodstuffs [63]. If contaminated lakes are used in power production or as drinking water supplies, the lake volume may alter significantly, leading to the occasional exposure of contaminated bottom sediments, enhanced external exposure and the risk of contaminated sediments becoming airborne. Due to the self-shielding of water, external doses from recreational use of contaminated lakes and rivers are often relatively low, although there may be contaminated floodland adjacent to some rivers.

In general, population doses from aquatic pathways are often lower than from terrestrial pathways, depending on food habits. A focus is, therefore, often on critical groups who gather aquatic products themselves. Intervention in aquatic systems for ingestion of aquatic species involves:

- Reducing contamination reaching the water body;
- Altering the water chemistry to reduce direct radionuclide uptake (e.g. via fish gills) and trophic transfer of radionuclides to edible aquatic species;
- Reducing consumption of contaminated feed by farmed fish.

3.2.3. Forest ecosystems

Forested areas are used by humans for forestry, grazing livestock, recreation and as sources of wild foods (such as game animals, mushrooms and berries). Dose pathways for forests may include external exposure from the forest floor and contaminated trees, handling of contaminated forestry material and industrial production using contaminated wood. Internal exposure can arise from inhalation of radionuclides following forest fires or combustion of contaminated wood [64, 65], but is more commonly due to consumption of forest foods. Some of the management options listed in Section 4 may be applicable for animals grazing in forest areas, especially those options which do not require daily handling of the animals. Other available management options include selective harvesting to avoid the most contaminated wild foods and wood, preventing fires, providing advice on use of wood ash and reducing soil–plant uptake [64, 65].

3.3. CRITERIA USED FOR EVALUATING MANAGEMENT OPTIONS

3.3.1. Effectiveness and feasibility

The effectiveness of the available techniques used to reduce radionuclide activity concentrations in agricultural products varies. Effectiveness also varies for different radionuclides as they may have different forms, biological half-lives in animals and effective half-lives in different ecosystems [5].

Effectiveness can be affected by the (i) skills of the operator, (ii) application rates, (iii) type of materials used, (iv) extent of adherence to required procedures (compliance), (v) acceptability and (vi) systems of quality control. Effectiveness is also influenced by many environmental and time related factors including: (i) when the option is applied relative to the time of deposition; (ii) the type of intensive or extensive agricultural, aquatic or forest system in which the options are applied; (iii) duration of treatments; and (iv) changes in radionuclide bioavailability with time in different soil types.

Information on effectiveness is often presented as a reduction factor [33]. Alternatively, a percentage reduction in activity concentration in the target medium (i.e. soils, crops) after implementation can be given. The latter is most often used for food treatment options and has, therefore, been used here for these options.

There are some procedures, such as live monitoring of animals, which do not directly reduce doses, but which assess the requirement for, and effectiveness of other options, and which may also provide reassurance [37]. Monitoring of foodstuffs can also be used to ensure that the food products are below the action levels.

Implementation of some management options may require specific equipment or resources which are not in normal usage in the production systems requiring remediation. Therefore, information on all of the equipment, resources and facilities required to carry out relevant management options should be evaluated to enable the formulation of an effective remediation strategy [5, 6, 37].

Given the high variability in the effectiveness of management options, it is advisable to test their impact in relevant practical conditions in contaminated areas before using them on a wide scale [5, 33, 37, 66].

3.3.2. Economic cost

Many factors influence the monetary cost of implementing management options. Direct costs are associated with implementation of the management options, such as the cost of labour, consumables, equipment, transport and waste disposal. There are other indirect costs of remediation, such as loss of production and retail sales through disruption and/or closure of businesses, loss of market share and regional impacts on tourism. Such indirect costs are often just as important as the direct costs but are more difficult to quantify, partly because they can have an impact over much broader areas and populations than the contaminated area itself [33, 37]. Conversely, some management options can have direct monetary benefits, such as maintaining or enhancing trade due to ensuring confidence in a product, or offering job or market opportunities linked to the remediation itself.

3.3.3. Waste

Waste disposal management options have been summarized in the EURANOS recovery handbook [37] and are only summarized briefly here where they are relevant for remediation. Waste disposal issues are considered, where relevant, in relevant management options described in Section 4 rather than being considered as separate management options in this report.

Several management options produce contaminated by-products and routes for their disposal must be considered, preferably before implementation. Contaminated produce that might require disposal includes food above action levels, by-products from food processing and slurry (excreta) from animals fed contaminated feed and soil. If topsoil removal is implemented, the large quantity of contaminated soil generated, even from small areas, requiring long term waste disposal is a significant challenge.

Waste treatment options that can be carried out on-site include composting, land spreading of milk and slurry, and ploughing in of contaminated feed. Off-site options include biological treatment (digestion) of milk, burial of carcasses, disposal of contaminated milk in the sea, incineration of crops, landfill, processing and storage of milk products for disposal and rendering of animal carcasses (which converts waste animal tissue into stable, value added materials).

There can often be different attitudes to whether on-site or off-site treatment is preferred, largely related to perceptions on whether a ‘dilute and disperse’ or ‘contain and concentrate’ strategy is the more justified [54].

Waste disposal schemes for contaminated waste should preferably be planned before the waste is generated, with potential disposal sites and resources identified where possible. As many specific IAEA publications consider these issues, they will not be discussed here [67–73]. The selection of suitable disposal sites needs to take account of the proximity, cost, hydrogeological characteristics of the site, geological stability and future land use.

3.3.4. Social and ethical issues

Implementation of many management options raises a variety of social and ethical issues [54, 74, 75]. The consequences of implementation of remedial actions need to be evaluated with respect to potential impacts, such as the effect on current and future generations, sustainability and the relative harm to the environment compared with benefits to humans.

If social aspects are respected, there is a greater likelihood that the implementation of remedial actions will be acceptable to both the public and operators [2, 12, 48]. Thus, the impact on both individuals and communities needs to be considered. Local stakeholders often have valuable experience that can aid in evaluation of management actions, and should be consulted in the identification of potential problems and their solution [76].

Some management options may have a negative impact on society by causing disruption (e.g. through restricting access or activities); anxiety and stress (e.g. by causing panic, upheaval); and stigma (e.g. by affecting businesses or tourism). Nevertheless, recognition of social issues can also serve to support remediation actions, for example, from the positive impacts of provision of reassurance and improvements to living conditions. Likewise, ethical aspects of management options can include: provision of self-help options that reinforce liberty and dignity; the distribution of doses over space and time, and between different members of the community; animal welfare; environmental risk and consequences for future generations [74, 75].

With respect to environmental risk, the acceptability of remediation options with the potential for changing ecosystems will be highly dependent on the ecological status of the area and the degree to which the actions diverge from usual practice. The impacts and, hence, acceptability of deep-ploughing in an intensively agricultural area will not be the same as those in a semi-natural ecosystem, even though the effectiveness of the action may be much higher for the latter situation. In most cases, environmental legislation must also be considered [12, 74].

Studies on effectiveness of remediation implementation in many areas of the former USSR affected by the Chernobyl accident have identified a variety of factors that had a highly detrimental impact on the economic and social activities in contaminated areas. Some management actions imposed a stigma on the areas with contaminated environments [48, 74]. Similar problems with consumer trust have also been observed in some European countries [74], as well as more recently in the immediate aftermath of the Fukushima accident [77]. In the former USSR, these psychosocial effects constrained or prevented export of even high quality products to unaffected areas, constrained economic and social development of those regions, and promoted migration of some of the working age population to areas with lower contamination levels. As a consequence, economies and social structures in affected communities deteriorated, accompanied by an apparent increase in poverty [48].

To avoid such negative effects, the provision of information and how that information is communicated will have a significant influence on how the authorities manage the situation, on society's response to the problem and on the overall success of the remediation strategy. Maintaining public confidence is paramount. Obviously, in an emergency situation, stakeholder engagement and the provision of information present great challenges [77] but in both emergency and non-crisis situations, the basic philosophy and principles of communication share many features [76]. Trust is easily lost and difficult to regain, so it is important to create a framework for information and communication. The engagement of stakeholders is more straightforward under non-crisis conditions, hence not respecting this is more likely to meet with criticism. The type of information disseminated should be targeted to meet a variety of needs. The form of communication should be adapted to different levels of understanding and the prevailing circumstances to address the relevant issues, and should be implemented at the same time as the development of restoration strategies.

Implementation of management options is generally the responsibility of the authorities and is carried out by designated personnel. Nevertheless, self-help implemented by the affected population can also be considered, and is often efficient and cost effective, as well as ethically robust [54]. Some of the simple management options do not require specific skills or experience (such as options involving soil treatment) and can be carried out by local people with minimal training and advice [2]. The involvement of affected persons in actions to improve their own situation can be psychologically beneficial and give a better feeling of control of the situation, which also prevents undue anxiety. Health and safety issues need to be carefully considered for people carrying out such 'self-help' options. Careful communication is needed and procedures need to be conducted with adequate supervision of individuals to ensure that they are implemented correctly.

3.3.5. Side effects

Environmental impacts occurring due to the application of management options can be positive or negative, direct or indirect. Such impacts can lead to social disruption or damage to the environment. Conversely, the impacts may even benefit ecosystems — for example, if areas become inaccessible to humans or if intensive agriculture is replaced by other land uses [78, 79].

Implementation of soil based agricultural actions can change soil properties, leading to direct environmental impacts, including changes in biodiversity, soil fertility and structure, and enhanced soil erosion. There can also be associated effects which reduce the quality of air and aquatic ecosystems. Some side effects of the application of agricultural management options can be beneficial. A good example is the increase in crop yield associated with enhanced fertilizer application. The increase in mass, apart from being of benefit to the farmer, may also dilute radionuclide activity concentrations in crops. Enhancing the productivity of grassland may also improve the conditions of livestock and the effect may be particularly pronounced in previously less intensively managed systems.

Indirect effects may be less immediately obvious and may also include human exploitation of the environment. These could include restrictions to an individual’s ability to follow their selected lifestyle. Other management options might change the landscape and its use, impacting the economic or recreation leisure value of an area [4, 33, 78–81].

Successful remediation can also include management to restore ecosystems, and secure livelihoods and the social structure of affected populations, or stabilize the economic situation [48]. For example, a study of the aftermath of Chernobyl in Norwegian farming communities found that some farmers felt that the accident had actually resulted in social benefits, by bringing communities together [82].

A good example of the diversity of potential side effects is associated with the imposition of restrictions on utilizing forests. If all access by the public is restricted or limited, major losses to the population could include a lack of: wood that can be collected for cooking, fires and other domestic and industrial purposes; berries and mushrooms; and access to forest meadows used for livestock. The cost of forestry is also increased due to limitations on the time which forest workers can spend in contaminated forests, which, in turn, can lead to deterioration in the maintenance of forests, with negative ecological consequences. Application of restrictive management options, such as limited access to forests in the areas affected by the Chernobyl accident, had negative psychological and sociological consequences. The economic losses were also large [12, 79]. On the other hand, one might argue that the forest ecosystems benefited from the absence of human exploitation [83], and provision of local counting equipment may allow the public to monitor their own food, and improve autonomy and empowerment.

For some management options, there may be an additional dose received by people who implement the management option. The magnitude of the doses received will depend on many variables, such as the type of radionuclide released, the exposure pathways (external, inhalation, ingestion, irradiation of the skin) resulting from carrying out the management options (including disposal of wastes) and the length of exposure time. Doses to implementers are controllable, so the International Commission on Radiological Protection (ICRP) principles of protection, namely justification, optimization and dose/risk limitation apply [2, 84, 85].

3.3.6. Constraints

The application of many management options can be limited by a range of factors which should be evaluated before application. The constraints can include administrative and regulatory issues, such as: (i) legal constraints; (ii) guidelines regulating the use of land and foodstuffs; (iii) environmental protection criteria; (iv) animal welfare issues; and (vi) cultural or heritage protection. Constraints can also originate from more practical factors, including the characteristics of the affected environment, which may limit the ability to apply some management options, such as soil type, slope or topography of the contaminated area [5, 37, 86].

4. MANAGEMENT OPTIONS FOR REMEDIATION

S. Fesenko
International Atomic Energy Agency

B.J. Howard
Centre for Ecology and Hydrology
Lancaster, United Kingdom

V. Kashparov
Ukrainian Institute of Agricultural Radiology
Kiev, Ukraine

N. Sanzharova
Russian Institute of Agricultural Radiology and Agroecology
Obninsk, Russian Federation

M. Vidal
University of Barcelona
Barcelona, Spain

This section focuses on the management options which have been identified, often through practical experience, to be appropriate to consider in a remediation strategy. Many of them are similar to those given in a previous IAEA publication [1], and in the RODOS [64, 80, 87], STRATEGY [5, 66] and EURANOS [7, 37] projects, but in some cases there are differences in the options considered and their content. The descriptions of the various management options given here do not aim to provide a detailed description as a comprehensive analysis of many of them has been provided elsewhere [5, 33, 34, 37, 66, 87, 88]. Instead, the descriptions give selected information, describe key issues that are relevant to the implementation of management options based on practical experience, and provide some guidance on their usefulness as part of a remediation strategy. Although it is clearly important to achieve optimal cost effectiveness, the relevance and importance of other factors, outlined in Section 3, need to be considered in evaluating whether a management option is a realistically achievable and effective procedure to adopt.

There are some aspects of the application of remediation which are generally applicable to most of the management options. They are, therefore, discussed at the start of each section where relevant. Some aspects mentioned in Section 3 that can be important for remediation are only included in the management option descriptions where relevant. Although options presented in this section were studied largely for ^{90}Sr and $^{134/137}$Cs, many of them could also be used for other radionuclides, such as ^{60}Co, ^{106}Ru, ^{110m}Ag, ^{144}Ce, $^{238–240}$Pu and ^{241}Am.

4.1. AGRICULTURAL SYSTEMS

4.1.1. Soil based management options

4.1.1.1. Basic mechanisms behind soil based management options affecting radionuclide mobility

Soils constitute the main long term reservoir of radionuclides in terrestrial ecosystems. Therefore, many of the management options used within remediation strategies to decrease the incorporation of radionuclides into the food chain are applied at the soil scale, aiming to modify the soil parameters that affect radionuclide mobility. Soil based management options can be divided into those that alter the soil structure (mechanical treatments) and those that directly modify the chemical characteristics of the soil. The application of these measures has the advantage that they are easy to implement on most farms as the necessary equipment and expertise are already present. The fundamental principles underlying the two approaches are described below.

Mechanisms related to mechanical treatments

Radionuclide migration in soil is a relatively slow process in most types of soil, and radionuclides deposited on the soil surface remain in the upper soil horizons for a long time. Mechanical treatments are intended to decrease the pool of radionuclides in the rooting zone by a dilution effect caused by mixing the contaminated topsoil layer with deeper soil layers which have a lower radionuclide content. Mechanical treatments, such as shallow, deep or skim and burial ploughing, will have the following positive effects:

- Dilution, leading to a lower radionuclide activity concentration in crops;
- Transfer of radionuclides down to a soil horizon below the crop rooting area;
- Decrease in the resuspension of contaminated soil;
- Decrease in the adhesion of contaminated soil to plants;
- Decrease of external dose.

The relative importance of each of the above varies with different radionuclides. For instance, soil adhesion on crops can account for a relatively large proportion of radionuclides associated with food crops as some radionuclides (such as plutonium) are only taken up to a small extent from soil by plant roots.

Ploughing is restricted to certain types of soil. Examples where ploughing, disking or harrowing may not be feasible include: (i) wet, dry or frozen soils where there would be damage to the soil structure; (ii) shallow soils; (iii) sandy soils which may crumble; and (iv) stony soils. Furthermore, the use of machinery may be difficult on land with steep slopes >15° [33, 37]. Ploughing may also be restricted under some environmental protection schemes intended to avoid excessive soil erosion from floodplain meadows [33]. There may, therefore, be some resistance in these areas to ploughing since the procedure can lead to changes in landscape [37]. All ploughing options will move radioactive contamination closer to the groundwater, to different extents, and, thus, there is a potential for transfer of radionuclides to other areas via groundwater [33, 34, 61]. Therefore, characteristics such as the depth of the water table and the potential extent of vertical and lateral movement of radionuclides need to be evaluated, especially for deep ploughing [37].

An important radiological issue with regard to ploughing of contaminated land is that ploughing severely complicates any subsequent attempts to remove the radioactive contamination because radionuclides are dispersed within a much greater volume of soil. Fertilization may also be required to avoid losses in soil fertility in the upper rooting zone [33, 34]. Mechanical treatments may also modify the capacity of soils to immobilize radionuclides. Particular examples include situations where the radionuclide contaminated layer is mixed with a soil layer of different mineralogical composition, or when soil loosening causes a change in the amount of sorbing surface which determines the extent of binding of radionuclides.

Mechanisms related to management options aiming at changing the chemical characteristics of soils

These management options aim at reducing radionuclide root uptake, which is often the major pathway for radionuclide soil–plant transfer. Identification of appropriate remedial management options is dependent on understanding the mechanisms governing root uptake.

The activity concentration of radionuclides in plants depends on that in the soil solution and on the ion uptake process. The concentration of radionuclides in the soil solution depends on the total concentration in the solid phase, the radionuclide solid–liquid distribution coefficient (K_d)[5] and the reversibly sorbed fraction [89]. For many radionuclides, after some time has elapsed since sorption, the reversibly sorbed fraction will be of a similar order of magnitude for soils with similar properties. Thus, the range of variation should be narrower than the range of variation of K_d for all soils and, therefore, radionuclide availability is often quantified solely in terms of K_d. The ion uptake process from soil solution to the plant includes plant physiological aspects, related to nutrient uptake and selectivity. Therefore, the soil solution–plant concentration ratio (CR_{ss})[6] is assumed to depend on the activity concentrations of radionuclide competitive species in the soil solution. Summarizing, the soil–plant concentration ratio (F_v)[7] may be described by the following relationship: $F_v = CR_{ss}/K_d$. Therefore, the F_v values decrease with increases in the K_d and/or with decreases in the CR_{ss} [89].

Regarding radiostrontium, its solid–liquid distribution coefficient (K_d(Sr)) can be predicted from the ratio of the Ca and Mg in the exchangeable complex, $(Ca + Mg)_{exch}$, versus the sum of the concentrations of Ca and Mg in the soil solution, $(Ca + Mg)_{ss}$. Other approaches to predict (K_d(Sr)) on the basis of general soil properties make use of the cation exchange capacity (CEC; in soils with a saturated exchange complex) or of the sum of exchangeable bases instead of $(Ca + Mg)_{exch}$ [89]. The Sr soil solution–plant concentration ratio (CR_{ss}(Sr)) depends inversely on $(Ca + Mg)_{ss}$. However, at high $(Ca + Mg)_{ss}$ (>6–7 mM), the CR_{ss}(Sr) remains reasonably constant. Thus, any management option leading to a direct or indirect modification of the Ca + Mg status and/or CEC provoking an increase in the K_d(Sr) and/or a decrease in the CR_{ss}(Sr) will have a beneficial effect in decreasing radiostrontium crop uptake [90].

Changes in Cs soil sorption properties are mainly connected with changes in both the radiocaesium interception potential (RIP) values and the K and NH_4^+ concentrations in the exchange complex and soil solution [91, 92]. The RIP estimates the capacity of a given soil to specifically sorb Cs and can be readily determined based on routine laboratory experiments [92, 93]. The value of RIP is related to the content of expandable clays, especially illite and other 2:1 phyllosilicates, in which frayed edge sites (FES) specifically sorb Cs. Other sites are of little relevance for Cs sorption, except for soil types in which the number of FES is relatively low (soils with a high organic matter content; mineral soils with

---

[5] The distribution coefficient is the ratio of the mass activity density (A_m in Bq/kg) of the specified solid phase (usually on a dry mass basis) to the volumetric activity density (A_v in Bq/L) of the specified liquid phase.

[6] The soil solution–plant concentration ratio, CR_{ss}, is the ratio of the radionuclide activity concentration in the plant (Bq/kg plant dry mass) to that in the soil solution (Bq/L).

[7] The concentration ratio, F_v, is the ratio of the radionuclide activity concentration in the plant (Bq/kg dry mass) to that in the soil (Bq/kg dry mass).

extremely low clay content). In such soils, the role of regular exchange sites (RES) should be taken into account [94]. To date, attempts to predict the RIP value based on soil properties have only been partially successful, because the RIP value is multivariantly dependent not only on the clay content but also on the type of clay and geological origin of the soil. However, a few correlations can be found in the literature [95–97].

The Cs solid–liquid distribution coefficient at FESs (K_d^{FES} (Cs)) accounts for most of the total Cs sorption process [94]. The K_d^{FES}(Cs) can be predicted by dividing the RIP value by the sum of K ($\mathrm{K_{ss}}$) and $\mathrm{NH_4^+}$ concentrations in the soil solution ($\mathrm{NH_{4ss}}$), with the $\mathrm{NH_{4ss}}$ multiplied by the $\mathrm{NH_4^+}$:K trace selectivity coefficient at FES ($K_C^{\mathrm{FES}}(\mathrm{NH_4/K})$) [91, 98, 99]. A total K_d(Cs) may be calculated by adding the Cs sorption in the RES (K_d^{RES}(Cs)), estimated by dividing the sum of the exchangeable K and $\mathrm{NH_4^+}$ by $(\mathrm{K} + \mathrm{NH_4^+})_{\mathrm{ss}}$.

The $\mathrm{CR_{ss}}$(Cs) varies inversely with $\mathrm{K_{ss}}$ and $\mathrm{NH_{4ss}}$. However, beyond $\mathrm{K_{ss} + NH_{4ss}}$ values higher than 0.5–1 mM, the $\mathrm{CR_{ss}}$(Cs) remains reasonably constant [90, 100]. Therefore, a major increase in $\mathrm{NH_{4ss}}$ may lead to an increase in F_v(Cs) due to the different mechanisms affecting the changes in the K_d(Cs) (the $\mathrm{NH_{4ss}}$ is multiplied by the $K_C^{\mathrm{FES}}(\mathrm{NH_4/K})$) and in the $\mathrm{CR_{ss}}$(Cs) (in which $\mathrm{NH_{4ss}}$ has the same weight as $\mathrm{K_{ss}}$) [94].

For those radionuclides that do not have competitive species in the soil solution and, thus, are not taken up by plants in a similar manner to a plant nutrient, it is more difficult to predict changes in their F_v according to differences in soil properties. However, it is generally assumed that their F_v could also depend on their K_d. The soil pH, organic matter and clay content affect the sorption and, thus, the F_v of actinides and heavy metal radionuclides [101]. Chemical speciation may also affect the K_d values of several radionuclides, since different species may have contrasting sorption behaviour [101].

Effects of general agricultural treatments on K_d and F_v: The application of potassium to soils is most effective in reducing F_v(Cs) when $K_{\mathrm{exch}} < 0.5$ meq/100 g soil, that is, for $\mathrm{K_{ss}}$ in the micromolar range (<0.5–1 mM). Over this range, additional doses of K fertilizer may have a negative effect on F_v(Cs) transfer, because the decrease in the K_d(Cs) is not compensated for by an increase in the dilution effect in the soil solution, and then in the $\mathrm{CR_{ss}}$(Cs) [90, 100].

Liming may be an effective option with respect to Cs because in soils with an optimum $\mathrm{K_{ss}}$ (over 1 mM), the F_v(Cs) may decrease due to competition between Cs and Ca + Mg for exchange sites in the apoplast of the root cortex [102]. Furthermore, the increase in $(\mathrm{Ca + Mg})_{\mathrm{ss}}$ may increase the K_d(Cs) in soils, due to the masking of RES, an expansion on clay interlayers or a decrease in the concentration of monovalent species in the soil solution [103].

Liming is relatively more important for Sr than for Cs because the application of liming to soils modifies their pH and Ca + Mg status. Besides enhancing biomass production, application of liming will decrease F_v(Sr) if it provokes a significant increase in (Ca + Mg)$_{exch}$, especially in soils with an initially low Ca + Mg concentration. The addition of liming should ensure an increase in pH to >6 for organic soils, and >7 for mineral soils, and a (Ca + Mg)$_{exch}$ of around 3 cmol$_c$/kg for sandy soils. For other soil types, the normal Ca + Mg content is usually high and application of liming would have little benefit as a potential remediation management option for Sr. This is because at high (Ca + Mg)$_{ss}$ (>6–7 mM), the CR$_{ss}$(Sr) remains reasonably constant despite further increases in the Ca + Mg concentration [90]. Indeed, a slight increase in F_v(Sr) has been observed when using high doses of liming for soils with an already high Ca + Mg status [90, 104]. This is because the increase in (Ca + Mg)$_{ss}$ would lead to a decrease in the K_d(Sr) value which, as the CR$_{ss}$(Sr) is constant, would then lead to an increase in the F_v(Sr). Therefore, doses of lime should ensure a particular (but variable) maximum (Ca + Mg)$_{exch}$ because beyond this value no effect may be anticipated. These concentrations can be deduced from the K_d(Ca + Mg) for different soils and the maximum recommended (Ca + Mg)$_{ss}$. For instance, using K_d(Ca + Mg) best estimates [96], a concentration of 6.5 mM of (Ca + Mg)$_{ss}$ leads to a value of (Ca + Mg)$_{exch}$ of about 3–4, 10 and 15 cmol/kg, for sandy, loamy and clay soils, respectively, whereas for organic soils, with a much higher K_d(Ca + Mg), the equivalent value of (Ca + Mg)$_{exch}$ would generally be within the 30–50 cmolc/kg range.

For other radionuclides (such as heavy metal radionuclides and actinides), a beneficial effect of liming can be expected due to the increase in soil pH in soils that were initially acidic.

Effects of the application of organic and mineral materials on K_d and F_v: Application of natural organic and mineral materials to soils is a standard agricultural practice in some regions. The addition of such amendments, usually applied with fertilizers, may improve the agrochemical properties of the soil, thus leading to an increase in crop yields, and it may also enhance soil sorption properties [105, 106].

The application of these sorbent materials to the soil modifies the soil solid phase which influences radionuclide uptake in two ways: (i) by increasing the sorbing capacity for radionuclides and (ii) by modifying the composition of the soil solution.

To be effective, such materials must increase the radionuclide sorption potential (or K_d) of the soils. For Sr, this can readily be achieved by increasing the CEC or the (Ca + Mg)$_{exch}$ whereas for Cs, the RIP must be increased. As only low doses of amendments can be used for an economically justifiable remediation strategy, the K_d of the target radionuclides in the amendments should exceed the normal values in soils by several orders of magnitude to have a significant effect at field level. Therefore, sorption characteristics of the materials have to be determined in the laboratory before being used in farms [107, 108]. Additionally, the final selection of materials should be based on the local/regional availability and cost [108, 109].

The addition of organic material leads to an increase in the (i) organic matter in soil, (ii) contents of nutrients and microelements, (iii) CEC and (iv) $(Ca + Mg)_{exch}$. Organic materials have been widely used to reduce the F_v of some radionuclides, such as ^{90}Sr and ^{60}Co in mineral soils [110].

The mechanical and chemical management options for soils are described below, separately for arable soils and for grasslands used for fodder production. There is, intentionally, some repetition of the most important principles described above.

4.1.1.2. Deep ploughing for arable soils

Management option description: For a fertile soil with a depth of more than 50 cm, such as peaty soils and Chernozems, an ordinary single-furrow mouldboard plough can be used to invert the top 0–45 cm of the soil profile. Much of the contamination at the surface will be buried more deeply in the vertical profile, which: (i) may reduce radionuclide uptake by plant roots depending on their specific rooting behaviour; (ii) reduce external exposure; and (iii) reduce resuspension of radionuclides and subsequent soil adhesion onto plants. Deep ploughing was used as a management option in the former USSR following both the Kyshtym and Chernobyl accidents [12]. The limited application of this option for the latter can be explained by the environmental constraints in its application, since most of the soils in the contaminated areas have a thin fertile layer.

Effectiveness: An average reduction factor for root uptake of 2- to 4-fold may be achieved from deep ploughing with a maximum reduction factor of ten [12, 33, 111–113]. The external dose may be reduced by 2- to 20-fold with the highest reduction factors achieved for complete inversion of soil [12, 33]. While observed data on the effectiveness of this measure are limited to Sr and Cs, it is reasonable to expect similar reduction factors for other radionuclides as the management option results in mechanical redistribution of the (contaminated) soil profile. To be effective, deep ploughing should only to be applied once and should not be carried out again because the buried radionuclides can then be placed higher up the soil column and in the rooting zone once more. Key factors influencing effectiveness include the efficiency of inversion of the upper layer, the radionuclide distribution within the soil profile after inversion and the rooting depths of different crops.

Side effects: Deep ploughing may substantially change the landscape. Other potential environmental effects may include long term changes in the physical characteristics of the soil and in the structure of the surface horizons, such as enhanced mineralization of organic matter and changes in nutrient status. Soil fertility may be markedly reduced, so substantial amounts of fertilization may be required for crop production. There may also be negative effects on biodiversity, particularly for soil dwelling organisms and, therefore, soil functioning, such as decomposition rates. Field drainage systems may be destroyed, leading to waterlogging [33, 37].

Social aspects: Farmers/operators require information on implementation of deep ploughing and its application: (i) for areas of land which are not normally ploughed; and (ii) when ploughing is to be undertaken at unusual times of the year. There needs to be a dialogue regarding selection of areas suitable for deep ploughing and to clarify the costs and benefits to farmers [37].

Constraints: Soil profiles must be >0.5 m deep to implement this option. The measure would not be suitable in regions with thin topsoils as soil fertility and structure would be detrimentally affected. There may be resistance to topsoil burial because of the associated impact on soil dwelling organisms, and other flora and fauna. Future restrictions on deep tilling may be imposed although subsequent normal ploughing (to a depth of ca. 25 cm) will not bring much contamination back to the surface [33, 37].

4.1.1.3. Skim and burial ploughing for arable soils

Management option description: If no plants are present, a specialist plough with two ploughshares can be used. The first ploughshare skims off a thin layer of contaminated topsoil (ca. 5 cm; but adjustable) and buries it at a depth of about 45 cm. The deeper soil layer (ca. 5–50 cm) is lifted by the second ploughshare and placed at the top without inverting the 5–45 cm horizon. Therefore, much of the contamination at the surface will be buried deeply in the soil profile. This procedure reduces both external exposure and root uptake from the contaminants, the negative effect on soil fertility which occurs in deep ploughing is minimized and resuspension is also reduced. Skim and burial ploughing were used as a management option in the former USSR following the Chernobyl and Kyshtym accidents [33, 39, 114, 115].

Effectiveness: More than a 10-fold reduction in the contamination of the upper soil layers may occur if the skim and burial ploughing is optimized according to the contaminant distribution in the soil. An associated reduction in soil to plant transfer of 10-fold and in external dose of around 20-fold may be achieved [12, 33, 39, 114, 115]. While observed data on the effectiveness of this measure are limited to Sr and Cs, it is reasonable to expect similar reduction factors for the other targeted radionuclides as the management option results in mechanical redistribution of the (contaminated) soil profile. Factors influencing effectiveness include the soil type and condition, rooting depths of different crops and radionuclide distribution within the soil profile. In particular, sandy soils are friable and may crumble during ploughing, so the inversion may be incomplete and the effectiveness reduced.

Feasibility: Sufficient skim and burial ploughs need to be available for this management option to be applied on a large scale and this may be a problem in the initial stages of remediation as these ploughs are not normally in widespread use. Any farm with ploughing capability (tractor (minimum 90 kW) and access to a skim and burial plough (which can be shared between many farms) would be able to manage this option. A suitable road network for transporting ploughs should be available. Additional instruction would be required to ensure that farmers/agricultural workers possess the necessary skills for implementation [37].

Side effects and constraints: The side effects are similar to those above for deep ploughing. In areas affected by the Chernobyl accident, the option was used on a limited scale because of similar environmental constraints to those outlined for deep ploughing (namely thin topsoils, soil fertility and detrimental effect on soil structure).

4.1.1.4. Application of lime to arable soils

Management option description: Liming of soil is part of conventional agricultural practice and has the potential to reduce plant uptake of some radionuclides. Lime ($CaCO_3$) can be applied in a variety of different forms including dolomite powder, calcareous tuffs (travertine[8]) and marlstone[9] [116–118]. The amount of lime used depends on pH and other soil properties (CEC, calcium status, granulometric composition, organic content). Lime is normally applied as an ameliorant[10] to soils with a low pH or low Ca status, but the frequency of application is determined by the soil fertility. It is normally ploughed into the soil before the planting/sowing of arable crops. If the total amount intended to be applied over a growing season exceeds 8 t/ha, then the lime is applied in two doses: half during ploughing and half during the plant growth period as this has a greater sustained impact on soil fertility [113]. The effectiveness of liming is mainly based on neutralization of soil solution acidity, displacement of hydrogen ions from the soil sorbing complex and calcium saturation in the exchangeable complex. A single

---

[8] Travertine is a terrestrial sedimentary rock formed by the precipitation of carbonate minerals from solution in groundwater and surface water.

[9] Marlstone is a calcium carbonate or lime-rich mud or mudstone which contains variable amounts of clays and aragonite.

[10] A substance added to soil to improve the growing conditions for plant roots.

(or dual) application of lime is usually effective for both radiocaesium and radiostrontium over 4–5 years if used as part of a remediation strategy. Soil liming was used widely in the former USSR for contaminated arable soils following the Chernobyl accident. The application rates recommended were 1.5- to 2-fold higher than those used normally according to need estimated by soil acidity. For comparison, in European countries (with higher levels of soil fertility compared with former USSR countries), maintenance liming normally takes place every 5 years (0.5–2 t $CaCO_3$/ha; depending on the soil pH), with the aim of reaching pH7 in mineral soils and pH6 in organic soils [119, 120].

Effectiveness: Liming may reduce ^{90}Sr and ^{137}Cs transfer to farm products by 2.0- to 4.0-fold and 1.5- to 4.0-fold, respectively, depending on factors, such as the original soil pH, CEC and calcium status, hydrological regime of the soil, productivity and type of crops [112, 113, 116–118, 121, 122]. The application of large amounts of lime reduces the content of ^{90}Sr in plants more than that of ^{137}Cs. The effectiveness is usually higher on organic soils than on mineral soils [33]. Application of lime requires lime production facilities with access to suitable materials, such as dolomite powder or marlstone, and a distribution network to distribute the lime product. Lime application in windy conditions may be difficult and respiratory protection should be considered, especially in dry areas.

Side effects: Liming can change soil nutrient status and soil microbiology, potentially leading to associated changes in flora and fauna diversity. Changes in bioavailability and mobility of nutrients and pollutants may lead to effects on water quality. There is a potential secondary negative effect on radiocaesium transfer in soils with a low potassium adsorption ratio (much higher Ca than K concentrations) and low K concentration (<0.5 mM) in the soil solution. In these cases, there may be a partial loading of Ca at the FES, leading to a lower K_d(Cs) [103]. Therefore, liming should be accompanied by K fertilization to prevent this process. Liming may induce microelement deficiencies in crops (in particular, Mn and Zn) and additional application of microfertilizer[11] may be necessary. A beneficial side effect is that liming prevents some diseases that attack crops.

Social aspects: Liming can lead to changes in ecosystem characteristics and provide potential environmental risks in terms of impact on species associated with extensively managed land.

Constraints: Liming must be restricted in farms with organic farming status or in areas which are associated with environmental protection schemes. Liming is not allowed where crops are cultivated on acid soils, such as flax. Application

---

[11] Microfertilizers are fertilizers containing microelements, i.e. chemical elements which the plant requires in microquantities.

may need to be restricted near watercourses and on floodplains because of possible transfer of lime to water bodies [37].

4.1.1.5. Application of organic materials to arable soils

Management option description: Application of organic materials is a regular agricultural practice. Organic material applied specifically to decrease radionuclide transfer to plants may be of different origins and include manure, straw and plant derived fertilizers (species such as lupin and serradella) [34, 123, 124]. Peat and sapropel may also be used as soil ameliorants [33, 87, 124]. Sapropel is formed from bottom sediments in natural lakes, and consists of plant and animal residues decomposed in anaerobic conditions. The main advantages of sapropel are a high content of organic matter (up to 70%), with a high content of humic acids and nitrogen, high CEC, the presence of mineral matter and mobile forms of nutrients [81]. However, a disadvantage of sapropel is that it may be acidic (pH4.5–6.5). Depending on the background soil acidity, this may lead to some increase in radionuclide transfer to plants [87]. Organic materials are normally applied to soils with a low organic content and of light granulometric texture. Organic fertilizers are easy to apply and increase plant production by enhancing the nutrient and microelement content of treated soils. The conventional application rate of organic material depends on soil properties, including the organic content, CEC and granulometric composition, as well as the type of crop. Increased application rates of organic fertilizers were used widely in the former USSR following the Chernobyl accident on arable land, with deposition densities above 185 kBq/m^2 [12]. The application rates recommended were 1.5- to 2-fold higher than those used normally [12, 33, 34, 124, 125]. The timing of organic fertilization is crop dependent. For example, peat–manure compost is applied in spring for a planned yield of medium and late cultivars of potato, whereas for early potato it is applied in autumn during winter ploughing.

Effectiveness and feasibility: The application of organic materials may reduce ^{90}Sr, ^{60}Co and ^{137}Cs transfer to plants by 1.3- to 3-fold [12, 33, 35, 110, 116–118, 121–127]. The effectiveness of organic material fertilizers on both ^{90}Sr and ^{137}Cs accumulation in plants is higher on light sandy soil than on loamy soils, due to the major difference in the CEC values. Effectiveness is very low on highly fertile soils. The local availability of some of the organic materials may be limited, notably for sapropel [125].

Side effects: As organic fertilizers are routinely applied on intensively managed arable soils, the side effects are minimal. Crop yield may be increased by up to 2-fold and an associated improvement in soil fertility can be expected. Changes in mobility of nutrients may lead to effects on water quality. If a peat/manure mix is applied excessively and inappropriately, there may be pollution of water sources. Furthermore, if manure is not adequately decomposed, there may be soil pollution by pathogenic microorganisms. Peat, which is highly acidic, needs to be composted with manure or lime, ash or phosphorite meal before it can be used as an organic fertilizer. Peat–manure composts are made during the winter period based on a ratio of 1:1. Application of organic fertilizers, such as manure and acid peat, may increase the uptake of radiocaesium by plants in the first year after application because of changes of soil accidity. However, in the second year after application, organic fertilizers may produce a decrease in radiocaesium uptake by plants due to mineralization in soil leading to an increase in the content of potassium in the soil solution.

Costs: Application of organic fertilizers may be costly if they involve high transport costs. Sapropel is inexpensive, where locally available, and easy to apply. However, long distance transport of wet sapropel is not practicable. The need to dry sapropel can also increase its cost if carried out on a commercial scale but drying can be carried out at a local level for smaller quantities by laying out to dry in the sun.

Social aspects: Organic fertilizers are a natural resource. Application of organic fertilizers may lead to the exploitation of local deposits of peat and sapropel, the extraction of which can provide new employment opportunities for local people.

Constraints: The use of some fertilizers (primarily manure) must be limited if close to recreation and residential areas, or open water bodies. Application may need to be restricted near watercourses and on floodplains.

4.1.1.6. Application of mineral sorbents to arable soils

Management option description: Application of mineral sorbents is not part of conventional agricultural practices in many countries. Mineral sorbents added to soil enhance the sorption capacity of the soil, so they should have a much higher sorption capacity for the target radionuclide than that of untreated soils [34, 128–130]. A recommended particle size for mineral sorbents added to soil is 1 mm or smaller to maximize sorption capacity. Mineral sorbents may have a diverse origin. The most commonly used materials are clays (such as bentonites and palygorskite) and zeolites (such as clinoptilolite) because these materials have a high sorption affinity for certain radionuclides. Zeolites can be used instead of lime, due to high pH, and can also be added to peat–manure compost. The application methods used for the sorbent materials is the same as those used for liming. The dry sorbent material is uniformly spread on the soil surface and then the soil is reploughed. The mass of the applied material depends on the contamination level and soil properties. Application rates vary from 5–30 t/ha; the upper value was recommended for light sandy soil following the Chernobyl accident. When zeolite is applied, increased doses for these soils of P and K must also be used, and the rate of N fertilizers must be increased because the sorbents can also bind some of the added microelements and fertilizers [127].

Effectiveness and feasibility: The use of mineral sorbents may reduce radiocaesium transfer to crops up to 2.5-fold depending on soil texture [33, 127]. The maximum effectiveness is observed for light sandy soil with low fertility. No effects are observed when applying clay minerals to clay soils with high fertility (and high CEC status). Due to the relative difference in sorption properties, sorbents are more effective on soils with low K_d values, such as sandy soils. The effectiveness of mineral sorbent addition tends to increase with time. Positive effects from the use of zeolites, for instance, appear from the second or third year after application when there has been an adequate amount of time for the clay to form a sorbing complex with radiocaesium in the soil [81]. Mineral sorbents for soils need to be available in large amounts to be applicable at field level.

Side effects and cost: Application of mineral sorbents can change the nutrient status and CEC of soil. Soil fertility and, hence, crop yield may be increased when mineral sorbents are applied together with mineral fertilizers. The use of sorbents can stabilize the sorption properties of soil and improve its fertility, providing positive effects for crop planting. The cost of application of mineral sorbents is high, largely because of high application rates and associated high transport costs. Furthermore, the cost compared with reduction factors (cost–benefit) is relatively high. If there are local deposits of mineral raw materials close to the contaminated areas, these costs may be reduced.

4.1.1.7. Application of mineral fertilizers to arable soils

Management option description: Mineral fertilizers are routinely applied in agriculture to optimize crop yields. They are normally comprised of nitrogen, phosphate and potassium (NPK) based fertilizers and are mixed in soil by harrowing or ploughing before the planting/sowing of arable crops. They can also be applied to grasslands (see the surface or radical improvement sections). NPK application rates should be justified according to these crop characteristics and should take into account the soil conditions, crop cultivation technologies and farming practice [33–35, 37, 105]. Application of mineral fertilizers as a management option involves a change in both ratio and application rates of the individual elements (i.e. N, P and K) in the NPK mix applied on contaminated land. The numerous studies performed in the former USSR, largely after the Chernobyl accident, have made it possible to identify the optimal ratios of nutrients on land contaminated by radiocaesium and radiostrontium in contaminated areas. In particular, because potassium is a chemical analogue for caesium, its application in elevated rates was identified as an effective management option to reduce the accumulation of radiocaesium in crops [33, 105, 131, 132]. Application of phosphates can reduce Sr availability to plants because strontium phosphate is relatively insoluble [131, 133]. In the former USSR, the highest effect in reducing radiocaesium accumulation was achieved at N:P:K = 1:1.5:2; for ^{90}Sr, it was N:P:K = 1:2:1.5 [34]. The ratios given are the relative amounts used for each element (N, P and K) for remediation compared with those used for normal application rates. Thus, an N:P:K ratio of 1:1.5:2 means the same amount for N, 1.5-fold higher for P and 2-fold higher for K.

During crop cultivation on contaminated soils, N fertilizers need to be applied with respect to the expected yield. Increasing N application can increase radiocaesium and radiostrontium transfer to products due to soil acidification and its effect on K_d(Cs) [35]. Ammonium fertilizers should be avoided and N fertilizer should be applied in the form of nitrate [33, 34, 122]. Supplementary Mg fertilization and liming may be required to maintain an optimal ionic equilibrium in the soil and plants. On acidic and weakly acidic soils, mineral fertilizers are applied only after liming, since the use of mineral fertilizers alone, especially acidic forms, increases the acidity of the soil solution and leads to increases in radiocaesium and radiostrontium uptake by plants.

Effectiveness and feasibility: Application of mineral fertilizers, as recommended in the first post-Chernobyl recommendations for the long term period [34], may reduce radiocaesium transfer to plants by 2- to 5-fold. Enhancing the rate of P fertilizer application within an NPK fertilizer produces the highest effect on radiostrontium transfer from soil to plants, with a reduction factor of 3- to 5-fold. The use of increased rates of P fertilizers reduces radiocaesium uptake by plants on mineral soils by 1.5- to 3-fold. Factors influencing the effectiveness of the option for radiocaesium are potassium status of the soil/soil solution (see above) and type of crop [33]. Information on appropriate application rates of mineral fertilizers should be provided to the operators and will be soil and crop specific [37].

Side effects and social aspects: Although there may be changes in nutrient status, etc., the impact is likely to be small for intensively managed arable soil where mineral fertilizers are routinely applied at normal rates. The key elements which improve soil fertility are K and P, and, therefore, increases in their application rates often lead to higher crop yields. Assuming that this management option is carried out for soils where the exchangeable K is sub-optimal for the crop, there will be a potential increase in crop yield and quality. Application of phosphates may reduce the availability of essential micronutrients whose phosphates are also of low solubility. Information to operators on appropriate application rates should be provided. Advice may be required for dairy farmers to avoid detrimental effects on potassium–magnesium metabolism in livestock due to application of too much potassium.

4.1.1.8. Combined application of NPK fertilizers, liming and organic fertilizers

Combined use of mineral, organic fertilizers and liming is the most effective way to reduce radionuclide accumulation in farm crops. The combined use of lime and organic matter may reduce radiostrontium transfer to plants by up to 3- to 5-fold and the effects persist into the second and third years after the application. The use of increased application rates of phosphate and potassium (PK) fertilizers combined with liming reduces transfer of radiostrontium and radiocaesium by 5- to 7-fold and 3- to 5-fold, respectively. Thus, a combined use of liming and increased rates of PK fertilizers together with normal application rates of N can decrease radionuclide accumulation in farm crops up to 2- to 4-fold more than after liming alone. Many crops are sensitive to a deficiency in microelements. Therefore, in management options, such as liming and use of increased doses of P fertilizers, additional application of microfertilizer[12] is essential.

4.1.2. Management options for fodder production

4.1.2.1. General issues for fodder production management options

Land used for fodder production includes both uncultivated and cultivated grassland. Management of fodder production should ensure both an increase in grass productivity (or other types of fodder) and a reduction in the plant uptake of radionuclides down to activity concentrations that guarantee production of animal-derived food which is in compliance with the action levels. The effectiveness of these types of management options depends on the state and type of land used for fodder production. Factors influencing the effectiveness of the procedure include the type of meadow, the hydrological regime, soil type, nutrient status and pH. The selection of the plant species for re-seeding is also important as transfer of radionuclides to different species can vary substantially [33–35, 55, 134–138].

At certain times of the year, the ground can be too wet for ploughing. Normally, on waterlogged grassland, field drainage and other soil treatments (removal of trees, shrubs and hills, surface cleaning) should be performed before application of the management option.

On drained lands, radionuclide uptake by grass depends on the level of the groundwater. On peaty and peat–gley soils, minimal radionuclide uptake is achieved at groundwater levels, which should be at least 90–120 cm from the soil

---

[12] Microfertilizers are fertilizers containing microelements, i.e. chemical elements which the plant requires in microquantities.

surface. A rise in groundwater to a depth of 40–50 cm from the topsoil increases radionuclide uptake by plants.

Unimproved grasslands may be within environmentally protected areas or associated with farms which have organic status. In these areas, some practices (e.g. NPK application) might be unsuitable. If the area is perceived to be ‘natural’, there may be resistance to changes in the ecosystem and landscape which result from this rather intensive management option. Areas of pasture with steep slopes and shallow or stony soils cannot be ploughed or drained.

4.1.2.2. Ordinary ploughing

Management option description: An ordinary, single-furrow mouldboard plough can be used to mix the top 20–30 cm of the soil profile. Much of the contamination at the surface will be buried more deeply in the vertical profile, which may: (i) reduce radionuclide uptake by plant roots depending on their specific rooting behaviour; (ii) reduce external exposure; and (iii) reduce resuspension of radionuclides and subsequent soil adhesion onto plants. Such relatively shallow ploughing was widely used as a management option in the former USSR following the Chernobyl accident [12, 33, 111–113].

Effectiveness: Data on the effectiveness of this measure are limited to radiocaesium and radiostrontium for which plant uptake may be reduced by up to 4-fold, with an average reduction factor of two. A similar effect would be expected for most radionuclides as it depends on a purely mechanical modification. External dose may be reduced from 2- to 5-fold, depending on the depth of ploughing [139–143]. It is reasonable to expect similar reduction factors for other targeted radionuclides as the management option results in mechanical redistribution of the contaminated soil profile. Shallow ploughing is effective if it is only applied once. Repeated application of shallow ploughing will not have any additional radiological benefit and may bring radionuclides into the rooting zone. The factors influencing the effectiveness of this option are: soil properties, depth of root-containing zones of plants and radionuclide distribution in the soil profile. The effectiveness of the reduction in external dose needs to be considered separately for each radionuclide as it will depend on the type of radiation emission.

Side effects: This management option may result in resuspension of radionuclides associated with small soil particles during and after ploughing until the formation of a new root mat in the upper soil layer.

4.1.2.3. Surface improvement of grasslands

Management option description: This management option aims at improving the productivity of land used for fodder and leads to reductions in radionuclide activity concentrations in the fodder. Various approaches are used to enhance the productivity of haylands and pastures, including land improvement (extraction of shrubs, small hillocks of grass, weedy plants control), agricultural practices (disking of the root mat which involves disrupting the root mat using heavy discs in 2–3 cuts) and enhanced mineral fertilization. The option includes additional sowing of grasses in the third year following the commencement of its application, thereby improving productivity of plants and ensuring appropriate ratios among the different species in the grass mix [33, 34, 113, 125, 139–144]. Surface improvement changes the status of land from an unimproved, extensive system with natural vegetation to one of being managed, either totally or partially [33]. It is primarily implemented on erosion prone sites and low productivity grassland, such as those in floodplain areas. The agrochemical measures suitable for fodder land include application of lime materials (on acidic soils) and increased amounts of P and K within an NPK fertilizer. The enhanced rates of NPK application (the values recommended here are based on experience in the former USSR) are the same as those suggested for arable soils, namely, 1:1.5:2 for ^{137}Cs and 1:2:1.5 for radiostrontium compared with normal rates of fertilizer application [34, 127, 135, 144, 145]. On radioactively contaminated land, cereal grasses are preferable since accumulation of radionuclides by cereal grasses is ca. 2- to 3-fold lower than that by legume grasses. The grass composition used for surface improvement may include up to 20% legume grasses (white clover, vetch). A proportion of land may be sown with perennial grasses which are suitable for both hay production and animals grazing in early spring (in the Russian Federation, 20% brome grass was recommended after the Chernobyl accident [35]). This management option was used extensively in the former USSR after the Chernobyl accident [12, 49].

Effectiveness: Surface improvement of fodder lands is effective when soil is contaminated with either radiostrontium or radiocaesium. Reduction factor values for soil–plant transfer of radiocaesium following surface improvement range from 1.3 to 2.0 and from 1.5 to 3.5 for mineral and organic (peat) soils, respectively, while reduction factors for radiostrontium soil–plant transfer vary in a range from 1.5 to 2.5. On peaty soils, the reduction factor was, on average, 2-fold higher than on mineral soils in the former USSR [137, 138]. Surface improvement of wet peat soil with drainage (where required) may reduce radiostrontium and radiocaesium accumulation in grass by up to a factor of ten [12, 125, 145]. The option remains effective for 3–5 years depending on animal production rates and weather conditions, and should be applied again thereafter [81]. After repeated surface improvement, reduction factors decline to 1.5- to 2.0-fold for both radiostrontium and radiocaesium transfer to plants [12, 138, 145]. There are no data for the effectiveness of this management option for radionuclides other than those of Cs and Sr. However, a reduction in soil–plant transfer could be expected for the other target radionuclides on the basis of their known chemical and environmental behaviour.

Feasibility: Agricultural workers and farmers should be instructed carefully about the objectives of the option, the application rates of lime, fertilizers and required consumables. The option may also require consumables associated with fencing and drainage operations.

Side effects: The option can have potentially high environmental side effects because of the change of ecosystem from natural to cultivated grassland. Disking, application of lime and fertilizers, and re-seeding will change the ecological characteristics of the land with possible reductions in biodiversity. Grasslands are often the habitat of endangered species and a change in nutrient status may be harmful to these species. A significant increase in NPK application can lead to pollution of groundwater and surface water by these elements. When applied on floodplain grassland, water body contamination by fertilizers may occur. Higher productivity of grassland should be anticipated since surface improvement of haylands and pastures increases their productivity by 25–50% at a minimal cost which can be recovered within 1–2 years. If improvement is carried out under a rolling programme, there should be no significant loss of grazing. There may be disruption to farming and other related activities, although there are also benefits to the farmer who will have more improved pastures in the long term. The availability of additional improved grazing can reduce wintering costs and result in higher prices for improved stock.

Waste: Application of surface improvement can generate some contaminated materials that can be classified as waste, including trees, shrubs and dry grass stand. Burial in trenches dug in close vicinity to the site may be a reasonable waste disposal option, given the normally low biomasses involved.

Constraints: The application of surface improvement will only be possible in areas where the soil structure and landscape are suitable. The option cannot be applied on grassland located on waterlogged soils or on sites where the upper organic horizon is less than 10 cm deep. In the Chernobyl affected areas, surface improvement is only applied to dry grassland on soddy-podzolic soils if the resulting plant species stand contains at least 50–60% of valuable fodder cereal grasses and 25–30% of legume grasses.

4.1.2.4. Radical improvement of grasslands

Management option description: Radical improvement of fodder lands is a conventional practice to increase productivity of grassland. Radical improvement consists of similar measures to those of surface improvement with additional soil ploughing. Thus, radical improvement includes removal of shrubs, small hillocks of grass, root mat destruction, ploughing, disking, roto-tilling and chiselling, liming of acidic soil (if necessary), application of increased amounts of PK within NPK fertilizers and the selection of grass mixtures with the minimum possible accumulation of radionuclides [135, 138, 144]. As above, drainage can also be included for wet soil. The optimal administration rates (active substance per hectare) designed to meet the radiological standards for fodder which ensure production of safe animal products in the areas most affected by Chernobyl are: (i) $N_{120}P_{90}K_{120}$[13] for dry grassland on mineral soils; (ii) $N_{120}P_{90}K_{120}$ for dry grassland on floodplain soils; or (iii) $N_{180}P_{120}K_{180}$ for wet grassland on floodplain soils. Liming is obligatory on acid soils with application rates which are 1.5- to 2-fold higher than those normally estimated by the soil solution acidity for fodder land. It is recommended that grass mixtures be comprised mostly of cereals which accumulate 1.5- to 3.0-fold less radionuclides compared with legume grasses. Radical improvement was used extensively in the former USSR after the Chernobyl accident and was the key element for remediation of land used for fodder production in contaminated areas [12, 49].

Effectiveness: Radical improvement may decrease the transfer of radiocaesium and radiostrontium to fodder by 2- to 10-fold. This management option was highly effective in the former USSR after Chernobyl. Reduction factors for soil–plant transfer of radiocaesium following radical improvement were in the range, for mineral soils of 2- to 4-fold and for organic soils of 3- to 6-fold. For radiostrontium, reduction factors in the range of 3- to 6-fold may be achieved for mineral soils and 3- to 10-fold for organic soils [12, 138, 144, 146]. A combined option such as drainage and radical improvement of fodder lands may reduce accumulation in grass of radiocaesium and radiostrontium by up to a factor of ten. If applied to wet peat soil, this option can lead to a reduction factor of 15-fold. The option remains effective over 3–5 years and should be applied again after that period although it will then have a lower effectiveness. In repeated radical improvement, the reduction factors for transfer to plants are 2.0- to 3.0-fold for radiocaesium and 1.5- to 2.0-fold for radiostrontium [12, 145] for the repeated treatments. The effectiveness of radical improvement depends on

---

[13] The notation '$N_xP_yK_z$' indicates a mineral fertilizer application rate where x kg of active N per hectare, y kg of active P per hectare and z kg of active K per hectare are applied.

the meadow type, hydrological regime of the land, soil type, productivity and plant species selected for re-seeding. The effectiveness of radical improvement is also influenced by application rates of NPK and lime, and implementation of draining. For example, an unbalanced use of N, P and K can enhance radiocaesium uptake by the plant root system and increase the resulting radiocaesium activity concentrations in the plant.

Feasibility: Additional machinery is needed to improve drainage (if appropriate for sites with wet peat soil) including: trench digger, bulldozer, excavator and vehicle for transport of waste. The option may also require consumables associated with fencing and drainage operations. Agricultural operators should be instructed carefully about the objectives, application rates of lime, fertilizers and other consumables required.

Waste: Application of radical improvement can generate some contaminated materials that may be classified as waste, including trees, shrubs, dry grass stand, etc. containing radionuclides. Burial in trenches in close vicinity to the site could be used as a reasonable waste disposal option.

Side effects, social aspects and constraints: Ploughing, application of lime and fertilizers, and re-seeding would change the ecological status of the land and biodiversity may be affected. A significant increase in NPK application can lead to pollution of groundwater and surface water. Some changes in landscape and the hydrological regime of the treated area may be expected. Contamination of the water by fertilizers may be anticipated when applied on floodplain grassland. The option should provide more productive grassland than that prior to application. Additional stock may be required to ensure adequate grazing pressure and to maintain the areas of improved land. Alternatively, grass could be cut for use as stored feed. The availability of additional improved grazing can reduce wintering costs and result in higher prices for improved stock. Fertilization and liming may restrict subsequent use of the land (e.g. for organic farming). Disruption to farming and other related activities may occur although farmers will have access to improved pastures in the long term. There is a need for dialogue regarding selection of areas for treatment of grassland and waste disposal between land owners/farmers, scientists and the public. The constraints are similar to those for surface improvement. Additionally, radical improvement of fodder land which includes liming cannot be applied in river floodplains.

4.1.3. Crop based options

4.1.3.1. Selection of crops with lower accumulation of radionuclides

Management option description: Radionuclide accumulation is highly variable as it is influenced by the physical and chemical properties of radionuclides, soil properties and the characteristics of different plant species [33, 80, 133, 134, 139, 147–149]. The differences between species or even plant cultivars can be exploited if suitable species and cultivars of crops with the lowest rates of accumulation of radionuclides have been or can be identified. The sources of variability in transfer include:

- Differences in metabolic and biochemical mechanisms of radionuclide uptake by plants;
- Crop requirements for certain nutrients (e.g. analogues for radionuclides: K for Cs, Ca and Mg for Sr or Ra);
- Detoxification and exclusion mechanisms;
- Distribution of roots in the soil;
- Rhizosphere properties, such as the presence of mycorrhiza;
- Duration of the vegetative period;
- Plant crop yield.

Radionuclides often transfer to a greater extent into leaves and stems than into other plant parts, such as generative tissues including grains and seeds, and lignified tissues. Crops are cultivated using normal agricultural practices taking into account the deposition density of soils and reported F_v values for different crops/cultivars.

Effectiveness: Radionuclide accumulation shows high variability with interspecies variation of up to an order of magnitude. The difference between minimum and maximum radiocaesium or radiostrontium transfer factor values for different crop species can be as much as 100-fold and higher [50, 150, 151]. The effectiveness of this option, in terms of crop contamination, can vary on average from 5- to 10-fold but can be even higher.

Side effects: When crops are included in an established crop rotation change, there may need to be a reassessment of fertilization schemes due to a modification of nutrient cycling.

Social aspects: Information/dialogue with farmers or other operators regarding which crop substitution is appropriate and to ensure suitable modified agricultural practices will be required. A market for the alternative crop should exist or should be created.

4.1.4. Animal based management options

Food products from animals are important sources of internal dose in many of the circumstances considered in this report. The main aim of using animal based management options is to reduce activity concentrations of radionuclides in meat and milk of farmed livestock to below action levels.

To set action levels, information is needed on the diets of agricultural animals and on the transfer rates from the feed to animal products, such as milk and meat. Transfer parameter values from ingested feed to milk and meat for many radionuclides are given in the Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments [52], supplemented by additional information in Refs [152, 153]. The appropriate transfer value to use should consider different factors, such as the quality and quantity of available information, its relevance to the site specific conditions and the need to be cautious. Thus, the geometric or arithmetic mean, or the 90th/95th percentile values might be used (all of which are available or can be derived from Ref. [152]), depending on the quantity and quality of the data used to derive the parameter value and the circumstances for which it is applied. These values can then be used, together with other socially relevant factors, to set action levels for animal feed to ensure that the radionuclide activity concentrations do not exceed the action levels. During planning of remediation, local site specific feeding schemes and transfer of radionuclides to milk and meat should be measured. This information could then be used to help derive site specific action levels for animal feed. Higher action levels may be applied if animals are given additives or binders (see the management options below), thereby avoiding unnecessary challenges for feed production.

4.1.4.1. General issues for animal management options

Reassurance, via monitoring programmes, would be necessary to show that animal products have radionuclide activity concentrations which are below action levels. Live monitoring for some gamma emitters prior to slaughter is a key, cost effective method which allows efficient control of management options for animals and also allows selection of animals that need to be decontaminated or that are suitable for slaughtering. Management options which are similar to normal farming practices and are, therefore, less likely to disrupt animal production, are among the most feasible and acceptable measures.

All options bring about direct or indirect economic costs, which can sometimes be high. However, in practice, many of the options are more cost effective than the common alternative of rejecting animal products, which may lead to the need for animal slaughter, waste disposal of animal carcasses and/or food, and the need for compensation payments.

The first two options considered below involve the management of the use of animal feed according to the extent of contamination:

- Clean feeding, where animals are provided with feed which is either uncontaminated or contains low levels of contamination;

- Optimizing the use of contaminated feed where animals used for meat production or as breeding stock are given contaminated feed and then decontaminated before entering the human food chain.

Management of these options relies on knowledge of the rate at which animals can be decontaminated, i.e. the biological half-lives of the radionuclides in the animal.

4.1.4.2. Retention of radionuclides in animals

The rate of loss of a radionuclide from an animal food product (meat, milk or eggs, or other tissues such as offal) once the animal has been removed from a contaminated diet, is termed the biological half-life ($T_{1/2b}$). This is defined as the time required for the radionuclide activity concentration in a given tissue to decrease by one half, excluding physical decay. The rates of uptake and loss of radionuclides varies between animals and tissues. For some radionuclides, such as radiocaesium, $T_{1/2b}$ seems to be associated with the basal metabolic turnover rate. For others, it is controlled by stable element status. For instance, radiostrontium release from tissues is affected by changes in calcium metabolism, including mobilization of a body storage site such as bone during periods of high metabolic turnover rates (e.g. peak lactation in dairy animals). For most radionuclides, the major excretion routes from an animal are faeces, urine and milk.

The biological half-life of radionuclides in animals is an important factor influencing the effectiveness and practicality of many management options targeting animal derived foodstuffs (i.e. clean feeding, change of grazing regime or additive based management options). Although a single value of the biological half-life is sometimes given for a tissue or the whole body, the dynamics of loss are generally multi-compartment. Fast losses are usually determined by rapidly turning over pools, and longer term, slower losses by the dynamics of the radionuclide in the major storage organ(s).

The rate of decline of radionuclide activity concentrations in milk is often rapid. Reported half-lives (for the short term and often dominant component of loss) for both Cs and Sr in different dairy ruminants are all in the range of 0.5–3.5 d [154–157]. For Cs and Sr, a double exponential function is often used with the second component being typically about 10–20 d [155] and 30 d [157], respectively.

Radiocaesium biological half-lives for muscle in agricultural animals derived from a linked series of experimental studies are shown in Table 1, where *a* is the proportion of the radionuclide loss that is accounted for by each exponential. The biological half-lives are estimated as either a single or double

TABLE 1. MEASURED EFFECTIVE HALF-LIVES OF ^{137}Cs IN THE MUSCLE OF DIFFERENT ANIMALS [158,159]

Livestock	a^1	$T^1_{1/2}$ (d)	a^2	$T^2_{1/2}$ (d)
Bulls 18–20 months (n = 50)	0.48 ± 0.05	11 ± 1	0.52 ± 0.05	38 ± 5
Bulls 10–12 months (n = 20)	0.65	7.3	0.35	43
Heifers (n = 50)	0.7 ± 0.1	8.3 ± 0.7	0.3 ± 0.1	46 ± 10
Cows (n = 50)	0.63 ± 0.05	7 ± 2	0.37 ± 0.05	48 ± 5
Pigs 65–70 kg (n = 25)			1	15 ± 3
Geese 4 kg, 3 years (n = 75)			1	11 ± 2

Note: a^1 is the fraction of loss of radionuclide in the muscle explained by each biological half life.

(fast ($T^1_{1/2}$) and slow ($T^2_{1/2}$) components) exponential model, and the equation fits are shown in Fig. 4.

These experimental data and review studies (e.g. Ref. [160]) show that the biological half-life of radiocaesium in meat increases with increasing live weight

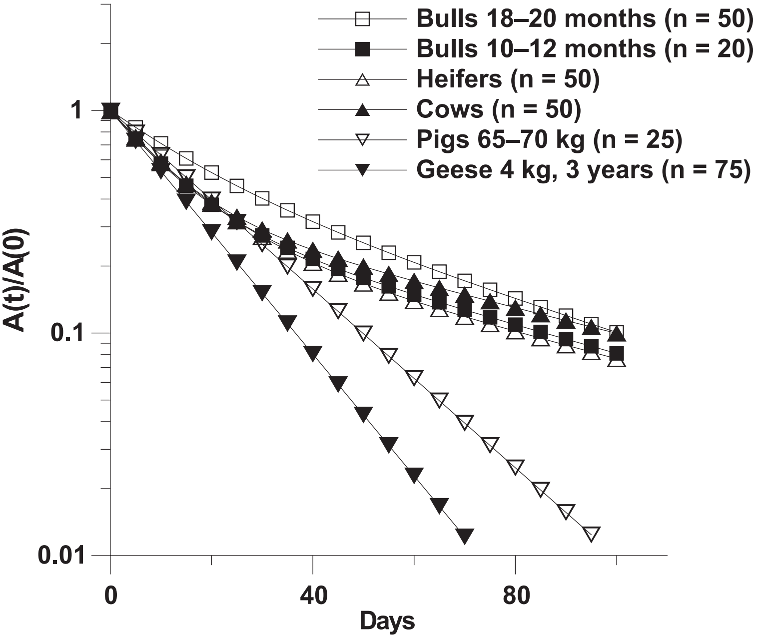


FIG. 4. Change with time in ^{137}Cs activity concentrations in muscle of various livestock (A(t)) normalized to initial concentration (A(0)) [158, 159].

TABLE 2. PARAMETERS FOR ALLOMETRIC RELATIONSHIPS DESCRIBING THE BIOLOGICAL HALF-LIFE OF A RANGE OF RADIONUCLIDES IN ANIMALS *(based on values from Refs [161, 164])*

Radionuclide	a	b
Am, Pu	1140	0.73
Ce	352	0.8
Co	13.6	0.24
Cs (ruminants and pigs)	5.2	0.3
Cs (hens)	22.3	0.33
I	16.7	0.13
Ra	277	0.28
Sr	645	0.26
Th	888	0.8
U	5.5	0.28

of the animal. Whereas data on gastrointestinal absorption and transfer parameter values have been compiled recently, there has been no similar recent review of biological half-lives in food products from animals. From the observations of Stara et al. [160], weight dependent relationships for monogastric animals and ruminants for a range of radionuclides have been derived [161]. The differences observed between species are probably related to the higher metabolic rates of small compared with large animals. Other weight dependent (or allometric) relationships for the long component of $T_{1/2b}$ for a range of radionuclides in animals (for the purposes of modelling transfer to wild species) have been derived [162–164]:

$$T_{1/2b} = \mathrm{a} \times (\text{live weight})^{\mathrm{b}}$$

Values of the constants a and b where live weight is in units of kilograms are presented in Table 2.

4.1.4.3. *Clean feeding*

Management option description: The objective of this management option is to prevent the contamination of animal products by ensuring contaminated feed is not ingested by agricultural animals. It is particularly useful for lactating dairy animals to ensure continuous production of milk below the action levels. It can be used to decontaminate animals after the emergency situation has passed, in which case the duration of clean feeding will depend on the initial contamination level in the animal and the biological half-life (see next option). Clean feeding involves agricultural animals being given nutritionally balanced diets comprising either uncontaminated feed or contaminated feed with low radionuclide activity concentrations so that animal products (normally milk or meat) have activity concentrations below a specified limit. Clean feeding also has the benefit of reducing the quantity of waste milk and meat produced from otherwise contaminated animals. Livestock would ideally be confined to an area of improved pasture or housed in farm buildings with appropriate penning, ventilation and feeding arrangements, to minimize or prevent grazing of contaminated fodder and soil in the pasture. If contamination levels in forage grown on the improved pasture prevent successful clean feeding, it should be removed from the diet and replaced by uncontaminated fodder, such as haylage or silage, or less contaminated feed, such as root crops and cereals. If the dietary balance for animals is substantially changed, for instance by addition of root crops (with contaminated soil removed) and cereals, a period of adaptation to a changed diet is desirable to minimize welfare issues, the length of which will depend on the extent of the change in the diet. Clean feeding should be accompanied by a pasture and grass production management programme to: (i) provide fodder with sufficiently low radionuclide activity concentrations to be fed to the animals; (ii) ensure that action levels are not exceeded when the animals are reintroduced to pasture; and (iii) maintain pasture quality. Clean feeding was used extensively after the Chernobyl accident in the former USSR, Norway and Sweden [12, 34, 48, 57].

Effectiveness: The management option is highly effective for most radionuclides as it removes or reduces the principal source of contamination. It will effectively prevent or reduce radionuclide contamination of milk, meat and other products from animals. The effectiveness of clean feeding for some gamma emitters (notably radiocaesium) can be monitored rapidly using live monitoring techniques (see Section 2).

Feasibility: The key requirement for this management option is an adequate supply of uncontaminated feed with an adequately low level of contamination. The requirement for clean feeding and the availability of conserved feed will depend on the time of year which is most critical in the first year after deposition occurs. If the initial deposition occurs in winter, there would be little impact for housed livestock being fed covered stored feeds. However, finishing animals which are still outdoors grazing pasture would have to be housed and given conserved clean feed. Just before the growing season (e.g. mid- to late spring in many parts of the world) would be the worst time in some agricultural management regimes for a contamination event, since some animals would be grazing outside, stocks of previously harvested, uncontaminated fodder would be low and no new season hay or silage would have been harvested. Although it is preferable to continue to grow and feed fodder which is locally grown, it is also possible to buy uncontaminated feed from a wide variety of suppliers worldwide. The effectiveness of clean feeding requires information on contamination levels in feed. If it is combined with live monitoring, this helps to maintain public confidence in the products. Therefore, there must be an adequate capacity to measure feed, and live monitoring expertise. Many large farms will have access to suitable buildings to house animals but they may not be available to some smaller and/or subsistence farms.

Costs: Uncontaminated feed with a low contamination level has to be available, and the quantity of such feed required may be higher than normal. Therefore, such feed may need to be purchased. The associated costs may be high and will depend on the level of contamination, the type of animals requiring the feed, the time of year and the distance from the supplier. Thus, compensation may need to be provided to the affected farming community.

Side effects: If available housing and associated infrastructure is inadequate, there can be problems associated with animal welfare, especially in summer when temperature and ventilation could be a problem due to high humidity or concentrations of ammonia in buildings, but also in late autumn and winter in colder climates (due to low temperatures). Animal welfare issues may also arise when enclosures are used as the parasite burden may increase and general animal hygiene may decline. Housing of livestock produces large volumes of excreta (slurry). For many livestock farms, animals are normally housed for at least some of the year, so facilities will be available to handle slurry which must be stored and disposed of appropriately. The side effects for decontamination of animals are considered in the option below.

Social aspects: An important advantage of this management option is that it provides the opportunity for farmers themselves to be positively involved in remediation in a way that the benefits are clearly seen. Although some farmers/herders may have difficulties adapting to the new regime, practical experience has shown that farming communities are often willing to change their farming practices as they see clear benefits and are able to continue to produce their products, even though the management of their land may have to change. Public confidence that the problem of contamination is being effectively managed for animal products may be improved or enhanced because the method is readily understandable and clean feeding is usually acceptable to all major stakeholders. As for many management options, the public needs to have confidence that feed limits are being respected, correct clean feeding procedures are being used and adequate monitoring is in place. Otherwise, there may be a loss of confidence that farm produce and derivative products (such as yoghurt and cheese) from affected areas are ‘safe’. If public confidence is lost, there may be a loss of employment in both the agricultural, food manufacturing and retail sector, leading to the need to support and maintain impacted farming and associated communities.

Constraints: Standards of animal husbandry and welfare, and regulations governing feed storage would need to be observed. Some certification schemes, such as those for ecologically focused farming, may be contravened. Further constraints include the suitability and acceptability of new feed with respect to animal welfare issues (e.g. diet less palatable, lower in fibre/energy levels etc.).

4.1.4.4. Optimizing use of contaminated fodder or forage[14] *combined with decontamination*

Some of the text for clean feeding is relevant for this closely related option and is not repeated here. Conversely, much of the text here is relevant to the decontamination of animals which are contaminated after an emergency situation.

Management option description: Animals can be given fodder or permitted to graze pasture which is classified as contaminated, and can then be transferred to uncontaminated fodder or forage, or given Cs binders to decontaminate them before being slaughtered [34, 57, 125]. The temporary prior provision of fodder or grazing of forage with radiocaesium activity concentrations in excess of action levels for non-dairy animals and breeding stock prior to gestation allows continued utilization of contaminated plants. The finishing period for animals may be prolonged if radionuclide activity concentrations in meat do not decline rapidly enough to allow slaughter (see also the clean feeding option) [33]. This option is similar to clean feeding, but focuses on adapting the level of radionuclides which animals ingest to optimize the use of fodder or forage which may be contaminated to differing extents. The option allows the sustainable use of farmland and reduces the quantities of contaminated crops and milk requiring disposal as waste. The radionuclide activity concentration in meat that would arise from feeding available contaminated fodder can be predicted using transfer parameters or models [51, 52, 152, 153]. When clean feeding is applied, the radionuclide activity concentrations in animal products will decline at a rate determined by the animal's biological half-life. The rate of loss will be slower if the provided feed is contaminated. The option is most suitable for radionuclides, such as radiocaesium, with short biological half-lives in meat or other edible tissues. Clearly, the option is not appropriate for radionuclides, such as Pu and

---

[14] 'Fodder' refers to plant material which has been cut and fed to livestock, whereas 'forage' refers to plant material grazed by livestock.

Am, which have biological half-lives that are similar to or exceed the normal lifespan of an animal. This option can be useful in maintaining a livestock production system in contaminated areas. Optimizing the use of contaminated feed was used extensively after the Chernobyl accident in the former USSR.

Feasibility: There must be adequate time available to decontaminate the animal after feeding contaminated fodder or grazing contaminated pasture. Live monitoring can be used to identify animals that need further decontamination and/or to ensure that the meat meets the action levels to avoid slaughter of animals which do not conform to action levels. Crops will deteriorate in storage unless processed and will need to be provided in a suitable form to be used as animal feed. Some radionuclides are largely accumulated in tissues other than meat (such as liver and bone), so it may, therefore, be possible and more practicable to prevent entry of the target organ into the food chain, while allowing the consumption of less contaminated meat.

Costs: Farmers would need to be compensated for the loss in value of crops originally grown for human consumption and the additional work associated with the processing of extra food required for animal feed. Additional concentrate supplements may be required to provide animals with a balanced diet. Extra manpower may also be required to provide suitable fencing to enclose areas.

Side effects: Decontamination clean feeding of animals, such as finishing beef cattle, will lead to contaminated slurry (to an extent which will decline with time) and appropriate disposal routes would need to be identified, depending on the activity concentrations present. If inadequate or inappropriate disposal of additional slurry/manure slurry occurs, there could be pollution of water courses. Feeding housed animals can change the quality, visual characteristics and taste of animal products, making them less acceptable to the food industry/consumers. For example, feeding high levels of cereal concentrates to lambs can result in the body fat being soft. It is likely that a greater than normal proportion of animal carcass would have to be used for low grade meat products, such as mince, sausages and pies, than for prime cuts. Other prices for skin may apply if slaughter is performed at a time when the pelt quality has changed [37]. Potential changes in meat quality and proportion/type of fat is an issue in Japan after the Fukushima accident because the marketability and acceptability of meat from animals with a prolonged finishing period is reduced.

Social aspects and constraints: There may be problems with the acceptability to farmers, the food industry and consumers of deliberately feeding contaminated feed to animals destined for the human food chain. There may be legal restrictions on the disposal of contaminated slurry. The food industry/consumers may not accept residual levels of contamination in animal products which may be present, depending on the selected decontamination time period. Some countries have set action levels for radionuclide activity concentrations in animal feed. Transport of contaminated feeds to areas not affected by fallout is unlikely to be acceptable. Processing industries need to be willing to manufacture animal feed from contaminated crops.

4.1.4.5. Manipulation of slaughter time

Management option description: The option is intended to reduce radionuclide activity concentrations in meat, by changing the slaughter time to a season of the year when the contamination level is at its lowest. The option applies to animals with large seasonal differences in diet and radionuclide intake, including animals released onto pastures for part of the year. Free ranging animals may graze areas where highly contaminated fungi or lichen can be abundant, leading to greatly enhanced radiocaesium activity concentrations in their muscle. Slaughter can be early/advanced or postponed to avoid the resulting seasonal peak of radiocaesium contamination in meat.

Effectiveness: The effectiveness of the option is highly variable. After the Chernobyl accident, a 3- to 4-fold reduction in reindeer meat contamination was obtained in Norway by slaughtering in autumn instead of in winter [165]. Similarly, in extensive farming conditions in the former USSR, a 1.5- to 4-fold reduction was obtained by postponing slaughter of cattle grazing low productivity pastures within forested areas (with abundant fungi) [64, 65]. The effectiveness depends on the magnitude of the seasonal increase which usually coincides with slaughter and the radiocaesium activity concentrations normally present [49, 58, 64].

Feasibility and cost: A change in slaughter time may result in changes in animal numbers in farms, which could cause logistical problems with regard to accommodation and also have implications for animal welfare. If the change in slaughter time brings about a need for additional feed, the option is a variant of clean feeding with associated costs for feed and animal maintenance. A change in quality of animal products (e.g. meat, pelt) may be associated with a change of slaughter time, and compensation may need to be provided.

Side effects, social aspects and constraints: Changes in the vegetation/landscape may occur if there are prolonged alterations in grazing pressure. Some environmental protection schemes limit grazing intensity at certain times of the year [33, 37, 58]. Changing slaughtering periods can have an impact on the annual cycles of farming and herding, which may affect the need for manpower and the provision of feed over longer periods, etc. Markets may be prone to seasonal gluts and shortages [37].

4.1.4.6. Selective grazing regime

Management option description: Pastures can be classified with respect to predicted radionuclide activity concentrations in plants based on available soil monitoring data. This allows farm animals to be moved to pastures with lower contamination in the herbage. This can be done on a long term basis or at appropriate times before slaughter to allow contamination levels in the meat to fall to below the action level at slaughter (see also clean feeding options). Livestock can also be physically excluded from highly contaminated areas by the erection of temporary barriers, such as electric fences. Selective grazing regimes were used widely in regions of the former USSR affected by the Chernobyl accident [12, 34, 49]. This would most efficiently be carried out within a farm, but could also include moving animals much larger distances. Such long distance transfer may be a normal part of farm management. The principles of moving livestock to less contaminated lowland pasture was similar to the normal system used in upland parts of the United Kingdom contaminated by Chernobyl fallout. Movement from upland to lowland pasture resulted in sheep losing their radiocaesium with a half-life of about 10 d [58, 166]. The system was allowed to proceed with restrictions placed on movement and slaughter based on measured radiocaesium levels in the upland flocks, using a live monitoring scheme. The scheme aimed to ensure that lamb meat had radiocaesium activity concentrations below the action level to maintain public confidence in lamb.

Effectiveness: The effectiveness of the option depends on the availability of pastures with lower radionuclide activity concentrations in herbage and on the ratio of activity concentrations of radionuclides in herbage on the former contaminated pasture to those where the animals are transferred. The effectiveness of selective grazing ranges from 2- to 5-fold, according to data from the former USSR [33, 34, 49, 141, 146].

Feasibility: The capability to implement this option depends on the availability of data on radionuclide activity concentrations in, and characteristics of the soil, and associated relevant transfer parameter values [51, 52] for corresponding herbage.

Cost: Additional costs include those for transport of livestock to areas with less contaminated pastures and construction of fences to restrict access of animals with high fodder contamination, if required. Temporary barriers, such as electric fences, can be used to restrict access of animals to contaminated land, and may also be required for transport of livestock to areas with less contaminated pastures. Compensation costs to farmers for the extra labour required in moving animals to less contaminated pastures as well as for lost grazing areas may be required [37]. However, it may be more cost efficient to treat contaminated pastures to reduce uptake by plants.

Side effects, social aspects and constraints: There are possible changes in landscape due to low levels of grazing of contaminated pasture and associated changes in biodiversity. Changing slaughtering periods can impact on the annual cycles of farming and herding which may affect the need for manpower and the provision of feed over longer periods, etc. There may be restrictions on where temporary fences can be erected in protected areas, such as national parks [37].

4.1.4.7. Administration of additives to animal feed

Feed additive management options have currently only been developed for radiocaesium and radiostrontium, and intensive or extensively managed agricultural animals. Two main types of additives are used. For radiocaesium, a binding agent which prevents radiocaesium being absorbed in the gut can be administered. These additives are most often used to prevent animals becoming contaminated. Some of these compounds can be highly effective and were used extensively after the Chernobyl accident. For radiostrontium, the intake of a competing cation, calcium, is increased to reduce uptake in the gut of radiostrontium. In the latter case, the efficiency and rate of decontamination will depend on the extent of binding or competition, as well as the biological half-life.

The management options which involve the administration of a novel compound, such as some natural sorbents or other Cs binders, may be perceived as ‘unnatural’ and face resistance from farmers. However, stakeholders may consider that the use of additives for animals, even if they have some concerns regarding their application, is preferable to substantial, long term changes in farming systems. Some management options for animals may be perceived as impacting on the ‘natural’ perception of some products (e.g. meat from free ranging animals). Similarly, changes in management may lead to the loss of status for farms registered in ecological schemes (e.g. ‘organic’ farms).

Administration of natural sorbents to feed

Management option description: Natural sorbents, including clay minerals, such as bentonites, vermiculites and also zeolites, bind (or sorb) onto caesium ions. Therefore, when added to feed, preferably by being incorporated into a concentrate mix (at 5 or 10%), they can reduce gut uptake of radiocaesium by livestock [55, 57, 60]. These binders, therefore, reduce activity concentrations of radiocaesium in the meat, milk, offal and other animal products. The method is most appropriate for animals which are frequently handled, such as dairy ruminants. Bentonite was used in the former USSR and Norway (where it was used for sheep, goats and reindeer [167]) during the first year after the Chernobyl accident, when it was incorporated into concentrates for sheep, goats, cattle and reindeer. Administration of natural sorbents can also be used to decontaminate animals prior to slaughter. In Sweden, bentonite was used in conjunction with clean feeding [168, 169], but the cost was considered to be high relative to the additional ‘effect’ over clean feeding so the practice was discontinued [169].

Effectiveness: Natural sorbents originate from different sources, have different binding capacities for Cs and, therefore, vary in their ability to reduce transfer of radiocaesium to animal products [60, 170, 171]. Data on binding rates are not available for many types of such materials. Effectiveness varies with the type of sorbent and the amount administered, with reduction factors varying up to 8-fold [60]. For bentonite, reductions of about 2-fold in milk and meat radiocaesium activity concentrations can be achieved by a rate of about $0.5\ \text{g} \cdot \text{kg}^{-1}$ live weight $\cdot\ \text{d}^{-1}$. A maximum reduction of about 5-fold can be achieved at an administration rate of $1\text{–}2\ \text{g} \cdot \text{kg}^{-1}$ live weight $\cdot\ \text{d}^{-1}$ [37] but these high rates may have side effects (see below). The option is only effective if the method of administering the natural sorbent ensures that the daily consumption of the binder is adequate, and that dietary intake rates by the treated animals are not reduced. If used for decontamination, the rate of loss of radiocaesium will depend on the initial radiocaesium activity concentration and the biological half-life in the animal.

Feasibility and costs: Natural sorbents, such as bentonite and zeolites, are extensively quarried and used on an industrial scale for many different applications, including incorporation into animal feed, for instance, to reduce scouring (diarrhoea). A factory to incorporate natural sorbents into pelleted feed rations during manufacture is required. A period of adaptation to pelleted feed may be required. If incorporation into concentrate mix is not possible, farmers/herders could add natural sorbents to feed as long as guidance were provided. Daily administration of natural sorbents is impractical for free grazing animals unless the animals can be confined to enclosures which may be feasible for a short time period.

Side effects, social aspects and constraints: There may be animal welfare issues associated with feeding high quantities of natural sorbents, such as a reduction in trace element absorption [172]. The reduction of radionuclides in cow milk or meat increases as the rate of administration increases, but administration rates exceeding 900 g/d do not seem to enhance effectiveness. Furthermore, refusal to consume the sorbent, and an associated loss of appetite and weight have been observed if too much sorbent is given [168, 173]. It may be necessary to provide animals with additional water [60]. The use of natural sorbents may encounter resistance from the public/farmers due to animal welfare issues. A possible trace element deficiency in pastures may occur if ‘large’ quantities of sorbents are spread onto land with slurry/manure. The addition of sorbents to feed was one of the options preferred by most stakeholders in the

EURANOS project [7, 37] as it was thought to sustain farming practices and cause a minimal impact on the environment. Bentonite is a legal feed additive in some countries to prevent scouring although labelling may be required.

Addition of hexacyanoferrate to feed for animals

Management option description: Hexacyanoferrate compounds (also known as Prussian blue) are radiocaesium binders which may be added to the diet of livestock to reduce radiocaesium transfer to milk, meat and other animal products by reducing absorption in the gut. The form most commonly used for remediation is ammonium ferric hexacyanoferrate (AFCF). The binder can be used readily within normal agricultural practice and is most suited to animals which are frequently handled. Dairy animals can be readily treated when the animals are being milked. Meat producing animals would only need to be fed AFCF for a suitable period prior to slaughter. In a similar manner to decontamination clean feeding, the rate of loss of radiocaesium from the animal would depend on the biological half-life. AFCF was used extensively after the Chernobyl accident in the Russian Federation and Belarus (where it was called ferrocyn) as well as in western Europe (Norway and Sweden).

Effectiveness: Hexacyanoferrate compounds are highly effective binders of radiocaesium and relatively small amounts need to be given to the animals [170, 174, 175]. AFCF supplements can be added to the diet of animals as a powder mixed with the feed (as often happened in the former USSR after the Chernobyl accident) or be incorporated into pelleted concentrate, as happened in Norway [167]. Administration rates and associated reduction factors from the former USSR are given in Table 3. Administration of AFCF is a cost effective option [176] and was one of the most effective management options used in Norway and the former USSR after the Chernobyl accident [12, 39, 49, 176].

Feasibility and cost: There are costs associated with hexacyanoferrate production and provision. Currently, AFCF used for this purpose is manufactured in Germany, Belarus and the Russian Federation.

Greater effectiveness may be achieved if animals are given commercially prepared concentrates with AFCF incorporated due to the better control of required intake rates. Farmers may have to pay higher costs for manufactured, modified concentrate, so they will need to be compensated for the difference compared with normal concentrates. Effectiveness may be more variable when AFCF powder is mixed with farm produced feed. Farmers need to be trained to ensure that AFCF is mixed adequately if this is carried out on the farm, so that the required daily dose is consumed by the livestock.

Side effects: Toxicological studies have shown that AFCF has no adverse effects on animal or human health [170, 175, 177]. While some soils may contain

TABLE 3. ADMINISTRATION RATES AND ASSOCIATED REDUCTION FACTORS FOR AFCF IN THE FORMER USSR [12, 49, 167, 174, 175]

Livestock	AFCF administration rate (g/d)	Reduction factor
Sheep	1	5–8
Goats	1.5	3–4
Dairy cows	3	3–5
Bull calves	3	4–5
Pigs	1.5–2	4–6
Chickens	1.5	3–5

bacteria or fungi capable of degrading AFCF to its components, which include cyanide, toxic levels of this compound should not arise under field conditions. Faeces from treated animals will be more contaminated than from untreated animals which can lead to a higher external dose for people handling the manure from housed farm animals. However, this did not reach levels of concern, in practice, after the Chernobyl accident. A beneficial side effect is that radiocaesium uptake in plants from soils fertilized with manure from treated animals is lower than that from soils fertilized with manure from untreated animals [178]. The use of AFCF will possibly change the production status of farms, such as those that emphasize their ‘natural’ status.

Social aspects: Communication is needed to inform farmers of the benefits of using AFCF as some people may be discouraged by the presence of cyanide or simply by the blue colour of the additive (which is not so evident when mixed into concentrate at a factory). Furthermore, there may be some reluctance by farmers to administer AFCF because it could be perceived as an unnecessary additive. Public reassurance may also be required to show that milk and meat did not contain AFCF or its breakdown products and that there are no toxicity concerns. Generally, stakeholder reaction to this measure varies, but farming groups have supported the option provided they were satisfied that there were no long term effects or animal suffering.

Constraints: Permanent authorization has been given by the European Union and for affected former USSR countries for AFCF to be used as a feed additive for the purposes of binding radiocaesium. AFCF cannot be fed on a daily basis to free-grazing animals. Methods of doing this are considered in the management option below. Some of the description and comments for this option also apply to the use of hexacyanoferrate in boli and saltlicks described below, so that they are not repeated in these subsequent sections.

Administration of AFCF boli to ruminants[15]

Management option description: Slow release boli containing AFCF have been developed to reduce the gut uptake of radiocaesium in ruminants in agricultural and semi-natural environments where animals are infrequently handled [167]. The objective is to reduce radiocaesium activity concentrations in meat and milk to below action levels. The boli are produced by compression of a mixture of AFCF, barite and wax. To ease swallowing, the boli are immersed in liquid paraffin prior to administration. The boli (normally 2–3) are inserted into the rumen and gradually release AFCF. The release rate of AFCF follows first order kinetics. Boli are particularly suitable for free-grazing ruminants and can be administered when they are gathered for routine handling operations. A particular benefit of using AFCF boli is that normal animal management/grazing regimes can be maintained in extensively farmed areas. In Norway, AFCF boli were given to ruminants 2–3 months prior to slaughter for meat producing animals [167]. For milk producing animals, boli are given at varying intervals depending on the species. In the former USSR, dairy cows were given 2–3 boli every 6–8 months, which achieves a reduction factor of two to four [174].

Effectiveness: AFCF boli are potentially highly effective, providing a 2- to 5-fold reduction in different types of animals. Effectiveness is rather variable — some treated animals can regurgitate boli after administration, thereby reducing the effect. Furthermore, some animals may be missed when they are being collected for administration of the boli. Thus, marking treated animals helps to identify untreated individuals. The effectiveness of boli declines with time and these should be applied every 2–3 months to maintain the effect. The presence of a wax coating delays the release of AFCF and enhances the long term effectiveness. Hence, coated boli may be more appropriate for some management systems.

Feasibility and costs: The AFCF boli cannot be used for monogastric animals such as pigs. Factory infrastructure is required to manufacture AFCF boli. Currently, there are no commercial facilities making AFCF boli within Europe and production is generally carried out by research associated organizations. For sheep, cows and goats, the farmer can administer by hand or adapt dosing guns used for other intra-devices, so they require little additional training. For reindeer, a specifically designed instrument is needed for placing the bolus in the rumen because of the reindeer's narrow oesophagus. In Norway, the involvement of a veterinarian is required as reindeer deaths occurred due to incorrect usage of the device. Boli must be an appropriate size to administer to the

---

[15] See previous option for generally applicable information about hexacyanoferrates.

target group of animals. For instance, standard Norwegian sheep boli were too large to be administered to hill lambs in areas of the United Kingdom affected by the Chernobyl accident. Smaller boli were developed and tested, which required increasing the AFCF content to a feasible maximum while maintaining the integrity of the boli [57, 179]. Costs include hexacyanoferrate production and incorporation into the boli. Labour costs may be associated with collecting and returning the animals to their grazing areas and for boli administration (which may require about 0.5–1 min per animal). There are additional costs for boli administration if veterinarians are required.

Social aspects and side effects: Boli are used for medical and other purposes in livestock farming and will be familiar to many farmers, so they are likely to be acceptable. For farmers who do not routinely use boli, this option may be more problematic and the use of boli would need to be explained and demonstrated. Farmers, their unions and welfare organizations would need to be satisfied that there were no long term effects or animal suffering.

Distribution of saltlicks containing AFCF[16]

Management option description: Hexacyanoferrate can be added to saltlicks (at 2.5–6%) [167]. This may assist in allowing normal animal management/grazing regimes to be maintained, especially in inland salt deficient areas where saltlicks are normally placed on pastures to supplement the salt of grazing animals. The distribution of saltlicks in areas with contaminated game may also be implemented. Theoretically, the same approach could be used for feed blocks. Saltlicks with AFCF were used in the former USSR and Norway after the Chernobyl accident.

Effectiveness: Incorporation of AFCF into a saltlick reduces radiocaesium uptake by up to 2-fold for a flock or herd. However, there is considerable variation in effectiveness between animals due to varying rates of using the saltlicks. Effectiveness is greatest in areas of salt deficiency, and the option is only worth considering in such areas. Live monitoring of animals prior to slaughter is comparatively important for this option due to the variation between animals in the use of saltlicks.

Feasibility and cost: Manufacturing plants, which normally produce and distribute saltlicks, have to be willing to incorporate AFCF into their saltlicks that are sent to the affected areas. There are costs of hexacyanoferrate incorporation into saltlicks which can be significantly more expensive than normal versions,

---

[16] See previous options for generally applicable information about hexacyanoferrates.

especially if there are additional transport costs. The use of saltlicks is one of the few feasible options for game.

Side effects and constraints: Using saltlicks containing AFCF will possibly change the production status of farms, such as those that emphasize their ‘natural’ status.

Addition of calcium to concentrate ration

Management option description: The absorption of radiostrontium from an animal’s diet is controlled by the level of dietary Ca intake and the animals’ requirement for Ca. Enhancing the intake of Ca relative to the Ca status of the animal will reduce the transfer of radiostrontium into milk. Therefore, additional Ca (e.g. as calcium carbonate) may be added to the daily ration of lactating animals to reduce radiostrontium transfer to milk [33, 57, 146, 180]. This can be achieved by: (i) mixing Ca with the concentrate ration; (ii) feeding pelleted concentrates with enriched levels of Ca; or (iii) feeding crops with naturally high Ca concentrations such as legumes [33, 146]. Increasing the Ca intake of animals was carried out extensively after the Kyshtym accident in the former USSR.

Effectiveness: Doubling Ca intake results in roughly a 2-fold reduction in the transfer of radiostrontium to milk as the absorption of radiostrontium (and, hence, transfer to milk) is inversely proportional to Ca intake [146, 154]. It may be beneficial to incorporate enhanced Ca into pelleted feeds during manufacture as ingested Ca intakes can be quantified more accurately [33, 146, 154, 180].

Feasibility and cost: Calcium sources are readily available and cheap. In many countries, farmers will know the Ca intake of their animals (from both commercial and home grown fodder). Such knowledge would facilitate the optimal use of Ca at each farm. In some countries, especially those which do not have intensive farming systems, it is likely that the Ca intake of animals could be doubled without exceeding advised levels (see below). Compensation may be payable for the extra costs associated with Ca added to the ration; such costs could be higher if Ca were incorporated into purchased concentrates. Daily Ca supplementation is not feasible for free-grazing animals [37].

Side effects and social aspects: No adverse effects would be expected if advised Ca intakes (1–2% of dry matter intake) are not exceeded and the dietary Ca:P ratio should not exceed 7:1 for prolonged periods [33]. This is important since high levels of Ca intake can influence the absorption of other essential nutrients. As administration of calcium supplements to livestock could affect animal health, there may be some reservations among the farming community which would need to be consulted and have access to the required information on the Ca status of their animals [37]. However, the enhancement of Ca intake was used for many years in the former USSR after the Kyshtym accident and was considered acceptable by the farming community and local consumers [146, 154].

Administration of alginates

Management option description: Alginates can be administered to agricultural animals to reduce the transfer of ingested radiostrontium to milk. Alginates are structural carbohydrates consisting of polymerized mannuronic and guluronic acids, and are present in brown seaweeds. Alginates should be incorporated into concentrate pellets for administration to animals to ensure palatability. The use of alginates was tested experimentally after both the Kyshtym and Chernobyl accidents but has not been applied as a management option.

Effectiveness: Alginates have been shown to be effective strontium binders in both monogastric animals and ruminants. Alginates reduced the transfer of radiostrontium to milk by 1.5- to 1.7-fold without affecting diet palatability [180]. Alginates with lower mannuronic:guluronic acid ratios have greater strontium binding capacity [180] but few experimental data are currently available to identify the most effective alginate to use as a binder in agricultural animals. Some studies report higher effectiveness but this may be due to an enhanced Ca intake associated with the alginate itself.

Feasibility and cost: Commercial varieties of alginate are extracted from brown seaweed, including the giant kelp and *Laminaria*. Alginates are widely used for many different applications and are approved as feed additives in many countries. However, currently tested sources of alginate would not be cost effective [180] and more research is needed to test the many different available forms to identify a suitable, cost effective source.

Side effects: Side effects of alginate consumption are not expected as ruminants can utilize the structural carbohydrates of seaweed, and calcium alginate has previously been demonstrated to be fermentable by the rumen microbiota of dairy goats [181]. Alginates should not be administered in the form of a viscous gel which is unpalatable to animals and reduces dietary intake [182].

4.2. NON-AGRICULTURAL SYSTEMS

4.2.1. Aquatic ecosystems

As in agricultural systems, the uptake of radiocaesium and radiostrontium in aquatic ecosystems is strongly influenced by competition from their stable element analogues, potassium and calcium, respectively. For a given radionuclide activity concentration in water, the uptake to fish is inversely proportional to the calcium content of water for ^{90}Sr [183] and to the potassium content for ^{137}Cs [184, 185]. Addition of calcium or potassium based materials has, therefore, been tested as a measure to reduce radiostrontium or radiocaesium concentrations, respectively, in fish. The first two options consider the addition of these elements to water bodies and have some features in common which are described in the first option (lime), but are not repeated in the second (potassium).

4.2.2. Application of calcium or potassium in aquatic systems

4.2.2.1. Addition of lime to lakes or catchments

Management option description: The uptake of radiocaesium and radiostrontium in freshwater fish can be reduced by lime added either to the lake water directly (and in the winter period to the frozen surfaces of a lake) or to part of all of the catchment areas for affected water bodies. For lakes, the Ca level, pH and alkalinity of the lake would need to be raised considerably, but the duration of water chemical response may be relatively short, depending on the water residence time of the lake. For catchment application, a possible ‘liming spike’ is avoided and the duration of an effect considerably prolonged. There is considerable experience in application of lime in relation to acidification. However, such experience is rather limited for radionuclides. This measure was tested in Scandinavian countries after the Chernobyl accident [183, 186] but the measure has not been used extensively as a management option.

Effectiveness: The effectiveness is highly site specific and often low, and is likely to be more effective in lakes with long water retention times, allowing increased calcium concentrations to be maintained more easily. Effectiveness depends on water chemistry (e.g. initial Ca concentration, pH, total P concentration), amount and type of Ca applied, and water retention time. Modelling assessments show that a reduction of about 1.3- to 1.7-fold in fish could be obtained [61]. However, in Sweden after the Chernobyl accident, low reduction factor values of 1.05–1.1 were reported for perch fry [186]. Addition of lime in a lake in Finland [183] was not effective for radiostrontium in fish because a 2-fold reduction in the fish:water concentration ratio was negated by a corresponding increase in ^{90}Sr content in water, leading to no overall reduction in activity concentration in fish.

Feasibility and cost: Equipment is needed to deliver lime to the appropriate areas and may include helicopters, pontoon boats and fertilizer spreaders. Tractors could be used if liming were applied to frozen lakes. For large scale application, infrastructures such as an airport or landing strip are needed for helicopters, and roads for transport if boats or large fertilizer spreaders are used [37]. Application of lime to lakes can be costly dependent on the associated transport costs. Fishing in lakes and rivers does not tend to be associated with significant economic activity. Many people fish to provide food for their families and/or as recreation. Therefore, the application of lime may not be cost effective.

Side effects and social aspects: Liming of naturally acid systems can lead to profound, structural changes in the ecosystem. Potential negative ecosystem effects related to liming operation include: (i) wetland flora may be modified; (ii) bog moss may be replaced by leaf mosses and sedges; (iii) sensitive species (e.g. lichens) may be damaged due to wind drift of lime to adjacent areas (especially if using helicopters). Added calcium can compete with Sr in bottom sediments causing Sr to be returned to the water column [183]. Consequent increased water concentrations of radiostrontium might have an impact on water quality, and may mean that the lake water is not suitable to be used for irrigation or for other purposes. Conversely, the buffering capacity of lakes can be temporarily improved with liming, which has a stabilizing effect on a lake. The method is, therefore, beneficial for lakes (and food chains) that are susceptible to acidification. Catchment liming may lead to improved conditions for animals and plants in streams and rivers due to reduced transport of metals such as Fe and Al into the lake from the catchment area [61]. A potential impact on local industries, such as fishing or tourism as well as loss of amenity/social value, may be anticipated.

Constraints: Adding lime to water can be restricted by environmental protection regulations. The rationale for choosing this management option may need to be explained to the public as part of a wider communication and information strategy [37].

4.2.2.2. Addition of potassium to lakes

Management option description: The radiocaesium activity concentration in freshwater species may be reduced as a result of chemical dilution by adding potassium to lake water. Practical experience of this option has been gained in Sweden and Belarus, but has not been used extensively.

Effectiveness: The effectiveness is highly site specific and depends on water chemistry (e.g. initial K concentration, pH, total P concentration), amount and type of K applied and water retention time. For lakes with rapid inflow and outflow of water, many repeated applications would be necessary. A low effectiveness of 1.1-fold for perch fry was reported in Sweden after the Chernobyl accident [186]. Addition of potassium chloride to Lake Svyatoe, Belarus (a lake low in natural potassium content) was more successful [61].

The measure led to a 10-fold increase in the potassium content of the lake water and a 2- to 3-fold reduction in radiocaesium activity concentration in fish.

Feasibility and cost: see above for lime.

Side effects and social aspects: These are as above for lime with additional points described here. Potassium is a nutrient, so the countermeasure will alter the nutrient content of lakes. Application of mixed K, NH_4, P fertilizer may cause eutrophication, whereas K applied as KOH may increase the pH in lake water, though the potential importance of this has not been assessed — it may be minor. Application of potassium leads to increased radiocaesium activity concentration in water (in one experiment, by about 3-fold [184]) due to competition with K in sediments, making it unlikely to be acceptable if water is used for drinking or irrigation.

Constraints: Adding K to water can be restricted for many water bodies. The addition of nitrates, phosphates and sulphates should be avoided due to the side effects.

4.2.2.3. Construction of dykes or barriers

Management option description: Construction of dykes or barriers between rivers and floodplains prevents the remobilization and runoff of contaminants and can, thus, decrease long term radionuclide transfer to rivers or lakes [61, 63]. Dykes were used for aquatic ecosystems in the Chernobyl area (Pripyat river floodplain) to limit the additional contamination of water from contaminated floodplains. A protective dyke on the Pripyat floodplain successfully reduced radiocaesium and radiostrontium activity concentrations downstream of the Kiev reservoir after Chernobyl [63]. However, since the dyke only had an effect during relatively rare flood periods, its cost effectiveness is open to question [61].

Effectiveness: The effectiveness is highly site specific and depends on the size of the contaminated area(s) prone to flooding, frequency of (major) flood events, and size and extent of the dyke. Overall, the effectiveness of the option is low for large scale use because only a small additional fraction would be prevented from entering the waters through dykes or barriers compared with the total amount of radioactive material deposited in aquatic ecosystems and their catchments.

Cost, side effects and constraints: The application of the option can have significant adverse effects on floodplain ecology. Cost–benefit analysis is essential in advance of such a large project.

4.2.3. Forest ecosystems

There are relatively few effective and practical measures that can be carried out in forest ecosystems. However, the importance of forests can increase with time for radiocaesium due to its high, sustained transfer into game animals and mushrooms [27, 48, 57, 64, 187]. While restriction on access to forests and consumption of forest products may be effective for a few years, it is unlikely to be sustainable in the long term. Therefore, the provision of advice about external doses, which products are likely to be contaminated and the availability of monitoring stations to measure contamination is probably a more practically realistic approach to consider. It also allows people to make their own well informed choices about the intake of radiocaesium [48, 145, 182].

4.2.3.1. Forest soil treatment with fertilizer

Management option description: As for agricultural soil, surface application of fertilizers (NPK or PK) in the forest can reduce root uptake of radiocaesium by vegetation and increase plant growth [64, 188, 189]. This option was tested in the former USSR after the Kyshtym and Chernobyl accidents, but was not used on a large scale [48, 64, 189].

Effectiveness: Typical reduction factors of 1.5–2 can be observed; however, the effectiveness is highly site specific [64, 189]. Fertilizer application is generally more efficient in boreal forests than in Mediterranean forests, and is fairly efficient in deciduous forests. Major environmental factors influencing effectiveness include: (i) soil characteristics (e.g. organic matter content, clay content, basic cation supply, nutrient status); (ii) type and age of forest; (iii) plant species present [189].

Feasibility and cost: Equipment to deliver and to spread the fertilizers in the forest is required and may include helicopters, tractors and fertilizer distributor devices. Therefore, some infrastructure, such as airports or landing strips and roads, in the forest for transport may be required. Application of lime to forest soil can be expensive because of the high transport costs.

Side effects and constraints: Increases in nutrient status of forest soil may have an impact on forest ecosystems, including a reduction in biodiversity and replacement of one forest species by others. The use of fertilizer in forest ecosystems may not be allowed within some environmental protection schemes. The need to gain access to affected, and potentially extensive, forest areas is also a significant constraint.

4.2.3.2. Modification of tree felling schedules

Management option description: The management option is based on changes in the timing of tree harvesting, intermediate felling and other forest services. The aim is to minimize root uptake of radiocaesium and radiostrontium in stem wood, or to delay wood harvesting to let processes such as soil immobilization, vertical migration down the soil profile or physical decay of radionuclides reduce the contamination in the wood. Early felling is most suitable for mature or nearly mature trees soon after the time of contamination, while delayed felling is most suitable for young trees reaching maturity about 20 years after contamination [64, 187, 188].

Effectiveness: The effectiveness depends on factors such as which radionuclides dominate in the long term and their activity concentrations in the forest, and forest characteristics such as age of trees, productivity, forest soil, type of understory, etc. A model approach (including early and delayed felling), presented in Frissel et al. [187], can be used in assessment of long term contamination patterns in wood. Overall, reduction factors assessed based on the model approach for early felling can reach 2- to 10-fold, while delayed felling can lead to a reduction as high as 1.5- to 2-fold compared to the normal felling programme.

Feasibility: Measurements of radionuclides in growing forests and modelling assessments of variation in contamination of wood with time are essential for adequate guidance of when to fell trees. A well parameterized forest model describing contamination of wood would be helpful in assessment of the effectiveness of the option and to justify such remediation. Feasibility may be limited for mature trees due to increasing activity concentration in wood (10–20 years after fallout) and a possible increase in the frequency of root rot in ageing stands, leading to a loss in revenue [37, 48, 64].

Side effects and social aspects: Intermediate cutting or thinning will improve the growth rate of trees remaining on-site and can, thereby, dilute radionuclide activity concentrations in wood [64]. There is a possible loss of employment/income from reductions in forest industries which may necessitate supporting forestry and associated communities [37].

Cost and constraints: Divergence from standard forestry practice can result in economic losses because of delays, losses or additional costs in harvesting the timber. Increased transport costs are also expected if nearby areas cannot be used as sources of wood for industry. Forestry operation plans may need to be approved by the regional forestry administration. Markets may experience seasonal gluts and shortages, so alternative wood sources to compensate for the delay in harvesting should be available. If large forest areas are clear-felled, the hydrology of the site must be considered, especially with respect to possible erosion in the catchment [37].

4.2.3.3. Change of hunting season

Management option description: Due to seasonal variation in diet, radiocaesium contamination of some game species varies significantly with season. In particular, radiocaesium activity concentrations in muscle of game from areas where fungi can be abundant in certain years can be much higher than the average annual values [64, 65, 190–194]. Hunting is usually restricted to certain periods of the year. By changing or restricting the hunting season to the time of year when the contamination levels in the game meat are not enhanced due to dietary preferences, the internal dose to humans consuming game meat can be reduced. A change of hunting season was used in the former USSR and some Nordic countries (such as Norway and Sweden) following the Chernobyl accident [48].

Effectiveness and feasibility: Varying hunting times can achieve a 2- to 3-fold reduction of radiocaesium activity concentrations in moose meat, with even higher reduction factors, up to 4- to 6-fold, for meat from roe deer, wild boar and wild reindeer. Effectiveness is greater if the fungi produce large quantities of mushrooms, a phenomenon which does occur in the autumn of some years [64]. Different seasons may require alternative equipment, for instance, when game is transported out of the hunting area [37, 48].

Side effects and social aspects: The impact of changes in hunting season on breeding should be considered for each species. The continuous management of large game animals through hunting licences is important in controlling the populations of game animals at sustainable levels. It is, thus, important to continue hunting or recommence hunting as soon as possible after contamination occurs. Increased grazing on adjacent agricultural land may occur if the hunting season is delayed. If hunting is performed earlier than normal, lower slaughter weights may be anticipated. If hunting is restricted to winter, harsh climates may make hunting less attractive in some countries. Reduced financing of game management due to cancellation of hunting licences for big mammals may occur. Some traditional seasonal activities may be lost or affected [37].

Constraints: Existing hunting seasons have a legal status in most countries. For instance, in European Union countries, hunting seasons are strictly based on biological and ecological factors for various categories of game animals and, therefore, prolonged seasons do not apply. The changed hunting season must not coincide with breeding and other seasons sensitive for animal populations [191].

4.2.3.4. Optimization of forest management

Management option description: Forests can be classified on the basis of monitoring data for radionuclide activity concentrations in soil and wood, and on forest soil properties [48, 65]. Logging may be transferred to areas with low external doses and to areas with lower radionuclide activity concentrations in wood. The same approach can be used for other forest products [64]. Recommendations on tree felling and gathering of mushrooms or berries in areas of the former USSR affected by the Chernobyl accident are largely based on such an approach and led to lower external doses to foresters or other people gathering food in the forest, as well as substantial reductions in internal dose due to radiocaesium [48, 188, 189].

Effectiveness: The effectiveness depends on differences in contamination densities between forest sites. A reduction of the external dose of 2- to 3-fold may be achieved. For forest products (harvested wood, berries or mushrooms), reductions of 2- to 5-fold are achievable [64, 188, 189].

Cost, side effects and social aspects: Implementation will involve some compensation costs because of changes in planned forest activities [188]. Additional cost for transport of wood from less contaminated areas may be required. Possible economic losses of forest products may also be anticipated. Detrimental ecological effects arising from the retention of old and damaged trees may be anticipated, and the cost effectiveness of the forest economy and associated industry can decrease [189]. Negative social and psychological impacts caused by partial loss of traditional activities may be anticipated that are associated with, for instance, the loss of cheap or free natural food sources for people using the forest [189].

Constraints: Optimal forest management is only possible if there are sites available with adequately low levels of contamination within the area of responsibility of the authority responsible for forest management [189].

4.3. GENERALLY APPLICABLE OPTIONS

4.3.1. Selection of alternative land use

Management option description: Contaminated land may be used for crop production instead of animal production (milk and meat) or for non-food production, such as cotton/flax for fibre; rapeseed for biodiesel; sugar beet for bioethanol; perennial grasses or coppice for biofuel. Agricultural land may also be used for the production of leather and wool. In situations where the land is highly contaminated, it may be used for forestry or the placement of suitable industrial enterprises. Selection of alternative land use, such as the options listed above, was used in the former USSR following both the Chernobyl and Kyshtym accidents [12, 39, 48, 50].

Effectiveness: The ingestion pathway is no longer relevant since inedible crops have replaced crops grown for the food chain. The option is, therefore, almost completely effective if alternative uncontaminated foodstuffs are supplied and there are no higher external on internal doses associated with the alternative land use. The efficiency of alternative land use is affected by the extent of available expertise in growing alternative crops and supporting different livestock. There needs to be evidence of the profitability of proposed alternative products in advance of investment and access to alternative relevant food sources.

Feasibility: The ease of substitution of non-edible crops for farmers and associated industries needs to be considered. Acceptability of alternative crops or livestock to farmers is also important to justify and implement this option. Other special techniques for sowing/harvesting may be necessary for the alternative land use. Other issues to be considered are availability of: (i) seed stock of alternative crops; (ii) alternative livestock; (iii) animal feed; and (iv) expertise in cultivation of alternative crops and livestock. Respiratory protection for farmers should be considered if environmental conditions are dry. There must be a market for the new products.

Waste: The amount and properties of waste depend on the non-food crop selected and the production process. In particular, contaminated by-products from, for example, the refining of rapeseed and sugar beet to biodiesel and bioethanol may be generated in processing plants.

Side effects and social aspects: The option may lead to changes in environmental characteristics and dominating crop types. Redistribution of dose from consumers to those involved in producing and using alternative crop and animal products will also occur. The acceptability to processors and the public of using contaminated crops/animal products to make non-food products needs to be considered as markets may be limited for the alternative products. In communities affected by overproduction, the associated diversification may be advantageous. Alternative practices may not be as economically viable or profitable as those used previously (e.g. wool and leather production versus normal animal production regimes).

4.3.2. Topsoil removal or replacement

Management option description: The top few centimetres of soil can be removed using road construction equipment, such as graders, bulldozers, front end loaders, excavators and scrapers or a turf harvester. Removal of the upper soil will remove much of the contamination. The depth of the soil layer which can be removed depends on the thickness of the fertile layer of contaminated soil and the radionuclide content of any remaining ‘clean’ soil from the fertile layer used to replace that removed [39]. If the original depth of the fertile soil layer is not sufficient, the removed soil would need to be replaced by fertile soil with acceptably low radionuclide activity concentrations (topsoil replacement). The removal of much of the contamination at the surface will greatly reduce (i) radionuclide uptake by plant roots, (ii) external exposure and (iii) resuspension of radionuclides from the soil [39]. Topsoil removal (or replacement) was used as a management option in the former USSR following the Chernobyl accident, in Spain after the Palomares incident and in some other countries including Brazil after the Goiânia incident [12, 39, 49].

Effectiveness: The reduction of contamination of the soil can reach 10- to 100-fold, if optimized according to the contaminant distribution in the soil. Furthermore, the reduction in soil–plant transfer can be 10- to 20-fold [39, 49, 111, 112]. In some cases, it may be advantageous to remove part of the vegetation cover before removing the layer of soil. The efficiency of removal of the surface layer may be affected by the degree of optimization achieved in a wide range of factors. These include: (i) estimating the thickness of the removed layer, (ii) surface unevenness, (iii) presence of rock and stones, (iv) soil texture and moisture content, (v) vegetation cover, (vi) vertical radionuclide distribution, (vii) operator skill in ensuring contamination is not ploughed into the uncontaminated soil surface during removal, (viii) acceptability of implementation to farmers and the public, and (ix) appropriate selection of priority areas [37].

Feasibility: Removal of the surface layer requires specialized techniques and equipment, some of which might be readily available. Soil moving machines can be used to efficiently remove soil horizons (root mat, soil, etc.) as thin as 5–15 cm or thicker than 35 cm and transport the soil distances of 150 m without reloading or stopping. Roads and vehicles to transport waste are required. Importantly, facilities and sites suitable for waste disposal should be organized which can accommodate the amounts of contaminated waste generated [111]. The topsoil removal (and replacement) option can be carried out by appropriately skilled operators, such as municipal workers and other operators who could be instructed within a day [49]. The required safety precautions include respiratory protection (tractor cabin pressurization, respirators) in very dry conditions, and dose limits for workers should be assessed and established. A key element to prevent the spread of contamination during earth removal is dust suppression which can be achieved by water sprays [37].

Waste: Removal of the surface layer forms a large volume of contaminated waste. For example, if 5 cm of topsoil is removed, 60–70 kg/m^2 of waste would be produced from an area of 1 ha which would have a volume of 500 m^3 and a mass of about 700 t [37]. Factors influencing waste management include:

(i) contamination level of waste, (ii) volume of waste, (iii) acceptability of waste disposal options, and (iv) location of disposal site, especially if it is outside the contaminated area. Disposal of radioactive waste should be carried out according to the regulations of the affected country. When the amount of waste is taken into consideration, this management option is only readily applicable on a small scale [49].

Side effects and social aspects: There is a potential for redistribution of dose to workers, as well as inequity due to redistribution of dose from communities in contaminated areas to those living close to waste disposal areas. There may also be soil erosion associated with disruption of the soil structure and depth. Ecosystem effects include impacts on soil biota and associated decomposition processes, loss of biodiversity and changes in landscape. All of the effects will be greatly enhanced if topsoil is removed but not replaced. Fertilization may be required to promote growth in newly established vegetation, even if soil is replaced [33]. The underlying soil may be compacted, making subsequent cultivation more difficult. There must be some prior consideration of criteria used to identify disposal sites and there is potential for disputes between stakeholders regarding the location of waste disposal sites. The removal of highly contaminated topsoil may be considered to be very important in some cultures and might, therefore, be prioritized despite the high costs and problems associated with waste disposal [66].

Constraints: Topsoil removal may be restricted under some environmental schemes due to changes to landscape and other environmental effects. Resistance may occur due to the burial of associated valued habitat components, such as rare or ecologically important flora and fauna. Soils that are shallow and stony cannot always be treated [37]. Soil structure can limit application of topsoil removal. It can be difficult to use large machinery on wet, peaty soils. On heavy clay soils, decontamination may be limited to times of the year when the soil is workable [49]. Sandy, structureless soils cannot be removed effectively as a thin layer.

4.3.3. Attenuation of external dose from contaminated soil

Management option description: The surface of contaminated soil can be covered by a layer of a ‘clean’ material (sand, clay, rubble, asphalt, concrete, soil, etc.) to reduce external irradiation and radionuclide resuspension. Covering the radioactive contamination at the surface is intended to reduce external exposure, resuspension and lateral migration of radionuclides. This is potentially important in rural working and inhabited areas (such as agricultural yards, farms, schools, etc.). The design of the covering system should be as simple as possible. Attenuation of contaminated soil was used following the Chernobyl accident in the former USSR and other countries [49]. Secondary contamination of sites adjoining contaminated territory where attenuation was implemented was very small, amounting to less than 0.1% per year of the radionuclide contamination density in the adjoining contaminated area [49].

Effectiveness: The efficiency of attenuation of contaminated soil is affected by the degree of optimization in the properties and thickness of the covering layer. Factors influencing the effectiveness include: (i) the characteristics of the material used according to the main aim (e.g. the density of the covering material — for reduction of external irradiation); (ii) the strength of a material — which affects the durability of the covering layer; (iii) water permeability — a low permeability will reduce radionuclide migration; (iv) radionuclide activity concentrations in the 'clean' covering materials; (v) rooting depths of different crops; and (vi) acceptability of the methods used to farmers and the public [49]. The reduction of contamination in the surface layer is normally about 9-fold or more, and the associated reduction in resuspension is up to 1000-fold. The reduction factor in external dose due to gamma radiation for a 20 cm cover soil layer is more than 10-fold [39].

Feasibility: The option is only applicable on a small scale as it requires large amounts of available uncontaminated materials to be used for attenuation. The machinery to place the covering material onto the soil should be commonly available. Roads and sufficient vehicles are needed to transport the 'clean' materials. The option can be carried out by appropriately skilled operators such as municipal workers and other operators who could be instructed within a day. The required safety precautions include respiratory protection (tractor cabin pressurization, respirators) that should be used in dry conditions, and dose limits for workers should be assessed and established [49].

Side effects: Changes in the physical characteristics of the surface of the ground will occur. Changes in landscape and potential ecosystem change/damage should also be anticipated, including impacts on biodiversity, particularly for soil dwelling organisms. Fertilization may be required [49].

Social aspects and constraints: There is a need for dialogue regarding selection of areas for treatment between farmers, scientists and the public which should clarify the costs and benefits to farmers and communities before decisions on implementation are made. Provision of information to operators on the correct application of the procedure is required. Future restriction on land use would include banning deep tilling of soil although subsequent normal ploughing at a depth less than the thickness of the clean covering layer will not bring much contamination back to the surface. Attenuation of contaminated soil may be restricted under some environmental schemes. Associated environmental effects are likely to be contested and resistance from farmers is possible [49].

4.3.4. Prevention of fire

Management option description: Forest fires may be an important source of radionuclide resuspension; for example, up to 5–10% of the ^{90}Sr and ^{137}Cs stored in forest (vegetation, litter and soil) could be released into the atmosphere during a fire [195–197]. This option is intended to prevent fires, and if fires start to prevent their subsequent spread, so that there is less risk of radionuclide resuspension and subsequent transfer to areas used for agricultural production. The risk of inhalation of radionuclides by resuspension from contaminated soil may also be decreased. The risk is particularly pronounced in dry areas, especially during summer [197]. In dry periods, closing forests and semi-natural areas to the public and banning any practices likely to cause fires (e.g. agricultural burning, campfires, etc.) would greatly reduce the risk of fire starting due to human negligence [188]. This ban would need to be actively policed and enforced. Some areas may be more at risk than others. Areas which are most prone to fires should be treated as a priority (e.g. railways, roads, electric lines, rubbish dumps). Measures taken would include [188]:

- Installing and maintaining concrete barriers, safety fences or netting;
- Widening the road hard shoulders;
- Improving inspection and surveillance networks;
- Organizing appropriate fuel management;
- Clearing dry vegetation from shrubland, semi-natural areas and adjacent to sensitive sites;
- Increasing readiness for fire fighting in affected areas;
- Ensuring rapid availability of fire fighting equipment and suitably trained personnel in the sensitive areas (in highly contaminated areas, the preference would be to use aircraft capable of deploying water over large areas).

Prevention of fire in forests, shrubland and other areas vulnerable to fire risk is normal practice.

Effectiveness: The effectiveness of the option is difficult to quantify but it is never completely effective as it is impossible to guarantee total closure of large contaminated areas, avoiding deliberate arson and accidental fires (e.g. due to lightening). Factors influencing the effectiveness of the procedure include provision of information, encouraging acceptability and willingness of the affected population to follow fire prevention guidance (e.g. cigarette butts, barbecues), adequate policing, extent of the contaminated area, number of access points, human and technical resources for monitoring and long term maintenance of contaminated areas, appropriate selection of priority sensitive areas, degree to which the management option diverges from normal practice, availability of water, acceptability of disposal/treatment procedures, and compliance and availability of operators to carry out procedures [188, 196, 197].

Feasibility: Prevention of fire in forests, shrubland and other sensitive areas is carried out on a regular basis. Operators (such as forest workers, drivers, wardens) would have the skills required for monitoring and clearing, but must be informed carefully in advance about the objectives and required safety precautions as would fire fighters, including aircraft crew. Safety precautions may include respiratory protection [197].

Waste: The option may generate some vegetative waste, including woody material. Normal treatment of waste, including recycling, would not be applicable to contaminated material. Possible reduction of waste by composting or incinerating could be considered. The amount of waste is highly dependent on the extent of the contaminated area, vegetation density, type and actual measures taken [188, 196].

Side effects, social aspects and constraints: Application of many of the measures listed above can lead to negative effects due to imposed restrictions on liberty and autonomy (such as the loss of the possibility to gather free food and wood). Modifying the management of forests may have negative effects on their ecological balance for plant and animal species. Preventing sensitive forest areas from catching fire will also prevent fires on agricultural land. Growth of wild animal populations due to restrictions on human usage and frequency within forests may affect agricultural productivity. Relevant legislation at national European levels concerning the management of fire risk in semi-natural and forest areas should be considered. Forest workers may be reluctant to perform tasks in the event of radioactive contamination because of the possibility of relatively high external exposure levels [188].

4.4. FOOD PROCESSING BASED OPTIONS

4.4.1. General issues for food processing management options

The activity concentration of radionuclides in food can be affected by industrial and domestic processes, such as extraction during boiling, removal of certain parts of the raw food (e.g. bran, peel, shell, bone) and drying or dilution [198]. Neglecting radionuclide losses during food processing can lead to an overestimation of the ingestion dose. Processing of raw materials of vegetable and animal origin is often the most effective option for reducing the radioactive contamination of the foodstuff to permissible (action) levels or below. High effectiveness can be achieved by many of the normal practices used in the preparation, cooking and processing of food, both domestically and in industrial processing of food. Experience gained after the Chernobyl accident has shown that many commonly used methods of domestic and industrial processing of food products result in significant decreases in contamination and, hence, of internal radiation doses to people [12, 49]. The effects of processing on contaminated food depend on the radionuclide, the type of foodstuff and the method of processing. The effectiveness of radionuclide removal from raw material during processing can vary widely, but can remove all of the radionuclide present (for instance, in the production of ethanol and vegetable oil) [198, 199].

In addition, standard food preparation techniques will be used irrespective of whether food is contaminated with radionuclides or not. Therefore, when evaluating the radiological impacts of routine releases, for instance in the context of optimization studies, consideration may need to be given to the degree to which doses are affected by food processing methods. Finally, the waste streams generated in food processing may be contaminated by radionuclides and the radiological impacts of disposal or recycling of this material, for instance in animal feed, may need to be addressed. Data on the behaviour of many radionuclides during food processing are scarce with the exception of radioisotopes of caesium, strontium and iodine. A summary on the efficiency of processing is provided in the IAEA's Technical Reports Series No. 472 [52]. In reporting the effectiveness of management options connected with food processing, the following parameters are applied [198]:

(a) Food processing retention factor (F_r), which is the fraction of activity of radionuclides that is retained in the food after processing. F_r is defined as the total amount of a radionuclide in processed food divided by the total amount of the radionuclide in the original raw food (becquerels processed per becquerel raw, i.e. F_r cannot exceed one).
(b) Processing factor (P_f)[17] for a foodstuff, which is the ratio of the radionuclide activity concentrations (analogous to concentration ratio) in the food before (SA_{rf}) and after (SA_{pf}) processing (becquerels per kilogram processed per becquerels per kilogram raw or fresh weight).
(c) Processing efficiency (P_e), which is the ratio of the fresh weight of processed food (M_{pf}) divided by the weight of the original raw material (M_{rf}).

---

[17] In some publications [200], this parameter is called the 'food processing retention factor'. It should be noted that values of P_f can exceed one.

There is a simple relationship between these three factors. F_r is the product of P_f and P_e:

$$F_r = P_f \cdot P_e \tag{1}$$

4.4.2. Processing of crops, vegetables and other plant products

Management option description: There are many ways to process crops and vegetables which allow the production of final food products with low radionuclide activity concentrations. Commercial food processing, such as washing, peeling, fermentation, distillation, blanching and canning, may achieve some reductions in activity concentration of many radionuclides in various processed foodstuffs. The option was widely used in areas contaminated by the Chernobyl and other radiation accidents [12, 39, 49].

Effectiveness: Washing or peeling vegetables, berries and fruits removes between 10–50% of radionuclides (based on total contamination of the plant) and >50–90% from the surface of plants. The efficiency of only washing the surface of fruit and vegetables is rather low, reducing the radiocaesium content by up to 10–30% of the initial activity. More vigorous processing methods can be more effective [198]. Thus, the radiocaesium content is reduced by 30–80% after boiling, salting, pickling, and juice and wine production [12]. More than 50% of radiocaesium contamination can be removed during blanching or boiling. For fruits consumed raw, rinsing has some effect in removing both fresh deposition and soil contamination. In general, 10–20% of radiocaesium and radiostrontium contamination is removed by rinsing (grapes, redcurrants, blackcurrants, lingberries, strawberries) [198]. Rinsing apples three times removed about 60% of radiocaesium and radiostrontium 1 d after deposition. About 30–40% of radiocaesium and 90–95% of radiostrontium can be removed by the various techniques in juice production (pressing, pectolytic enzymation, liquefaction and extraction) [52]. Stewing (and discarding juice) causes a 30% reduction in radiocaesium. The reduction of radiocaesium and radiostrontium contamination by lye peeling (dipping in a hot 7–18% KOH (lye) solution) of peach is variable, lying between 30 and 95%. Mechanical peeling of peaches reduces radiocaesium contamination by 50% [198]. Alcoholic processing removes an important part of the radioactive contamination of grapes, depending on the purity of the final product: Cs is reduced by 40% in red wine, by 30–85% in rosé wine and by 70% in white wine; Sr is reduced by 40% in red wine and by 80% in rosé wine. Pure alcohol is completely decontaminated from both radionuclides. Polishing of rice removes 90% of the Cs and 80% of the Sr of the raw product [198]. Milling grain of cereals (wheat, rye, barley, oats, grain) to flour reduces the concentration of radionuclides by 2- to 10-fold. Pressing of olives into cake and oil removes

60 and 90% of Cs contamination, respectively. The Cs activity concentration in sugar will be 100- to 1000-fold lower than in initial raw materials (sugar beet); in starch, it is 30- to 50-fold lower in comparison with potato. After processing rapeseed to oil, the activity concentration of Cs and Sr in oil will be 250- and 500-fold below that in the raw materials. The most effective processing techniques for mushrooms are washing, soaking (reduction factor for Cs of about two), boiling, pickling and salting (reduction factor for Cs of about ten, depending on the number of changes of water and boiling time) [34, 37, 198].

Feasibility: Industrial and domestic processes, such as extraction during boiling, removal of certain parts of the raw food (e.g. bran, peel) and drying or dilution, are normal operations during cooking and processing of raw products. Processing equipment is already available. There may be problems in utilizing food processing plants if there is: (i) reluctance to move contaminated raw materials to a plant located outside an affected area; (ii) limited capacity to accept additional raw crops; or (iii) reluctance by commercial plants to take the contaminated produce [33, 37].

Waste: Contaminated waste may include food processing residues (i.e. materials remaining after processing of primary products, such as peel and foliage). This may include large volumes of water and salt from blanching and boiling processes which may be disposed of appropriately at the processing plant or retained in a treatment pond. Solid residuals, such as peel and foliage, may be converted into useful by-products, depending on the type of residual (e.g. to be used as animal feed). Alternatively, these products could be incinerated at the processing site or disposed of to landfill [33, 37, 198].

Side effects, social aspects and constraints: There could be an indirect environmental impact depending on the disposal route chosen for the by-products. Foodstuffs with activity concentrations that have been brought below action levels by processing may not be acceptable to the retail trade when foodstuffs can be obtained from other sources. There may be disruption in farming and related industrial activities, such as the reliability of supply of crops to the food industry and the potential for market shortages. Information to industry on handling of wastes would need to be provided. Treated products may need to be labelled.

4.4.3. Processing of milk

Management option description: Milk is one of the most important foods that can contribute to internal radiation doses. Processing contaminated milk with radionuclide activity concentrations exceeding the action allows the milk to be used for human consumption. Processing raw milk into butter and cream can reduce the activity concentrations of radiocaesium and radiostrontium.

Contaminated milk should not be used for producing dried milk because the drying process does not remove radionuclides. Milk processing was widely used following the Chernobyl and other accidents [12, 37, 48, 60, 198].

Effectiveness: Data on effectiveness of milk processing are given in Table 4. Milk products prepared by isolating the fat and/or protein components from the aqueous fraction tend to be depleted in radiocaesium compared with raw

TABLE 4. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR DAIRY PRODUCTS [52, 198]

Product	Food processing retention factor F_r				P_e	
	Sr		Cs			
Cream	**0.04**	0.02–0.25	**0.05**	0.03–0.16	**0.08**	0.03–0.24
Sour cream	**0.1**	0.10–0.13	**0.1**	0.1–0.2	**0.1**	0.1–0.2
Skim milk	**0.93**	0.75–0.96	**0.95**	0.85–0.99	**0.92**	0.76–0.97
Butter	**0.006**	0.0025–0.012	**0.01**	0.003–0.02	**0.04**	0.03–0.05
Buttermilk	**0.06**	0.03–0.07	**0.05**	0.02–0.13	**0.04**	0.03–0.14
Butterfat	**0.002**	0.001–0.002			**0.04**	0.04
Milk powder (dried)	**1.0**	1.0	**1.0**	1.0	**0.12**	0.12
Condensed milk	**1.0**	1.0	**1.0**	1.0	**0.4**	0.37
Cheese[a]						
Goat		0.6	**0.1**	0.07–0.15	**0.12**	0.08–0.17
Cow rennet	**0.7**	0.025–0.80	**0.07**	0.05–0.23	**0.12**	0.08–0.18
Cow acid	**0.08**	0.04–0.08	**0.06**	0.01–0.12	**0.10**	0.08–0.12
Cottage cheese rennet	**0.1**	0.07–0.17	**0.03**	0.01–0.05		
Cottage cheese acid	**0.5**	0.2–0.7	**0.1**	0.1	**0.12**	0.10–0.14
Whey[a]						
Rennet	**0.5**	0.20–0.80	**0.8**	0.73–0.96	**0.90**	0.70–0.94
Acid	**0.8**	0.70–0.90	**0.8**	0.75–0.90		0.82
Casein[a]						
Rennet		0.10–0.85		0.01–0.08		0.03–0.06
Acid		0.05–0.08		0.01-0.04		0.01–0.06
Casein whey[a]						
Rennet		0.08–0.16		0.77–0.83	**0.76**	0.73–0.79
Acid		0.67–0.86		0.83–0.84	**0.78**	0.75–0.79

[a] Separate values are given for the rennet and acid coagulation procedures.

Note: Bold denotes expected values.

milk [33, 60]. Radiocaesium is concentrated in the water phase of milk, whereas radiostrontium is bound by casein and milk protein. Neither radionuclide preferentially associates with the fat content of milk, so they do not accumulate in high fat products [60, 198]. Radiocaesium activity concentrations after processing of cream, sour cream, butter, natural hard cheese, Greek 'feta' cheese, cottage cheese and casein are 1–30% of that in raw milk. Radiostrontium closely follows the behaviour of calcium. Hence, products, such as cottage cheese, cream and butter, with high fat content, which are relatively low in calcium, tend to have low levels of radiostrontium (1–30% of those in raw milk), while high calcium products, such as skimmed milk and cheese, have higher levels of radiostrontium [198].

Overall, the factors which influence the effectiveness of milk processing include the radionuclide(s) present, the fat content of the milk and the type of process used [33].

Feasibility and waste: Standard methods and techniques of processing milk can be used. Capacity within some of the processing plants which receive milk from contaminated areas may have to be enhanced, especially if there were some reluctance to move contaminated milk to a processing plant located outside of a contaminated area. Fractions by mass of by-products generated (with varying amounts of radionuclide) during the production of various milk products for consumption are: cheese — 90% is cheese whey; butter — 50% is buttermilk; cream — 90% is skimmed milk; cottage cheese — 80–90% is cottage cheese whey. Milk powder/skimmed milk powder only generates 80–90% water as a by-product which is not contaminated by either Cs or Sr. Contaminated water from washing and rinsing of tankers should also be disposed of [26, 33, 34, 198].

Side effects, social aspects and constraints: Disruption/adjustment of farming and related industrial activities may be anticipated. Processing produces some contaminated by-products. There may be resistance of: (i) drivers to transport contaminated milk; (ii) owners and/or operators of processing plants to accept contaminated milk; and (iii) consumers to purchase the milk and associated products [37, 48]. Foodstuffs with radionuclide activity concentrations that have been brought below the relevant action level by processing may not be acceptable to the retail trade when foodstuffs can be obtained from other sources. Processed milk and its associated products may have a low market value. Although there is no direct impact on the environment, there could be an indirect environmental impact, depending on the disposal route chosen for the by-products. Informed consent for implementation of this option may be required [48].

4.4.4. Processing of meat and fish flesh

Management option description: Meat processing is an effective method of reducing the radiocaesium content in food. Boiling and pickling wet, and soaking in salt (salting) or acid solution (marinating) are the most effective types of meat or fish flesh processing [26, 52, 198]. Mechanical removal of bone removes radiostrontium contamination from meat [33]. Meat from livestock slaughtered with activity concentrations of radiocaesium above action levels may undergo salting, either at commercial facilities or in the home as this procedure reduces the activity concentration of radiocaesium and radiostrontium. During salting, meat pieces (ca. 200 g) are soaked in dilute NaCl brine (5%) using two successive treatments that each last 2 d. Meat and fish processing was widely used as a management option following the Chernobyl and other accidents [12, 34, 48].

Effectiveness: Radiocaesium and radiostrontium activity concentrations can be reduced by 20–50% after boiling meat from mammals (cow, pig, sheep, deer, rabbit), birds and fish (Table 5). After soaking in salt solution, radiocaesium and radiostrontium contamination of meat may both be reduced by >80% (although the effectiveness may be as low as 10% for radiocaesium) [198]. Factors influencing the effectiveness of the procedure are: radionuclide(s) present, size of the meat pieces treated — treatment of large pieces gives the maximum reduction in radiocaesium contamination of 40–50%; volume of water or salt solution; concentration of salt solution; length of treatment [33].

TABLE 5. FOOD PROCESSING RETENTION FACTOR (F_r) AND PROCESSING EFFICIENCY (P_e) FOR MEAT [52]

Method of processing of raw material	Food processing retention factor F_r					P_e
	Sr		Cs		Ru	
Boiling meat of mammals (cow, pig, sheep, deer, rabbit)	0.5	0.4–0.9	**0.4**	0.2–0.7	**0.3**	0.5–0.7
Boiling bone of mammals		1.0	**0.3**	0.2–0.3	**0.7**	1.0
Pickling wet (salting), marinating meat of mammals			**0.5**	0.1–0.7		0.9–1.0
Boiling bird meat		0.5				0.4–0.7
Boiling fish flesh		0.9	**0.5**	0.2–0.9		0.5–0.9

Note: Bold denotes expected values.

Feasibility and waste: Many of the issues for milk processing apply for this option. Large waste volumes of contaminated water or salt solution may be created following implementation, depending on the quantity of meat being treated and its level of contamination. These wastes may require on-site treatment plants and sewage treatment facilities.

Side effects, social aspects and constraints: Acceptability and marketability of the end products may be a problem and efforts will then be needed to support the marketing of the treated products [37]. The distribution of costs and benefits may be an issue (e.g. possible inequity due to a reduction in the market value of salted meat, leading to lower income populations buying the treated food). Disposal of salt solution should have a minimal environmental impact.

4.5. REASONS FOR THE POTENTIAL EXCLUSION OF SOME MANAGEMENT OPTIONS

Some management options may be excluded from a remediation strategy for a variety of reasons, such as:

- They are not sustainable, i.e. they do not sustain normal socioeconomic activities.
- They are largely relevant as countermeasures for the emergency situation and would preferably be avoided if the subsequent remediation strategy were functioning effectively.
- They are technically effective but have significant disadvantages such as cost.
- They are currently inadequately supported by scientific evidence of cost effectiveness.
- They are not likely to be technically effective.
- They have significant side effects which preclude the option.

Examples of excluded options are described below. The exclusion of these options does not necessarily mean that the management options are not worthy of consideration. Rather, it means that more rigorous analysis and/or experimental studies would be needed in a site and situation specific context before inclusion in a remediation strategy. Furthermore, we do not include management options which are primarily relevant for the emergency situation.

4.5.1. Food bans

A remediation strategy needs to be carefully considered from many perspectives and one aim would be to try to establish a programme of application of effective management options which would remove the need for food bans, or at least severely reduce their extent. Furthermore, compliance with a food ban that has been imposed for many years is difficult to enforce. Therefore, in this publication, we have not included a food ban management option (which is highly relevant for the emergency situation), but rather have focused on provision of advice on food where there is high transfer and long effective half-lives, including the transfer of radiocaesium to some wild food products.

4.5.2. Dilution of food

Some normal food production activities involve dilution. A key example is that of milk, which is often collected from each farm by tankers. The milk in tankers is often transferred to large storage facilities in dairies before, for instance, pasteurization. The continuation of these normal activities, which may involve collecting milk with varying amounts of radionuclide present, would not be considered to be deliberate food dilution or part of a remediation strategy. EURANOS reported that actively intending to carry out food dilution for other food products as a management option was considered unacceptable by stakeholders as it would knowingly contaminate the foodchain and reduce consumer confidence [37].

4.5.3. Decontamination techniques for milk

One reported decontamination option for milk is the use of resins to remove radionuclides. This procedure has not been adopted in practice because although a reduction of ^{137}Cs, for instance, in milk of 4–30% can be achieved, the resin also removes important nutrient elements from the milk and leads to a substantial decrease in the quality of the final food product [201].

4.5.4. Phytoremediation

Some plants have a particularly high uptake of certain radionuclides. Therefore, if these plants are periodically harvested and disposed of in an appropriate manner, this option provides the potential to remove radionuclides from the main environmental sink, the soil. However, until now, there has been no small or large scale adoption of this method at existing sites for radionuclides. There are three main reasons why this option has not been adopted: (i) the total amount of radionuclide removed from the soil is a very small fraction of the total radionuclide content present, even for those radionuclides with a comparatively high transfer from soil to plant; (ii) the process would need to be continued for decades before the soil became adequately decontaminated to be used for food production; and (iii) the option generates waste which would then have to be disposed of appropriately, generating additional costs.

4.5.5. Administration of stable analogues for radiocaesium

Some studies have investigated the potential use of potassium or sodium, which are analogues of caesium, or stable caesium to reduce radiocaesium transfer to milk. In a review of the relevant data for K, Voigt [60] concluded that changes in diet K levels within a range which can be achieved in practical feeding situations were not expected to reduce radiocaesium accumulation in farm animals. There is limited evidence that the administration of stable Cs with sheep and goats [202, 203] may reduce radiocaesium transfer to animal products, but further evidence is needed before it can be recommended. Overall, there is, therefore, currently inadequate evidence to justify the use of stable analogues as a management option for radiocaesium.

4.5.6. Application of fixatives and stabilizers to soil (permanent and temporary)

In situ chemical or physical treatments can be applied to immobilize radionuclides in the soil. The treatments include cement based solidification and chemical immobilization with polymers. Reasons for exclusion include: (i) insufficient published information to prove effectiveness; (ii) lack of applicability to large areas; (iii) detrimental effect on soil functioning and/or biodiversity; and (iv) being an unsustainable approach. Furthermore, depending on the substances applied, the option may prevent re-establishment of vegetation.

4.5.7. In situ leaching of soil to remove radionuclides

There are in situ biological and chemical leaching techniques which could be applied to soil to remove radionuclides, such as soil washing, flotation, chemical extraction and bio-leaching. Reasons for exclusion include all of those mentioned above for fixatives and stabilizers, and also that this option may (i) require specialized equipment to implement, (ii) require large quantities of the leaching substance, and (iii) contaminate surface and groundwaters.

5. REMEDIATION PLANNING, OPTIMIZATION AND DECISION AIDING TECHNOLOGIES

S. Fesenko
International Atomic Energy Agency

5.1. OPTIMIZING A REMEDIATION STRATEGY

There are many technical and non-technical factors that need to be taken into account as part of the process of preparing an adequately justified remediation strategy. The effectiveness of remedial actions, and the cost and resources required for their implementation can vary considerably depending on these factors. Therefore, generalized recommendations which do not take the diversity of local site specific conditions into account can result in inadequate decision making and may not be feasible to implement.

The radiation safety system recommended by the ICRP is based on three principles, namely: justification of practice, optimization of protection and limitation of individual doses [2]. These principles can be challenging to implement in practice for remediation of contaminated areas because some of the required decisions are subjective. For instance, expert judgements are needed about the relative importance of different technical and non-technical factors determining the effectiveness of remediation. Additionally, consideration of the balance between risks and benefits of the implementation of remedial actions plays a key role in the process of remediation planning.

Decision aiding techniques are useful tools for making decisions on how to implement remediation in contaminated areas by defining key trade-offs between the various factors and constraints involved in the process. This can only be achieved if all relevant available management options are identified and there is information available on each of them outlining the factors and constraints involved in their implementation and quantifying their effectiveness and how it varies. In the early 1970s, the ICRP recommended the use of cost–benefit analysis for such a purpose. In cost–benefit analysis, the cost of radiological detriment (i.e. total dose) that can be averted, expressed in monetary terms, is compared with the cost of the protective measures (management options) [204–206].

However, many relevant factors cannot be quantified in monetary terms or by a consideration of resources, although they may be quantifiable in other units or by ranking parameters. In these circumstances, application of cost–benefit analysis has limitations and a more appropriate approach is that of multi-attribute utility analysis (MAUA). Application of MAUA can facilitate identification of optimal remediation strategies by considering many different attributes of the complex issues involved. Optimization of remediation strategies is the process of developing the strategy so that the optimal effect is achieved with respect to many different relevant factors. Recent ICRP publications emphasize the important influence of social and political factors on decisions concerning remediation and also encourage the use of tools such as MAUA for optimization of remediation [207].

The basic principle of MAUA is to construct a scoring scheme (or multi-attribute utility function) for each management option on the basis of all significant criteria (identified in Section 4) which characterize the management options (including effectiveness in terms of contamination reduction, cost of remediation, feasibility and applicability, side effects, collective or individual doses attributed to implementation, perception of management options by the population, etc.). When the different potential remedial management options have been identified, MAUA defines the relevant criteria for the decision process. These criteria normally include radiological, economic and societal attributes; environmental side effects and ethical considerations; public opinion; and the interests of various population groups [208].

Each remediation alternative (i.e. remediation strategy) must be evaluated according to some or all of the above criteria (or attributes), either quantitatively or qualitatively. To enable inclusion of qualitative attributes in the quantitative decision options, a scale from best (100) to worst (0) should be constructed. Thus, each attribute level (score) should be associated with a corresponding numerical value. The notion of a score refers to the value (i.e. utility) of a consequence, and, hence, score assessment is the process of determining the value of consequences with regard to the attributes. This approach allows all qualitative attributes to be placed on the same scale and removes the problems associated with attempting to compare different types of attributes (such as reduction of radionuclide transfer to plants, applicability of the management option for the stakeholders or severity of side effects) with inherently different scales. For this step in the attribute rating process, each attribute is rated on the same scale without reference to other attributes. In further steps, weighting coefficients are assigned to each criterion (attribute) to account for their relative importance. The weighting step is often the most important and difficult step in MAUA. Nevertheless, several techniques are available to derive each set of values. The choice of weighting coefficients should be justified, so that the process is transparent [207].

The single utility associated with each criterion also needs to be defined either as a linear function of the value expressing the criterion or as a non-linear function to incorporate the preferences of the decision makers into the analysis.

For example, it is possible to define utility functions which incorporate risk aversion according to the level of individual or collective exposures [207].

Formally, each management option is qualified by its total utility (U) calculated as follows:

$$U_i = \sum k_j \cdot u_{ij} \tag{2}$$

where

i is the number of the management options (or alternative) which can be used to remediate the environment;
j is the number of the criterion (attribute) considered;
k_j is the weighting coefficient showing the relative importance of each option (normalized $\sum k_j = 1$);

and u_{ij} is the utility of management option i in respect to criterion j.

Finally, the management options which lead to the highest total utility should be selected. Since most of the weighting factors generally rely on decision makers' judgements, it is highly recommended that a sensitivity analysis be performed using different sets of weighting coefficients to test the 'robustness' of the results [208].

5.2. ENVIRONMENTAL DECISION SUPPORT SYSTEMS

5.2.1. Introduction

Experience gained after major radiation accidents has demonstrated that generalized recommendations which do not account for the diversity of local site specific conditions can often result in inadequate decision making and may not be feasible to implement. These multiple factors must be reconciled within a single optimization approach and there is a significant challenge in finding a balanced solution to the multidimensional problem that each contamination scenario presents. This task can be facilitated with EDSSs capable of providing advice on remediation strategies at different levels of the decision making process, which take temporal and spatial variation into account for each of the factors. A conceptual framework and basic elements of such systems intended for support in remediation of contaminated areas are illustrated in Fig. 5.

Following the Chernobyl accident, various decision making frameworks, EDSSs or models which underpin them, have been produced. These include

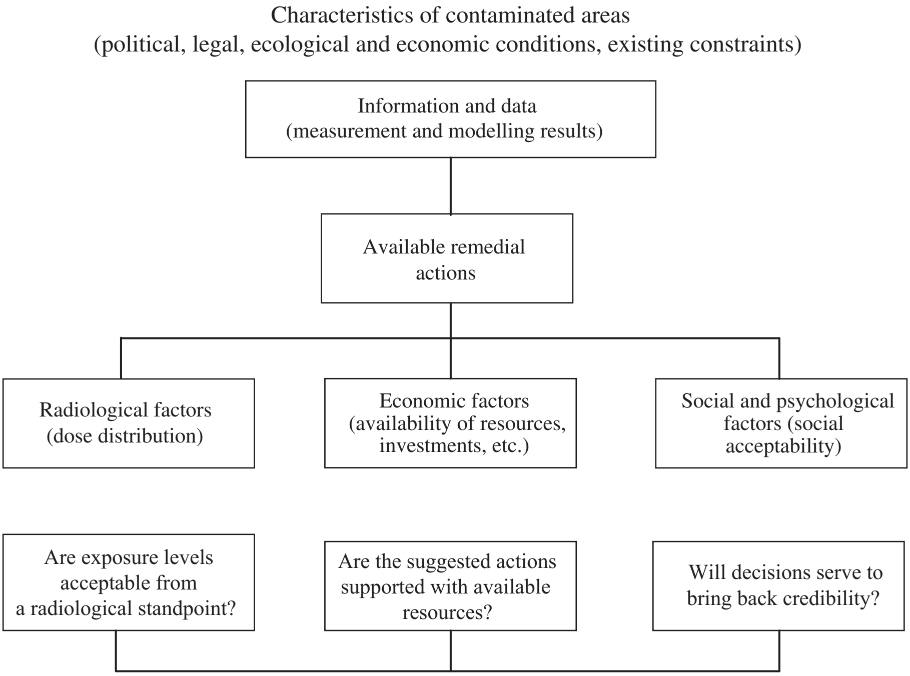


FIG. 5. Key elements of the EDSS for remedial management options on contaminated areas [209].

FORCON [210], SAVE [28], RESTORE [211], CESAR [212], MOIRA [213], EURANOS [7] and ReSCA (remediation strategies after the Chernobyl accident) [214–216], each of which have enhanced the ability to optimize remediation strategies in contaminated areas.

Decision aiding techniques are useful tools to identify an optimal remediation strategy with respect to the various factors and constraints involved, taking into account inherent uncertainties and value judgements. This can only be achieved on the basis of a clear identification of available alternative management options and the factors and constraints involved in the processes [217].

An important part of the decision making process is predicting how the situation may evolve as a result of the application, or lack of application, of management options. The changes may be due to natural processes (such as radioactive decay, soil radionuclide sorption or radionuclide migration) or as a result of the implementation of the management options. Radioecological models are used extensively to predict changes in the radiological situation due to these different factors.

Within the last 15–20 years, decision aiding technologies based on application of user friendly computer programmes have received considerable attention in remediation planning in areas affected by the Chernobyl accident. They have also made a substantial contribution to the improvement of existing emergency planning. One of the lessons learned from these experiences is that the decision aiding technologies for optimizing remediation strategies in contaminated areas always require information which can only be provided by models simulating a wide diversity of processes occurring during implementation of remediation. In addition to these models, decision making systems should include databases with the characteristics of management options (technical and non-technical, economic, social and environmental), as well as relevant regulatory advice and standards. Thus, to be used effectively, decision aiding technologies have to be supported with components, such as:

- Models for radionuclide transfer in the environment relevant to different exposure pathways for the public and workers involved in land use in contaminated areas;
- Dose models and radiation risk models;
- Information on the available management options, including their non-technical characteristics;
- Regulatory frameworks for decision making.

Thus, the current trend in the development of the EDSSs consists of the combined use of several components comprising two main groups:

- Databases: on the (i) effectiveness of possible remedial options; (ii) parameters of the environments which influence effectiveness of remedial actions and radionuclide transfers; and (iii) parameters of management options that need to be considered for identification of optimum remediation strategies, especially within the decision aiding module.
- Models: temporally and spatially variable radioecological and dosimetric models.

Together they facilitate analyses of the different alternatives and support decisions taken (see Fig. 6).

Ideally, EDSSs containing all of these modules are coupled with a GIS, and have a user friendly interface facilitating application of the software for the evaluation of the management options. Illustrating this approach, Fig. 7 demonstrates the user interface of the RESTORE environmental decision support system with the open model dialogue box [4].

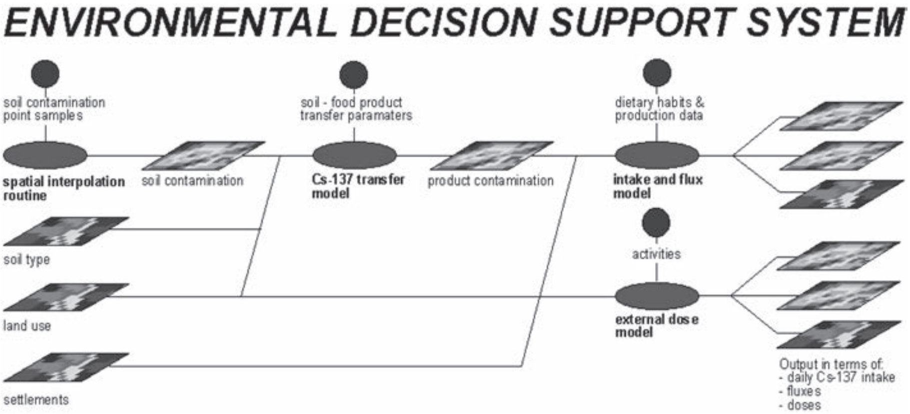
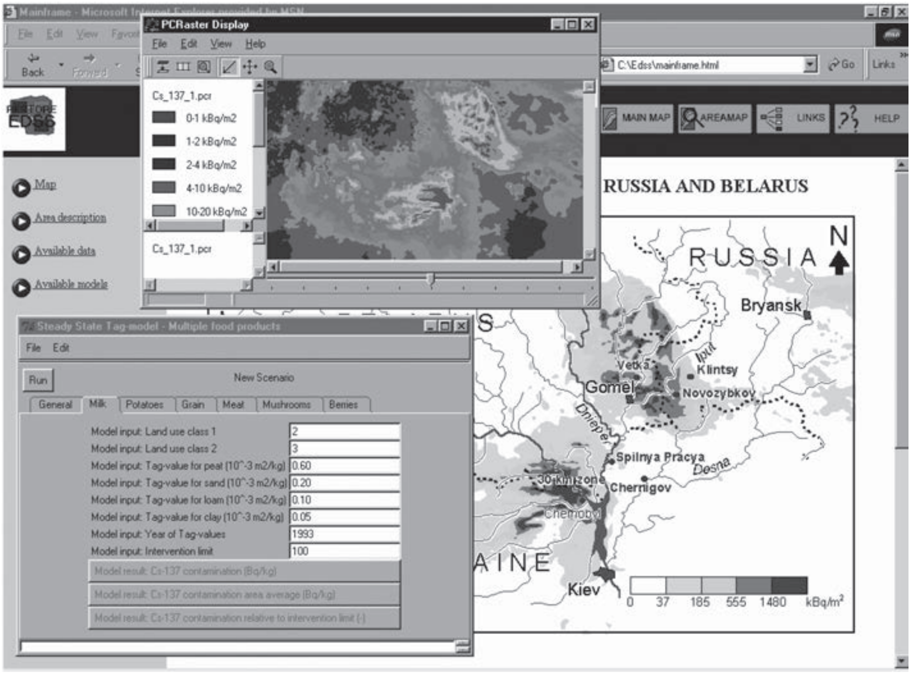


FIG. 6. Schematic overview of data processing and radionuclide transfer modelling with an EDSS [4].



Model input: Land use class 1: 2
Model input: Land use class 2: 3
Model input: Tag-value for peat (10^-3 m2/kg): 0.60
Model input: Tag-value for sand (10^-3 m2/kg): 0.20
Model input: Tag-value for loam (10^-3 m2/kg): 0.10
Model input: Tag-value for clay (10^-3 m2/kg): 0.05
Model input: Year of Tag-values: 1993
Model input: Intervention limit: 100
Model result: Cs-137 contamination (Bq/kg)
Model result: Cs-137 contamination area average (Bq/kg)
Model result: Cs-137 contamination relative to intervention limit (-)

FIG. 7. User interface of the RESTORE EDSS. Examples of the model dialogue box and the PC raster display are also shown [209].

The application of EDSSs can be usefully explained with reference to examples given below.

5.2.2. Application of environmental decision support systems for remediation of affected rural areas

The ReSCA EDSS and its application to the Chernobyl accident has been selected to demonstrate application of EDSSs for remediation of rural areas affected by the accident. One of the recommendations of the IAEA Chernobyl Forum was to develop an internationally agreed methodology for deriving optimized remediation strategies in rural areas that are still affected by the Chernobyl accident [48]. For this purpose, a software tool called ReSCA was developed by the IAEA to facilitate remediation planning in areas affected by the accident. The tool utilizes the concept of the representative person recently introduced by the ICRP [218] and is in full compliance with the latest ICRP recommendations [2] and the BSS [10].

Relevant information was summarized for all rural settlements in Belarus, the Russian Federation and Ukraine for which the official catalogue annual dose to the representative person in 2004 from the Chernobyl accident exceeded 1 mSv. The dose to the representative person is defined in the tool by the sum of the averages of the upper ten percentiles of the effective dose distributions from external and internal exposures. All such identified settlements were defined as affected by the Chernobyl accident and were eligible for consideration of implementation of management options.

Remediation of the contaminated territories is carried out through implementing certain management options, termed remedial actions in the tool. These include soil, crop and animal based, social, managerial and other actions, all of which have the potential to reduce population exposure in the selected settlements. Of the options available, seven were selected as particularly relevant to the situation and were included in the evaluation [214], namely:

(a) Radical improvement of grassland;[18]
(b) Surface improvement of grassland;
(c) Hexacyanoferrate application to cows;
(d) Clean feed for pigs;
(e) Mineral fertilizers for potato fields;
(f) Information campaign on mushroom consumption;
(g) Removal of contaminated soil.[19]

---

[18] For areas with wet, peaty soils, this action also includes drainage.

[19] See ‘topsoil removal’ management option in Section 4.

The effect of a remedial action r is expressed by a reduction factor for a pathway f, defined as numerically equal to the ratio of the annual dose before the remedial action is applied.

Remedial actions result in reduction of the population dose, which is expressed as the averted collective dose. The latter represents the dose averted due to application of a remedial action in the considered settlement. The attitude of the population to remedial actions can vary considerably: from completely rejecting an action to enthusiastic acceptance. Experience of remediation after the Chernobyl accident has shown that remedial actions aimed at improving the quality of pastures are generally well accepted, while decontamination of the settlement accompanied by upper soil removal is generally strongly disliked [12, 48]. It is, therefore, clear that the attitude of the population to certain remedial actions has to be accounted for in planning the strategy of remediation.

A sequence of remedial actions undertaken in the settlements of a region or a country is called a remediation strategy within this approach. The total cost of the strategy is a sum of the costs of each single remedial action. The total effect of the remediation strategy is a result of all of the remedial actions applied. Theoretically, the cost per averted dose criterion would result in the creation of the most cost effective strategy. However, the actual effectiveness of a remedial action is often affected by the degree of acceptability of remedial actions in the population (that often implements them). In the present work, the criterion used for the selection of the remedial actions to be included in the remediation strategy combines cost per averted dose, i.e. a ratio of cost and averted dose for single remedial actions, and the degree of public acceptance of a remedial action. All remedial actions are evaluated according to this combined criterion and are sequentially included in the remediation strategy being constructed.

Remediation options are considered by the tool with respect to three aspects: radiological, economic and social. The approach provides an opportunity to make flexible decisions within the limitation on funds allocated for remediation purposes. The expressions given below are used for prioritization of the remediation actions:

$$\beta \cdot \frac{\min(CD_r)}{CD_r} + (1-\beta) \cdot DA_r \tag{3}$$

where

CD_r is the cost of 1 man Sv averted as a result of the application of remediation option r;

and DA_r is the degree of acceptability of the corresponding action.

Parameter β allows the user to give preferences either to economic or social aspects of the remediation planning. Thus, for a β value equal to one, the remedial actions are ranked according to the costs per averted dose, while for a minimum β value of 0.01, the ranking is based mainly on the acceptance of remediation actions. The remediation strategy is constructed as a list of separate remediation actions until the total cost becomes higher than the total amount of funds allocated for remediation purposes. Thus, for the given input and model parameters, several strategies can be generated, varying by the amount of available funds and/or user priorities.

The tool provides a variety of output results: from individual fields to all affected settlements considered for the evaluation. Examples of EDSS application to remediation planning in the test settlements are given in Figs 8 and 9. Two strategies based on alternative priorities were suggested, forming a basis for further analysis. The first strategy was based on ranking remedial actions according to their costs per averted dose (radiological strategy), while the second was based on ranking according to public acceptance of remediation actions (social strategy). The first example considers the level of individual settlements typical for the affected regions of Belarus, the Russian Federation and Ukraine, and the second provides an example of large scale assessments.

Information from the first example of local-scale assessments using ReSCA, based on the data for the Yelne settlement in the Rivno region (Ukraine), is given in Fig. 8. The radiological strategy provides more flexible and cost

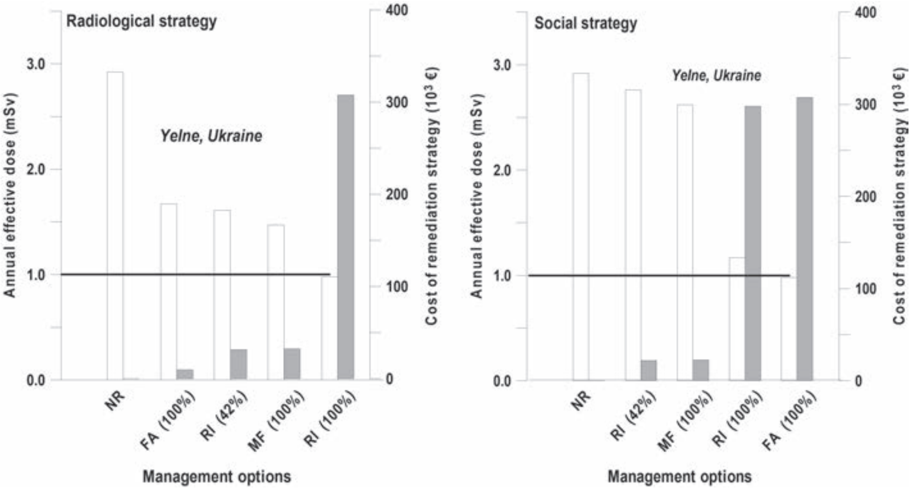


FIG. 8. Effectiveness of selected remedial actions in terms of dose reduction and the related costs. Effective doses are shown by empty bars (left axis) and remediation costs by shaded bars (right axis). NR = no remedial actions; FA = hexacyanoferrate application to cows; RI = radical improvement of grassland; MF = mineral fertilizers for potato fields [216].

effective scenarios of remediation, based on applications of AFCF to cows followed by radical improvements. Decontamination of certain parts of the populated areas for Russian Federation and Belorussian settlements was also suggested. In contrast, the social strategy gives priority to radical improvement followed by fertilization of potato fields and application of AFCF to cows. Removal of soil from the populated areas is consistently ranked at the bottom of the remediation strategy due to its high cost and low acceptability.

The large scale evaluation is presented in Fig. 9. The criteria for evaluation of the remediation actions at the large scale level (e.g. reduction of dose to the representative person) are different from those used at the local level.

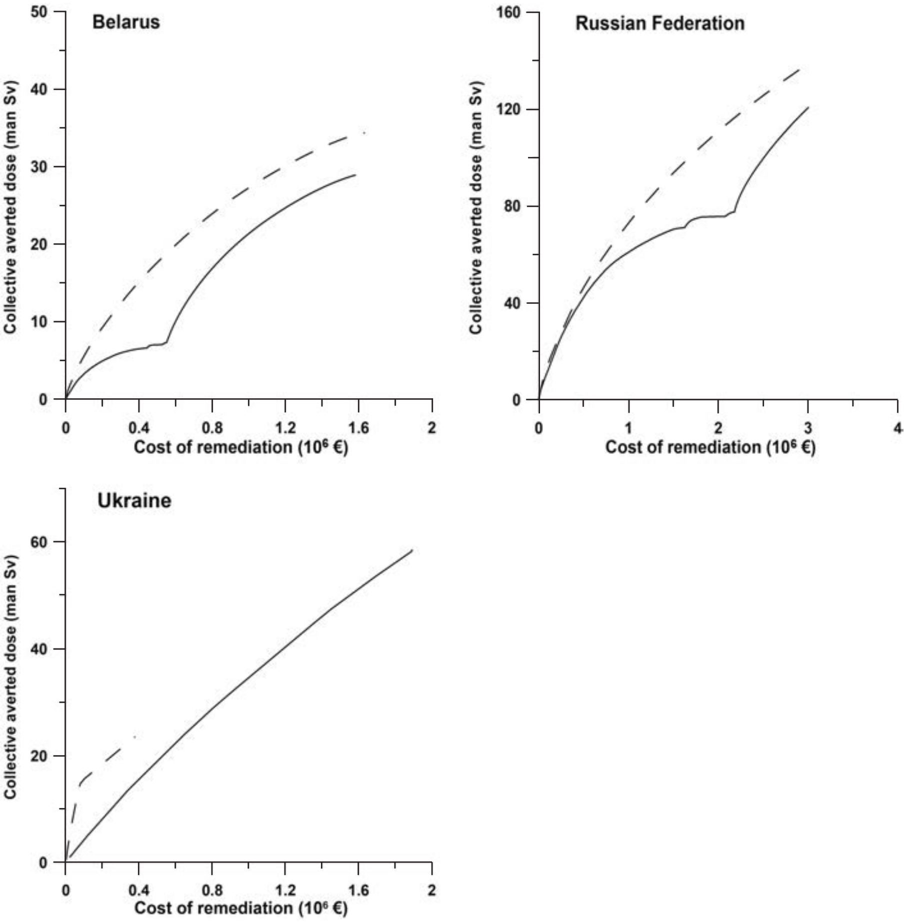


FIG. 9. Total averted collective dose as a function of funds invested in remediation in Belarus, the Russian Federation and Ukraine, calculated for 2010. The solid line corresponds to the social strategy and the dashed line to the radiological strategy [216].

For the large scale evaluation, the criteria include aspects such as the cost effectiveness of the funds allocated for remediation and the decrease in the number of settlements where annual doses to the population (or representative man) are above the reference level of 1 mSv/a. The relationships between averted doses and remediation costs differed among the three affected countries (Fig. 9). In Belarus, the trend of increasing averted dose with the invested funds is similar for the two strategies considered if the funds available for remediation purposes exceed €1 million. In Ukraine, the same is true if the available funds exceed a 10-fold lower value of €100 000. In addition, in Ukraine, the radiological strategy reduces annual doses in all affected settlements below 1 mSv with costs of less than €400 000. The calculations presented in Fig. 9 were stopped at this point, since there were no settlements where remediation could be applied beyond that level of funding for the radiological strategy. On the contrary, the social strategy did not allow the achievement of such an effect with such limited funding, and calculations were continued up to a cost of remediation of €2 million for which all of the settlements could be considered as remediated within the social strategy. In the Russian Federation, the significant difference between the two strategies persists up to several million euros of available funds, because of the larger number of affected settlements (Fig. 9). In contrast to Belarus and Ukraine, the cost effectiveness of the two different strategies is similar in the affected Russian Federation settlements, if the available resources are below €500 000. Above this value, the social strategy begins to be less cost effective compared with the radiological strategy (see Fig. 9).

The above examples demonstrate that, overall, the social strategy is considerably less cost effective and requires more resources for remediation compared to the radiological strategy. However, compared to international values for the cost effectiveness of actions for reducing occupational exposures, both remediation strategies are still quite cost effective, varying from €14 000/man Sv (Ukraine, the radiological strategy) to €47 000/man Sv (Belarus, the social strategy). The averted collective doses associated with these strategies are similar and quite high, averting 120–130 man Sv depending on the remedial actions implemented [216].

5.2.3. Application of environmental decision support systems for remediation of contaminated forests

Several studies were carried out after the Chernobyl accident to provide optimization of remediation strategies in contaminated forests [219, 220]. The Novozybkov district of the Bryansk region of the Russian Federation, located 180 km north-east of the Chernobyl nuclear power plant, was selected as a case study area for the application of the FORESTLAND EDSS for justification of forest management strategies. The average deposition density of ^{137}Cs in this district was about 750 kBq/m^2 while the contamination of forest soils varied from 150 to 2500 kBq/m^2 [65].

The assessments carried out for this area indicated that the application of management options will be necessary up to 2025; however, some options could be considered even after this time [206]. The forest pathways play a dominant role (contributing >70% of the total dose) in terms of individual exposure pathways to the reference person. Therefore, the application of forest management options would seem to be the most effective way to decrease the long term impact of radiocaesium contamination. The most important pathway is the consumption of milk from cows grazing forest meadows. Consumption of forest mushrooms and berries only contributes an average of 23% of the total average of 57% due to all forest exposure pathways. The acceptability of the different management options was assessed with the aid of a questionnaire performed in the area in 2000–2001 [188]. Some input data used for assessments are given in Table 6.

In common with the ReSCA remediation tool, the FORESTLAND EDSS [205, 206] includes databases with forest characteristics, effectiveness of forest management options and supplementary data on associated costs, secondary effects and applicability of different options for the stakeholders. A decision analytical tool based on a PRIME (preference ratios in multi-attribute evaluations) technique [221] was used as a decision aiding technology to justify an optimal remediation strategy. In the PRIME decision tool, the ability to express a preference is given in intervals (i.e. a subjective relative grading) to simplify the selection of preferences, since it is often difficult to justify the exact value for a preference, while a rough estimate (e.g. ‘this is a bit better than that’) is a more readily achievable alternative. Intervals help in the modelling of opinions as mathematical constraints, thus ‘good’ might be from 2- to 3-fold better than ‘poor’ [221]. The following steps allowing the identification of a reasonable decision are considered:

- Identification of relevant management options, their attributes and overall objectives;
- Preference elicitation;
- Determination of the best alternative: calculation with PRIME and evaluation of the outputs.

TABLE 6. EFFECTIVENESS OF FOREST MANAGEMENT OPTIONS IN TERMS OF ANNUAL EFFECTIVE DOSE REDUCTION, COST PER HECTARE, ACCEPTABILITY AND COST OF 1 man Sv AVERTED AFTER REMEDIATION [220]

Management option	Reduction of effective dose (%)	Cost per hectare ($)	Acceptability	Cost of 1 man Sv ($)
Restrictive management options				
(A) Abandonment	83–88	105–107	Very low	300–870
(B) No access for foresters	79–84	109–111	Low	230–770
(C) No public access	15–20	104–110	Very low	
(D) Restriction on grazing of domestic animals or using forest grass for animal feed	54–58	4.3	Moderate	17–54
(E) Restriction on mushroom collection	9–11	24–26	Low	14–53
(F) Restriction on berry collection	0.9–1.8	14–15	Low	90–310
Optimization of forest management				
(G) Limiting tree harvesting to areas with low doses	2–5	0.48	Very high	250–790
(H) Limiting mushroom collection to species with low accumulation	3–4	0.64	Moderate	5.8–22
(I) Processing mushrooms before consumption	3–4	0.46	Moderate	6.6–22
(J) Decreasing contamination of ‘forest milk’: application of Cs binders	30–49	0.14	High	1.5–5.2
Soil based options (for berries only)				
(K) Liming	0.5–1.0	12.7	Low	>1000
(L) Application of potassium	0.4–0.9	130	Low	>1000

The objectives of the first step are identification and characterization of possible management options. Based on cost effectiveness considerations, the following options were taken forward as alternatives to be considered for inclusion in further analysis:

- Abandonment;
- No access for foresters;

- Restriction on grazing of domestic animals or using forest grass for animal feed;
- Limiting tree harvesting to areas with low doses;
- Decreasing contamination of ‘forest milk’: application of Cs binders.

The objective of the preference assessment is to identify priorities in the selection of optimal forest management options. The first phase in the assessment is to weight each of the attributes. The weighting, ranging from 0 to 100, is a subjective ranking based on expert judgement of each management option.

The parameters associated with each management option, such as reduction of effective dose, acceptability of the management option to the stakeholders, cost of averting 1 man Sv and cost of remediation (see Table 5) were taken as the attributes for each management option. Levels of acceptability were transformed into a numeric scale as follows: ‘very low’ — 5, ‘low’ — 25, ‘moderate’ — 50, ‘high’ — 75 and ‘very high’ — 90.

Regarding the ReSCA tool, two major possible strategies of remediation in the long term after the Chernobyl accident were considered: a radiological strategy with the aim of maximizing the reduction of effective dose, and a social strategy with the aim of maximizing acceptability of the management options. Taking into account these preferences, the attributes were weighted in two ways:

(a) Reduction of effective dose (100) > acceptability (70–90) > cost of 1 man Sv averted (60–80) and cost of remediation (40–50) for the radiological (dose reduction) strategy;

(b) Acceptability (100) > the effective dose (70–90) > cost of 1 man Sv averted (60–80) and finally cost for countermeasure application (40–50) for the social strategy.

The first phase in preference elicitation is to assess scores. The notion of a score refers to the value (i.e. utility) of a consequence and, hence, score assessment is the process of determining the value of consequences with regard to attributes. Thus, the term ‘value’ is not considered as a simple monetary term. It is an aggregated parameter which reflects the value in terms of achieving the final goal of the calculations — determination of the fully optimized option. The higher a value is related to a specific option, the more optimal this option is in terms of criteria used for its assessment, i.e. reduction of effective dose, acceptability of the management option to the stakeholders, cost of averting 1 man Sv and cost of remediation.

The second phase in preference elicitation is to assess the weights of the attributes. PRIME defines the weight of an attribute as the gain in overall value obtained by a change from that attribute’s worst to its best consequence. PRIME

Decisions uses swing with intervals as its weighting method, which means that the greatest utility is represented as an interval of (100, 100). The weights of the other attributes are compared with this value and are given an interval with bounds ranging from 0 to 100 [221].

Based on the above input information, the tool calculates a variety of outputs which can be used to select the best alternative. The outputs include bounds of value intervals, weights related to different options, information on specific dominance of one option over another one, and represent the mathematical solutions of a linear programming technique, such as the simplex method [222].

The notion of the value interval of the management options refers to the management options value interval of the main goal, since it contains the total value of management options (Fig. 10) and the value interval represents the range of possible values.

Figure 10 shows that ‘abandonment’ (alternative A) and ‘no access for foresters’ (alternative B) are superseded by the other options because the lowest possible value of ‘limiting tree harvesting to areas with low doses’ (alternative G) is higher than the highest possible value for alternatives A and B. ‘Restriction on using forest grass for animal feed’ (alternative D[20]) or using Prussian blue for ‘decreasing contamination of ‘forest milk’: application of Cs binders’ (alternative J) in combination with ‘limiting tree harvesting to areas with low doses’ (alternatives D&G and J&G) are likely to dominate the selection of optimal management options for critical population groups. However, this information does not lead to a final decision because of overlapping of the value intervals calculated for different management options or their combinations [221].

Decision rules assist the decision maker in determining the best alternative. The available rules are ‘maxi-max’, ‘maxi-min’, ‘central values’ and ‘mini-max regret’ [222]. Maxi-max (optimistic decision rule) assumes that the most probable value lies at, or near, the greater bound of the alternatives’ value intervals, and, hence, it selects the alternative with the greatest upper bound. Conversely, maxi-min (pessimistic decision rule) assumes that the worst case for the chosen alternative will happen, so it selects the alternative with the greatest lower bound of the value interval. Similarly, central values select the alternative with the greatest midpoint. Mini-max regret takes a different approach and calculates ‘the possible loss of value’ for each alternative by using dominance data. ‘Regret’ is the difference between the payoff from the best decision and all other decision payoffs. The decision maker should avoid ‘regret’ by selecting the

---

[20] Designations of alternatives in this picture are given according to Table 6.

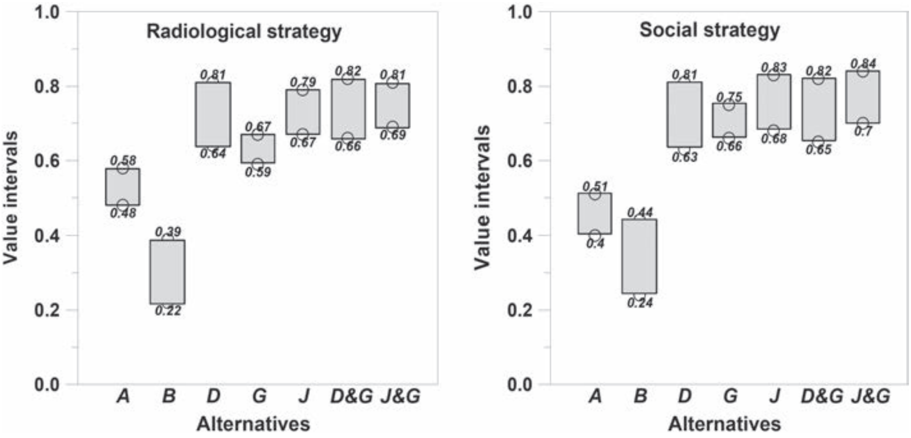


FIG. 10. Value intervals of forest management options. Management options are labelled according to the notifications given in Table 6.

decision alternative that minimizes the maximum ‘regret’ and mini-max selects the alternative with the least possible loss of value. Mini-max regret takes a different approach to the selection of the best alternative and calculates the possible loss of value for each management option by using dominance data. This technique selects the alternative with the minimal possible loss of value [222]. The results of such calculations show that for both ‘dose reduction’ and ‘acceptability’ strategies, the management options in alternative J (‘decreasing contamination of ‘forest milk’: application of Cs binders’) for the critical population group are the most appropriate (Fig. 11) [220].

Overall, the results show that an application of the decision support tools, based on combined consideration of radioecological, social and economic aspects of management options, is useful for the selection of optimal long term remediation. The conclusions are that restrictive management options and soil based forest management options are not advisable in the long term after the accident. Instead, more attention in the long term after the accident should be given to optimization of the use of forest food and forest products [220].

5.3. CONCLUSION

An effective response to contamination of the environment should be based on a multidisciplinary approach. The main challenge is to quantify the remediation strategies on the basis of multiple attributes. In recent years, many remedial actions (management options) have been developed and tested in areas contaminated with radionuclides. In particular, following the major radiation

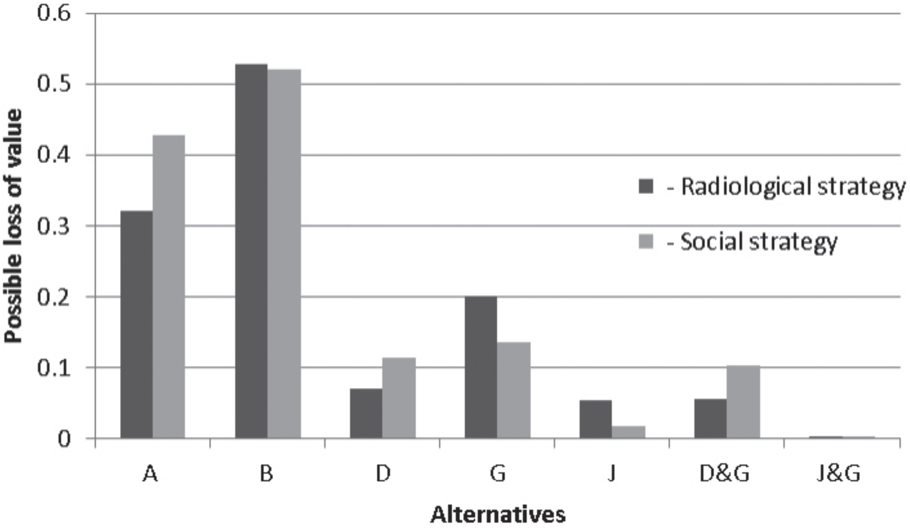


FIG. 11. Loss of value for alternatives in application of forest countermeasures (data given for critical population group). Management options are labelled according to the notifications given in Table 6.

accidents in Kyshtym and Chernobyl, various measures have been implemented and vast amounts of data on their effectiveness have been generated together with information on ancillary factors, such as the required resources and costs. These measures vary considerably in effectiveness, cost, feasibility, side effects and constraints in actual situations (see Section 4). As a result, the selection of these management options based only on the advice of radiation protection or other experts may lead to inadequate decisions. On the other hand, the presented examples demonstrate that the social strategies are often less cost effective and require more resources for remediation compared with strategies based only on radiological criteria. This emphasizes the need for the development of decision aiding technologies and EDSSs capable of providing advice on remediation strategies. This section demonstrates examples for selection of optimal management strategies based not only on specific information on individual management options such as those given in Section 4, but also on the use of MAUA which considers the involvement of stakeholders as one of the key components.

6. REMEDIATION OF CONTAMINATED ENVIRONMENTS: DESCRIPTION OF CASE STUDIES

S. Fesenko
International Atomic Energy Agency

V. Kashparov
Ukrainian Institute of Agricultural Radiology
Kiev, Ukraine

N. Sanzharova
Russian Institute of Agricultural Radiology and Agroecology
Obninsk, Russian Federation

6.1. REMEDIATION OF AREAS AFFECTED BY THE KYSHTYM ACCIDENT

6.1.1. Contamination of the environment and early management options

The radiation accident on 29 September 1957 at a military plant producing weapons grade plutonium in Chelyabinsk-40 (now Ozersk), eastern Urals was a severe radiation accident. A thermal explosion in a high activity, liquid waste tank released radioactive substances into the environment. The contaminated area is known as the Eastern Ural radioactive trace (EURT) and the accident itself is often called the Kyshtym accident (the name of the nearest town) in the literature. Strontium-90 was the most long lived and one of the main dose-forming radionuclides in the mixture of radionuclides released. It dominated the long term radiation risk and determined the need for remediation. Therefore, ^{90}Sr was considered to be the 'reference' radionuclide for the Kyshtym accident, against which other radionuclide contamination and consequences of the accident were compared.

The EURT area (23 000 km^2) was designated as the area where the ^{90}Sr deposition density was higher than 3.7 kBq/m^2 (0.1 Ci/km^2)[21] at the time of the

---

[21] The curie (Ci) is the original unit for measuring radioactivity. 1 Ci = 3.7×10^{10} radioactive disintegrations per second. In the International System of Units, the curie has been replaced by the becquerel (Bq), where 1 Bq = 1 radioactive disintegration per second = 2.703×10^{-11} Ci.

accident. In the EURT area, there were 217 settlements with a total population of 270 000 inhabitants [223]. A deposition density of 74 kBq/m^2 of ^{90}Sr was taken as the criterion to identify territories that needed remediation [39, 224]. These territories were in a narrow band and covered an area of 1000 km^2 (5% of the EURT area). Most of these areas are characterized by high fertility clay and loam soils (leached Chernozem, grey forest soil) which resulted in low radionuclide transfer to plants and subsequently to animal products [39, 49, 223].

For the first time in history, a maximum permissible ^{90}Sr deposition density in the environment (soil) was established [39, 49]. As a criterion for the safe residence of the population, a deposition density of ^{90}Sr was defined of 74 kBq/m^2 (or 300 μR/h[22] of the initial total radiation dose rate). Economic activity within that area was terminated [224]. Overall, 106 000 ha of land was abandoned; agricultural land accounted for 55% of the total area (29% arable land). The remaining 45% was covered by forests (36%) and lakes (9%) [39].

The major contributor to the total exposure of the population during the first month following the accident was external γ radiation which declined 10-fold over the next two months. In the most affected settlements, the exposure dose rate reached 200–400 μrem/s, which corresponded to 0.015 μrem/s (1.3 mrem/d) per 1 kBq/m^2 of initial ^{90}Sr contamination [223]. The dose contribution of γ radiation in the first year was 86% of the overall dose calculated for the entire period up to 1990; 97% of the total dose was accumulated within the first five years after the explosion [39, 224].

The highest total activity concentrations of radionuclides in agricultural products taken from the nearest area to the source of contamination during the first few weeks after the accident reached 10–10 000 kBq/kg dry mass. The main contributors to food contamination (60–70%) were initially ^{144}Ce and ^{95}Zr, except for milk where ^{90}Sr constituted around 70% of the radioactivity present [224]. Five to eight years after the accident, only ^{90}Sr and, to a small extent, ^{137}Cs were present at levels requiring consideration for remediation in the environment [39, 223, 224]. Forty years after the accident, the radioactive contamination present within the EURT area had fallen by more than 50-fold, and associated dose rates had decreased 4000-fold, largely due to radionuclide decay [39].

In 2000, 80–85% of ^{90}Sr was still present in the upper 0–20 cm soil layer, and transfer of ^{90}Sr from soil to plants had declined by 7- to 10-fold [224]. The ^{90}Sr activity concentrations in food products decreased with time after the accident. In particular, a two component exponential model fitted the decline of

---

[22] The röntgen (R) is the original unit used to measure the ionization produced in air by X ray or gamma radiation. It was defined as the amount of gamma or X rays required to produce ions resulting in a charge of 0.000258 C/kg of air under standard conditions.

^{90}Sr in milk with ecological half-lives of 1 a (for the first five years after the deposition) and 15 a (for a time period of 5–45 a) [39, 225].

Since the accident, radionuclide transfer to humans via foodstuffs has continuously declined and, over 30–40 years, the annual ^{90}Sr and ^{137}Cs intake by humans has been reduced by, on average, 200- and 2000-fold, respectively, because of radiation decay, natural processes (sorption of radionuclides in soils and vertical migration) and implementation of remedial management options [39].

In the area affected by the Kyshtym accident, consumption of food products containing radionuclides was the key factor responsible for the long term total exposure of people living in the affected area. The contribution of internal dose to total exposure exceeded 70% [49, 225]. Therefore, dose reduction from internal irradiation was the focus of the remediation strategy and changes to agricultural practices (as well as forestry and freshwater management) were the main remediation management options adopted. The major objective of the remediation strategy in the Kyshtym affected region was to comply with the criteria for action levels determined by the radiation safety standards adopted at that time [39].

The main factors that affected ^{90}Sr activity concentrations in the agricultural chain ‘soil–plant–animal’ were deposition density and soil properties, notably the content of exchangeable calcium. The effect of soil Ca status was generally 40-fold higher than the combined influence of all other soil factors for determining the extent of ^{90}Sr root uptake [226–228].

The ^{90}Sr activity concentrations in farm animals and their derived products were directly proportional to those in their feed. As strontium is an osteotropic element, ^{90}Sr is mainly deposited in animal bones and the rate of its removal from the bone tissues is slow [39, 223, 225]. Therefore, there is a long biological half-life of ^{90}Sr in the body accompanied by sustained secretion of ^{90}Sr into milk (which is enhanced if there is chronic ^{90}Sr intake by dairy animals).

6.1.2. Remediation in agriculture, forestry and water management

6.1.2.1. Agriculture

The EURT area was subjected to application of intensive remediation for agriculture from the first growing season in the spring of 1958 onwards. Application of these actions generated much novel information on the effectiveness of remedial management options which were then widely used in the aftermath of the Chernobyl accident. The data on effectiveness of major management options implemented after the Kyshtym accident are summarized in Table 7.

TABLE 7. EFFECTIVENESS OF REMEDIAL ACTIONS FOR ^{90}Sr ON LAND AFFECTED BY THE KYSHTYM ACCIDENT [39, 49, 114, 223, 225]

Management option	Soil type	Reduction factor of ^{90}Sr in crops
Mouldboard ploughing, depth of cultivation: 50 cm	Mineral	2–3
Ploughing with turnover of upper layer (to a depth of 30 cm)	Mineral	10–16
Topsoil removal	Mineral	5–15
Liming	Mineral	up to 3
Mineral fertilizers:		
$N_{90}P_{180}K_{90}$	Mineral	1.1–1.4
$N_{60}P_{90}K_{120}$	Mineral	1.3–1.9
Selection of crops and varieties	Any soil	3–58
Addition of calcium to concentrate ration		3–10
Clean feeding		3–4
Food processing		
Milk to butter		10–20
Grain to flour, groats		2–3
Grain to alcohol		50–100
Potato to starch		up to 100
Vegetables to oil		50–100

For crop production, the most effective measure was ploughing of soil with burial of the upper contaminated layer into deep soil horizons which are not normally accessed by plant roots (deep ploughing). This was conducted as soon as possible after the radioactive contamination occurred. To achieve this management option, specially designed equipment was developed, namely modified ploughs and ‘plough-shifters’ which could move the soil layers as described above. The modified plough buried the contaminated soil layer to a depth of 30–40 cm, thereby reducing ^{90}Sr activity concentrations in the arable soil layer by 5-fold. The plough-shifter removed the top contaminated soil to a depth of 30–70 cm (reducing ^{90}Sr content in the arable layer by 10- to 50-fold) (Table 7).

After the application of these special ploughs, ^{90}Sr accumulation in food products dropped, for instance, by up to 4-fold in wheat and more than 10-fold in potatoes with shallow root distribution (Table 7). Ploughing was especially effective on Chernozem (heavy clay) soils with a thick humus horizon (of up to

0.5 m). On low fertility soils with a thin humus horizon, the application of such ploughs was generally not feasible (see also Section 4) [39].

The decontamination effect from deep ploughing was enhanced by regular addition of mineral fertilizers to the arable layer. This dual technique, which was widely used in practice, reduced ^{90}Sr activity concentrations in crops by 10-fold compared with conventional ploughing.

Soil liming and mineral fertilizer application were the agrochemical measures which were most widely used to reduce ^{90}Sr transfer to plants [39, 223]. Application of these products improved the physico-chemical properties of soil which resulted in increased soil fertility, increased crop yield and decreased ^{90}Sr activity concentrations in crops. Mineral fertilization at balanced rates (according to plant demand for mineral nutrients) reduced ^{90}Sr uptake by plants on grey forest soils and leached Chernozem by 1.5- to 2-fold [39, 223]. Liming of acid soils resulted in a higher reduction of 3-fold [39]. Further reductions in the ^{90}Sr intake by humans via plant products (and by treating animal feed crops) was achieved through cultivation of plants with low ^{90}Sr accumulation (crop selection). Crop selection enabled the production of plant agricultural products which were up to 58-fold less contaminated with ^{90}Sr compared with formerly cultivated plant varieties [223].

In addition to reducing ^{90}Sr uptake to plants, ploughing soon after radioactive fallout reduced the external dose rate of γ radiation. Normal ploughing (20–25 cm) initially led to a 1.1- to 2.4-fold decrease in the dose rate of γ radiation, while ploughing with burial of the top layer decreased the external dose rate by up to 3-fold [49, 114].

Direct decontamination of soil, by removal of the contaminated topsoil layer using machines, such as bulldozers, graders and scrapers, with subsequent burial in specially designated burial facilities was a reasonably effective management option. It was only suitable for small plots due to the amount of waste produced. This successful, but costly method, achieved a 5- to 15-fold decrease in ^{90}Sr transfer to crops if the upper contaminated 5–10 cm layer of soil was removed (Table 7) [39, 49]. However, due to the costs of topsoil removal, this option was not widely applied.

Data on ^{90}Sr accumulation by a variety of crop types on soils with similar properties and the same ^{90}Sr deposition density showed that maximum ^{90}Sr activity concentrations in plant products occurred in grass (or hay) from natural meadows (referred to as pastures in earlier sections) [226]. In contrast, the lowest ^{90}Sr activity concentrations were observed in potatoes and root vegetables [226]. Strontium-90 uptake by cereals and legume crops was between the grass and root crops. Overall, ^{90}Sr accumulation by different crop species varied by a factor of 300 [39, 227].

Processing of raw agricultural products led to substantial reductions in ^{90}Sr activity concentrations. The most commonly used method was processing of milk to fermented milk products and butter, which reduced ^{90}Sr activity concentrations in butter by 20-fold compared with raw milk. Conventional processing of grain to flour and groats (hulled grains of various cereals) reduced ^{90}Sr activity concentration in the final products by 2- to 3-fold. Starch, alcohol and vegetable oil produced from the contaminated agricultural produce was virtually free of ^{90}Sr contamination [114, 227].

In contrast to plants, which do not show selectivity in relation to Ca and Sr in root uptake, animal metabolism distinguishes these elements by their chemical nature, giving preference to Ca. As a result, the ratio between Ca and Sr in meat was 2.5-fold lower than that for the contaminated fodder; the equivalent ratio for milk was 10-fold lower (i.e. less ^{90}Sr was transferred than Ca). There are large differences in Ca concentrations in animal tissues and organs (for instance, Ca concentrations of 150, 1.0 and 0.1 g/kg occur in cattle bones, milk and muscular tissues, respectively; similarly, the lowest ^{90}Sr activity concentrations were in muscle (and other soft tissues) while milk was about 40-fold more contaminated than meat [225]. Thus, meat production was recognized as the preferred animal farming management option in the contaminated areas. Overall, for agricultural production on ^{90}Sr contaminated agricultural land, animal soft tissue products exhibited significantly lower ^{90}Sr activity concentrations compared with plant products [39, 225].

The normal, pre-accident, agricultural practice for livestock was based on the use of feed (normally fodder) from uncultivated pastures. Management options to reduce ^{90}Sr accumulation in animal products mainly consisted of selection of fodder species with low ^{90}Sr content [39, 49, 225, 226]. The most effective way to achieve this was to feed animals with potatoes, root vegetables and grain which contained lower ^{90}Sr activity concentrations than fodder from uncultivated pastures. An additional management option for farm animals was to reduce ^{90}Sr uptake by the oral administration of Ca additives or providing fodder with a high natural concentration of Ca such as legume crops. This method resulted in up to a 3- to 10-fold reduction in ^{90}Sr activity concentrations in milk [39]. For finishing cattle (i.e. prior to slaughter), a reduction in the ^{90}Sr content in meat was achieved by feeding with ‘clean’ or less contaminated fodder [49].

Overall, the implementation of a range of management options for livestock resulted in a decrease in the ^{90}Sr activity concentrations of meat and milk from specialized agricultural farms by 2- to 7-fold and 3- to 4-fold, respectively, compared with unremediated farms [39, 114, 223]. These management options were less effective in private holdings, where animals largely grazed in meadows or were fed natural grass (hay) characterized by higher ^{90}Sr root uptake compared with fodder from cultivated areas.

6.1.2.2. *Forestry*

The following management options were recommended to be implemented in forestry [39, 114, 223]:

- Establishment and introduction of radiation limits for forest products including free food products such as berries, mushrooms, game and wood: The adopted maximum permissible level for the ^{90}Sr deposition density of forested soil was 92 kBq/m^2 when the land was used as a grazing meadow or for haymaking and 3.7 MBq/m^2 for production of wood for construction.
- Reduction of the amount of land used as grazing meadows or for haymaking and restriction of their use by the population: This was achieved either by forest planting in regions with a ^{90}Sr deposition density above 370 kBq/m^2 or by transferring the priority right to use these lands to specialized farms, while limiting access by the local population.
- Restriction on the use of wood by the population as a fuel from areas with a ^{90}Sr deposition density above 74 kBq/m^2: For heating of workplaces, it was permitted to use wood produced on land with a ^{90}Sr deposition density of up to 1.11 MBq/m^2 combined with obligatory burial of ash in land outside the agricultural areas.
- The use of industrial wood was allowed for industrial construction, but not for construction of civil buildings. Removing the bark was recommended to be carried out at the harvest site to remove ^{90}Sr and ^{137}Cs contained in the bark.
- Establishment of specialized forestry firms in 1960, to ensure that the work practices fully complied with normal forestry practice and the above remedial strategy requirements.

6.1.2.3. *Aquatic systems*

Initial restrictions on the economic use of water bodies (fishing, use of aquatic vegetation as fodder for farm animals) were imposed on lakes located in areas with a ^{90}Sr deposition density above 74 kBq/m^2. Due to a natural reduction with time in ^{90}Sr activity concentrations in these lakes (^{90}Sr effective half-life of 5–6 a), renewed utilization of lakes located in the peripheral EURT area for fish breeding was allowed by 1970 [228].

6.1.3. Management strategy in areas affected by the Kyshtym accident

Following the Kyshtym accident, the introduction of criteria based on maximum permissible concentrations (i.e. action levels or temporary permissible levels (TPLs)) of radionuclides in food products (in this case ^{90}Sr) was implemented for the first time in history. Due to the strong influence of Ca on ^{90}Sr transfer, the limits were based on the ^{90}Sr activity concentration per unit weight of Ca. An initial limit of 200 strontium units was introduced (where 1 strontium unit = 1 pCi ^{90}Sr normalized to 1 g of Ca); this limit was later made three times stricter by reducing the value to 66 strontium units [39, 49, 223–225].

The long term remediation strategy was focused on two approaches: changes in land use and development of new economic structures which should be applied to every affected region and, if possible, every farm. The decisions on suitable land use between agriculture, forestry and other branches of the economy using soil, plant and water resources were based on assessments of ^{90}Sr activity concentrations in products produced after remediation in comparison with the action levels [39]. In particular, if farming was not feasible in the affected region (due to action levels being exceeded), economic activity was refocused on the production of industrial (non-food) goods such as the development of forest and local industry or exploitation of peat, sand, gravel and other mineral resources. In some cases, such activities included production of crops as raw materials for non-foods, for industrial applications (e.g. production of potatoes for starch and alcohol, grain for alcohol), and for production of seeds of cereals, potato, vegetables and grasses [49].

The remediation strategy for contaminated agricultural land after the Kyshtym accident took account of variation in crop uptake of radionuclides. The approach for farm management was to change land use and, in particular, to select sites with high ^{90}Sr deposition density for crops with lower rates of ^{90}Sr uptake, namely potatoes, root vegetables and cereals. Conversely, land with lower ^{90}Sr activity concentrations in soil was used for fodder production and grazing animals [223].

Overall, remediation of agricultural land within the EURT area followed a graded approach [39]:

- Less contaminated areas (74–185 kBq/m^2 for ^{90}Sr) were allocated for food crops.
- Animal husbandry was intensified, controlling the animal diet and excluding fodder produced from uncultivated meadows. Furthermore, animal diets were modified to include concentrates, potatoes and root vegetables.
- Fodder for dairy cattle was produced in areas with ^{90}Sr deposition densities which were 3- to 4-fold lower than those allowed for meat cattle.

— For animal production, preference was given to pig and poultry production (due to the low ^{90}Sr transfer to muscle compared with other animal derived products).
— Grain and potatoes with ^{90}Sr activity concentration above the TPL were only used for industrial applications.
— Special attention was paid to monitoring of ^{90}Sr activity concentrations in food products from private households where ^{90}Sr radionuclide activity concentration was noticeably higher than that produced in the collective sector for a number of reasons (cattle grazing on more highly contaminated meadow with higher root uptake of ^{90}Sr, lower intensity of management option implementation, etc.).

The classification outlined in Table 8 was intended to ensure adequate radiation protection of the population, which could potentially consume any products obtained on land involved in economic use.

As a result of the remediation strategy adopted after the Kyshtym accident, a substantial decrease in effective annual doses to the local population was achieved. This ensured that doses to the affected local population were lower than the radiation safety standards existing in the former USSR at the time.

6.1.4. Return of abandoned lands to economic use

From 1958 to 1959, remediation extended over an area of 20 000 ha, where ploughing and forest planting was carried out. With the establishment of radiation

TABLE 8. COMPARISON OF MAXIMUM DEPOSITION DENSITIES OF ^{90}Sr CONTAMINATION ALLOWED FOR PRODUCTION OF DIFFERENT ANIMAL PRODUCTS IN AREAS WITH OR WITHOUT REMEDIATION [225]

Animal production type	Without remediation, including grazing meadows (kBq/m^2 (Ci/km^2))*	With remediation (e.g. collective farms) (kBq/m^2 (Ci/km^2))*
Meat	370 (10)	740 (20)
Milk	93 (2.5)	185 (5)
Pork	3700 (100)	3700 (100)

* Strontium-90 limits in products in 1958 were as follows: milk — 55 Bq/kg; grain, meat, vegetables — 185 Bq/kg; fodder — 3700 Bq/kg; seed grain — 1850 Bq/kg. In 1968, these were reduced: milk — 12.6 Bq/kg; meat — 11.8 Bq/kg. In 1979: food grain — 7.4 Bq/kg; milk — 5.5 Bq/kg; meat and vegetables — 3.7 Bq/kg; potatoes — 1.85 Bq/kg.

standards in the 1960s, the safety of residence with respect to radiation was guaranteed to the population in areas with ^{90}Sr contamination densities below 150 kBq/m^2. In 1961, all lands in the Sverdlovsk region (^{90}Sr deposition density below 300 kBq/m^2) and 2000 ha in the Chelyabinsk region were returned to economic use and allocated to specialized farms. By 1982, half of the contaminated 32 000 ha of agricultural land with ^{90}Sr contamination densities of 74–3700 kBq/m^2 were successfully returned to economic use [49, 114].

The remediation consisted of several stages involving increasingly more contaminated areas with agricultural land being returned to economic use [114]:

- Land with a ^{90}Sr contamination density of 74–300 kBq/m^2 (by the mid-1960s);
- Land with a ^{90}Sr deposition density of 300–920 kBq/m^2 (by the end of the 1960s);
- Land with a ^{90}Sr deposition density up to 1850–3700 kBq/m^2 (by the end of the 1980s).

By 1993, more than 80% of the land had been returned to economic use within the ^{90}Sr deposition density of 74 kBq/m^2 isoline [114].

For the most contaminated part of the EURT, where ^{90}Sr contamination densities ranged between 3.7 and 150 MBq/m^2, remediation was not implemented. The East Urals State Reserve was established in 1966 in this area for long term field radioecological observations. The total reserve area is 16 616 ha, with a perimeter length of 90 km [225]. The establishment of such a zone was the first worldwide example associated with management of a highly contaminated environment after an accident. Later on, a similar approach was used for the most contaminated areas affected by the Chernobyl accident [39, 49].

6.2. REMEDIATION OF SITES CONTAMINATED AFTER NUCLEAR TESTS

6.2.1. Background information

Nuclear tests were conducted at a total of 16 sites, the most well known of which are the Nevada test site (United States of America); Bikini and Enewetak (Marshall Islands); Emu, Maralinga and Monte Bello Islands (Australia); Mururoa and Fangataufa (French Polynesia); Semipalatinsk (Kazakhstan); Novaya Zemlya (Russian Federation) and Lop Nor (China) [229–236]. In total, about 29 t of fission yield was associated with radionuclides locally deposited at the test sites [232]. Another source of local contamination at the test sites was safety tests, in which nuclear weapons were destroyed using conventional explosives to simulate a possible accident [229].

Only two of these sites (namely Enewetak and Maralinga) have been remediated. Remediation at the other test sites was either not carried out or was only partly performed, either because of: (i) low residual contamination (fractions of long lived radionuclides in many types of nuclear explosions are low); (ii) high financial costs; (iii) the remoteness of the site from populated areas; or (iv) other political reasons. Even if a full remediation strategy was not applied at these sites, some remedial actions were usually conducted, especially where considerable amounts of plutonium residues resulting from safety tests were present [234].

6.2.2. Bikini Atoll test site

Nuclear tests were conducted by the United States of America at Bikini Atoll, Marshall Islands from 1946 to 1958. The 167 inhabitants of Bikini Island were evacuated prior to the first nuclear test in 1946.

The most significant nuclear testing at the Bikini Atoll test site was the Castle Bravo test conducted on the Bikini Atoll on 1 March 1954. The Bravo test was an experimental thermonuclear device with an estimated explosive yield of 15 t. The fallout from these tests caused widespread contamination of the Bikini Atoll and forced the evacuation of Marshallese people living on Rongelap and Utrik Atolls [234]. About 50% of the fission yield associated with near surface nuclear detonations was deposited on a local or regional scale [237].

In August 1968, resettlement of the Bikinian people on the Atoll was allowed and about 100 people returned to the Atoll. In 1975–1978, in response to concerns expressed by Bikini residents about the safety of living on the Atoll, a set of additional investigations were carried out, gathering data for more precise dose estimates [238]. In 1978, a 10-fold increase in the body content of ^{137}Cs in Bikinian people compared with that measured in 1970 was identified, based on whole body measurements [239]. The increase in ^{137}Cs content was attributed to the consumption of coconut fluid due to the limited availability of drinking water. In August and September 1978, in response to the intake of ^{137}Cs by the population, the Bikinians who had returned to Bikini Atoll were relocated once again [234].

The total annual dose to the potential residents of the Atoll (above the natural background dose) was estimated in 1999 to be 4.0–15 mSv, depending on the ratio of local to imported foods in the diets of inhabitants. Caesium-137 was identified as the main radionuclide contributing to the dose (and was, therefore, the ‘reference radionuclide’), while contributions of ^{90}Sr, ^{239}Pu, ^{240}Pu and ^{241}Am were much lower. The intake of marine foods, stored rain water and groundwater, and inhalation of resuspended soil together accounted for less than 1% of the dose [238, 240].

Although full scale remedial actions at the site have not been applied, a few management options for Bikini were implemented and studied in detail. These interventions were based on a projected dose to a hypothetical critical group. The assessed annual dose of 15 mSv [241] was higher than the action dose level for intervention of 10 mSv accepted at that time. Therefore, the implementation of remediation was considered to be highly justified [234].

The key remedial management options used were: (i) washing-out ^{137}Cs from the soil with large quantities of salt water; (ii) application of ameliorants such as zeolites to soil to make ^{137}Cs less available for plant uptake; (iii) planting vegetation with high biomass to remove ^{137}Cs from the soil (a form of phytoremediation) and then burial of the contaminated biomass; (iv) soil removal (40 cm top layer); and (v) treating soil with potassium fertilizers [234].

Soil removal and treatment with potassium fertilizers were identified as the most effective management options. Soil removal in rural areas would have necessitated moving about 30 000 mature coconut, pandanus and papaya trees and breadfruit, and was, therefore, a complex and extremely expensive operation [234]. In contrast, soil removal from dwelling areas was more cost effective and the best option used was to remove soil from around each house and replace it with a layer of crushed coral to minimize external exposure and possible ingestion of the remaining soil. Consideration was given to the potential ecological effects of the proposed potassium fertilizer treatment; at the specified levels, there was no significant alteration in soil chemistry and the potential transfer of potassium to groundwater was low [241, 242]. Application of potassium fertilizer was needed every four or five years to maintain the low ^{137}Cs activity concentrations in local foods. After the potassium treatment of soil and the replacement of soil from around the living areas, the dose rate, based on the assumption that residents were consuming only local food, was reduced by as much as a factor of ten or slightly higher compared with the levels before the application of remedial actions [243].

6.2.3. Maralinga test site

Tests of the United Kingdom Nuclear Programme at the Maralinga test site located on the Nullarbor Plain in South Australia began in 1955. The site was abandoned in 1967 following the advent of the Treaty on the Non-Proliferation of Nuclear Weapons and the banning of atmospheric nuclear tests because the site was not suitable for underground tests. Seven nuclear tests were performed at the site, with approximate yields ranging from 1 to 27 kt. The site was also used for hundreds of minor trials from 1955 to May 1963, many of which were safety tests intended to investigate the effects of fire or non-nuclear explosions on atomic weapons [244–246].

Since 1967, numerous surveys have been carried out to characterize the contamination within the site. Substantial contamination densities were found at many test sites, particularly at the Taranaki site. Several square kilometres of land were contaminated to levels exceeding 300 kBq/m^2 of ^{239}Pu (the initial reference radionuclide), and even 10- or 100-fold more in some limited areas. Initially, plutonium contamination consisted of the following isotopes: ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu; radioactive decay resulted in ^{241}Pu being gradually replaced with ^{241}Am [235, 246].

The first efforts to remediate the Maralinga site began in 1964. Initially, contaminated debris and most of the remaining infrastructure were buried in pits at a depth of 2–3 m. The plutonium content of each of these pits was not well quantified, but was estimated to be in kilogram quantities [244]. In 1967, further steps were taken to reduce the plutonium surface concentrations by turning over and mixing the surface soil. Following the remediation, the site was closed with a series of fences erected to enclose the burial pits containing significant quantities of plutonium at Taranaki and other sites [234].

Later assessments made for nomadic Aborigines living a mainly outdoor lifestyle identified the inhalation dose pathway as the main contributor to the total doses to both adults and children [245]. As a result of this survey, a much more extensive remediation project was initiated at the site, within which three sets of criteria were established, using ^{241}Am as a reference radionuclide, for making decisions on the remediation process, namely [234]:

(a) Contaminated soil was removed where: (i) the levels of dispersed ^{241}Am exceeded an average of 40 kBq · m^{-2} · ha^{-1}; or (ii) contaminated particles exceeding 100 kBq were found; or (iii) the density of particles exceeding 20 kBq was greater than 1 in 10 m^2 (soil removal criteria).

(b) Once soil was removed, the residual levels of dispersed contamination in the cleared area was not to exceed an average of 3 kBq/m^2 for ^{241}Am, and particulate contamination was to meet the soil removal criteria (clearance criteria).

(c) Permanent occupancy and unrestricted land use was only to occur where levels of dispersed contamination were less than 3 kBq/km^2 for ^{241}Am, averaged over 3 km^2, and the particulate contamination met the soil removal criteria (unrestricted use criteria).

To reduce the inhalation risk, the remediation criteria were guided by conservative principles and estimation of doses with realistic scenarios. These included the possibility of an Aboriginal group living for an entire year on the edge of the non-residential area in regions of the highest activity permitted (approximately 3 kBq/m^2 of ^{241}Am).

The first stage of the remediation project consisted of defining the boundaries at the sites contaminated with plutonium, followed by bulk removal of contaminated soil from the sites and burial in excavated burial trenches under at least 5 m of clean rock and soil. At the end of the remediation process, carried out from 1994 to 2000, a compliance assessment was carried out to ensure that the whole Maralinga area had been made safe [246].

Following the remediation by removal and burial at depth of contaminated surface soil, all areas at Maralinga were shown to be within acceptable absorbed dose limits for all envisaged land uses. A restriction on permanent occupancy within the 'restricted land use' (non-residential) boundary surrounding Taranaki was set as a precautionary measure as the inhalation doses for permanent occupancy of all but a few areas (essentially within the untreated plumes) were well below the prevailing 1 mSv/a limit for members of the public [234].

6.3. REMEDIATION OF AREAS CONTAMINATED AFTER THE CHERNOBYL ACCIDENT

6.3.1. Contamination of the environment and early management options

The accident at the Chernobyl nuclear power plant on 26 April 1986 was the most serious radiation accident that has ever occurred. The Chernobyl nuclear power plant was surrounded by vast tracts of agricultural land, lakes, rivers and forests and there was an extremely severe impact on the largely rural economy and population of all three of the most heavily contaminated countries, Belarus, the Russian Federation and Ukraine. The Chernobyl fallout contaminated large areas of the terrestrial environment, not only within the former USSR but also in many other countries in Europe [247–249].

The most up to date estimates of the amounts of radionuclides released, presented in a United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) report [250], are similar to those reported previously [251], except for the refractory elements, which as it was recently found were about 50% lower [252] than given in the UNSCEAR report of 2000. However, these changes do not influence the assessment of radiation doses, which are based on direct human and environmental measurements [48].

Extremely large areas were contaminated with about 150 000 km^2 receiving deposition densities of ^{137}Cs above 37 kBq/m^2 (Table 9). About a third of the contaminated area was agricultural land (Table 10). Large scale contamination of agricultural and semi-natural land (meadows and forests) led to significant

TABLE 9. THE TOTAL AREAS OF BELARUS, THE RUSSIAN FEDERATION AND UKRAINE WITH A DEPOSITION DENSITY OF ^{137}Cs ABOVE 37 kBq/m^2 [49]

Country	Total area (thousands of km^2)		
	Estimated for 10 May 1986	Estimated in 1998	Estimated in 2006
Russian Federation (European part)	3800	59.8	65.1
Belarus	210	46.1	46.1
Ukraine	600	38.2	42.8
Total across the former USSR	4610	144.1	154

TABLE 10. TOTAL AGRICULTURAL AREAS (ha) CATEGORIZED BASED ON DEPOSITION DENSITIES OF ^{137}Cs in 1987 [12]

Country	Agricultural area by ^{137}Cs deposition density (kBq/m^2)			
	37–185	185–555	555–1480	Total
Belarus	946 200	375 900	112 200	1 434 300
Russian Federation (European part)	1 562 500	368 200	98 300	2 029 000
Ukraine	774 650	90 387	27 039[a]	892 076
Total across the former USSR	3 283 350	834 487	237 539	4 355 376

[a] In Ukraine, agricultural land with ^{137}Cs contamination levels >555 kBq/m^2 has been withdrawn from agricultural use.

exposure of humans via foodstuffs. The most contaminated agricultural land and foodstuffs were in three regions of Belarus (Gomel, Mogilyov and Brest), four regions of the Russian Federation (Bryansk, Kaluga, Tula and Oryol) and five regions of Ukraine (Kiev, Zhitomir, Rivno, Volyn and Chernigov). The population was resettled from the most radioactively contaminated territories, constituting 6200 km^2 in Belarus, 170 km^2 in the Russian Federation and 4200 km^2 in Ukraine (including 2000 km^2 outside the 30 km Chernobyl nuclear power plant exclusion zone). Traditional economic activity within these areas was abandoned or strictly limited [12, 48, 253].

Both Ukraine and Belarus have land inside the 30 km exclusion zone. Overall, in 1986–1991, 264 000 ha of agricultural land in Belarus (including 176 250 ha outside the 30 km exclusion zone), and 158 300 ha in Ukraine (including 101 300 ha outside the 30 km exclusion zone) were excluded from economic use. In the Russian Federation, 17 300 ha of land (all outside of the 30 km exclusion zone) was excluded from economic use [48].

At the time of the accident, more than 15 000 settlements with a population of around six million people were located in areas with a ^{137}Cs deposition density above 37 kBq/m^2. In the areas affected most severely, with a deposition density of ^{137}Cs exceeding 555 kBq/m^2, there were 640 settlements with around 270 000 inhabitants [48, 251]. Implementation of remedial options in agriculture was one of the main elements in the general remediation strategy adopted in the affected regions after the Chernobyl accident [12].

The major dose-forming radionuclides in the remediation phase in the contaminated area around the Chernobyl nuclear power plant were $^{134/137}Cs$, except for the period of the emergency situation during and immediately after the accident, when short lived and intermediate lived radionuclides played an important role. In 1987, the radionuclide content in both plants and animals was largely determined by the $^{134/137}Cs$ deposition density in soil, which is the main reservoir of long lived radionuclides deposited on terrestrial ecosystems. The behaviour of radionuclides in soil controls their migration down the soil column, the extent of long term food contamination and eventual transport into groundwater layers. Thus, estimates of the radiological consequences of accidental releases from the Chernobyl nuclear power plant, as well as planning and implementation of remediation, were based on spatial and temporal variation in ^{137}Cs deposition density and/or activity concentrations in soil.

By the end of 1986, the contaminated areas were classified according to the deposition density of ^{137}Cs, and this classification also served as a basis for remediation. Four classes of deposition density of ^{137}Cs were identified [254]:

(a) Land with a ^{137}Cs deposition density <555 kBq/m^2: No countermeasures or remedial options and no restriction on agricultural production were applied.
(b) Land with a ^{137}Cs deposition density between 555 and 1480 kBq/m^2: A zone of strict control with restrictions on inhabitants (children and pregnant women were relocated); agricultural production was possible only if special management options were applied to protect workers and inhabitants.
(c) Land with a ^{137}Cs deposition density between 3700 and 1480 kBq/m^2: Evacuated zone with agricultural production under strict control to limit contamination of agricultural products.
(d) Land with a ^{137}Cs deposition density >3700 kBq/m^2: Agricultural production ceased and arable land was forested.

Determination of the deposition density of $^{134/137}Cs$ was carried out with a sampling grid of 10 km in 1986 and with a more intense sampling grid of 1 km^2 in 1991. The numbers of sampling points for ^{90}Sr and plutonium radioisotopes were

10- and 100-fold lower, respectively, than those for ^{137}Cs. Experience in agricultural production on contaminated territory showed that detailed maps of contamination for each field were needed rather than averaged data derived from the available large scale maps. Therefore, individual field surveys were initiated in 1987 and continued until 1993 [12].

Unexpectedly high ^{137}Cs activity concentration in milk was found in 1987–1988 in some regions of the Belorussian and Ukrainian Polesye (at a distance up to 300 km from the Chernobyl nuclear power plant), where there were relatively low levels of ^{137}Cs deposition density in soil (37–110 kBq/m^2). The abnormally high transfer of ^{137}Cs from soil to plants was associated with specific properties of the peat and peat-bog soils in these particular provinces.

Most of the soil in the above affected areas are soddy–podzolic (Podzoluvisols) low fertility, light texture (sand and loamy sand) and peat (Histosol) soils. These soils are characterized by high radiocaesium mobility (especially for Histosols) and are most prevalent in the Gomel, Brest, Bryansk, Zhitomir and Rivno regions [12, 255]. The widespread distribution of these soils was one of the major factors determining the high and long term impact on agriculture in areas affected by the Chernobyl accident due to their limited ability to sorb radiocaesium. In western Europe, soils of low fertility are used for extensive agriculture, mainly for grazing of ruminants (e.g. sheep, goat, reindeer, cattle) [120, 256–258]. Such areas include alpine meadows and upland pastures in western and northern Europe with organic soils. These soils were also identified as radioecologically sensitive to radiocaesium in contaminated areas after the Chernobyl accident [12, 29, 57].

In part of the contaminated areas in the former USSR, there were soil types such as soddy–podzolic, grey forest and Chernozem (Eutric Podzoluvisols, Haplic Chernozems (Chernozems Chernic)) with a relatively high clay content which are, in general, more fertile than the dominant soil types. In these soil types, there was a low bioavailability of radiocaesium compared with soils with lower clay content. Such soils are present in the Oryol and Tula regions, and in the southern part of the Kiev regions [12, 255].

The mitigation of consequences of the Chernobyl accident for agriculture in former USSR countries required several forms of intervention described below. They comprised the implementation of a wide set of management options based on the general principle to do more good than harm and their practical implementation was optimized, so that they could produce a maximum net benefit. The action limits at which these options must be applied have been subdivided into two types: dose limits and TPLs (equivalent to action levels) for foodstuffs [12]. The first TPLs approved by the former USSR Ministry of Health on 6 May 1986 concerned ^{131}I activity concentrations in some foodstuffs. Further TPLs, adopted on 30 May 1986, were primarily focused on the ecologically mobile and long lived caesium radionuclides but also concerned the content of all beta emitters in food products caused by surface contamination. Later TPLs put in force since 1988 and 1991 referred to the sum of ^{134}Cs and ^{137}Cs activities. The TPL of 1991 included TPLs for both caesium radioisotopes and ^{90}Sr [259–261] for the first time.

A radiation monitoring network for foodstuffs was established within a few weeks of the accident. A live monitoring technique for in vivo measurements of radiocaesium in animals that effectively reduced the production of contaminated meat was developed and used from 1987 onwards. In 1991–1992, about 12 000 people were employed in 73 local agrochemical units, and 749 veterinary laboratories and control stations within the Ministries of Agriculture in Belarus, the Russian Federation and Ukraine [48].

No conceptual basis had been developed for long term remediation by the time of the first post-accidental harvesting season in July–October 1986. This was due to lack of knowledge and experience of long term planning of agricultural production under the adverse conditions caused by the multiple impacts, including social and economic stresses. In 1986–1987, farmland with ^{137}Cs deposition densities >1480 kBq/m^2 was withdrawn from agricultural use. In Belarus and Ukraine, agricultural land with ^{137}Cs deposition densities >555 kBq/m^2 was withdrawn from agricultural use in 1991 [48, 253].

At the time of the accident, agricultural production in the former USSR relied on two different systems: large collective farms and small private farms. Collective farms routinely use land rotation combined with ploughing and fertilization to improve productivity. Traditionally, small private farms, in contrast, seldom apply artificial fertilizers and often use manure for improving yield. They have one or a few cows, producing milk mainly for personal consumption. Their grazing regime was initially limited to utilization of marginal land not used by the collective farms, but nowadays includes some better quality meadows [12].

In the first years after the accident, management options were carried out mainly in large collective farms, and from the early 1990s there was an increased focus on small private farms. From 1987, high radiocaesium activity concentrations in agricultural products were only observed in animal products, and application of management options aimed at lowering ^{137}Cs activity concentrations in milk and meat were the key focus of the remediation strategy for agriculture.

6.3.2. Remediation in agriculture, forest and aquatic ecosystems

6.3.2.1. Agriculture

For long term remediation, intervention in agricultural systems was a more practical measure to reduce internal doses than the decontamination of settlements aimed at reducing external exposure. Therefore, wide scale application of special management options in agriculture was, and continues to be, a priority. In the 26 years since the accident, many measures have been implemented and a large amount of data on their effectiveness has been generated, together with information on ancillary factors, such as the required resources and costs. The effectiveness of different agricultural countermeasures in actual use on farms after the Chernobyl accident is summarized in Table 11 where reduction factors achieved by each management option are given.

The problems of high radiocaesium deposition were much more significant than those for radiostrontium. The extent of high radiostrontium deposition was limited to the exclusion zone and to some areas of Belarus and Ukraine [12, 262, 263]. In response, some management options (similar to those developed for ^{137}Cs) were applied for ^{90}Sr (Table 11). A 2- to 4-fold decrease in ^{90}Sr activity concentrations in grass and a roughly 2-fold reduction in grain were achieved following radical improvement of fodder lands and mineral fertilizer application, respectively [33].

In the first ten years after the accident, the priority in remediation of contaminated areas was focused on amelioration of soil (‘soil based management options’), with the aim of reducing radiocaesium transfer to plants, with special attention to those species used for animal feed (Fig. 12). After 1994, because the application of different caesium binders (AFCF) was found to be very effective, it became one of the most widespread actions allowing production of acceptable animal products in contaminated areas (Fig. 13).

The extent to which each management option was used varied between the three countries. The recommendations on application of management options were repeatedly revised and updated, depending on changes in the radiological status of contaminated areas, economic constraints and the perception of the management option by stakeholders and the general public.

The general approach used for the development of soil based countermeasures was to insert the ‘protection’ element into normal agricultural practice to ensure sustainable and environmentally sound development [33, 34]. Even though the application of ploughing was only feasible in areas with fertile soils with a deep organic horizon, both deep and shallow ploughing were used extensively. The effectiveness of ploughing in reducing radiocaesium transfer to plants varied from reduction factors of 2-fold for shallow ploughing to 15- to 20-fold for skim and burial ploughing, and the effect persisted for many years [12, 31, 33, 39, 48, 111].

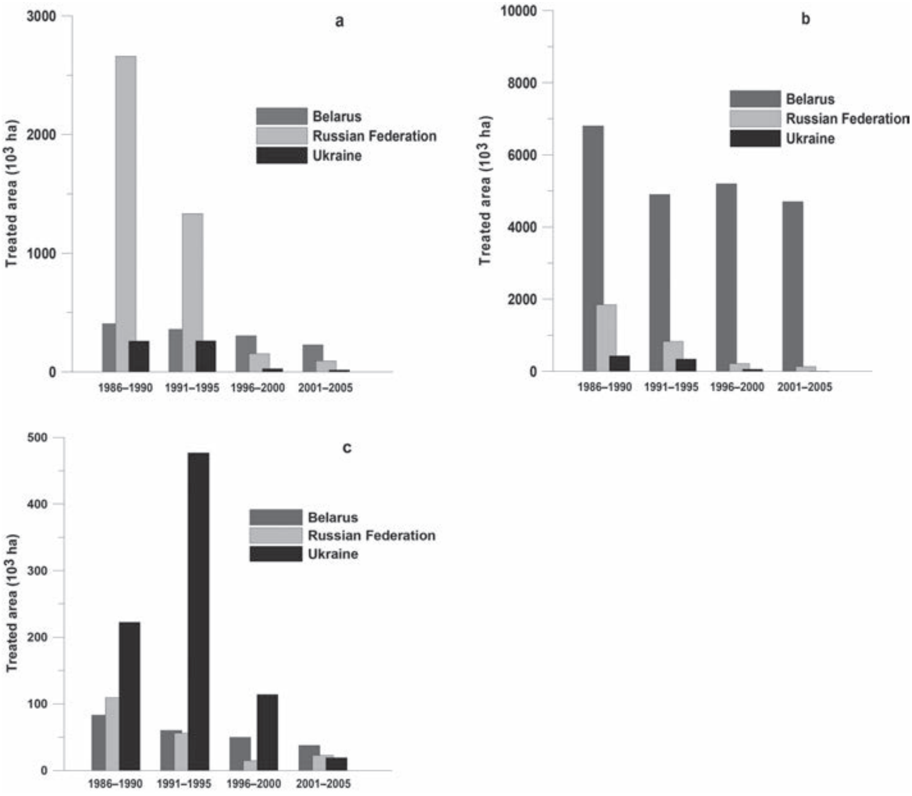


FIG. 12. Changes over time in the extent of agricultural areas treated with (a) liming, (b) mineral fertilizers and (c) receiving radical improvement in thousands of hectares [12].

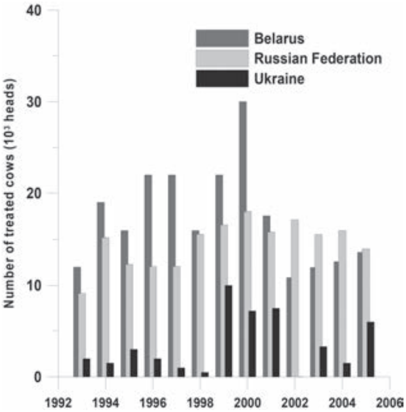


FIG. 13. Changes over time in the use of AFCF in Belarus, the Russian Federation and Ukraine after the Chernobyl accident [12].

TABLE 11. SUMMARY OF REDUCTION FACTORS FOR MAJOR MANAGEMENT OPTIONS TO DECREASE CONTAMINATION OF AGRICULTURAL PRODUCTS IMPLEMENTED AFTER THE CHERNOBYL ACCIDENT IN THE FORMER USSR IN 1986–2006 [12, 34, 53, 56, 86, 264–276]

Management option	^{137}Cs	^{90}Sr
Soil based options		
Normal ploughing (first year)	2.5–4.0	n.d.
Skim and burial ploughing	8–16	n.d.
Liming	1.5–3.0	1.5–2.6
Application of mineral fertilizers	1.5–3.0	1.0–2.0
Application of organic fertilizers	1.5–2.0	1.2–1.5
Radical improvement:		
First application	1.5–9.0*	1.5–3.5
Further applications	2.0–3.0	1.5–2.0
Surface improvement:		
First application	2.0–3.0*	2.0–2.5
Further applications	1.5–2.0	1.5–2.0
Change in fodder crops	3–9	n.d.
Animal based options		
Clean feeding of animals	2–5 (time dependent)	2–5
Administration of Cs binders to animals	3–5	n.a.
Administration of clay minerals to animals	2–3	n.a.

* Up to 15 for wet peat with drainage.
Note: n.a. = not applicable; n.d. = no data.

Liming was normally applied to mineral soils, particularly to those that are acidic. The liming dosage rates applied every 4–5 years typically ranged from 2 to 10 t/ha, providing, on average, a 1.5- to 3-fold decrease in plants [266, 267].

Mineral fertilizers have been used extensively in all three countries to reduce radiocaesium uptake in plants. The optimum ratio of mineral fertilizers to achieve the maximum reduction (1.5- to 3-fold) in root uptake of radiocaesium on contaminated land was an N:P:K ratio of 1:1.5:2 (of active substance) [34] compared with that of 1:1:1[23] normally used for uncontaminated land [12, 33, 268–273].

Since the first year after the Chernobyl accident, radical improvement has been a key management option carried out extensively in practically all contaminated areas of Belarus, the Russian Federation and Ukraine [12]. Radical improvement included removing vegetation, ploughing, liming, fertilization and re-seeding, and has been effective in field conditions, achieving an average reduction in root uptake of radiocaesium of 2- to 3-fold (Table 11) [274–276]. For organic soil, the effectiveness was increased to 3- to 5-fold, with a maximum effectiveness (with drainage) of 10- to 15-fold in wet peat soil [12, 104, 274, 275].

Surface improvement, which is a normal agricultural practice in the area, involved soil disking, fertilization (with a ratio of N:P:K of 1:1.5:2), surface liming and sowing additional grass. Surface improvement is generally applied in areas with light sandy soils, where it is impossible to plough, and where radical improvement was not recommended. This option was around 15–20% cheaper, but less effective than radical improvement [12, 31, 48, 135].

Some plant species take up more radiocaesium than others and the difference can be as great as a factor of a hundred depending on soil and plant properties [33, 34, 148]. The extent of the difference is considerable, and fodder crops, such as lupine, peas, buckwheat and clover, which accumulate high amounts of radiocaesium, were completely or partly excluded from cultivation [33, 34]. Thus, the contamination of agricultural produce and, hence, the need for remediation, depended on both the soil type and the plant species associated with the different types of land use. Such land-use related variation needed to be considered when selecting a possible alternate land use for contaminated regions, together with any variation in TPLs for different agricultural products. Management options, such as a conversion of arable land into meadow and converting agricultural land to forestry, were implemented in some of the most contaminated areas [12, 49].

In Belarus, the conversion of some land use to rape seed production was applied in highly contaminated areas, with the aim of producing two products: edible oil and protein cake as an animal fodder [86, 199]. Irrespective of the original extent of radiocaesium contamination in rape seed, the rape oil always contained very low amounts of radiocaesium because of low food processing factors [198].

---

[23] The application rate for each fertilizer is calculated based on soil characteristics and the mineral nutrition demands of the crop.

The provision of uncontaminated (or less contaminated) feed to previously contaminated animals for an appropriate period before slaughter effectively reduces radionuclide contamination in meat and milk at a rate depending on the animal's biological half-life for each radionuclide [33, 146, 154, 158]. Clean feeding reduces intake of the contaminating radionuclides and was one of the most important and frequently used countermeasures for meat from agricultural animals in both the former USSR countries and western Europe after the Chernobyl accident [12, 31, 33, 56, 276–279]. Clean feeding is routinely used in all three countries for meat production and is combined with live monitoring of animals, so that if an animal's muscles are above TPLs they can be returned to the farm for further clean feeding.

Various sorbents have been tested in former USSR countries to reduce radiocaesium activity concentrations in animal products. They were either chemicals or clays which were added to concentrates or mineral supplements for animals, or administered in the form of slow release boli placed in the gut for free grazing animals. It has been broadly accepted that the most effective Cs binders are AFCF compounds [57–59]. AFCF compounds have been used to reduce $^{134/137}$Cs contamination in animal products since the beginning of the 1990s (Fig. 13). The maximum effectiveness of AFCF application in terms of ^{137}Cs activity concentration reduction in animal products was up to 10-fold, but typically in field conditions it was 3- to 5-fold.

A set of methods for milk processing to butter and sour-milk products has been developed and successfully implemented in food processing practice (Table 12). Depending on the method of milk processing, ^{137}Cs and ^{90}Sr activity concentrations in a final food product can be reduced by up to 7- to 10-fold in comparison with the initial product. Using food processing, a number of processed food products (starch, vegetable oil, spirit, etc.) can be prepared which comply with radiation safety standards whereas the original unprocessed contaminated raw material would fail.

6.3.2.2. Forestry

Prior to the Chernobyl accident, management options to offset doses due to large scale contamination of forests had not been given any significant attention. In the former USSR countries, actions were taken to restrict activities in the most contaminated zones which included significant areas of forestry [64, 65]. These actions were, in general, rather simple and involved restrictions on basic activities, such as accessing forests and gathering wild foods and firewood.

TABLE 12. PROCESSING FACTORS[a] (RATIO OF ACTIVITY CONCENTRATIONS IN THE PRODUCT AFTER AND BEFORE PROCESSING) FOR VARIOUS FOODSTUFFS [12]

Food processing option	^{137}Cs	^{90}Sr
Processing grain to flour	0.3–0.9	0.2–0.4
Processing vegetables, berries and fruits to juice	0.4–1	0.01–0.5
Processing of beet to sugar	0.01–0.08	n.a.
Processing of potatoes to starch	0.12–0.17	n.a.
Boiling mushrooms	0.1–0.3	n.a.
Soaking and pickling mushrooms	0.1	n.a.
Processing milk to butter	0.2–0.3	0.1–0.5
Processing milk to cream (10–30% fat)	0.7–0.9	0.7–0.9
Processing milk to condensed milk	2.7	2.7
Dried milk	8	8
Processing milk to cheese (rennet)	0.5–0.6	6–8
Processing milk to casein	0.03	4
Boiling meat	0.1–0.5	n.a.
Soaking meat	0.02–0.7	n.a.
Processing rapeseed to oil	0.004	0.002

[a] These data are based on experience after the Chernobyl accident. The data for these factors in Section 4 are based on a wider set of data from a variety of sources and can differ from those in Table 12.

Note: n.a. = not applicable.

Restriction of access to contaminated forests and restriction of the use of forest products has been the main management option applied in former USSR countries [39, 48]. These restrictions can be categorized as follows:

- Restricted access for both the public and forest workers to reduce both external and internal exposures: This option was complemented by the provision of information from the local monitoring programme and education on issues such as food preparation.

- Restricted harvesting of food products such as game, berries and mushrooms by the public to reduce internal doses: In former USSR countries, mushrooms are often consumed and, therefore, this restriction has been particularly important.
- Restricted collection of firewood by the public to prevent exposure in homes and gardens when the wood is burned; the ash is disposed of or used as fertilizer.
- Alteration of hunting practices aiming to avoid consumption of meat with high seasonal levels of radiocaesium.
- Fire prevention, especially in areas with large scale radionuclide deposition, aiming to avoid secondary contamination of the environment.

This category of management options includes the use of machinery and/or chemical treatments to alter the distribution or transfer of radiocaesium in the forest. However, the cost effectiveness of many technological management options was questionable, especially when applied on a large scale [39].

6.3.2.3. Aquatic systems

Measures to reduce doses via freshwater foodstuffs may be required over longer timescales as a result of bioaccumulation of radionuclides through the aquatic food chain. Reviews of aquatic countermeasures [61] have considered both direct (restrictions) and indirect management options to reduce doses at the following stages of the aquatic dose pathway:

- Restrictions on water use or changing to alternative supplies;
- Restrictions on fish consumption;
- Water flow control measures (e.g. dykes and drainage systems);
- Uptake by fish and aquatic foodstuffs from contaminated water;
- Processing of fish prior to consumption.

No management options were required, or applied, in marine systems after the Chernobyl nuclear power plant accident.

Preventing contamination of surface waters

Dredging of canal-bed traps to intercept suspended particles in contaminated rivers was carried out on the Pripyat River [279–281]. These canal-bed traps were highly inefficient for two reasons: (i) flow rates were too high to trap small suspended particles which were carrying much of the radionuclide load; (ii) a significant proportion of the radionuclides present (and most of the ‘bioavailable’ activity) was in dissolved forms and was not intercepted by the sediment traps [280].

One hundred and thirty zeolite-containing dykes were constructed on smaller rivers and streams around the Chernobyl nuclear power plant to intercept dissolved radionuclides. These were also very ineffective: only 5–10% of the ^{90}Sr and ^{137}Cs in the small rivers and streams were sorbed by these zeolite barriers [48].

Fish and aquatic foodstuffs

Bans on consumption and on the sale of freshwater fish were applied in many water bodies affected by the Chernobyl accident. It is believed that such bans were often ignored by fishermen. Raising farmed fish could be used as an alternative to freshwater fish in areas affected by fishing bans because they are fed with uncontaminated food, and do not significantly accumulate radiocaesium or radiostrontium from the water. In most cases, addition of lime and potassium to the water to reduce radioactivity in fish had little effect on the uptake of ^{137}Cs in fish [61, 183–186]. Experience of lake liming, in conjunction with artificial feeding of fish in Ukraine, has been summarized in Ref. [279].

Different methods of food preparation may reduce radiocaesium in fish by about 2-fold. An effective option to reduce consumption of radiostrontium is to remove the bony parts of fish prior to cooking since strontium is mainly concentrated in the bones and skin. Various other food preparation methods are discussed in IAEA-TECDOC-1616 [51].

Groundwater

Some measures were taken to protect groundwater from seepage of radionuclides from the ‘shelter’ and from waste sites in the Chermobyl nuclear power plant exclusion zone. These focused mainly on the construction of engineering and geochemical barriers around the local hot spots to reduce groundwater fluxes to the river network. There have been no measures to protect groundwater supplies following atmospheric deposition of radioactivity because only very small amounts of radiostrontium and radiocaesium percolate from surface soils to groundwater after atmospheric deposition [61, 63].

Irrigation water

Irrigation did not significantly add to radionuclide contamination of crops which had previously been affected by atmospheric deposition of radionuclides (except for rice). Thus, no management options were directly applied to irrigation waters. However, experience [279–281] showed that a change from sprinkling to drainage irrigation of agricultural plants (e.g. for vegetables) can reduce the transfer of radionuclides from water to crops severalfold. This, in combination with improved fertilization of irrigated lands, can effectively reduce radionuclide activity concentrations in crops irrigated by water from reservoirs affected by radioactive contamination.

6.3.3. Evaluating and optimizing remediation strategies

The effectiveness of management options and their associated required resources and costs vary considerably as do the many other issues which are described in Section 3 [4, 5, 12]. This generated a need for the development of new approaches and EDSSs for optimizing remediation strategies in the different environments described above. Application of remediation in contaminated areas after the Chernobyl accident had three major radiation protection goals:

(a) To guarantee foodstuff production within TPLs (or action levels);
(b) To provide an annual effective dose to local inhabitants lower than 1 mSv/a as soon as achievable;
(c) To minimize collective doses to the general public based on the ALARA principle.

Large scale application of the range of management options described earlier made it possible to achieve a sharp decrease in the number of agricultural products with radiocaesium activity concentrations above action levels in all three countries from August 1986. The most difficult issue remaining was the production of milk in compliance with the standards.

The maximum effect from management option application was achieved in 1986–1992. As a result of implementation of countermeasures and remedial management options in affected areas (mainly radical improvement and clean feeding), contamination levels in agricultural products were constantly reduced. Since 1991, the proportion of animal products with radiocaesium activity concentrations exceeding action levels is <10% of the gross output from contaminated areas.

Due to financial constraints in the mid-1990s, the use of environmental management options was drastically reduced and their application rates were insufficient, not only for remediation but also for conventional food production. However, by optimizing available resources, the remediation effort for $^{134/137}$Cs remained at a level which was sufficient to maintain an acceptable ^{137}Cs content in most food products.

The decrease in ^{137}Cs activity concentrations in foodstuffs was due to three groups of factors: natural biogeochemical processes, management options and radioactive decay. From 1987 to 1994, the contribution of management options to the decrease of contamination in agricultural products in the region with intensive remediation was 60%. In contrast, in the regions with limited application of management options, the dominant contribution to the decrease of ^{137}Cs in products (up to 70%) was from natural biogeochemical processes [282].

Intensive application of countermeasures and remediation management options in agriculture after the Chernobyl accident achieved a considerable reduction in both individual and collective doses to the local population. The estimation of the total averted doses for the three most affected countries was approximately 12 000–19 000 man Sv [12]. Compared with the data given by the Chernobyl Forum report [48], which gives total external and internal collective doses of 30 000 and 22 000 man Sv, respectively, across the three countries, the implementation of all agricultural management options averted 30–40% of the internal collective dose (excluding thyroid dose) or around 20–25% of total collective dose that would have been received by the residents of contaminated areas without the use of management options [12].

The contributions of each remedial option to the reduction in collective dose were dependent both on the type of agriculture and the characteristics of each option. Generally, the main contributors to a reduction of collective dose were management options in animal breeding because milk was the biggest contributor to internal exposure of the population after the Chernobyl accident. In the areas where agricultural countermeasures were applied on the largest scales (e.g. the Bryansk or Gomel regions), such management options contributed 65–75% of the total averted dose [12].

The contributions of remedial actions to the reduction of collective dose to the local population varied in different time periods after the accident. Thus, in the initial few years, the contribution of restrictions on the use of privately produced milk and other foodstuffs reached 90%, whereas after 1990 it dropped to 50–60%. The contribution of radical improvement in the 1990s overall was less than 10%, being about 25–30% in 1991–1995, but much less thereafter as the use of these management options greatly decreased. In contrast, the effectiveness and scale of the application of Cs binders increased with time, contributing 10% of the averted dose in 1994–1995 and up to 40–50% in 2004–2005 [273].

The Chernobyl accident led to an extensive set of actions in former USSR countries; the authorities introduced a range of short and long term environmental management options in the emergency and subsequently that aimed at reducing the accident’s negative consequences. Their implementation on more than 4.4 million hectares of agricultural land has made it possible to continue to produce food in these areas and has substantially reduced the number of products with radionuclide activity concentrations above TPLs in all three countries. The response also provided a substantial dose reduction to the population [48]. Practically all of the long term remedial management options implemented on a large scale on contaminated lands of the former USSR can be recommended for use in the event of future accidents. However, the effectiveness of most soil based remedial options varies at each site. Therefore, analysis of soil properties and farming practices before their application is of great importance [12].

Experience after the Chernobyl accident has shown that the perception of the public of the introduction, performance and withdrawal of management options during and after emergencies is an important issue that requires more sociological research. The development of socially focused management options aimed at involvement of the public in these processes at all of the stages of the decision making process would enhance current capability to develop successful remediation strategies [12, 72, 140, 199].

7. CONCLUSION

Management options intended for environmental remediation vary considerably in their effectiveness, cost, feasibility and practicability, and need to be combined in a manner which is appropriate to the particular characteristics of the existing situation being addressed. Therefore, remediation of areas contaminated with radionuclides is a complex process, involving many technical and social factors, and they need to be evaluated in the context of the specific situation. This means taking into account the characteristics of the contamination, ecosystem, land use, socioeconomic issues, cultural preferences, and the local and national priorities for remediation.

This report provides information on management options applicable for existing exposure situations and includes information on some of the underlying mechanisms controlling the effectiveness of management options. The report is not intended to provide a detailed description of the various management options since comprehensive analyses have been provided elsewhere [5, 6, 33, 37]. Instead, it focuses on the most important information, describes key issues that are relevant to implementation and provides some guidance on their usefulness as part of a remediation strategy. The development of radioecological models which can predict the effectiveness of management options based on an understanding and quantification of processes rather than empirical approaches would potentially enhance cost effectiveness and enable better optimization of remediation.

The complicated, multidimensional nature of remediation planning can be facilitated by the use of decision aiding techniques. A variety of approaches to decision making have been developed, including ones that can help to optimize application of different management options. This is consistent with the need to adopt an integrated approach, suitable for conforming to current regulatory frameworks for remediation of contaminated areas, especially with a target of sustainable development of the environment. Studies on the application of multi-criteria analysis, considered in Section 5, indicate that a strategy which takes into account the views of stakeholders may be considerably less cost effective, requiring larger resources for remediation compared with a radiological strategy focused only on averting dose. However, compared with international values for the cost effectiveness of actions for reducing occupational exposures, both types of remediation strategies are still relatively cost effective.

This report is intended for individuals and authorities dealing with remediation projects and includes an overview of the current state of knowledge on remediation planning for stakeholders at different levels of decision making. It can be used to inform those planning a remediation strategy to ensure that they meet the key relevant international recommendations and standards laid out in the recent ICRP Publication 111 [2] and the BSS [10].

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidelines for Agricultural Countermeasures Following an Accidental Release of Radionuclides, Technical Reports Series No. 363, IAEA, Vienna (1994).

[2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Application of the Commission's Recommendations to the Protection of People Living in Long-term Contaminated Areas after a Nuclear Accident or a Radiation Emergency, Publication 111, Elsevier, Amsterdam (2009).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2007 Edition, IAEA, Vienna (2007).

[4] VOIGT, G., et al., A wider perspective on the selection of countermeasures, Rad. Prot. Dosim. **92** (2000) 45–48.

[5] HOWARD, B.J., et al., The STRATEGY project: decision tools to aid sustainable restoration and long-term management of contaminated agricultural ecosystems, J. Env. Radioact. **83** (2005) 275–295.

[6] VOIGT, G., FESENKO, S. (Eds), "Remediation of areas contaminated after radiation accidents and incidents", Remediation of Contaminated Environments, Elsevier, Amsterdam (2009).

[7] NISBET, A.F., et al., Decision aiding handbooks for managing contaminated food production systems, drinking water and inhabited areas in Europe, Radioprotect. **45** (2010) S23–S37.

[8] FESENKO, S., ZEILLER, L., VOIGT, G., "Site characterisation and measurement strategies for remediation purposes", Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 41–120.

[9] Naturally Occurring Radioactive Material (NORM V) (Proc. 5th Int. Symp. Seville, 2007), IAEA, Vienna (2008).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards — Interim Edition, IAEA Safety Standards Series No. GSR Part 3 (Interim), IAEA, Vienna (2011).

[11] SHAW, G., "Introduction", Radioactivity in the Terrestrial Environment (Shaw, G., Ed.), Elsevier, Amsterdam (2007) 1–19.

[12] FESENKO, S.V., et al., An extended review of twenty years of countermeasures used in agriculture after the Chernobyl accident, Sci. Total Env. **383** (2007) 1–24.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Remediation of Areas Contaminated by Past Activities and Accidents, IAEA Safety Standards Series No. WS-R-3, IAEA, Vienna (2003).

[14] INTERNATIONAL ATOMIC ENERGY AGENCY, Remediation Process for Areas Affected by Past Activities and Accidents, IAEA Safety Standards Series No. WS-G-3.1, IAEA, Vienna (2007).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Release of Sites from Regulatory Control on Termination of Practices, IAEA Safety Standards Series No. WS-G-5.1, IAEA, Vienna (2006).

[16] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental and Source Monitoring for Purposes of Radiation Protection, IAEA Safety Standards Series No. RS-G-1.8, IAEA, Vienna (2005).

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Programmes and Systems for Source and Environmental Radiation Monitoring, Safety Reports Series No. 64, IAEA, Vienna (2010).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Compliance Monitoring for Remediated Sites, IAEA-TECDOC-1118, IAEA, Vienna (1999).

[19] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples, ISO 18589-2:2007, ISO, Geneva (2005).

[20] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 3: Measurement of Gamma-emitting Radionuclides, ISO 18589-3, ISO, Geneva (2007).

[21] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 4: Measurement of Plutonium Isotopes (Plutonium-238 and Plutonium-239 + 240) by Alpha Spectrometry, ISO 18589-4, ISO, Geneva (2007).

[22] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 5: Measurement of Strontium-90, ISO 18589-5, ISO, Geneva (2007).

[23] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 6: Measurement of Gross Alpha and Gross Beta Activities, ISO 18589-6, ISO, Geneva (2007).

[24] SANZHAROVA, N.I., et al., Changes in the forms of ^{137}Cs and its availability in plants as dependent on properties of fallout after the Chernobyl Nuclear Power Plant accident, Sci. Total Env. **154** (1994) 9–22.

[25] FESENKO, S.V., SANZHAROVA, N.I., SPIRIDONOV, S.I., ALEXAKHIN, R.M., Dynamics of ^{137}Cs bioavailability in a soil-plant system in areas of the Chernobyl nuclear power plant accident zone with a different physico-chemical composition of radioactive fallout, J. Env. Radioact. **34** (1996) 287–313.

[26] FESENKO, S.V., et al., The dynamics of the transfer of caesium-137 to animal fodder in areas of Russia affected by the Chernobyl accident and doses resulting from the consumption of milk and milk products, Rad. Prot. Dosim. **69** (1997) 289–299.

[27] FESENKO, S., et al., Important factors governing exposure of the population and countermeasure application in rural settlements of the Russian Federation in the long term after the Chernobyl accident, J. Env. Radioact. **56** (2001) 77–98.

[28] HOWARD, B.J., WRIGHT, S.M. (Eds), Spatial Analysis of Vulnerable Ecosystems in Europe: Spatial and Dynamic Prediction of Radiocaesium Fluxes into European Foods (SAVE), Final Rep., Commission of European Communities, Brussels (1999).

[29] HOWARD, B.J., The concept of radioecological sensitivity, Rad. Prot. Dosim. **92** (2000) 29–34.

[30] INTERNATIONAL ATOMIC ENERGY AGENCY, Radioactive Particles in the Environment: Sources, Particle Characterization and Analytical Techniques, IAEA-TECDOC-1663, IAEA, Vienna (2011).

[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Characterization of Radioactively Contaminated Sites for Remediation Purposes, IAEA-TECDOC-1017, IAEA, Vienna (1998).

[32] Multi-Agency Radiation Surveys and Site Investigation Manual (MARSSIM), NUREG-1575, Rev.1, EPA 402-R-97-016, Rev.1, DOE/EH-0624 Rev.1, August 2000, http://www.epa.gov/radiation/marssim/index.html

[33] ALEXAKHIN, R.A., KORNEYEV, N.A. (Eds), Agricultural Radiology, Ecology, Moscow (1991) (in Russian).

[34] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Guide on Agriculture Administrating in Areas Subjected to Contamination as a Result of the Accident at the Chernobyl NPP for 1991–1995 (ALEXAKHIN, R.M., Ed.), State Commission of the USSR, Council of Ministers on Food and Purchases, Moscow (1991) 57 pp. (in Russian).

[35] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, “Manual on farming in conditions of radioactive contamination of some areas in the Russian Federation and the Republic of Belarus”, Collection of Regulatory and Methodological Documents for Farming Regulation on Chernobyl Contaminated Lands, Vol. 3, Obninsk (2006) (in Russian).

[36] BRYNILSEN, L., STRAND, P., A rapid method for the determination of radioactive caesium in live animals and carcasses and its practical application in Norway after the Chernobyl accident, Acta Veterin. Scand. **35** (1994) 401–408.

[37] NISBET, A.F., et al., Generic Handbook for Assisting in the Management of Contaminated Food Production Systems in Europe Following a Radiological Emergency, Vol. 2, EURANOS(CAT1)-TN(09)-01 (2009), http://www.euranos.fzk.de

[38] INTERNATIONAL COMMISSION ON RADIATION UNITS, Sampling for Radionuclides in the Environment, Report 76, J. ICRU **6** 1 (2006).

[39] ALEXAKHIN, R.M., “Remediation of areas contaminated after radiation accidents and incidents”, Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 177–222.

[40] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Agricultural Food Products — Layout for a Standard Method of Sampling from a Lot, ISO 7002:1986, ISO, Geneva (1986).

[41] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Soil Quality — Sampling, Part 1: Guidance on the Design of Sampling Programmes, ISO 10381-1:2002, ISO, Geneva (2002).

[42] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Soil Quality — Sampling, Part 5: Guidance on the Procedure for the Investigation of Urban and Industrial Sites with Regard to Soil Contamination, ISO 10381-5:2005, ISO, Geneva (2005).

[43] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement of Radioactivity in the Environment — Soil, Part 2: Guidance for the Selection of the Sampling Strategy, Sampling and Pre-treatment of Samples, ISO 18589-2, ISO, Geneva (2007).

[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Soil Sampling for Environmental Contaminants, IAEA-TECDOC-1415, IAEA, Vienna (2004).

[45] UNITED STATES DEPARTMENT OF ENERGY, EML Procedures Manual, HASL-300, 27th edn, HASL-300-ED.27, Vol. 1, Environmental Measurements Laboratory, USDOE, Washington, DC (1990).

[46] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Radiochemical Analytical Procedures for Analysis of Environmental Samples, Milk and Milk Products — Guidance on Sampling, ISO 707:2008, ISO, Geneva (2008).

[47] INTERNATIONAL ATOMIC ENERGY AGENCY, Measurement of Radionuclides in Food and the Environment — A Guidebook, Technical Reports Series No. 295, IAEA, Vienna (1989).

[48] INTERNATIONAL ATOMIC ENERGY AGENCY, Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience, Report of the UN Chernobyl Forum Expert Group “Environment”, Radiological Assessment Reports Series No. 8, IAEA, Vienna (2006).

[49] ALEXAKHIN, R.M., FESENKO, S.V., SANZHAROVA, N.I., Serious radiation accidents and the radiological impact on agriculture, Rad. Prot. Dosim. **64** (1996) 37–42.

[50] FESENKO, S.V., ALEXAKHIN, R.M., SANZHAROVA, N.I., “Site characterisation techniques used in restoration of agricultural areas on the territory of the Russian Federation contaminated after the accident at the Chernobyl NPP”, Site Characterization Techniques Used in Environmental Restoration Activities, IAEA-TECDOC-1148, IAEA, Vienna (2000) 129–152.

[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009).

[52] INTERNATIONAL ATOMIC ENERGY AGENCY, Handbook of Parameter Values for the Prediction of Radionuclide Transfer in Terrestrial and Freshwater Environments, Technical Reports Series No. 472, IAEA, Vienna (2010).

[53] PRISTER, B.S., PEREPELYATNIKOV, G.P., PEREPELYATNIKOVA, L.V., Countermeasures used in the Ukraine to produce forage and animal food products with radionuclide levels below intervention limits after the Chernobyl accident, Sci. Total Env. **137** (1993) 183–198.

[54] OUGHTON, D.H., FORSBERG, E-M., “Non-radiological perspectives — holistic assessment of countermeasure strategies”, Radioactive Contamination in Residential Areas (ANDERSSON, K., Ed.), Elsevier, Amsterdam (2009) 260–294.

[55] HOVE, K., et al., Countermeasures for reducing radioactive contamination of farm animals and farm animal products, Sci. Total Env. **137** (1993) 261–271.

[56] ALEXAKHIN, R.M., Countermeasures in agricultural production as an effective means of mitigating the radiological consequences of the Chernobyl accident, Sci. Total Env. **137** (1993) 9–20.

[57] HOWARD, B.J., BERESFORD, N.A., VOIGT, G., Countermeasures for animal products: a review of effectiveness and potential usefulness after an accident, J. Env. Radioact. **56** (2001) 115–137.

[58] HOWARD, B., BERESFORD, N., HOVE, K., Transfer of radiocaesium to ruminants in natural and semi-natural ecosystems and appropriate countermeasures, Health Phys. **61** 6 (1991) 715–725.

[59] HOWARD, B.J., Management methods for reducing radionuclide contamination of animal food products in semi-natural ecosystems, Sci. Total Env. **137** (1993) 249–260.

[60] VOIGT, G., Chemical methods to reduce the radioactive contamination of animals and their products in agricultural ecosystems, Sci. Total Env. **137** (1993) 205–225.

[61] SMITH, J.T., VOITSEKHOVITCH, O.V., HAKANSON, L., HILTON, J., A critical review of measures to reduce radioactive doses from drinking water and consumption of freshwater foodstuffs, J. Env. Radioact. **56** (2001) 11–32.

[62] SMITH, J.T., SASINA, N.V., KRYSHEV, A.I., BELOVA, N.V., KUDELSKY, A.V., A review and test of predictive models for the bioaccumulation of radiostrontium in fish, J. Env. Radioact. **100** (2009) 50–54.

[63] ONISHI, Y., VOITSEKHOVITCH, O.A., ZHELEZNYAK, M., Chernobyl — What Have we Learned? The Successes and Failures to Mitigate Water Contamination Over 20 Years, Springer, Berlin (2007) 290 pp.

[64] FESENKO, S., BROWN, J., Review of Countermeasure Options for Semi-natural Environments: Forests and Natural Meadows, NRPB-M1123, National Radiological Protection Board, Chilton, Didcot (2000).

[65] FESENKO, S.V., et al., Analysis of the contribution of forest pathways to the radiation exposure of different population groups in the Bryansk region of Russia, Rad. Env. Bioph. **39** (2000) 291–300.

[66] HOWARD, B.J., et al., A critical evaluation of the strategy project, Rad. Prot. Dosim. **109** (2004) 63–67.

[67] INTERNATIONAL ATOMIC ENERGY AGENCY, Planning for Cleanup of Large Areas Contaminated as a Result of a Nuclear Accident, Technical Reports Series No. 327, IAEA, Vienna (1991).

[68] INTERNATIONAL ATOMIC ENERGY AGENCY, Planning for Environmental Restoration of Uranium Mining and Milling Sites in Central and Eastern Europe, IAEA-TECDOC-982, IAEA, Vienna (1998).

[69] INTERNATIONAL ATOMIC ENERGY AGENCY, Factors for Formulating Strategies for Environmental Restoration, IAEA-TECDOC-1032, IAEA, Vienna (1998).

[70] INTERNATIONAL ATOMIC ENERGY AGENCY, Technologies for Remediation of Radioactively Contaminated Sites, IAEA-TECDOC-1086, IAEA, Vienna (1999).

[71] INTERNATIONAL ATOMIC ENERGY AGENCY, Site Characterization Techniques Used in Environmental Restoration Activities, IAEA-TECDOC-1148, IAEA, Vienna (2000).

[72] INTERNATIONAL ATOMIC ENERGY AGENCY, Non-technical Factors Impacting on the Decision Making Processes in Environmental Remediation, IAEA-TECDOC-1279, IAEA, Vienna (2002).

[73] INTERNATIONAL ATOMIC ENERGY AGENCY, Remediation of Sites with Dispersed Radioactive Contamination, Technical Reports Series No. 424, IAEA, Vienna (2004).

[74] OUGHTON, D.H., BAY, I., VOIGT, G., "Social, ethical, environmental and economic aspects of remediation", Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 428–453.

[75] OUGHTON, D.H., BAY-LARSEN, I., FORSBERG, E.-M., KAISER, M., HOWARD, B., An ethical dimension to sustainable restoration and long-term management of contaminated areas, J. Env. Radioact. **74** (2004) 171–183.

[76] OUGHTON, D.H., Promises and pitfalls of public participation, Energ. Environ. **19** (2008) 485–496.

[77] OUGHTON, D.H., HOWARD, B.J., The social and ethical challenges of radiation risk management, Ethics, Policy and Environment **15** 1 (2012) 71–76.

[78] SALT, C.A., RAFFERTY, B., Assessing potential secondary effects of countermeasures in agricultural systems: a review, J. Env. Radioact. **56** (2001) 99–114.

[79] SALT, C.A., et al., Impact Assessment Methodology for Side-effects of Countermeasures against Radionuclide Contamination in Food Products, Research Rep. No. 1, Nord-Troendelag College, Steinkjer, Norway (1999).

[80] WILKINS, B.T., Change in land use and crop selection, Sci. Total Env. **137** (1993) 169–172.

[81] WILKINS, B.T., et al., Comparison of data on agricultural countermeasures at four farms in the former Soviet Union, NRPB-R285 (1996).

[82] OUGHTON, D., et al., Long-term Rehabilitation of Contaminated Areas in Norway: Outcomes of Co-expertise Meetings, Deliverable Rep. for EURANOS, D8C3R1 for the European Commission (2008).

[83] SMITH, J., BERESFORD, N.A., Chernobyl Catastrophe and Consequences, Praxis Publishing/Springer, Chichester (2005).

[84] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Annals ICRP **21**(1–3), Elsevier, Amsterdam (1991).

[85] INTERNATIONAL COMMISION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Annals ICRP **37**(2–4), Elsevier, Amsterdam (2007).

[86] BOGDEVICH, I., SANZHAROVA, N., PRISTER, B., TARASIUK, S., "Countermeasures in natural and agricultural areas after the Chernobyl accident", Role of GIS in Lifting the Cloud off Chernobyl (KOLEJKA, J., Ed.), Kluwer-Academic, Amsterdam (2002) 60–73.

[87] BROWN, J., et al., Comparison of Data from the Ukraine, Russia and Belarus on the Effectiveness of Agricultural Countermeasures, NRPB-M597, NRPB, Didcot (1995) 27 pp.

[88] STRAHLENSCHUTZKOMMISSION, Übersicht über Maßnahmen zur Verringerung der Strahlenexposition nach Ereignissen mit nicht unerheblichen radiologischen Auswirkungen, Überarbeitung des Maßnahmenkatalogs Band 1 und 2, Empfehlung der Strahlenschutzkommission; Berichte der Strahlenschutzkommission, Heft 60 (GENKEL, S., Schnadt, H., Eds) (with CD-ROM), Bonn (2010).

[89] VIDAL, M., RIGOL, A., GIL-GARCIA, C.J., "Soil-radionuclide interactions", Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009) 71–102.

[90] CAMPS, M., RIGOL, A., HILLIER, S., VIDAL, M., RAURET, G., Quantitative assessment of the effects of agricultural practices designed to reduce ^{137}Cs and ^{90}Sr soil-plant transfer in meadows, Sci. Total Env. **332** (2004) 23–38.

[91] SWEECK, L., WAUTERS, J., VALCKE, E., CREMERS, A., "The specific interception potential of soils for radiocaesium", Transfer of Radionuclides in Natural and Semi-natural Environments (Desmet, G., Nassimbeni, P., Belli, M., Eds), EUR 12448, Elsevier Appl. Sci. (1990) 249–258.

[92] VANDEBROEK, L., HEES, M.V., DELVAUX, B., SPAARGAREN, O., THIRY, Y., Relevance of Radiocaesium Interception Potential (RIP) on a worldwide scale to assess soil vulnerability to ^{137}Cs contamination, J. Env. Radioact. **104** (2012) 87–93.

[93] WAUTERS, J., et al., Prediction of solid liquid distribution coefficients of radiocaesium in soils and sediments, Part one: a simplified procedure for the solid characterization, Appl. Geochem. **11** (1996) 589–594.

[94] VIDAL, M., et al., Two approaches to the study of radiocaesium partitioning and mobility in agricultural soils from the Chernobyl area, Analyst **120** (1995) 1785–1791.

[95] WAEGENEERS, N., SMOLDERS, E., MERCKX, R., A statistical approach for estimating the radiocaesium interception potential of soils, J. Env. Qual. **28** (1999) 1005–1011.

[96] GIL-GARCÍA, C., RIGOL, A., VIDAL, M., New best estimates for radionuclide solid-liquid distribution coefficients in soils. Part 1: radiostrontium and radiocaesium, J. Env. Radioact. **100** (2009) 690–696.

[97] GIL-GARCÍA, C.J., RIGOL, A., VIDAL, M., Comparison of mechanistic and PLS-based regression models to predict radiocaesium distribution coefficients in soils. J. Hazard. Mater. **197** (2011) 11–18.

[98] WAUTERS, J., VIDAL, M., ELSEN, A., CREMERS, A., Prediction of solid liquid distribution coefficients of radiocaesium in soils and sediments. Part two: a new procedure for solid phase speciation of radiocaesium, Appl. Geochem. **11** (1996) 595–599.

[99] RIGOL, A., VIDAL, M., RAURET, G., SHAND, C.A., CHESHIRE, M.V., Competition of organic and mineral phases in radiocaesium partitioning in organic soils of Scotland and the area near Chernobyl, Env. Sci. Technol. **32** (1998) 663–669.

[100] SMOLDERS, E., VAN DEN BRANDE, K., MERCKX, R., Concentration of ^{137}Cs and K in soil solution predicts the plant availability of ^{137}Cs in soils, Env. Sci. Technol. **31** (1997) 3432–3438.

[101] GIL-GARCÍA, C., TAGAMI, K., UCHIDA, S., RIGOL, A., VIDAL, M., New best estimates for radionuclide solid-liquid distribution coefficients in soils. Part 3: miscellany of radionuclides (Cd, Co, Ni, Zn, I, Se, Sb, Pu, Am, and others), J. Env. Radioact. **100** (2009) 704–715.

[102] SMOLDERS, E., SWEECK, L., MERCKX, R., CREMERS, A., Cationic interactions in radiocaesium uptake from solution by spinach, J. Environ. Radioactiv. **34** (1997) 161–170.

[103] RIGOL, A., VIDAL, M., RAURET, G., Effect of the ionic status and drying on radiocesium adsorption and desorption in organic soils, Environ. Sci. Technol. **33** (1999) 3788–3794.

[104] VIDAL, M., et al., Effectiveness of agricultural practices in decreasing radionuclide transfer to plants in natural meadows, Rad. Prot. Dosim. **92** (2000) 65–70.

[105] NISBET, A.F., Effects of soil-based countermeasures on solid-liquid equilibria in agricultural soils contaminated with radiocaesium and radiostrontium, Sci. Total Env. **137** (1993) 81–98.

[106] NISBET A.F., et al., Application of fertilizers and ameliorants to reduce soil to plant transfer of radiocaesium and radiostrontium in the medium to long term — a summary, Sci. Total Env. **137** (1997) 173–182.

[107] VALCKE, E., VIDAL, M., CREMERS, A., IVANOV, J., PEREPELYATNIKOV, G., The use of zeolites as amendments in radiocaesium and radiostrontium contaminated soils: a soil chemical approach, Part III: A soil chemical test to predict the potential effectiveness of zeolite amendments, Zeolites **18** (1997) 218–224.

[108] CAMPS, M., RIGOL, A., VIDAL, M., RAURET, G., Assessment of the suitability of soil amendments to reduce ^{137}Cs and ^{90}Sr root uptake in meadows, Env. Sci. Technol. **37** (2003) 2820–2828.

[109] VIDAL, M., et al., Soil-and-plant based countermeasures to reduce ^{137}Cs and ^{90}Sr uptake by grasses in natural meadows: the REDUP project, J. Env. Radioact. **56** (2001) 139–156.

[110] WASSERMAN, M.A., et al., The effect of organic amendment on potential mobility and bioavailability of ^{137}Cs and ^{60}Co in tropical soils, J. Env. Radioact. **99** (2008) 554–562.

[111] MAUBERT, H., VOVK, I., ROED, J., ARAPIS, G., JOUVE, A., Reduction of soil-plant transfer factors: mechanical aspects, Sci. Total Env. **137** (1993) 163–167.

[112] VOVK, I.F., BLAGOYEV, V.V., LYASHENKO, A.N., KOVALEV, I.S., Technical approaches to decontamination of terrestrial environments in the CIS, Sci. Total Env. **137** (1993) 49–63.

[113] BOGDEVICH, I.M. (Ed.), Recommendations on agricultural production in conditions of radioactive contamination of lands in Belarus, approved by the Ministry of Agriculture and Food of Belarus Republic, BRISSA (2002) (in Russian).

[114] NIKIPELOV, B.V., et al., The radiation accident in the South Urals in 1957, Atomnaya Energia **67** (1987) 74–80 (in Russian).

[115] ROED, J., ANDERSSON, K.G., PRIP, H., The skim and burial plough: a new implement for reclamation of radioactively contaminated land, J. Env. Radioact. **33** (1996) 117–128.

[116] GULYAKIN, I.V., YUDINTSEVA, E.V., MAMONTOVA, L.A., LEVINA, E.M., Effect of lime, peat and peat ash on accumulation of strontium and caesium in crops, Agrochimia **5** (1978) 109–115 (in Russian).

[117] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Reduction in the content of radioactive substances in plant products (Recommendations), Agropromizdat, Moscow (1989).

[118] RATNIKOV, A.N., ALEXAKHIN, R.M., ZHIGAREVA, T.L., SANZHAROVA, N.I., POPOVA, G.I., Effectiveness of a system of agro ameliorative measures in reducing ^{137}Cs accumulation in plant products in the Chernobyl affected zone, Agrochimia **9** (1992) 112–116 (in Russian).

[119] WOODMAN, R.F.M., NISBET, A.F., Deep Ploughing, Potassium and Lime Applications to Arable Land, Chilton, M1072, NRPB (1999).

[120] NISBET, A.F., WOODMAN, R.F.M., Options for the Management of Chernobyl-restricted Areas in England and Wales, NRPB-R305 (1999).

[121] GULYAKIN, I.V., YUDINTSEVA, E.V., Agricultural Radiology, Kolos, Moscow (1973) 272 pp. (in Russian).

[122] NISBET, A.F., Effects of soil-based countermeasures on solid-liquid equilibria in agricultural soils contaminated with radiocaesium and radiostrontium, Sci. Total Env. **137** 1–3 (1993) 81–98.

[123] BELOVA, N.V., DRAGANSKAYA, N.V., SANZHAROVA, N.I., Effects of organic fertilizers on ^{137}Cs biological mobility in soil, Plodorodie **20** (2004) 35–36 (in Russian).

[124] BOGDEVICH, I.M. (Ed.), Application of Organic Fertilisers on Lands Contaminated with Radionuclides, Recommendations, Minsk (2004) 23 pp. (in Russian).

[125] UKRAINIAN INSTITUTE OF AGRICULTURAL RADIOLOGY, Guide on Agriculture Management on Contaminated Territories, Ukrainian Institute of Agricultural Radiology, Kiev (1998) 102 pp. (in Ukrainian).

[126] VODOVOZOVA, I.G., "Notes about role of organic matter of the soil in migration of radionuclides", Fundamental and Practical Aspects of Effects of Low Doses of Ionizing Irradiation, Syktyvkar (1974) 23–25 (in Russian).

[127] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Recommendation on Plant Production in Areas of Russia Contaminated with Radionuclides, RIARAE, Obninsk (1997).

[128] SAWNEY, B.L., Sorption and fixation of microquantities of cesium by clay minerals: effect of saturating cations, Soil Sci. Soc. Am. J. **28** 2 (1964) 183–186.

[129] NISHITA, H., HAUG, R.M., HAMILTON, M., Influence of minerals on ^{90}Sr and ^{137}Cs uptake by bean plants, Soil Sci. **105** (1968) 237–243.

[130] BAKUNOV, N.A., YUDINTSEVA, E.B., Notes about decrease in ^{137}Cs accumulation by plants after application of natural sorbents, Agrohimiya **6** (1989) 90–96 (in Russian).

[131] YUDINTSEVA, E.V., GULYAKIN, I.V., Agrochemistry of radioactive isotopes of strontium and caesium, Atomizdat (1968) 472 (in Russian).

[132] KUZNETSOV, V.K., SANZHAROVA, N.I., ANISIMOV, V.S., KRUGLOV, S.V., BELOVA, N.V., Radiological and agrochemical justification of optimal parameters for content of mobile K forms in soils affected by radioactive contamination, Agrohimia **6** (2003) 74–82 (in Russian).

[133] ARKHIPOV, N.P., et al., Soil chemistry and root uptake of radionuclide in agricultural plants, Pochvovedenie **11** (1975) 40–52 (in Russian).

[134] KORNEYEV, N.A., FIRSAKOVA, S.K., MALYSHEVA, M.D., Uptake of strontium-90 by meadow grasses from different soil types of the non-chernozemic zone, Pochvovedenie **11** (1975) 53–59 (in Russian).

[135] FIRSAKOVA, S.K., Effectiveness of agrarian ameliorative measures for reduction of Cs-137 accumulation by plants on fodder lands in the zone of the Chernobyl accident, Doklady VASHNIL **3** (1992) 25–27 (in Russian).

[136] PRISTER, B.S., et al., "Behaviour of radionuclides in meadows including countermeasures application", The Radiological Consequences of the Chernobyl Accident, Minsk, CEC (1996) 59–68.

[137] PRISTER, B.S., et al., Post-accidental problems in the Ukraine, Agrarnaya Nauka **3** (1996) 8–11 (in Russian).

[138] SANZHAROVA, N.I., FESENKO, S.V., KOTIK, V.A., SPIRIDONOV, S.I., Behaviour of radionuclides in meadows and efficiency of countermeasures, Rad. Prot. Dosim. **64** (1996) 43–48.

[139] MINISTRY FOR AGRICULTURE OF THE USSR, Recommendations on Assessment of Consequences of Radioactive Contamination of Agricultural Land, Radiation Effects on Animals and Agricultural Production in Such Conditions, Kolos, Moscow (1973) (in Russian).

[140] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Manual on Farming in Conditions of Radioactive Contamination of Some Areas in the Russian Federation, Ukraine and Belorussia in the Spring–Summer Period 1987, USSR Gosagroprom, RIARAE (1987) (in Russian).

[141] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Recommendation on Agricultural Production in the Bryansk Region Areas Affected by Radioactive Contamination, USSR Gosagroprom, RIARAE, Moscow (1988) (in Russian).

[142] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Recommendation on Radical Improvement of Haylands and Pastures Affected by Radioactive Contamination in Western Districts of the Bryansk Region, USSR, Moscow (1988) (in Russian).

[143] RUSSIAN INSTITUTE FOR AGRICULTURAL RADIOLOGY AND AGROECOLOGY, Manual on Farming in Conditions of Radioactive Contamination of Some Areas in the Russian Federation, Ukraine and Belorussia for the Period 1988–1990, USSR Gosagroprom, RIARAE, Moscow (1988) (in Russian)

[144] TIMOFEEV, S.F., GREBENCHIKOVA, N.V., FIRSAKOVA, S.K., GRITSEV, V.S., PODOLYAK, A.G., "Influence of improvement of fodder lands located on basic soils of Belarus Polesye on radionuclide transfer of ^{90}Sr and ^{137}Cs to grass", Major Outputs in the Area of Radioecology for a 10 Year Period after the Chernobyl Accident, Gomel, Research Institute of Radiology (1996) 40–43 (in Russian).

[145] JACOB, P., et al., Remediation strategies for rural territories contaminated by the Chernobyl accident, J. Env. Radioact. **56** (2001) 51–76.

[146] KORNEYEV, N.A., SIROTKIN, A.N., KORNEYEVA, Y.V., Reduction of Radioactivity in Plants and Animal Products, Kolos, Moscow (1977) 208 pp. (in Russian).

[147] MOISEEV, I.T., TIKHOMIROV, F.A., RERICH, L.A., Influence of varietal characteristics of wheat and peas on the accumulation of ^{137}Cs and K in crops, Vestnik MGU, Pochvovedenie **3** (1977) 105–109 (in Russian).

[148] BONDAR, P.F., et al., "General regularities of contamination of plant products in areas subjected to contamination following accident at the Chernobyl NPP", Problems of Agricultural Radiology (LOSCHILOV, N.A., Ed.), UIAR, Kiev (1991) 88–105.

[149] SMOLDERS, E., Some principles behind the selection of crops to minimise radionuclide uptake from soil, Sci. Total Env. **137** (1993) 135–146.

[150] SANZHAROVA, N., et al., "Root uptake: temperate environment", Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009) 139–206.

[151] VELASCO, H., JURI AYUB, J., "Root uptake: tropical and sub-tropical environments", Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009) 207–238.

[152] HOWARD, B.J., BERESFORD, N.A., BARNETT, C.L., FESENKO, S., Radionuclide transfer to animal products: revised recommended transfer coefficient values, J. Env. Radioact. **100** (2009) 263–273.

[153] HOWARD, B.J., BERESFORD, N.A., BARNETT, C.L., FESENKO, S., Quantifying the transfer of radionuclides to food products from domestic farm animals, J. Env. Radioact. **100** (2009) 767–773.

[154] SIROTKIN, A.N., “Transfer of radionuclides to animal products”, Foundations of Radioecology of Farm Animals, Energoatomizdat, Moscow (1987) 100–140 (in Russian).

[155] VOIGT, G., et al., Experimental determination of transfer coefficients of ^{137}Cs and ^{131}I from fodder into milk of cows and sheep after the Chernobyl accident, Health Phys. **57** (1989) 967–973.

[156] SKUTERUD, L., et al., Transfer of ^{85}Sr and ^{134}Cs from diet to reindeer fetuses and milk, Radiat. Env. Biophys. **44** (2005) 107–117.

[157] SIROTKIN, A.N., BUROV, N.I., TYUMENOV, L.N., GRISHKIN, A.I., On the behaviour of strontium-90, radiocaesium, cerium-144, ruthenium-106, antimony-125 and zirconium-95 in cattle, Radiobiologia **10** (1970) 629–643 (in Russian).

[158] ASTASHEVA, N.P., ROMANOV, L.M., KOSTYUK, D.M., KHOMUTININ, Yu.V., “Dynamics of accumulation and elimination of radionuclides from the body of farm animals”, Problems of Agricultural Radiology, A Collection of Scientific Papers (LOSHCHILOV, N.A., Ed.), UIAR, Kiev (1991) 160–170 (in Russian).

[159] ASTASHEVA, N.P., ROMANOV, L.M., KHOMUTININ, Yu.V., CHERNYI, Yu.V., “Cs-137 metabolism in adult geese in conditions of a chronic administration”, Problems of Agricultural Radiology, A Collection of Scientific Papers (LOSHCHILOV, N.A., Ed.), UIAR, Kiev (1992) 148–154 (in Russian).

[160] STARA, J.F., NELSON, N.S., DELLAROSA, R.J., BUSTAD, L.K., Comparative metabolism of radionuclides in mammals: a review, Health Phys. **20** (1971) 113–137.

[161] COUGHTREY, P.J., THORNE, M.C., Radionuclide Distribution and Transport in Terrestrial and Aquatic Ecosystems, Rotterdam, AA Balkema (1983).

[162] UNITED STATES DEPARTMENT OF ENERGY, A Graded Approach for Evaluating Radiation Doses to Aquatic and Terrestrial Biota, Rep. DOE-STD-1153-2002, USDOE, Washington, DC (2002).

[163] HIGLEY, K.A., DOMOTOR, S.L., ANTONIO, E.J., A kinetic–allometric approach to predicting tissue radionuclide concentrations for biota, J. Env. Radioact. **66** (2003a) 61–74.

[164] BERESFORD, N.A., BROADLEY, M.R., HOWARD, B.J., BARNETT, C.L., WHITE, P.J., Estimating radionuclide transfer to wild species — data requirements and availability for terrestrial ecosystems, J. Radiol. Prot. **24** (2004) A89–A103.

[165] SKUTERUD, L., HANSEN, H., “Managing radiocaesium contamination in Norwegian reindeer twenty-two years after the Chernobyl accident — the need for a new regulation”, Radioecology and Environmental Radioactivity (Proc. Int. Conf. Bergen, 2008), (STRAND, P., BROWN, J., JØLLE, T., Eds), Norwegian Radiation Protection Authority (2008) 121–124.

[166] HOWARD, B.J., BERESFORD, N.A., BURROW, L., SHAW, P.V., CURTIS, E.J.C., A comparison of caesium 137 and 134 activity in sheep remaining on upland areas contaminated by Chernobyl fallout with those removed to less active lowland pasture, J. Soc. Radiol. Prot. **7** (1987) 71–73.

[167] HOVE, K., Chemical methods for reduction of the transfer of radionuclides to farm animals in semi-natural environments, Sci. Total Env. 1**37** (1993) 235–248.

[168] ÅHMAN, B., Effect of bentonite and ammonium-ferric(III)-hexacyanoferrate(II) on uptake and elimination of radiocaesium in reindeer, J. Env. Radioact. **31** (1996) 29–50.

[169] ÅHMAN, B., Transfer of radiocaesium via reindeer meat to man — effect of countermeasures applied in Sweden following the Chernobyl accident, J. Env. Radioact. **46** (1999) 113–120.

[170] GIESE, W.W., Countermeasures for reducing the transfer of radiocesium to animal derived foods, Sci. Total Env. **85** (1989) 317–327.

[171] UNSWORTH, E.F., et al., Investigations of the use of clay minerals and Prussian Blue in reducing the transfer of dietary radiocaesium to milk, Sci. Total Env. **85** (1989) 339–347.

[172] Hove, K., et al., "Use of caesium binders to reduce radiocaesium contamination of milk and meat in Belarus, Russia and Ukraine", Environmental Impact of Radioactive Releases (Proc. Symp. Vienna, 1995), IAEA, Vienna (1996) 539–547.

[173] BERESFORD, N.A., LAMB, C.S., MAYES, R.W., HOWARD, B.J., COLGROVE, P.M., The effect of treating pastures with bentonite on the transfer of Cs-137 from grazed herbage to sheep, J. Env. Radioact. **9** (1989) 251–264.

[174] RATNIKOV, A.N., et al., The use of hexacyanoferrates in different forms to reduce radiocaesium contamination of animal products in Russia, Sci. Total Env. **223** (1998) 167–176.

[175] GIESE, W.W., Ammonium-ferric-cyano-ferrate(II) (AFCF) as an effective antidote against radiocaesium burdens in domestic animals and animal derived foods, Br. Vet. J. **144** (1988) 363–369.

[176] BRYNILDSEN, L.I., SELNÆS, T.D., STRAND, P., HOVE, K., Countermeasures for radiocesium in animal products in Norway after the Chernobyl accident — techniques, effectiveness, and costs, Health Phys. **70** (1996) 665–672.

[177] PEARCE, J., Studies of any toxicological effects of prussian-blue compounds in mammals — a review, Food Chem. Toxicol. **32** (1994) 577–582.

[178] VANDENHOVE, H., VAN HEES, M., DE BROUWER, S., VANDECASTEELE, C., Effects of ammonium-ferric(III)-hexacyano-ferrate(II) and faeces addition on yield and soil-plant transfer of radiocaesium to rye-grass, J. Env. Radioact. **37** (1997) 235–246.

[179] BERESFORD, N.A., et al., The development and testing of an intraruminal slow-release bolus designed to limit radiocaesium absorption by small lambs grazing contaminated pastures, Small Ruminant Res. **33** (1999) 109–115.

[180] BERESFORD, N.A., et al., A comparative assessment of the potential use of alginates and dietary calcium manipulation as countermeasures to reduce the transfer of radiostrontium to the milk of dairy animals, J. Env. Radioact. **51** (2000) 321–342.

[181] BERESFORD, N.A., MAYES, R.W., MACEACHERN, P.J., DODD, B.A., LAMB, C.S., The effectiveness of alginates to reduce the transfer of radiostrontium to the milk of dairy goats, J. Env. Radioact. **44** (1999) 43–54.

[182] THOMPSON, J.C., WENTWORTH, R.A., COMAR, C.L., "Control of fallout contamination in the post attack diet", Proc. Symp. on Survival of Food Crops and Livestock in the Event of a Nuclear War (1971) 566–594.

[183] OUTOLA, L., RASK, M., Effect of liming on the behaviour of ^{90}Sr and ^{137}Cs in a lake ecosystem, J. Env. Radioact. **102** (2011) 780–787.

[184] SMITH, J.T., KUDELSKY, A.V., RYABOV, I.N., HADDERINGH, R.H., Radiocaesium concentration factors of Chernobyl-contaminated fish: a study of the influence of potassium, and "blind" testing of a previously developed model, J. Env. Radioact. **48** (2000) 359–369.

[185] SMITH, J.T., KUDELSKY, A.V., RYABOV, I.N., HADDERINGH, R.H., BULGAKOV, A.A., Application of potassium chloride to a Chernobyl-contaminated lake: modelling the dynamics of radiocaesium in an aquatic ecosystem and decontamination of fish, Sci. Total Env. **305** (2003) 217–227.

[186] HÅKANSON, L., ANDERSSON, T., Remedial measures against radioactive caesium in Swedish fish after Chernobyl, Aqua. Sci. **54** (1992) 141–164.

[187] FRISSEL, M.J., SHAW, G., ROBINSON, C., HOLM, E., CRICK, M., "Model for the evaluation of long term countermeasures in forests", Radioecology and the Restoration of Radioactive Contaminated Sites, IUR/NATO Handbook, NATO Advanced Science Institute Series (1996).

[188] BELLI, M. (Ed.), FORECO, Forest Ecosystems: Classification of Restoration Options, Considering Dose Reduction, Long-Term Ecological Quality and Economic Factors, Final Rep., ANPA Agenzia Nazionale per la Protezione dell'Ambiente, Rome (2000).

[189] IPATYEV, V.A. (Ed.), Forest. Human. Chernobyl. Forest Ecosystems after the Accident at the Chernobyl NPP: Condition, Prediction, Response of the Population, Ways of Rehabilitation, Gomel Retchinsk (2005) 540 pp. (in Russian).

[190] HOVE, K., PEDERSEN, O., GARMO, T.H., HANSEN, H.S., STAALAND, H., Fungi: a major source of radiocaesium contamination of grazing ruminants in Norway, Health Phys. **59** (1990) 189–192.

[191] JOHANSON, K.J., "Radiocaesium in game animals in the Nordic countries", Nordic Radioecology — The Transfer of Radionuclides through Nordic Ecosystems to Man (Dahlgaard, H., Ed.), Stud. Env. Sci. **62**, Elsevier, Oxford (1994) 287–301.

[192] JOHNSON, W., NAYFIELD, C.L., Elevated levels of caesium-137 in common mushrooms (*Agaricaceae*) with possible relationship to high levels of caesium-137 in whitetail deer, 1968–1969, Radiological Health Data Rep. **11** (1970) 527–531.

[193] JOHANSON, K.J., NIKOLOVA, I., "The role of fungi in transfer of ^{137}Cs in the forest ecosystem", Ten Years Terrestrial Radioecological Research Following the Chernobyl Accident (GERZABECK, M., Ed.), (Proc. Int. Symp. on Radioecology Vienna, 1996), Transactions of the Austrian Soil Science Society, Issue 53, Federal Environment Agency, Vienna (1996) 259–265.

[194] AVILA, R., JOHANSON, K.J., BERGSTROM, R., Model of the seasonal variations of fungi ingestion and ^{137}Cs activity concentration in roe deer, J. Env. Radioact. **46** (1999) 99–112.

[195] AMIRO, B.D., SHEPPARD, S.C., JOHNSTON, F.L., EVENDEN, W.G., HARRIS, D.R., Burning radionuclide question: what happens to iodine, cesium and chlorine in biomass fires, Sci. Total Env. **187** (1996) 93–103.

[196] YOSCHENKO, V.I., et al., Resuspension and redistribution of radionuclides during grassland and forest fires in the Chernobyl exclusion zone: Part II, Modeling the transport process, J. Env. Radioact. **87** (2006) 260–278.

[197] KASHPAROV, V.A., et al., Forest fires in the territory contaminated as a result of the Chernobyl accident: radioactive aerosol resuspension and exposure of firefighters, J. Env. Radioact. **51** (2000) 281–298.

[198] KASHPAROV, V., CONNEY, S., UCHIDA, S., FESENKO, S., KRASNOV, V., "Food processing", Quantification of Radionuclide Transfer in Terrestrial and Freshwater Environments for Radiological Assessments, IAEA-TECDOC-1616, IAEA, Vienna (2009) 577–604.

[199] BOGDEVITCH, I., PUTYATIN, Y.U., RIGNEY, C., CHUPOV, A., "Edible oil production from rapeseed grown on contaminated lands", Innovationsforum Wertschöpfungsketten in der Naturstoffverarbeitung, Gardelegen (2002) 148–156.

[200] INTERNATIONAL COMMISSION ON RADIATION UNITS, Quantities, units and terms in radioecology, J. ICRU **1** 1 (2001).

[201] RESEARCH INSTITUTE FOR RADIOLOGY, Development of Methods for Milk Cleaning from Caesium for Individual Farms in the Zone of Radionuclide Contaminated Territory after the Chernobyl Accident, RIR, Gomel (1990) 46 pp.

[202] OUGHTON, D.H., SALBU, B., HOVE, K., DAY, J.P., The Use of Stable Caesium to Reduce Radiocaesium Transfer to Meat, The Research Programme on Radioactive Fallout (GUNNEROD, T.B., GARMO, T.H., Eds), Agricultural University of Norway (1989) 117–127.

[203] OUGHTON, D.H., et al., Caesium dosing reduces uptake of radiocaesium by sheep, J. Env. Radioact. **14** (1991) 105–121.

[204] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Implication of Commission Recommendations that Doses Be Kept as Low as Readily Achievable, ICRP Publication 22, Pergamon Press, Oxford (1973).

[205] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, ICRP Publication 26, Pergamon Press, Oxford (1977).

[206] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Cost-benefit Analysis in the Optimisation of Radiation Protection, ICRP Publication 37, Pergamon Press, Oxford (1983).

[207] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Optimisation and Decision-making in Radiological Protection, ICRP Publication 55, Pergamon Press, Oxford (1989).

[208] LOCHARD, J., SCHNEIDER, T., "Application of decision aiding technologies for relocation strategies", Radioecology: Radioactivity and Ecosystems (VAN DER STRICHT, E., KIRCHMAN, R., Eds), Fortemps, Liege (2001) 55–78.

[209] SHERSHAKOV, V., FESENKO, S., KRYSHEV, I., SEMIOSHKINA, N., "Decision-aiding tools for remediation strategies", Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 121–176.

[210] FESENKO, S.V., SANZHAROVA, N.I., WILKINS, B.T., NISBET, A.F., FORCON: Local decision support system for the provision of advice in agriculture — methodology and experience of practical implementation, Rad. Prot. Dosim. **64** (1996) 157–164.

[211] VAN DER PERK, M., BURROUGH, P.A., VOIGT, G., GIS based modelling to identify regions of Ukraine, Belarus, and Russia affected by residues of the Chernobyl nuclear power plant accident, J. Hazard. Mater. **61** (1998) 85–90.

[212] JACKSON, D., et al., Establishing a method for assessing and ranking restoration strategies for radioactively contaminated sites and their close surroundings, Nucl. Ener. **38** (1999) 223–231.

[213] MONTE, L., et al., The project MOIRA: A Model-based Computerised System for Management Support to Identify Optimal Remedial Strategies for Restoring Radionuclide Contaminated Aquatic Ecosystems and drainage Areas, Final Rep. ENEA RT/AMB/2000/13 (2000).

[214] ULANOVSKY, A., et al., ReSCA: decision support tool for remediation planning after the Chernobyl accident, Rad. Env. Biophys. **50** (2011) 67–83.

[215] JACOB, P., et al., Rural areas affected by the Chernobyl accident: radiation exposure and remediation strategies, Sci. Total Env. **408** (2009) 14–25.

[216] FESENKO, S., et al., Justification of remediation strategies in the long term after the Chernobyl accident, J. Env. Radioact. (2012) (in press).

[217] SCHULTE, E.H., KELLY, G.N., JACKSON. C.A. (Eds), Decision Support for Emergency Management and Environmental Restoration, European Communities, Luxembourg (2002).

[218] INTERNATIONAL COMMISION ON RADIOLOGICAL PROTECTION, Assessing Dose of the Representative Person for the Purpose of Radiation Protection of the Public and the Optimisation of Radiological Protection: Broadening the Process, Publication 101, Elsevier, Amsterdam (2006).

[219] SHAW, G., ROBINSON, C., HOLM, E., FRISSEL, M.J., CRICK, M., A cost-benefit analysis of long-term management options for forests following contamination with ^{137}Cs, J. Env. Radioact. **56** (2001) 185–208.

[220] FESENKO, S.V., VOIGT, G., SPIRIDONOV, S.I., GONTARENKO, I.A., Decision making framework for application of forest countermeasures in the long term after the Chernobyl accident, J. Env. Radioact. **82** (2005) 143–166.

[221] GUSTAFSSON, J., PRIME: An Introduction and Assessment, Helsinki University of Technology, Helsinki (1999).

[222] FRENCH, S., Decision Theory: An Introduction to the Mathematics of Rationality, Ellis Horwood, Chichester (1986).

[223] BURNAZYAN, A.I. (Ed.), Results of the Studies and Experience of Mitigation of Consequences of the Accidental Contamination of the Territory by Uranium Fission Products, Energoatomizdat, Moscow (1990) (in Russian).

[224] AKLEEV, A.V., KISELEV, M.F. (Eds), Ecological and Medical Impacts of the 1957 Accident at the "Mayak", RF Ministry of Health, Moscow (2001) (in Russian).

[225] ROMANOV, G.N., DROZHKO, E.G., NIKIPELOV, B.V., TEPLYAKOV, I.G., SHILOV, V.P., "Summing up: restoration of economic activity", Environmental Impacts of Radioactive Contamination in the South Urals (SOKOLOV, V.E., KRIVOLUTSKY, D.A., Eds), Nauka, Moscow (1993) (in Russian).

[226] ARKHIPOV, N.P., EGOROV, A.V., KLECHKOVSKY, V.M., On the estimation of strontium-90 transfer from soil to plants and its accumulation in crop yield, Doklagy VASHNIL 1 (1969) 2–4 (in Russian).

[227] KLEHKOVSKEY, V.M., GULYAKIN, I.V., Behaviour of strontium, caesium, ruthenium and zirconium in soil and plants, Pochvovedeneye **3** (1958) 1 (in Russian).

[228] SOKOLOV, V.E., KRIVOLUTSKY, D.A. (Eds), Environmental Impacts of Radioactive Contamination in the South Urals, Nauka, Moscow (1993) 336 pp. (in Russian).

[229] AARKROG, A., "Manmade radioactivity", Radioecology: Radioactivity and Ecosystems (VAN DER STRICHT, E., KIRCHMAN, R., Eds), Fortemps, Liege (2001) 55–78.

[230] ANSPAUGH, L.R., CHURCH, B.W., Historical estimates of external exposure and collective external γ exposure from testing at the Nevada Test Site. I. Test series through Hardtack II, 1958 Health Phys. **51** (1986) 35–51.

[231] IZRAEL, Yu., BOGDEVITCH, I. (Eds), Atlas of Modern and Forward-looking Aspects of the Effects of the Chernobyl Accident in the Affected Areas of Belarus and Russia, Moscow-Minsk Foundation “Infosphere” — NIA-Priroda, Moscow (2009) 140 pp.

[232] BENNET, B.G., “Worldwide panorama of radioactive residues in the environment, from Restoration of Environments with Radioactive Residues”, Proc. Int. Symp. Arlington, VA, 1999, IAEA, Vienna (2000) 11–24.

[233] CARLSEN, T.M., et al., Radionuclide Contamination at Kazakhstan’s Semipalatinsk Test Site: Implications on Human and Ecological Health, Rep. UCRL-JC-143920, Lawrence Livermore Natl Lab., Livermore, CA (2001).

[234] DANESI, P.R., “Remediation of sites contaminated by nuclear weapon tests in the Marshall Islands and Australia”, Remediation of Contaminated Environments (VOIGT, G., FESENKO, S., Eds), Elsevier, Amsterdam (2009) 225–262.

[235] DONALDSON, L.R., SEYTNOUR, A.H., NEVISSI, A.E., University of Washington’s radioecological studies in the Marshall islands, 1946-1977, Health Phys. **73** (1997) 214–222.

[236] EISENBUD, M., GESELL, T., Environmental Radioactivity from Natural, Industrial and Military Sources, 4th edn, Academic Press, San Diego (1997) 656 pp.

[237] HAMILTON, T.F., “Linking legacies of the cold war to arrival of anthropogenic radionuclides in the oceans through the 20th century”, Radioactivity and the Environment, Vol. 6 (LIVINGSTON, H.D., Ed.), Elsevier Science, Amsterdam (2004) 30–87.

[238] ROBISON, W.L., PHILLIS, W.A., COLSHER, C.S., Dose Assessment at Bikini Atoll, Rep. UCRL-51879, Part 5, Lawrence Livermore Natl Lab., Livermore, CA (1977).

[239] MILTENBERGER, R.P., GREENHOUSE, N.A., LESSARD, E.T., Whole body counting results from 1974 to 1979 for Bikini Island residents, Health Phys. **39** (1980) 395–507.

[240] ROBINSON, W.L., NOSHKIN, V.E., Radionuclide characterization and associated dose from long-lived radionuclides in close-in fallout delivered to the marine environment at Bikini and Enewetak Atolls, Sci. Total Env. **237** (1999) 311–327.

[241] SIMON, S.L., GRAHAM, J.C., Findings of the first comprehensive radiological monitoring programme of the Republic of the Marshall Islands, Health Phys. **73** (1997) 66–85.

[242] SIMON, S.L., GRAHAM, J.C., TERP, S.D., Uptake of ^{40}K and ^{137}Cs in native plants of the Marshall Islands, J. Env. Radioact. **59** (2002) 223–243.

[243] ROBISON, W.L., BOGEN, K.T., CONRADO, C.L., An updated assessment for resettlement options at Bikini Atoll U.S. nuclear test site, Health Phys. **73** (1997) 100–114.

[244] SYMONDS, J.L., A History of British Atomic Tests in Australia, Australian Government Publishing Service, Canberra (1985).

[245] HAYWOOD, S.M., SMITH, J.G., Assessment of potential doses at the Maralinga and Emu test sites, Health Phys. **63** (1992) 624–630.

[246] PARKINSON, A., Maralinga Rehabilitation Project, National Conference-MAPW Australia (2000).

[247] IZRAEL, Yu.A., KVASNIKOVA, E.V., NAZAROV, I.M., FRIDMAN, Sh.D., Global and regional contamination of the territory of the European part of the former USSR by ^{137}Cs, Meteorol Hydrologia **5** (1994) 5–9 (in Russian).

[248] IZRAEL, Yu.A., Radioactive fallout after nuclear explosions and accidents, Env. Mon. Assess. **59** (1999) 121–122.

[249] EUROPEAN COMMISSION, Atlas of Caesium Contamination of Europe after the Chernobyl Accident, EUR 19801 EC (2001).

[250] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Report to the General Assembly, Sources and Effects of Ionizing Radiation, UNSCEAR 2008, Scientific Annex C, UNSCEAR, New York (2011) 1–44.

[251] UNITED NATIONS SCIENTIFIC COMMITTEE ON THE EFFECTS OF ATOMIC RADIATION, Report to the General Assembly, Sources and Effects of Ionizing Radiation, Scientific Annex C, UNSCEAR, New York (2000) 157–252.

[252] KASHPAROV, V.A., et al., Territory contamination with the radionuclides representing the fuel component of Chernobyl fallout, Sci. Total Env. **317** (2003) 105–119.

[253] KHOLOSHA, V.I. (Ed.), Radiological Situation in the Territories of the Zones of the Radioactive Contamination, Book Company Veta, Kyiv (2008) 54 pp.

[254] INTERNATIONAL ATOMIC ENERGY AGENCY, The International Chernobyl Project — Assessment of Radiological Consequences and Evaluation of Protective Measures, Vienna, IAEA (1991).

[255] FESENKO, S.V., et al., Twenty years' application of agricultural countermeasures following the Chernobyl accident: lessons learned, J. Radiol. Prot. **26** (2006) 351–359.

[256] BROWN, J., WILKINS, B.T., NISBET, A.F., Management Options for Food Production Systems Affected by a Nuclear Accident: Diversion of Crops Grown for Human Consumption to Animal Feed, NRPB-W18, Didcot (2002).

[257] DAHLGAARD, H. (Ed.), Nordic Radioecology — The Transfer of Radionuclides through Nordic Ecosystems to Man, Stud. Env. Sci. **62**, Elsevier, Oxford (1994).

[258] NISBET, A., HOWARD, B., BERESFORD, N., VOIGT, G., Stakeholder involvement in post-accidental management, J. Env. Radioact. **83** (2005) 259–435.

[259] NATIONAL COMMISSION ON RADIATION PROTECTION, NRB 76/87 (1988), Radiation Safety Standards (NRB-76/87) and the Basic Sanitary Code for Work with Radioactive Substances and Other Sources of Ionizing Radiation, OSP-72/87, 3rd revised and enlarged edition, Energoatomizdat, Moscow (1988) 160 pp. (in Russian).

[260] NATIONAL COMMISSION ON RADIATION PROTECTION, Radiation Safety Standards (NRB-69), 2nd edn, Atomizdat, Moscow (1970) 112 pp. (in Russian).

[261] NATIONAL COMMISSION ON RADIATION PROTECTION, Radiation Safety Standards (NRB-99), SP-2.6.1.758-99, RF Ministry of Health, Moscow (1999) 115 pp. (in Russian).

[262] KASHPAROV, V.A., et al., Soil contamination with ^{90}Sr in the near zone of the Chernobyl accident, J. Env. Radioact. **56** (2001) 285–298.

[263] KASHPAROV, V.O., et al., Comprehensive monitoring of contamination of agricultural products by ^{90}Sr, Bul. Agric. Sci. **4** (2001) 38–43 (in Ukrainian).

[264] DEVILLE-CAVELIN, G., et al., "Countermeasures in agriculture: assessment of efficiency", Fifteen Years after the Chernobyl Accident — Lessons Learned (Proc. Int. Conf. Kiev, 2001) 118–128.

[265] NADTOCHIY, P., et al., Experience of Liquidation of the Chernobyl Accident Consequences, Svit, Kiev (2003) 371 pp. (in Ukrainian).

[266] RATNIKOV, A.N., ALEXAKHIN, R.M., ZHIGAREVA, T.L., SANZHAROVA, N.I., POPOVA, G.I., Effectiveness of a system of agroameliorative measures in reducing ^{137}Cs accumulation in plant products in the Chernobyl affected zone, Agrohimia **9** (1992) 112–116 (in Russian).

[267] BOGDEVICH, I.M. (Ed.), Recommendations on Liming of Acid Soils of the Republic of Belarus, Minsk, BRISSA (1997) 26 pp. (in Russian).

[268] KUZNETSOV, V.K., SANZHAROVA, N.I., ANISIMOV, V.S., ABRAMOVA, T.N., Effects of phosphorous fertilizers on ^{137}Cs uptake by farm crops, Agrohimia **9** (2001) 47–53 (in Russian).

[269] KUZNETSOV, V.K., SANZHAROVA, N.I., ALEXAKHIN, R.M., PLESTSOVA, N.V., Factors influencing ^{137}Cs accumulation by plants in application of phosphorous fertilizers, Agrohimia **4** (2007) 62–67 (in Russian).

[270] PRISTER, B.S., PEREPELYATNIKOVA, L.V., KASHPAROV, V.A., LAZAREV, N.M., KALINENKO, L.V., The problems of countermeasures in agriculture in the early and late periods after the Chernobyl accident, News Agric. Sci. **5** (1999) 5–11 (in Russian).

[271] SANZHAROVA, N.I., et al., ^{137}Cs transfer to plants from soddy-podzolic soil as a function of K dose and its mobility, Agrohimia **7** (2004) 58–66.

[272] YUDINTSEVA, E.V., LEVINA, E.M., Role of potassium in availability of ^{137}Cs for plants, Agrohimia **4** (1982) 75–81 (in Russian).

[273] ZHIGAREVA, T.L., et al., Effectiveness of mineral fertilizers on radioactively contaminated lands, Chem. Agr. **1** (1996) 35–38 (in Russian).

[274] IL’IN, M.I., PEREPELYATNIKOV, G.P., PRISTER, B.S., Influence of radical improvement on radiocaesium transfer from soil to grass, Agrohimia **1** (1991) 101–105 (in Russian).

[275] KASHPAROV, V.A., YOSCHENKO, V.I., BONDAR, J.O., TANKACH, E.S., The radiological situation in Ukraine after the Chernobyl accident and the optimization of countermeasures at the present stage, Radiat. Hygiene **2** (2009) 15–19 (in Russian).

[276] PRISTER, B.S. (Ed.), Guide for Agricultural Practice on Radioactively Contaminated Territories of the Ukraine after the Chernobyl nuclear power plant accident for 1999–2002, Kiev (1998) 104 (in Russian).

[277] HEISKARI, U., NIEMINEN, M., Different Grass Fodders in the Winter Feeding of Reindeer, Finnish Game and Fisheries Research Institute, Fish and Game Rep. No. 314 (2004) (in Finnish, English abstract).

[278] NISBET, A.F., WOODMAN, R.F.M., BROWN, J., SMITH, J.G., WILKINS, B.T., Derivation of working levels for animal feedstuffs for use in the event of a future nuclear accident, NRPB-R299 (1998).

[279] VOITSEKHOVITCH, O.V., Management of Surface Water Quality in the Areas Affected by the Chernobyl Accident, Ukrainian Hydro-Meteorological Institute, Kiev (2001) (in Russian).

[280] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiological Conditions in the Dnieper River Basin — Assessment by an International Expert Team and Recommendations for an Action Plan, Radioecological Assessment Report Series No. 7, IAEA, Vienna (2006).

[281] VOITSEKHOVICH, O., HÅKANSON, L., "Remedial measures against high levels of radioisotopes in aquatic ecosystems", Modelling of the Transfer of Radiocaesium from Deposition to Lake Ecosystems — Report of the VAMP Aquatic Working Group, IAEA-TECDOC-1143, IAEA, Vienna (2000) 261–309.

[282] FESENKO, S.V., ALEXAKHIN, R.M., SPIRIDONOV, S.I., SANZHAROVA, N.I., Dynamics of ^{137}Cs concentration in agricultural products in areas of Russia contaminated as a result of the accident at the Chernobyl nuclear power plant, Rad. Prot. Dosim. **60** (1995) 155–166.

GLOSSARY[24]

acceptable limit. A limit acceptable to the regulatory body.

accident. Any unintended event, including operating errors, equipment failures and other mishaps, the consequences or potential consequences of which are not negligible from the point of view of protection or safety.

action level. The level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in chronic exposure or emergency exposure situations. An action level can also be expressed in terms of any other measurable quantity as a level above which intervention should be undertaken.

contamination. Radioactive substances on surfaces, or within solids, liquids or gases (including the human body), where their presence is unintended or undesirable, or the process giving rise to their presence in such places.

cost–benefit analysis. A systematic economic evaluation of the positive effects (benefits) and negative effects (disbenefits, including monetary costs) of undertaking an action.

countermeasure. An action aimed at alleviating the radiological consequences of an accident.

decommissioning. Administrative and technical actions taken to allow the removal of some or all of the regulatory controls from a facility (except for a repository or for certain nuclear facilities used for the disposal of residues from the mining and processing of radioactive material, which are 'closed' and not 'decommissioned').

decontamination. The complete or partial removal of contamination by a deliberate physical, chemical or biological process.

dose. A measure of the energy deposited by radiation in a target.

---

[24] This glossary includes definitions from the IAEA Nuclear Safety Glossary (INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary, Terminology Used in Nuclear Safety and Radiation Protection, 2007 Edition, IAEA, Vienna (2007)).

dose assessment. Assessment of the dose(s) to an individual or group of people.

dose limit. The value of the effective dose or the equivalent dose to individuals in planned exposure situations that is not to be exceeded.

emergency. A non-routine situation that necessitates prompt action, primarily to mitigate a hazard or adverse consequences for human health and safety, quality of life, property or the environment. This includes nuclear and radiological emergencies and conventional emergencies such as fires, release of hazardous chemicals, storms or earthquakes. It includes situations for which prompt action is warranted to mitigate the effects of a perceived hazard.

emergency exposure situation. An emergency exposure situation is a situation of exposure that arises as a result of an accident, a malicious act, or any other unexpected event, and requires prompt action in order to avoid or reduce adverse consequences.

environmental monitoring. The measurement of external dose rates due to sources in the environment or of radionuclide concentrations in environmental media.

evacuation. The rapid, temporary removal of people from an area to avoid or reduce short term radiation exposure in an emergency.

exemption level. A value, established by a regulatory body and expressed in terms of activity concentration, total activity, dose rate or radiation energy, at or below which a source of radiation may be granted exemption from regulatory control without further consideration.

existing exposure situation. An existing exposure situation is a situation of exposure that already exists when a decision on the need for control needs to be taken.

exposure. The act or condition of being subject to irradiation.

exposure pathway. A route by which radiation or radionuclides can reach humans and cause exposure.

feed. Any single or multiple materials, whether processed, semi-processed or raw, that is intended to be fed directly to food producing animals.

food. Any substance, whether processed, semi-processed or raw, which is intended for human consumption.

individual monitoring. Monitoring using measurements by equipment worn by individual workers, or measurements of quantities of radioactive material in or on their bodies.

intake. The act or process of taking radionuclides into the body by inhalation or ingestion or through the skin.

intervention. Any action intended to reduce or avert exposure or the likelihood of exposure to sources that are not part of a controlled practice or that are out of control as a consequence of an accident.

justification.[25] The process of determining whether a proposed intervention is likely, overall, to be beneficial, as required by the International Commission on Radiological Protection's System of Radiological Protection, i.e. whether the benefits to individuals and to society (including the reduction in radiation detriment) from introducing or continuing the intervention outweigh the cost of the intervention and any harm or damage caused by the intervention.

monitoring. The measurement of dose, dose rate or activity related to the assessment or control of exposure to radiation or radioactive substances, and the interpretation of the results.

optimization of protection (and safety). The process of determining what level of protection and safety makes exposures, and the probability and magnitude of potential exposures, "as low as reasonably achievable, economic and social factors being taken into account" (ALARA), as required by the International Commission on Radiological Protection System of Radiological Protection.

protective action. An intervention intended to avoid or reduce doses to members of the public in emergencies or situations of chronic exposure.

---

[25] For intervention.

radioecological sensitivity. The extent to which environmental properties of an ecosystem, or its utilization, influence radiation exposure to humans and other organisms. Highly radioecologically sensitive ecosystems or environmental pathways give rise to comparatively higher doses than those which are less sensitive (or resilient) systems.

radiological survey. An evaluation of the radiological conditions and potential hazards associated with the production, use, transfer, release, disposal or presence of radioactive material or other sources of radiation.

reference level. An action level, intervention level, investigation level or recording level.

relocation. The non-urgent removal or extended exclusion of people from a contaminated area to avoid chronic exposure.

remedial action. Action taken when a specified action level is exceeded, to reduce radiation doses that might otherwise be received, in an existing exposure situation.

remediation. Any measures that may be carried out to reduce the radiation exposure from existing contamination of land areas through actions applied to the contamination itself (the source) or to the exposure pathways to humans.

representative person. An individual receiving a dose that is representative of the doses to the more highly exposed individuals in the population.

risk. A multiattribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with actual or potential exposures. It relates to quantities such as the probability that specific deleterious consequences may arise and the magnitude and character of such consequences.

risk assessment. Assessment of the radiological risks associated with normal operation and possible accidents involving a source or practice.

site evaluation. Analysis of those factors at a site that could affect the safety of a facility or activity on that site. This includes site characterization, consideration of factors that could affect safety features of the facility or activity so as to result in a release of radioactive material and/or could affect the dispersion of such material in the environment, as well as population and access issues relevant to safety (e.g. feasibility of evacuation, location of people and resources).

temporary permissible level. A temporary level of dose rate or activity concentration above which remedial actions or protective actions should be carried out in emergency exposure situations.

waste management. All administrative and operational activities involved in the handling, pretreatment, treatment, conditioning, transport, storage and disposal of radioactive waste.

LIST OF ABBREVIATIONS

AFCF	ammonium ferric hexacyanoferrate
ALARA	as low as reasonably achievable
CEC	cation exchange capacity
EDSS	environmental decision support system
EURT	Eastern Ural radioactive trace
FES	frayed edge sites
GIS	geographical information system
ICRP	International Commission on Radiological Protection
MAUA	multi-attribute utility analysis
NPK	nitrogen, phosphate and potassium
PK	phosphate and potassium
PRIME	preference ratios in multi-attribute evaluations
RES	regular exchange sites
ReSCA	remediation strategies after the Chernobyl accident
RIP	radiocaesium interception potential
TPL	temporary permissible level
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation

CONTRIBUTORS TO DRAFTING AND REVIEW

Beresford, N.A.	Centre for Ecology and Hydrology, United Kingdom
Byron, D.	International Atomic Energy Agency
Danesi, P.	Consultant, Austria
Fesenko, S.	International Atomic Energy Agency
Howard, B.J.	Centre for Ecology and Hydrology, United Kingdom
Kashparov, V.	Ukrainian Institute of Agricultural Radiology, Ukraine
Mabit, L.	International Atomic Energy Agency
Monken, H.	International Atomic Energy Agency
Naletosky, I.	International Atomic Energy Agency
Oughton, D.H.	Norwegian University of Life Sciences, Norway
Pröhl, G.	International Atomic Energy Agency
Sakadevan, K.	International Atomic Energy Agency
Sanzharova, N.	Russian Institute of Agricultural Radiology and Agroecology, Russian Federation
Skuterud, L.	Norwegian Radiation Protection Authority, Norway
Smith, J.	University of Portsmouth, United Kingdom
Vidal, M.	University of Barcelona, Spain

IAEA
International Atomic Energy Agency

Where to order IAEA publications

In the following countries IAEA publications may be purchased from the sources listed below, or from major local booksellers. Payment may be made in local currency or with UNESCO coupons.

AUSTRALIA
DA Information Services, 648 Whitehorse Road, MITCHAM 3132
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

BELGIUM
Jean de Lannoy, avenue du Roi 202, B-1190 Brussels
Telephone: +32 2 538 43 08 • Fax: +32 2 538 08 41
Email: jean.de.lannoy@infoboard.be • Web site: http://www.jean-de-lannoy.be

CANADA
Bernan Associates, 4501 Forbes Blvd, Suite 200, Lanham, MD 20706-4346, USA
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: customercare@bernan.com • Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 1-5369 Canotek Rd., Ottawa, Ontario, K1J 9J3
Telephone: +613 745 2665 • Fax: +613 745 7660
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

CHINA
IAEA Publications in Chinese: China Nuclear Energy Industry Corporation, Translation Section, P.O. Box 2103, Beijing

CZECH REPUBLIC
Suweco CZ, S.R.O., Klecakova 347, 180 21 Praha 9
Telephone: +420 26603 5364 • Fax: +420 28482 1646
Email: nakup@suweco.cz • Web site: http://www.suweco.cz

FINLAND
Akateeminen Kirjakauppa, PO BOX 128 (Keskuskatu 1), FIN-00101 Helsinki
Telephone: +358 9 121 41 • Fax: +358 9 121 4450
Email: akatilaus@akateeminen.com • Web site: http://www.akateeminen.com

FRANCE
Form-Edit, 5, rue Janssen, P.O. Box 25, F-75921 Paris Cedex 19
Telephone: +33 1 42 01 49 49 • Fax: +33 1 42 01 90 90
Email: formedit@formedit.fr • Web site: http://www. formedit.fr

Lavoisier SAS, 145 rue de Provigny, 94236 Cachan Cedex
Telephone: + 33 1 47 40 67 02 • Fax +33 1 47 40 67 02
Email: romuald.verrier@lavoisier.fr • Web site: http://www.lavoisier.fr

GERMANY
UNO-Verlag, Vertriebs- und Verlags GmbH, Am Hofgarten 10, D-53113 Bonn
Telephone: + 49 228 94 90 20 • Fax: +49 228 94 90 20 or +49 228 94 90 222
Email: bestellung@uno-verlag.de • Web site: http://www.uno-verlag.de

HUNGARY
Librotrade Ltd., Book Import, P.O. Box 126, H-1656 Budapest
Telephone: +36 1 257 7777 • Fax: +36 1 257 7472 • Email: books@librotrade.hu

INDIA
Allied Publishers Group, 1st Floor, Dubash House, 15, J. N. Heredia Marg, Ballard Estate, Mumbai 400 001,
Telephone: +91 22 22617926/27 • Fax: +91 22 22617928
Email: alliedpl@vsnl.com • Web site: http://www.alliedpublishers.com

Bookwell, 2/72, Nirankari Colony, Delhi 110009
Telephone: +91 11 23268786, +91 11 23257264 • Fax: +91 11 23281315
Email: bookwell@vsnl.net

ITALY
Libreria Scientifica Dott. Lucio di Biasio “AEIOU”, Via Coronelli 6, I-20146 Milan
Telephone: +39 02 48 95 45 52 or 48 95 45 62 • Fax: +39 02 48 95 45 48
Email: info@libreriaaeiou.eu • Website: www.libreriaaeiou.eu

JAPAN
Maruzen Company, Ltd., 13-6 Nihonbashi, 3 chome, Chuo-ku, Tokyo 103-0027
Telephone: +81 3 3275 8582 • Fax: +81 3 3275 9072
Email: journal@maruzen.co.jp • Web site: http://www.maruzen.co.jp

REPUBLIC OF KOREA
KINS Inc., Information Business Dept. Samho Bldg. 2nd Floor, 275-1 Yang Jae-dong SeoCho-G, Seoul 137-130
Telephone: +02 589 1740 • Fax: +02 589 1746 • Web site: http://www.kins.re.kr

NETHERLANDS
De Lindeboom Internationale Publicaties B.V., M.A. de Ruyterstraat 20A, NL-7482 BZ Haaksbergen
Telephone: +31 (0) 53 5740004 • Fax: +31 (0) 53 5729296
Email: books@delindeboom.com • Web site: http://www.delindeboom.com

Martinus Nijhoff International, Koraalrood 50, P.O. Box 1853, 2700 CZ Zoetermeer
Telephone: +31 793 684 400 • Fax: +31 793 615 698
Email: info@nijhoff.nl • Web site: http://www.nijhoff.nl

Swets and Zeitlinger b.v., P.O. Box 830, 2160 SZ Lisse
Telephone: +31 252 435 111 • Fax: +31 252 415 888
Email: infoho@swets.nl • Web site: http://www.swets.nl

NEW ZEALAND
DA Information Services, 648 Whitehorse Road, MITCHAM 3132, Australia
Telephone: +61 3 9210 7777 • Fax: +61 3 9210 7788
Email: service@dadirect.com.au • Web site: http://www.dadirect.com.au

SLOVENIA
Cankarjeva Zalozba d.d., Kopitarjeva 2, SI-1512 Ljubljana
Telephone: +386 1 432 31 44 • Fax: +386 1 230 14 35
Email: import.books@cankarjeva-z.si • Web site: http://www.cankarjeva-z.si/uvoz

SPAIN
Díaz de Santos, S.A., c/ Juan Bravo, 3A, E-28006 Madrid
Telephone: +34 91 781 94 80 • Fax: +34 91 575 55 63
Email: compras@diazdesantos.es, carmela@diazdesantos.es, barcelona@diazdesantos.es, julio@diazdesantos.es
Web site: http://www.diazdesantos.es

UNITED KINGDOM
The Stationery Office Ltd, International Sales Agency, PO Box 29, Norwich, NR3 1 GN
Telephone (orders): +44 870 600 5552 • (enquiries): +44 207 873 8372 • Fax: +44 207 873 8203
Email (orders): book.orders@tso.co.uk • (enquiries): book.enquiries@tso.co.uk • Web site: http://www.tso.co.uk

On-line orders
DELTA Int. Book Wholesalers Ltd., 39 Alexandra Road, Addlestone, Surrey, KT15 2PQ
Email: info@profbooks.com • Web site: http://www.profbooks.com

Books on the Environment
Earthprint Ltd., P.O. Box 119, Stevenage SG1 4TP
Telephone: +44 1438748111 • Fax: +44 1438748844
Email: orders@earthprint.com • Web site: http://www.earthprint.com

UNITED NATIONS
Dept. I004, Room DC2-0853, First Avenue at 46th Street, New York, N.Y. 10017, USA
(UN) Telephone: +800 253-9646 or +212 963-8302 • Fax: +212 963-3489
Email: publications@un.org • Web site: http://www.un.org

UNITED STATES OF AMERICA
Bernan Associates, 4501 Forbes Blvd., Suite 200, Lanham, MD 20706-4346
Telephone: 1-800-865-3457 • Fax: 1-800-865-3450
Email: customercare@bernan.com · Web site: http://www.bernan.com

Renouf Publishing Company Ltd., 812 Proctor Ave., Ogdensburg, NY, 13669
Telephone: +888 551 7470 (toll-free) • Fax: +888 568 8546 (toll-free)
Email: order.dept@renoufbooks.com • Web site: http://www.renoufbooks.com

Orders and requests for information may also be addressed directly to:

Marketing and Sales Unit, International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 (or 22530) • Fax: +43 1 2600 29302
Email: sales.publications@iaea.org • Web site: http://www.iaea.org/books

12-34551

RELATED PUBLICATIONS

RADIATION PROTECTION AND SAFETY OF RADIATION SOURCES: INTERNATIONAL BASIC SAFETY STANDARDS — INTERIM EDITION
IAEA Safety Standards Series No. GSR Part 3 (Interim)
STI/PUB/1531 (138 pp.; 2011)
ISBN 978–92–0–120910–8 Price: €65.00

REMEDIATION PROCESS FOR AREAS AFFECTED BY PAST ACTIVITIES AND ACCIDENTS
IAEA Safety Standards Series No. WS-G-3.1
STI/PUB/1282 (39 pp.; 2007)
ISBN 92–0–113306–5 Price: €18.00

RELEASE OF SITES FROM REGULATORY CONTROL ON TERMINATION OF PRACTICES
IAEA Safety Standards Series No. WS-G-5.1
STI/PUB/1244 (37 pp.; 2006)
ISBN 92–0–101606–9 Price: €27.00

REMEDIATION OF AREAS CONTAMINATED BY PAST ACTIVITIES AND ACCIDENTS
IAEA Safety Standards Series No. WS-R-3
STI/PUB/1176 (21 pp.; 2003)
ISBN 92–0–112303–5 Price: €15.00

There are many areas around the world contaminated with radionuclides. Some of these sites were contaminated by nuclear testing or radiation accidents, while others became contaminated as a result of inadequate waste disposal practices. Contamination at such sites may present a risk to humans and the environment and may require remediation. This technical report summarizes world experience on management options for remediation of contaminated terrestrial and freshwater environments. The report also provides guidelines about sustainable remediation strategies based on the experience and lessons learned following previous severe radiation accidents and other existing situations.

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–134110–5
ISSN 0074–1914