ICRP ref: 4880-5912-8767

Annals of the ICRP

ICRP PUBLICATION 1XX

Radiological Protection in Areas Contaminated by Past Activities

Editor-in-Chief

C.H. CLEMENT

Associate Editors

T. YASUMUNE
K. NAKAMURA

Authors on behalf of ICRP

M. Boyd, A. Canoba, E. Lazo, S. Long, C. McGuire, A. Rood, S. Shinkarev,
G. Smith, M. Sneve, L. Vaillant, T. Yankovich, H. Yasuda

PUBLISHED FOR

The International Commission on Radiological Protection

By

Please cite this issue as ‘ICRP, 202x. Radiological protection in areas contaminated by past activities, ICRP Publication 1XX. Ann. ICRP xx(x).’

**Contents**

[ABSTRACT 3](#_Toc166586795)

[MAIN POINTS 4](#_Toc166586796)

[1. INTRODUCTION 5](#_Toc166586797)

[1.1. Background 5](#_Toc166586798)

[1.2. Scope 6](#_Toc166586799)

[1.3. Structure of publication 7](#_Toc166586800)

[2. CHARACTERISTICS OF EXPOSURES FROM CONTAMINATED AREAS BY PAST ACTIVITIES 8](#_Toc166586801)

[2.1. Exposure pathways and scenarios 8](#_Toc166586802)

[2.2. Overview of case studies 9](#_Toc166586803)

[2.3. Practical experience from case studies 13](#_Toc166586804)

[3. FUNDAMENTAL CONSIDERATIONS OF THE APPLICATION OF THE SYSTEM OF RADIOLOGICAL PROTECTION 15](#_Toc166586805)

[3.1. The radiological protection system and ethical considerations 15](#_Toc166586806)

[3.2. Type of exposure situation 16](#_Toc166586807)

[3.3. Justification of protection strategy 17](#_Toc166586808)

[3.4. Optimisation of protection 18](#_Toc166586809)

[3.5. Stakeholder engagement 19](#_Toc166586810)

[4. IMPLEMENTATION OF THE COMMISSION’S SYSTEM OF RADIOLOGICAL PROTECTION TO AREAS CONTAMINATED BY PAST ACTIVITIES 20](#_Toc166586811)

[4.1. General considerations 20](#_Toc166586812)

[4.2. Recognition of the exposure situation 21](#_Toc166586813)

[4.3. Characterisation of the exposure situation 22](#_Toc166586814)

[4.4. Planning of remediation 24](#_Toc166586815)

[4.5. Implementation of the remediation action plan 32](#_Toc166586816)

[4.6. Post-remediation management 32](#_Toc166586817)

[5. CONCLUSIONS 34](#_Toc166586818)

[REFERENCES 36](#_Toc166586819)

[ANNEX A. CASE STUDIES 39](#_Toc166586820)

[A.1. Stakeholder involvement in establishing radionuclide soil action levels at the Rocky Flats Plant 39](#_Toc166586821)

[A.2. Rehabilitation of the former nuclear test site at Maralinga 42](#_Toc166586822)

[A.3. Remediation of radium legacies from the Swiss watch industry 45](#_Toc166586823)

[A.4. Techa River 47](#_Toc166586824)

[A.5. Radium contamination at Dalgety Bay, Scotland 52](#_Toc166586825)

[A.6. References 56](#_Toc166586826)

[GLOSSARY 59](#_Toc166586827)

[ACKNOWLEDGEMENTS 60](#_Toc166586828)

|  |  |  |
| --- | --- | --- |
|  | ICRP Publication XXX |  |

**RADIOLOGICAL PROTECTION IN AREAS CONTAMINATED BY PAST ACTIVITIES**

ICRP PUBLICATION 1XX

Approved by the Commission in MMMMM 202X

# Abstract–This publication addresses the protection of workers, the public, and the environment in contaminated areas where radioactivity is present because of past activities, excluding exposures in the post-accidental phase after a nuclear emergency. In the ICRP system of radiological protection, exposures associated with these contaminated areas are managed in the framework of existing exposure situations. Making radiological protection decisions concerning the management of worker-health, public-health, and environmental risks arising from contaminated areas can be challenging. Sites contaminated with radioactivity will often contain other physical, chemical, or biological hazards that will need to be considered. The implementation of a remediation strategy can itself result in additional risks for remediation workers or the environment that should be considered and addressed. Therefore, an integrated and all-hazards approach to protection is required to simultaneously manage and balance worker, public, and environmental risks. The Commission recommends that its system for radiological protection should be applied to the management of contaminated areas as one element of a broad approach to identifying how to maximise the overall well-being of directly and indirectly affected stakeholders and the environment. Specific attention should be drawn to the production and management of waste arising from the implementation of the selected remediation strategy. Early, broad, and ongoing stakeholders’ involvement is central to designing and implementing a sustainable remediation strategy. The Commission recommends a graded approach be applied: the level of effort to address the situation should be commensurate with the level of risk that remediation workers, members of the public, and the environment are exposed to. In most cases, remediation workers will likely be considered and managed as occupationally exposed workers.

© 20YY ICRP. Published by SAGE.

*Keywords:* Existing exposure situation; graded approach; integrated approach; all hazards approach; stakeholders’ involvement; prevailing circumstances; sustainability; remediation; contaminated areas

MAIN POINTS

* **The Commission recommends managing exposures in areas contaminated by past activities as existing exposure situations. A graded and integrated all-hazards approach should be taken for the protection of the workers, public and the environment, addressing actual exposures and exposures not certain to occur, both now and in the future.**
* **The remediation process underpins the management of contaminated areas. It encompasses 5 phases: recognition, site characterisation, planning of remediation, implementation of the remedial action plan, and post-remediation management. Waste management is included as an important aspect to consider during the remediation process.**
* **Early, broad and ongoing stakeholder involvement in the remediation process, including the selection of relevant radiological criteria, is central to a sustainable strategy.**
* **The reference level for public protection should be selected in the lower range of the 1 to 20 mSv per year dose band, with the objective to progressively reduce exposure close to 1 mSv per year as the site situation improves.**
* **Remediation workers are, in most circumstances, managed as occupationally exposed workers. Nevertheless, the Commission recognises that flexibility in the use of regulatory tools to achieve protection may be required to implement an adequate protection strategy.**
1. INTRODUCTION

## Background

1. Since the discovery of radioactivity in 1896, its useful properties have been utilised in many ways for the benefit of society, such as power generation and medicine. The uses of radioactivity have evolved considerably, as have the standards, regulations, and societal expectations governing its use.
2. One notable example is radium, which was discovered by Marie Sklodowska Curie in 1898. All isotopes of radium are radioactive, but radium-226, which has the longest half-life of 1600 years and decays into a series of radioactive progeny, presents a particular public health concern. Until the second half of the 20th century, it was widely used in radioluminescent paint for the watch industry and in similar applications, along with other applications such as parlour tricks and medical quackery. The use of radium was not regulated then because its danger to human health outside of the work environment was not known or considered. This led to the presence of radioactive materials in buildings, on lands, and in dwellings that may have remained there after the use of radium was prohibited. The evolution of standards and regulations, as well as societal expectations, has led to a number of actions dedicated to the management of areas contaminated with radium due to past activities, such as the Radium Action Plan in Switzerland (see Section A.3). There are similar contaminated areas around the world where either natural or artificial radionuclides are present because of human activities. Management of these sites may have been carried out according to safety criteria and standards in place at the time but subsequently have become a cause for concern, or such sites may require appropriate management due to their recent discovery.
3. These contaminated areas, sometimes referred to as legacy sites, cover a wide variety of cases: large areas impacted by nuclear weapons testing, areas contaminated by uncontrolled radioactive releases from operating facilities, former industrial sites handling naturally occurring radioactive material (NORM), etc. (NEA, 2019; IAEA, 2022). Examples may include research laboratories, nuclear research reactors or military complexes that were shut down but not remediated or at least not remediated according to current standards and societal expectations. Former uranium, phosphate or rare earth element mines and related processing facilities may also fall within the scope of contaminated areas. There is a large variety of sites and corresponding prevailing circumstances to be considered while dealing with areas contaminated by past human activities, as has already been explored extensively in international forums in different contexts (NEA, 2019, 2021; DSA, 2020). In many cases, contaminants in addition to radionuclides, such as heavy metals or organic contaminants, need to be considered as part of an all-hazards approach for risk management, bearing in mind that the Commission is not in a position to make specific recommendations on their management.
4. In 1999, the Commission released *Publication 82*, which concerns the protection of the public in cases of prolonged radiation exposure (ICRP, 1999). It addressed the application of the Commission's system of protection, as described in *Publication 60* (ICRP, 1991), for the control of prolonged exposures resulting from practices and for the undertaking of interventions in such exposure situations. Optimisation was expected to be applied to ensure that doses were as low as reasonably achievable, taking into account economic and social factors. The Commission later provided updated guidance on the application of the optimisation principle in *Publication 101b* (ICRP, 2006b).
5. In *Publication 103* (ICRP, 2007), the Commission revised the system for radiological protection to supersede *Publication 60* (ICRP, 1991). The approach is now based on the characteristics of the radiation exposure situation instead of the process-based approach (i.e. practices and interventions) adopted previously. The system of protection considers three types of exposure situations (planned, emergency, and existing) and three categories of exposure (occupational, public, and medical). It also effectively extended the system of protection to address the protection of the environment, including flora and fauna, more explicitly. These recommendations set the objectives of environmental protection and explain the basis for the proposed Reference Animals and Plants (RAPs). In introducing the existing exposure situation, which includes exposures from contaminated sites affected by past activities addressed in this publication, *Publication 103* notes that *it may also be necessary to take radiological protection decisions concerning existing man-made exposure situations such as residues in the environment resulting from radiological emissions from operations that were not conducted within the Commission’s system of protection*.
6. Since 2007, the Commission has produced a set of publications dedicated to applying the system of radiological protection to existing exposure situations. *Publication 126* (ICRP, 2014b) updates the recommendations for protection against exposure to radon. *Publication 132* (ICRP, 2016) is devoted to radiological protection from cosmic radiation in aviation. *Publication 142* (ICRP, 2019) addresses exposures from naturally occurring radioactive material in industrial processes. *Publication 146* (ICRP, 2020), which accounts for the lessons derived from large nuclear accidents at Chernobyl (in 1986) and Fukushima Daiichi (in 2011) nuclear power plants, addresses emergency exposure situations and living in long-term contaminated areas following a radiological emergency.
7. The Commission clarified in *Publication 138* (ICRP, 2018) the ethical bases and values that underpin the system of radiological protection. These rely on four core ethical values: beneficence/non-maleficence, prudence, justice, and dignity. In this publication, these ethical values are considered an integral part of the recommended protection strategies for managing exposures associated with contaminated areas.
8. Also, following *Publication 103* (ICRP, 2007), several publications are intended to cover radiological protection of the environment more explicitly, particularly *Publication 108* (ICRP, 2008), which introduces the RAPs, and *Publication 124* (ICRP, 2014a), which deals with the application of radiological protection in the environment under different exposure situations. These ICRP publications are further referenced in this publication in the context of non-human biota protection in contaminated areas.
	1. Scope
9. The purpose of the present publication is to explain the application of the recommendations of the Commission on controlling radiological exposure associated with areas contaminated by past activities, which are managed in the framework of existing exposure situations. For exposures that are not certain to occur, a probabilistic approach is needed, noting that the term potential exposure is normally reserved for planned exposure situations.
10. This publication does not address the planned remediation of areas as part of the operation or decommissioning of facilities that were continuously maintained under adequate regulatory control, or cases of contamination of localised areas within the site boundary of an authorised facility, which are treated in the framework of planned exposure situations.
11. Emergency exposure situations in case of a severe nuclear power plant accident and subsequent post-accidental phase, which are addressed in *Publication 146* (ICRP, 2020), are not considered in the scope of this publication.
	1. Structure of publication
12. This introductory section is followed by four sections and an annex with 5 case studies.
* Section 2 presents the characteristics of exposures associated with areas contaminated by past activities, based on case studies described in Annex A.
* Section 3 describes the Commission’s system of radiological protection applied to exposures resulting from areas contaminated from past human activities, including the type of exposure situation, the category of exposure concerned and the basic principles to be applied.
* Section 4 provides guidance on the implementation of the system of radiological protection of the public, the environment and remediation workers over the lifetime of the remediation process.
* Section 5 summarises the main conclusions.
* The Annex includes 5 case studies each of which provides details of a particular existing exposure situation, and how the situation was managed.
1. CHARACTERISTICS OF EXPOSURES FROM CONTAMINATED AREAS BY PAST ACTIVITIES
2. From the initial use of radium in the late nineteenth and early 20th century, the generation and use of radioactive material have greatly expanded. Past activities and regulatory control not in accordance with current knowledge and standards has led to radioactive contamination of the soil, air, sediments, water and, in some cases, structures, with radioactive material. Areas of land (including soil, surface water, groundwater, and structures) that are now deemed to be contaminated by the historical use of radioactivity are sometimes referred to as legacy sites (NEA, 2019, 2021; DSA, 2020; IAEA, 2022).
3. Such areas cover a wide spectrum of facilities and activities that range from uranium mining and milling operations, nuclear weapons production, and nuclear weapons testing, accidental or intentional releases from operational nuclear facilities to releases from factories that utilised radioactive material in their production processes. Furthermore, past activities have sometimes resulted in dispersal of radioactive material through air and water resulting in contaminated areas outside the boundaries of the site. Therefore, a contaminated area may represent not only the geographical boundaries of the site, but areas outside its boundaries that have become contaminated as a result of release and transport of radionuclides present on the site.
4. This Publication uses the term ‘contaminated area’ to mean the geographical region defined by the extent of the radioactive contamination, rather than other limits such as site or facility boundaries. The exposure conditions of a contaminated area where the source is generally dispersed in the environment and exposure occurs to a population of individuals who may come in contact with the contamination, represent an existing exposure situation, as defined by the Commission. The source already exists when decisions on control are taken. Consequently, as the control of the source does not start initially, some options such as removal or full containment of the source may be impractical or impossible to achieve; there is chronic exposure but no prospect for an emergency, as doses are generally moderate, with no prospect in most areas for tissue reactions. However, both members of the public and remediation workers may be exposed to internal and external exposure. The actual levels of exposure cannot be assessed without characterising the situation.
5. Five case studies are presented in Annex A to highlight a range of contexts and aspects that need to be taken into account when developing protection strategies. A comparison of some key parameters across these case studies is presented in Table 1, and an overview of the five case studies is provided in Section 2.2.
	1. Exposure pathways and scenarios
6. The exposure pathway is the physical route taken by radionuclides in the environment to the receptor who receives the radiation dose. Internal exposure due to inhalation and ingestion and external exposure are the typical modes of exposure from contaminated areas. However, depending on site-specific factors, the total dose received by a representative user of the land will often be dependent on only one of these exposure pathways. Inhalation may arise from radionuclides resuspended from contaminated soil or radionuclides that migrate from the source to the atmosphere (e.g. radon). The ingestion pathway includes direct ingestion of contaminated water and ingestion of food products that contain radionuclides as a result of contamination of the air, soil, water, or sediments. External exposure is caused by gamma and, to a lesser extent, beta irradiation from environmental concentrations of radionuclides in air, soil, water, and sediments. Skin doses may need to be considered mainly in those cases of beta radionuclides for some specific scenarios.
7. In contaminated areas, effective doses to the public are estimated using modelled or measured activity concentrations in environmental media for the appropriate exposure scenarios. The exposure scenario describes the habits and behaviours of hypothetical persons that determine inhalation and ingestion intakes of radionuclides, as well as the duration and levels of external exposures. The exposure scenario assumptions have a direct impact on the estimated dose to hypothetical individuals. Because habits are variable across a given population, resulting in a distribution of doses, the Commission recommends that the values for these parameters be derived for the ‘representative person’ (ICRP, 2006a). The representative person may be hypothetical, but the habits (e.g. consumption of foodstuffs, breathing rate, location, usage of local resources) used to characterise the representative person should be typical habits of a small number of individuals representative of those most highly exposed and not the extreme habits of a single member of the population. The number of people exposed will also be relevant to the optimisation process. The Commission also recognises the need to maintain biological diversity, ensure species conservation, and protect the health and status of natural habitats, communities, and ecosystems (ICRP, 2007). The approach for radiological protection of the environment developed by the Commission is described in *Publications 108* and *124* (ICRP, 2008, 2014). Potentially relevant scenarios and exposure pathways for non-human biota may be different from those considered in the context of human protection.
	1. Overview of case studies
8. Five case studies are provided as examples of contaminated site remedial actions. Summary information is provided in Table 1. The first case study is the Rocky Flats Plant near Denver, Colorado, USA. It illustrates the stakeholder involvement process and prospective dose assessment (the land was and is unoccupied). Rocky Flats was part of the United States government weapons production complex that produced plutonium pits for the fission triggers on thermonuclear weapons. The plant began operations in the 1950s and continued operations until 1989. Plutonium contamination in soil resulted from leaking barrels containing plutonium shavings, cutting oil, and degreasing agents. Suspension of the contaminated soil during high wind events resulted in the estimated release over time of 110 GBq of plutonium that was primarily deposited in the industrial area and the buffer zone surrounding the site. Soil concentrations exceeded 30,000 Bq kg−1 in the industrial area where the barrels were stored and were as high as 185 Bq kg−1 in the buffer zone. After the closure of the site, public concern was expressed about the plutonium contamination in the industrial area and buffer zone. An independent public study was conducted to estimate the amount of plutonium that could remain in the soil to achieve an effective dose constraint[[1]](#footnote-2) of 0.15 mSv per year for unrestricted use. The study included extensive stakeholder involvement in developing exposure scenarios and modelling assumptions. The study recommended a plutonium soil action level[[2]](#footnote-3) of 1295 Bq kg−1 for a dose constraint of 0.15 mSv per year. These results were transmitted to the regulatory body, which ultimately adopted a clean-up level of 1800 Bq kg−1. Based on stakeholder input and to reduce remediation costs, the former site was designated a wildlife refuge.
9. The second case study is the former above ground nuclear test site at Maralinga that covers about 3300 km2 in southern Australia. It illustrates stakeholder involvement process, setting of reference levels, and consideration of other factors besides dose in the remediation decision. Major nuclear tests and about 600 minor trials were conducted from 1953 to 1963 and resulted in significant plutonium soil contamination within the test area. In the 1980s, detailed studies of the Maralinga site indicated that earlier judgments and decisions about Maralinga and the need for remediation had been based on limited and deficient information. Detailed studies including land use practices and the fate and transport of plutonium in the environment were begun in response. Local stakeholder involvement focused on the need to reduce annual doses while restricting remediation activities that involved soil removal to avoid having a significant environmental and cultural impact on the population. Thus, a reference level of 5 mSv annual effective dose was adopted based on stakeholder input and the importance of keeping as much of the environment undisturbed as practicable. A combination of remediation and land use restrictions were implemented using the reference level of 5 mSv annual effective dose.
10. The third case study is the remediation of radium contamination in the Swiss watch industry. It illustrates the setting of reference levels in a contaminated area that was not primarily land. From 1920 to 1960, radium was used in watch dials for its luminescent properties until other materials became available. Watch dials were painted in workshops and homes, contaminating an estimated 1000 individual areas. A government program administered by the Swiss Office of Public Health was established to identify and characterise sites with past contamination. The program involved surveys of sites identified by the local stakeholders as having possible contamination, followed by historical research and surveys of sites where radium might have been used. The remediation plan was to set a reference level of an annual effective dose of 1 mSv or less. The program is currently ongoing.
11. The fourth case study is the Techa River area in the Chelyabinsk Region of the Ural Mountains in the former Soviet Union, which is now in the Russian Federation. It illustrates a complex site where past, present, and future exposures need to be considered, along with evaluation of radionuclide transport and land use restrictions. Beginning in 1948, graphite-moderated reactors at the Mayak facility produced plutonium for the Union of Soviet Socialist Republics (USSR) weapons program. Plutonium chemical separation facilities at Mayak generated liquid radioactive waste containing a mixture of fission products including 90Sr and 137Cs. Authorised and accidental releases of liquid waste to the Techa River from 1949 to about 1956 resulted in the release of approximately 115 PBq of activity to the river. Releases into the Techa River resulted in contamination through its entire 240 km length and contamination of part of the Iset River where the Techa River inflows. This has led to actual exposure of the population, fluvial transport of the existing contamination, and large-scale remedial actions intended to limit the future migration of existing contamination. The aim is to reduce doses to persons living near the river and exposures to individuals in the future. In 1951, external exposure rates on the banks of the Techa River in the town of Metlino (7 km downstream of Mayak) were on average 1.5–2.0 mGy h−1(about 15,000 times background). Contaminated river water used as drinking water and consumption of fish from the river resulted in large internal doses. Remedial actions applied since 1951 to reduce doses to the public have included technology improvements to decrease radionuclide releases into the environment, relocation of residents from highly contaminated areas, and restrictions on land use. When discharges were occurring, people exposed to Techa River contamination were neither notified about radiation exposure nor involved in the process of developing remediation options. The exposure situation at Techa River was not reported by the press until the end of the 1980s. The focus of the current program implemented by the Russian Federation is the prevention of further migration of contamination, remediation and monitoring of contaminated lands, and long-term medical monitoring of the exposed population. Consideration has also been given to the possible impacts on non-human biota living in the Techa River (Shishkina et al., 2019).
12. The fifth case study involves 226Ra contamination from a former airfield and aircraft servicing base that operated from 1917 to 1959 in Dalgety Bay, Scotland, UK. Activities at the airfield are known to have included the luminising and servicing of aircraft components using paint containing radium, as well as the incineration and disposal of solid wastes from the dismantling of retired aircraft. Solid waste disposal from these activities resulted in contamination of the land. Erosion has led to contamination of the adjacent beach and, through coastal processes, the sediments in Dalgety Bay. Discrete particles of 226Ra were first discovered on the beach at Dalgety Bay in 1990, resulting in episodic monitoring and assessment of the site until 2011, when the detection of particles in greater numbers and of higher activities prompted more detailed investigation. Particles were heterogeneously distributed with some being detected on the surface of the beach, and others at varying depths in the sediment. Due to the nature of the contamination, the probability that an exposure occurs was substantially less than unity. Consequently, both the probability of an exposure occurring as well as the consequences of such an exposure if it were to occur were assessed. Stakeholder involvement included engagement with the UK Ministry of Defence, Dalgety Bay Community Council, various advisory groups, and local government. Various public protective actions were introduced by the relevant authorities whilst the work to characterise, assess, and remediate the site progressed.

Table 1. Comparison of key parameters in the case studies

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Case Study | Radionuclides of concern | Primary exposure pathway(s) | Levels of contamination | Reference Level (RL) or Remediation Goal (RG) | Size of affected area | Post-Remediation Land Use |
| Rock Flats, USA | Pu-239 | Dust inhalation | <185 Bq kg-1 to >30,000 Bq kg-1 | <1800 Bq kg-1 soil action level (RG), 0.15 mSv.year-1 (RL) | Industrial area: 5.29 km2 , Buffer area:19.7 km2 | Wildlife refuge (restricted use) |
| Maralinga, Australia | Pu isotopes, primarily Pu-239 | Dust inhalation; potential for ingestion and injection of particles in certain areas | Not provided | 5 mSv.year-1 (RL) | 3,300 km2 | Land use restrictions in place because of potential exposures |
| Swiss radium sites | Ra-226 (from radium dials) | External exposure | Not provided | 1 mSv.year-1 (RL) | 1,000 buildings (mostly appartments) with some outside areas (gardens) | Unrestricted following remediation |
| Techa River sites, RF | Mixed fission products including Sr-90 and Cs-137 | External exposure, drinking water and fish consumption | 115 PBq total released to the river | Not established | 240 km (length of Techa River downstream) | Many residences still exposed |
| Dalgety Bay, Scotland | Potential exposure to Ra-226 | Skin contact and inadvertent ingestion of discrete particles | Discrete particles ranging from ~1 kBq to ~76 MBq | Current or future probability of an individual receiving 1 mSv committed effective dose is less than 10−6.year-1 | ~1 km of coastline and foreshore | Public access restored following remediation |

* 1. Practical experience from case studies
1. All case studies required an estimation of the dose received by representative persons from real or hypothetical populations. To quantify doses that arise from an existing exposure situation, the environment must be appropriately characterised. Characterisation involves: 1) quantification of radionuclide activity concentrations in potentially relevant environmental media (such as air, soil, water, sediments and non-human biota) and in the impacted area, including at the location of exposure, as well as in unaffected, baseline areas; 2) sufficient system understanding to support identification of potential environmental transport pathways (Lindborg et al., 2021); and 3) identification and characterisation of human and environmental exposure pathways for both the present situation (including, in some cases, an assessment of past exposures) and in the future. In this context, the existing contaminated environment can be treated as a source according to the ICRP *Publication 103* definition of a source.
2. In many cases, an existing exposure situation involves radionuclides present in the environment that are currently resulting in radiation exposure to individuals and non-human biota. The amount of remediation is dependent on the intended use of the land and assumed exposure scenarios since this will affect doses incurred by a future population (see Rocky Flats case study in Section A.1). A radionuclide source (e.g. contaminated soil or water) may be isolated with no viable human exposure pathway. However, if left untreated (taking into account that in many cases, it is not possible to totally remove the source and there is residual, albeit lower, exposure after treatment), future migration of existing contamination may result in radiation doses to persons in the future. While the Techa River presents an existing exposure situation where actual exposures are occurring, it also represents this latter case for radionuclides remaining in river sediments, soils or groundwater in depopulated areas of the watershed that may be mobilised, resulting in exposure to persons downstream of the contamination. Thus, it is important for any characterisation effort to identify current contamination levels and how radionuclides may migrate in the future.
3. Radionuclide decay and transport can affect future levels of exposure in the environment, and these processes need to be considered in the remediation plan. An individual’s dose is highly dependent on individual’s habits and behaviour, and, for an exposed population, a distribution of doses is expected. In addition to characterising radionuclides in the environment, characterising the exposed population is also necessary for defining the appropriate representative person. This may include characterisation of local habits, cultural practices and related lifestyle factors that may determine the relevant internal and external exposure pathways. Suffice it to say that assumptions about the habits and behaviours of the exposed population have a direct effect on their estimated dose, and thus impact any remediation decision and the setting of reference levels or other criteria. It is important, therefore, that assumptions are realistic regarding potential exposure pathways, habits, behaviours, and exposure parameters that may affect the estimated dose to the representative person. Caution may be adopted in the absence of robust data – or as part of an assessment applying a graded approach, but the combination of assumptions made should not result in assessed doses that are very unlikely to occur unless the probability of that level of exposure is also taken into account in the decision making.
4. In addition to radiation dose, social and economic factors were also considered when setting the reference levels in the case studies, including, in most cases, the involvement of stakeholders in the decision-making process. For example, in the Maralinga case study (Section A.2), remediation of large amounts of soil to reduce annual effective doses below 1 mSv would have resulted in an unjustifiable expenditure of environmental and cultural resources. Thus a higher reference level was established after a stakeholder involvement process that included consultation with indigenous people and the traditional owners of the land. Likewise, the stakeholder-influenced decision for the creation of a wildlife refuge at Rocky Flats (Section A.1) took into consideration the economic, as well as environmental costs of removing large amounts of contaminated soil. Moreover, remediation decisions considered the radiation risks to workers performing the remediation and to the nearby public from the remediation activities themselves, in addition to the costs of the shipping and disposal of the waste material derived from remediation activities. Decisions regarding the ultimate remediation strategy thus considered not only the radiation dose but also the costs and risks of remediation, disruption of the environment, and cultural disruption.
5. Protection of the environment from radiation exposure has been included in the analyses of the above case studies but appears to have played little part in the decisions made. A more significant issue has been avoiding environmental damage from remediation processes, such as soil removal. Further examples and case studies are discussed in Copplestone et al. (2017, 2020).
6. FUNDAMENTAL CONSIDERATIONS OF THE APPLICATION OF THE SYSTEM OF RADIOLOGICAL PROTECTION

## The radiological protection system and ethical considerations

1. The system of radiological protection, as described in the 2007 Recommendations (ICRP, 2007), relies on three fundamental principles: justification, optimisation of protection, and application of dose limits. Justification and optimisation are applied to the three types of exposure situations considered by the Commission to organise radiological protection: planned exposure situations, emergency exposure situations, and existing exposure situations. Dose limits are applied in planned exposure situations other than medical exposures.
2. The system of radiological protection has a solid ethical foundation that underlies the three main principles of radiological protection. This ethical foundation is elaborated in *Publication 138* (ICRP, 2018), with particular attention given to four core ethical values: beneficence/non-maleficence, prudence, justice, and dignity.
* Beneficence/non-maleficence: promoting or doing good and avoiding doing harm. This is reflected, for example, in the primary aim of the system of radiological protection of providing an appropriate level of protection without unduly limiting desirable human actions.
* Prudence: making informed and carefully considered choices without full knowledge of the scope and consequences of an action. Prudence is reflected, for example, by considering the uncertainty of radiation risks for both humans and the environment.
* Justice: fairness in the distribution of advantages and disadvantages. Justice is a key value underlying, for example, individual dose restrictions that aim to prevent any individual from receiving an unfair burden of risk or costs.
* Dignity: the unconditional respect that every person deserves, irrespective of personal attributes or circumstances. Personal autonomy is a corollary of human dignity. This underlies, for example, the importance placed on stakeholder participation and the empowerment of individuals to make their informed decisions.
1. Implementation of a protection strategy for managing exposures resulting from contaminated areas from past activities should thus result in doing more good than harm, avoiding unnecessary risk, avoiding unfair distribution of risk, and treating people with respect. The system of protection also relies on procedural ethical values: accountability, transparency, and inclusiveness (ICRP, 2018).
2. While the system of radiological protection is concerned with ensuring adequate protection of people and the environment, its ethical values guide considerations of how protection is best achieved while being mindful of possible unintended consequences. The Commission continues to recommend that individuals and populations in the future should be afforded at least the same level of protection as the current generation.
3. The principles set out in the United Nations’ Rio Declaration on Environment and Development (United Nations, 1992) encompass concepts that are important to the application of sustainable remediation, such as intergenerational equity, environmental protection and waste minimisation. *Publication 91* (ICRP, 2003) highlights sustainable development as an important principle in environmental radiation protection, defining it as relating to *the need to recognise the interdependence of economic development, environmental protection, and social equity, and thus the obligation also to protect and provide for both the human and environmental needs of present and future generations*. Sustainable development is related to the System’s core ethical values of prudence and justice. As described in a recent Nuclear Energy Agency (NEA) report (NEA, 2019), the principle of ‘sustainability’ emphasises the importance of taking an intra- and intergenerational perspective for environmental protection. Sustainable remediation was defined by NEA (NEA, 2016) as: *Remediation actions that deliver a net benefit and are informed by the short‑ and long‑term impacts on safety and the environment, society and the economy, natural resources and climate change*. A recent IAEA document (IAEA, 2023) highlights that determining an agreed site end state is important to guide site activities so that the site is transitioned to a condition that meets social and economic expectations, is sustainable and protects people and the environment appropriately.
4. Sustainable remediation is based on actions and goals that reflect an understanding of the overall impact of remediation activities. It is informed by assessments of safety and environmental benefits and impacts, as well as social and economic benefits and drawbacks, in the short term and the long term. Hence, sustainable remediation requires not only the identification of a technical solution, but also social engagement in the form of an informed debate and a transparent decision-making process (NEA, 2019).

## Type of exposure situation

1. The Commission describes the processes leading to human exposures as a ‘network of events and situations’ that begins with a natural or artificial radiation source, the transfer of the radiation or radioactive materials through various pathways, and the resulting exposure of individuals or the environment (ICRP, 2007). Protection is achieved by taking actions at the source or at any point in the exposure pathways.
2. The Commission considers that exposures from areas contaminated by past activities should be managed as an existing exposure situation. As detailed in Section 2 and case studies in Annex A, the source is not deliberately introduced in the concerned area when the decision to manage exposures resulting from the source is made.
3. The doses resulting from contaminated areas may be low[[3]](#footnote-4) when the decision to manage the situation is taken. Nevertheless, depending on the areas, potential transport and exposure pathways, and source characteristics, contaminated areas could lead to higher exposures in the future. Exposures not certain to occur arising from contaminated areas over the medium- and long-term should also be considered to define a robust and sustainable remediation process.
4. There is usually no prospect of tissue reactions. However, in unusual circumstances and depending on the characteristics of the source (hot particles in the Dalgety Bay case study, for example), prevention of tissue reactions may need to be considered when defining the protection strategy.
5. The Commission indicated in Table 4 of *Publication 103* that *Exposures resulting from long-term remediation operations or from protracted employment in affected areas should be treated as part of planned occupational exposure, even though the source of radiation is ‘existing’* (ICRP, 2007). For these workers, once the situation is well characterised, exposure pathways leading to doses can be controlled. Consequently, the Commission recommends that exposure of workers involved in the remediation (remediation workers) of contaminated areas should be managed as planned occupational exposures.
6. In some cases, workers not involved in the remediation process can be exposed while performing their professional activities in the contaminated areas. These exposures are not regarded as occupational exposure and should be treated in the same way as exposure to members of the public.
7. A graded approach is appropriate for managing exposures in areas contaminated by past activities. It should be based on the characteristics of the contaminated area, experiences from managing similar situations, and expectations of local stakeholders.

## Justification of protection strategy

1. The principle of justification is one of the two fundamental source-related principles that apply to all exposure situations. The recommendation in Para. 203 of *Publication 103* (ICRP, 2007) requires, through the principle of justification, that any decision that alters the radiation exposure situation should do more good than harm. For existing exposure situations, the justification principle is applied when deciding whether or not to take actions to reduce exposure and avert further additional exposures.
2. Any decision made with respect to adopting a particular protection strategy will likely have advantages and disadvantages and should be justified in the sense that it should do more good than harm. In these circumstances, when managing areas contaminated by past activities, the principle of justification is primarily applied in deciding if a remediation strategy is to be implemented.
3. Remedial actions may affect people living in contaminated areas, including how they live. In the justification process, the positive attributes of remediation that should be considered include not only the reduction in dose but also affected stakeholders’ expectations. The negative attributes that should be considered include not only the financial costs of the remediation but also the societal, health and environmental impacts of the remediation work, such as the transfer of risks to remediation workers or the impacts of waste transport and management.
4. It is important, in the frame of the justification process, to include an analysis of the consequences if no remediation action is taken, as this could be the most appropriate decision.
5. The justification principle combines the ethical values of beneficence and non-maleficence, prudence, and dignity (ICRP, 2018). These ethical values support a broad view of justification that considers the well-being[[4]](#footnote-5) of individuals and the environment now and across future generations. Measurable expressions of these values may include a good quality of living or working and achievement of sustainable development goals (United Nations, 2015). Dignity implies the organisation of a proper dialogue with relevant and affected stakeholders and the provision of adequate information to allow informed decisions.
6. Justification decisions regarding radiological protection strategies in the case of areas contaminated by past activities benefit from a stakeholder involvement process. Nevertheless, responsibility for judging justification usually falls on national authorities to ensure that an overall benefit results to society and, thus, not necessarily to each individual.
7. Participation of relevant stakeholders in the decision-making process is an effective way to consider their concerns and expectations, as well as their knowledge. It enables the adoption of more effective and sustainable remedial actions (ICRP, 2018).
8. The elaboration of a protection strategy to control exposures from areas contaminated by past activities and associated decisions requires detailed radiological characterisation of the exposure situation. It should also take into account health, economic, environmental, societal, cultural, and ethical considerations, and possibly other specific local considerations.

## Optimisation of protection

1. When a decision has been taken to implement a protection strategy, optimisation of protection is defined by the Commission as the process of keeping the magnitude of individual doses, the number of people exposed, and the likelihood of incurring exposures as low as reasonably achievable. Optimisation of protection is guided by the choice of an appropriate individual dose criteria, taking into account economic and societal factors (ICRP, 2007). The impact on the environment should also be kept as low as reasonably achievable.
2. Optimisation of radiological protection results from a process that carefully balances the reduction of exposures with the associated societal, environmental, and economic impacts. The Commission outlines that optimisation of protection does not always result in the lowest dose to individuals (ICRP, 2021).
3. Optimisation of radiological protection is implemented through a process involving relevant stakeholders, which is based on a detailed characterisation of the contaminated area and an assessment of actual exposures and exposures not certain to occur, and includes:
	* + - the selection of an appropriate reference level;
			- the identification of possible actions to maintain or reduce exposure as low as reasonably achievable, taking into account economic and societal factors and the protection of the environment;
			- the selection and implementation of the most appropriate remedial actions under the prevailing circumstances;
			- the review of the exposure situation after remediation to evaluate if there is a need for further remedial actions or if new opportunities for improving protection have emerged; and,
			- short, medium or long-term monitoring of the environment, as required.
4. Detailed advice from the Commission on how to apply the optimisation of protection principle in practice has been provided previously (ICRP, 1983, 1990, 1991, 2006b). This includes the recommendation that, in the case of optimisation assessments, realistic models should be used.
5. To avoid serious inequity in the distribution of individual doses to humans, in line with the ethical value of justice (ICRP, 2018), the Commission recommends using individual dose criteria in the optimisation process (ICRP, 2007).
6. The Commission recommends the use of reference levels as dose criteria in existing exposure situations. The reference level applies to the dose associated with the contaminated area in excess of the natural background, provided that this excess is identifiable. The reference level is the value of dose used to guide and drive the optimisation process. It is expected that following the implementation of the protection strategy, the residual exposure of members of the public will be below the reference level.
7. For the protection of humans in existing exposure situations, the Commission recommends setting reference levels typically within the 1–20 mSv year−1 band as presented in Table 5 of *Publication 103* (ICRP, 2007). As shown in the case studies in the annex, areas contaminated by past activities usually give rise to low levels of individual exposure, of the order of a few mSv year−1. Consequently, for the management of exposure of the public in areas contaminated by past activities, the Commission recommends selecting, where possible, a reference level in the lower half of the 1 to 20 mSv per year band. The Commission recognises that in some circumstances, the reference level agreed between stakeholders could be less than 1 mSv year−1. Regardless of the reference level selected, it should be chosen based on the characteristics of the situation (ICRP, 2007, Para. 234) and following discussion with all relevant stakeholders as discussed in Section 3.5.
8. Resources and efforts spent on protection should be commensurate with the level of risks (graded approach), taking into account the various human health and environmental hazards.
9. Radon exposure, when present, should be managed according to ICRP *Publication 126* (ICRP, 2014b).

## Stakeholder engagement

1. Optimisation of protection, as a process, should be open and transparent from the beginning. The development and definition of relevant exposure scenarios should incorporate knowledge gained from local stakeholders, whose involvement is valuable and can contribute significantly to the quality of the optimisation process.
2. A traceable system for decision-making will allow controversial issues to be addressed appropriately and resolved, although not necessarily with complete agreement from all parties.
3. Local stakeholders will need to be informed about how relevant factors are taken into account to select the remediation options. A clear understanding of the reasons for the different approaches should be provided, to allow the differences to be understood. Local stakeholders are likely to contribute valuable input into selecting the most appropriate final status of the site after remediation and throughout the stages through which that end-state can be achieved, in the framework of an all-hazards approach. It is important to maintain dialogue with stakeholders in the decision-making process to build confidence in the solutions being developed.
4. Dialogue between local stakeholders and experts should be encouraged. A co-expertise process, as described in *Publication 146* (ICRP, 2020), may allow for local concerns to be better addressed (current and foreseen use of the land, local traditions, etc.) and contribute to more effective and sustainable decisions. This process of cooperation between experts, professionals and local stakeholders aims to share local knowledge and scientific expertise to evaluate and better understand the radiological situation, develop protective actions to protect people and the environment, and improve living and working conditions.
5. IMPLEMENTATION OF THE COMMISSION’S SYSTEM OF RADIOLOGICAL PROTECTION TO AREAS CONTAMINATED BY PAST ACTIVITIES
6. The considerations presented in this section include reference to the case studies presented in Section 2 and other examples to anchor the ICRP recommendations in the practical context. The section provides guidance on the implementation of the system of radiological protection of the public, the environment and remediation workers to areas contaminated by past activities.

## General considerations

1. The Commission considers exposures associated with an area contaminated by past activities as an existing exposure situation. Each situation is unique and presents specific features. Such a situation often gives rise to societal concerns.
2. Successful remediation of areas contaminated by past activities requires a well-developed remediation framework to establish and implement an adequate protection strategy. The remediation process should be based on a step-by-step or phased approach, applying the fundamental principles of protection: justification of the decision to implement a protection strategy (which includes the analysis of no action) and optimisation of protection. While each situation may present unique conditions, the Commission considers that the remediation framework shown in Fig. 1 may be suitable for most situations. The process consists broadly of 5 main steps: recognition of the exposure situation; characterisation of the situation; planning of remediation; implementation of the remediation action plan; and, post remediation management (as required). This approach is consistent with publications from the IAEA (IAEA, 2022; Yankovich et al., 2022) and the NEA (NEA, 2019).
3. An effective process is more likely to be successfully implemented when supported by a close dialogue between all the affected stakeholders from the start of the process (NEA, 2019). As noted in the Society for Ecological Restoration Australasia (SERA) report ‘National standards for the practice of ecological restoration in Australia’, *The practical implications for restoration are that restoration planners and project managers need to genuinely and actively engage with those who live or work within or near a site to be restored, as well as with others who have a stake in the area’s goods, services or values. This needs to occur at the outset of and throughout a restoration project. Not only will a restoration project be more secure if genuine dialogue occurs between managers and stakeholders, but also this dialogue, coupled with education about the ecosystem, can increase the level of practical collaboration, facilitating solutions best suited to local ecosystems and cultures* (SERA, 2017). Moreover, incorporating stakeholders’ inputs throughout the process is essential to building confidence in the overall process, including determining the final status of a site (site end state), associated decisions and management of uncertainties.
4. At all stages in the remediation process, communication with local stakeholders should occur, outlining the risks and hazards present, the basis of any decision made, progress of remedial action and implications on health. It is important that any communication with the public is two- way and at the appropriate level with respect to technical content.
5. Deciding on and implementing a selected protection strategy requires commitment at all levels in all concerned organisations, as well as having adequate processes, procedures and resources in place (ICRP, 2007). A well-defined understanding of the responsibility of each party in the overall process is needed.
6. In some cases, potential impacts of the remediation strategy on neighbouring countries may have to be considered. Representative organisations of these countries should then be involved and informed as required. Neighbouring countries should coordinate their remediation efforts where there are transboundary impacts.



Fig.1. Scheme for the phases involved in a remediation process.

* 1. Recognition of the exposure situation
1. The first step in addressing exposures from a contaminated area due to past activities is recognising the exposure situation of concern from a radiological point of view, based on a shared understanding of the area’s main features. Knowledge of the history of the affected area is essential and can be supported by interaction with local stakeholders. Indeed, attention should be paid from the very beginning to identifying stakeholders who should be involved in the development and implementation of the protection strategy. It is important to start communication and engagement early in the process by providing timely information and making information available, as requested, so stakeholders can fully participate. Communication of project information should be done in a form that is transparent and easily understood by the public. In this early dialogue, it is important to start to understand the values of local stakeholders, i.e. what is important to them.
2. Several challenges may be faced at this early stage, such as identifying ownership of the contaminated area, both in terms of physical, legal and financial ownership. In some cases, such as contaminated residential neighbourhoods, many owners may be involved (some of whom might own the property, but not necessarily the liability/legacy). Also, addressing sites with multiple hazards will often involve different regulatory authorities. It is important in such cases that the relevant regulatory authorities share a common understanding of the situation and, to the extent possible, take regulatory decisions in a pragmatic, harmonised manner.
	1. Characterisation of the exposure situation
3. Once the situation is recognised, the next step consists of performing a detailed characterisation of the situation and gathering all required information to identify exposure pathways and affected people and assess their actual and potential doses. The aim of the characterisation of the situation is to determine the extent to which the contaminated area poses a risk to human health and the environment. Also, the characterisation of the situation is a key input to justify whether the situation requires site remediation and the development of a protection strategy, and if restrictions on site access or use should be implemented temporarily or possibly over the long term.
4. Characterisation of the situation involves an in-depth review of the available documentation for the reconstruction of the site´s operational history as much as possible, as well as establishing a dialogue with individuals with knowledge of either the site’s history or the current situation.
5. Characterisation means, but is not restricted to, the distribution of radionuclides and their activity concentrations in the different compartments (air, water, sediment, soil) of the environment in the area(s) of concern as well as in baseline (background) areas, and their physical and chemical forms. It should be done using appropriate sampling and measurement techniques and, when direct or indirect measurement is not possible, the application of appropriate modelling techniques. These aspects are discussed in the context of legacy sites, which commonly include areas contaminated from past activities (NEA, 2021). The data should also include the environmental characteristics of the contaminated area, such as soil type, hydrogeology, land use and topography since they influence the effort and methods used for remediation and, therefore, the related costs. Predictive modelling is needed to assess how current conditions may change in the future.
6. It is important to assess not only the sources and extent of radiological contamination, but also the characteristics of non-radiological contamination and other hazards, as in many cases, non-radiological considerations might be the driving factor in the remediation process. To perform the non-radiological hazards assessment, arrangements are necessary between the competent authorities to maintain a consistent approach to the management of all hazards and to clearly assign the roles and responsibilities of each authority.
7. The assessment of concentration levels of the radionuclides present in an area to be remediated must differentiate between those radionuclides that are the result of the contamination from the past practice under analysis and those radionuclides that are naturally present in the environment to be remediated (such as radium and thorium series) or that did not originate from the past practice under analyses (such as caesium found in the environment from nuclear weapon testing). Establishing baseline information on radiation levels is important to analyse the contamination caused by the past practice. In the case of a NORM contaminated area to be remediated, the background activity level could be established by monitoring nearby uncontaminated areas of the same geology with respect to the site to be remediated.
8. An exposure pathway defines a route of exposure from a source of radionuclides to affected individuals through environmental media (external exposure from radionuclides deposited on the soil, internal exposure from ingestion of foods containing radionuclides, etc.). Characterising the area will help identify the main exposure pathways to the public and the environment and provide necessary input for performing dose assessments as indicators of the risk arising from exposure.
9. The involvement of local communities will help not only to achieve a better assessment of the local situation but also to keep stakeholders informed. The Commission recommends that authorities should promote the involvement of local communities and cooperate to share experiences and information. The participation of stakeholders from the beginning of the process would also contribute to developing a radiological protection culture necessary for understanding the risks and the ethical values on which decisions are based. Stakeholders may constitute a heterogeneous group with usually little knowledge and a great deal of uncertainty about any issue involving radiation as this field of expertise is not generally well understood by the public. The aim is to achieve a shared understanding of the situation and its implications. Economic, social, environmental, and health impacts of the management options should be transparent and discussed openly to maintain public trust and confidence and reinforce the sustainability of the selected protection strategy.
10. Assessments of radiation dose to members of the public and to non-human biota that could be exposed due to the contaminated area, on and in the vicinity of the site, should be addressed within the context of the site-specific conditions, considering relevant mechanisms of dispersion and migration of radionuclides. A thorough assessment of the extent and characteristics of radiological and non-radiological contamination and the possibility of further migration into the surrounding areas over time is important for identifying appropriate receptors and providing input to a conceptual site model. A corresponding quantitative site model can then be used to inform the selection of the most suitable protection strategy.
11. Dose assessment should be supported by site-specific data, assuming realistic exposure scenarios. It should avoid using compounding or overly conservative assumptions that result in unlikely outcomes. However, it may be appropriate to consider physically realistic exposures, even if they are unlikely, to establish the potential upper level of dose or risk in situations where exposure may continue for decades or even centuries into the future, as an input into decisions on protection strategy. In such cases, the likelihood of exposure should also be considered.
12. As stated in *Publication 101a* (ICRP 2006a), the representative person concept is used to estimate exposures to the public arising from residual radioactivity. The representative person is an individual receiving a dose that is representative of the doses to the more highly exposed individuals in the population under consideration. The representative person for a particular set of circumstances should be selected carefully. Appropriate attention should be paid to population groups with special living habits. Their living patterns and habits of food and water consumption could give rise to pathways and elevated exposure levels that are unanticipated by relying on the population average or majority habits in the analysis. In addition, potential habits that could reasonably be associated with the site should also be considered, including the production of different foods or the use of the land for various recreational activities (Griffault et al., 2022).
13. The characterisation phase must be fully documented to provide a robust basis for selecting possible remedial actions and judging their associated effectiveness.
14. Characterisation of the situation will support the decision of whether the implementation of a protection strategy is justified, taking into account dose reduction, technical feasibility, health, economic, environmental, societal, cultural, ethical, and other considerations, as appropriate. Evaluating economic, sustainability, and social factors is also important in developing a remediation strategy.
	1. Planning of remediation
15. Remedial actions need to be selected and tailored according to the characteristics of the situation, including the nature of radioactive contaminants, the extent of contamination, the physicochemical environment, and the exposure pathways. There may be circumstances related to the exposure situation or conditions of the area that imply that there are no advantages to implementing a remediation action. The ‘no action’ scenario should always be analysed to help decide if actions are justified for a given situation.
16. If, based on the characterisation of the situation, the implementation of a protection strategy and associated remedial actions is justified, the remediation planning phase should be initiated. Different remedial actions may be investigated and considered with regard to (but not only) the objectives of protection of remediation workers, the public and the environment. The definition of such objectives should consider a wide variety of aspects as well as views expressed by stakeholders.
17. Remediation planning involves establishing a reference level for the residual dose, which is used for applying optimisation of protection. Relevant authorities should select values that are appropriate with regard to the prevailing circumstances and that reflect discussions and agreements with relevant stakeholders (e.g. environmental conditions, characteristics of the area, surrounding population and habits, the availability of resources for remediation, cost for remediation, technical feasibility, etc.). Optimisation of protection is an iterative process that is applied to both planning and implementing remediation. According to ICRP *Publication 103*, the distribution of individual doses may be moved downwards stepwise to progressively improve the situation until the achieved level of protection can be considered as optimised. Local stakeholders need to be involved in discussions with the relevant authority concerning selecting the remediation end-state criteria to share their knowledge of the site and express their concerns. The objective of the process should be to achieve overall well-being, addressing all hazards and considering economic and societal aspects. The appropriate end state for a site in one location will not necessarily be the same as that for a site with similar conditions in another location. There may be important societal, economic, and environmental context differences in the decisions that will need to be made. It is necessary to clarify why actions taken in other circumstances for another site may not be appropriate for the current situation.
18. Adequate planning allows consideration of the factors that may have an impact on the outcome of remediation, such as: financial provisions; availability of proven technologies; dose assessment before, during and after remediation; effects on the environment; types and amounts of residual material; and generation, transport and disposal of waste. The approach to address radiological, and other safety aspects, including the assessment of stakeholder values, should be clearly described, as an important step in building confidence in the safety assessment results that will support decisions. These assessments will need to include an evaluation of the potential risks to the public, workers and the environment from the site and its immediate surroundings and include risks arising from any on-site and off-site waste management activities.
19. The remediation options should be clearly described in a document in which the benefits and disadvantages of the different options are presented. Once an option has been selected, a site-specific remedial action plan should be prepared, detailing the remedial actions and, as required, the post-remediation actions such as medium- or long-term monitoring, surveillance, and institutional control.
	* 1. **Protecting the public**
20. Remediation planning involves establishing a reference level to protect members of the public. The reference level is determined on a case-by-case basis and should not be considered as the endpoint of the remediation process. The endpoint should be an optimised dose below the reference level that accounts for the possible future uses of the area and associated restrictions (if any). Reference levels are not dose limits.
21. Factors to be considered for setting the reference levels for remediation of existing exposure situations include (but are not limited to) the feasibility of controlling the situation, time and cost for remediation, the potential volume of residual material/waste that could be generated, the impact on the environment, societal disruption that would be produced through remediation, and experience in the management of similar situations. There may be a desire from the exposed individuals, as well as from the authorities and other stakeholders, to reduce exposures to levels that are similar to situations considered as ‘normal’ (ICRP, 2007). Although complete removal of the source of exposure may be listed among the options, it is often either not feasible or the best option overall. Optimisation of protection is not minimisation of dose nor the minimisation of any single attribute. More broadly, minimising one detrimental impact is likely to result in other detrimental aspects not being minimised to the same extent. For example, optimised protection is the result of an evaluation that carefully balances the detriment of the exposure and the resources available for the protection of individuals, also taking into account the number of individuals exposed. The most appropriate option may not be the one resulting in the lowest dose (ICRP, 2007).
22. Members of the public may be exposed because their place of work is located in a contaminated area. The Commission considers these exposures as public exposures.
23. Based on the characteristics of the situation, the Commission recommends that an appropriate reference level should be selected in the lower half of the 1 to 20 mSv year−1 band, with the long-term objective of progressively reducing exposure close to 1 mSv year−1.
24. When it is determined that a contaminated area requires remediation, the remediation organisation, or a liable party, should optimise protection below a predetermined reference level. The Commission recognises that regulators and national authorities, working with stakeholders, may require, in specific circumstances, a reference level lower than 1 mSv year−1. National authorities should select reference level values that are appropriate and relevant for their circumstances, and apply the available radiation protection actions as appropriate to provide optimised protection.
25. In the case of contaminated areas involving natural radionuclides, public exposure to radon should be considered, as it can be a dominant exposure pathway. As described in *Publication 126* (ICRP, 2014b), the Commission recommends that the management of radon exposures should be mainly based on the application of the optimisation principle using a reference level derived, for practical reasons, as an activity concentration in air to facilitate its implementation. The Commission recommends in *Publication 126* (ICRP, 2014b) that national authorities should set selected reference levels for radon and thoron that are as low as reasonably achievable in the range of 100–300 Bq m−3, taking into account economic and societal circumstances. When concentrations still exceed this selected reference level following the application of radon mitigation measures, it may be necessary, within a graded approach, to undertake additional assessments to determine what further steps might be taken to address the situation. It is important to emphasise that the reference level selected for the protection of the public mentioned above does not include exposure from radon.
26. While selecting a reference level for the protection of the public, an ongoing dialogue should be held to ensure that well-informed and transparent decisions are made. Representatives of stakeholders should have the opportunity to express their views and expectations regarding the protection strategy and remedial actions. Sharing knowledge and information will facilitate the development of a mutual understanding and meaningful involvement in the decision-making process regarding the planning and implementation of remedial actions. Local engagement was fundamental in the agreement of long-term solutions in the rehabilitation of the former nuclear test site at Maralinga (Section A.2), balancing between restrictions on land use and soil removal, which could have a detrimental environmental and cultural impact. Anthropological studies, which included the diet and lifestyle of the Maralinga Aboriginal community, provided information against which more appropriate remediation decisions were made.
27. Reference levels are typically expressed in terms of annual effective dose above the dose from natural background. They are used for applying optimisation of radiological protection in existing exposure situations and should be used to propose possible remedial options and to contribute to the development of an optimal protection strategy.
28. While setting the appropriate reference level for the public, it is necessary to assess the level of exposures that are possible but not certain to occur for the different protection strategies. Addressing these types of exposures involves consideration of uncertainties associated with exposure scenarios. Advice on addressing uncertainties and variability in selecting assumptions for the exposure assessment is given in ICRP *Publication 101a* (ICRP, 2006a). Assessments of these possible exposures not certain to occur should be reasonably realistic instead of focusing on highly unlikely scenarios. The probability of an event and its consequences can be evaluated to assess the risk, comparing the assessment of the detriment with a criterion of acceptability that could take the form of a risk constraint, as is described in the Dalgety Bay case study. The results of the risk assessment should be used as input to the decision-making process. The assessment of low probability-high consequence scenarios is part of the justification of the protection strategy and should take into account stakeholder concerns. Furthermore, assessment of dose to the public should include not only exposure to any contamination in situ but also the exposure that may occur during remedial work, for example from the inhalation of dust blown from the site. Exposures that may arise during the treatment and disposal of wastes generated during remediation should also be considered. Assessment of dose to the public should be made for current as well as post-remediation exposures so that the potential impact of the planned remediation can be evaluated for compliance with the reference level.

*Health surveillance*

1. Although the levels of exposure in the affected areas are generally relatively low, the presence of contamination and its potential health impacts may remain a concern among the population. While a health surveillance programme is typically not needed, it may be warranted in exceptional cases where doses to the public from a site could be significant or stakeholder concerns are unresolved. In these situations, it is recommended that authorities explain to the population the usefulness of implementing a health surveillance programme, which is designed to follow the health status of the involved population in the contaminated area. Such a programme would likely include an initial medical evaluation and follow-up of health status. Its implementation requires the development of health surveys, health databases, and mechanisms for providing information and access to health support. Health monitoring of vulnerable groups (e.g. young children, pregnant women) would be particularly important.
2. Health surveillance of the population exposed from past activities may also include specific epidemiological studies designed to provide information on possible radiation health effects that could develop over time. In particular, these studies could help identify whether there is any excess incidence of cancer that could be attributable to radiation exposure.
3. It is recommended that authorities engage in a dialogue with concerned stakeholders and explain clearly and in plain language the sources of radiation to which the public are being or have been exposed, the magnitude of these exposures and the associated possible health risks in order to define the health surveillance programme adequate to cope with the situation.
	* 1. **Protecting the environment**
4. Remediation of contaminated areas should consider the protection of human and non-human biota in an integrated manner. The approach developed by the Commission in *Publication 108* (ICRP, 2008) and *Publication 124* (ICRP, 2014a) describes the protection of the environment through the protection of non-human biota using a set of RAPs and derived consideration reference levels (DCRLs). The Commission recommends that the remediation process reduce exposures to levels that are within or even below the DCRL bands for the relevant populations, with full consideration of the associated radiological and non-radiological consequences. However, the Commission recognises that it may be difficult, or impractical, to significantly reduce the concentrations or quantities of radioactive material in the affected environment (ICRP, 2014a).
5. The potential for environmental risk may be an important factor in decision making because some remediation technologies are more likely than others to produce adverse impacts on ecological receptors, including habitat disruption (e.g. soil removal can destroy natural habitats) or damage to natural resources. Environmental radiological protection includes more than protecting flora and fauna. It includes the conservation of other ecosystem components such as air, water, soils, sediments, and habitats. Protection of aquifers for drinking water is, for instance, very important for stakeholders.
6. With regard to radiological protection of the environment, there has been increasing interest in incorporating ecosystem services monitoring and assessment in many contexts related to environmental protection and policymaking. Ecosystem services are defined as the benefits humans derive from the workings of the natural world. Examples include providing nutritious foods and clean water, regulating disease and climate, supporting crop pollination and soil formation, and offering recreational, cultural, and spiritual benefits. Ecosystem services have been considered as part of baseline studies of specific projects, designed to assess whole impact studies, where relevant biodiversity values are examined (e.g. studies of fish, vegetation, and wildlife) alongside a growing understanding of the human uses of the area (cultural services, social, economic and health impact studies) to determine those services that could be negatively impacted by the project to be performed. Moreover, discussions are maintained with indigenous communities and local stakeholders to determine community values and concerns (Zoetica, 2021). There are also examples of standards for ecological restoration in which the identification of a reference ecosystem involves analysis of the composition (species), structure (complexity and configuration) and function (processes and dynamics) of the ecosystem to be restored on the site (SERA, 2017). Ecosystem services may support a more holistic approach that could be used in the decision-making process (Martinez, 2023).
7. Efforts devoted to the assessment of impacts on flora and fauna should be commensurate with the level of risk. An initial (screening) assessment is usually carried out using generic representative organisms. If this assessment indicates that there is no significant risk, then this is the end of the process and obtaining specific information on organisms at the site is not necessary. In cases where DCRLs are exceeded, further investigation can be undertaken to gain improved site-specific understanding to replace conservative assumptions and parameter values used in the initial assessment with site-specific assumptions and data. If DCRLs are still exceeded, then the application of risk-based assessments to evaluate the significance of possible impacts on non-human biota, including further site-specific investigations, is recommended. Environmental protection in the optimisation and decision-making processes should do more good than harm to both people and the environment, including wildlife.
8. Models, such as the ERICA or RESRAD-BIOTA assessment tools (ISCORS, 2004; Brown, 2008, 2016), can be used to convert activity concentrations in environmental media into dose rates to RAPs. Dose rates for different remediation options can be compared with the relevant DCRLs. In more detailed assessments, to assess the level of radiological impact for comparison with the reference criteria, the location of the representative organisms needs to be considered and carefully defined in relation to the distribution of radionuclides in the environment and the area occupied by the species that stakeholders identify as of protection interest (BIOPROTA, 2015; Griffault et al., 2022).
9. In many cases, the decision may be complicated. In addition to comparing the dose rates for the different remediation options with the relevant DCRLs, the assessment of impact should also consider a variety of factors beyond the estimated dose rate. As an example, the Maralinga case study (Section A.2) describes how remedial actions took into account a balance between restrictions on land use and soil removal, which could have had a significant environmental (due to destruction of the natural habitat) and cultural impact. The Commission recommends an integrated approach taking into account radiological and non-radiological aspects.
10. Protection of environmental resources, such as groundwater, soil and forests, should be considered. Implementation of the remediation strategy should ensure, to the extent possible, that sustainability aspects are addressed and that remedial actions will not prevent future land uses that are deemed desirable by local stakeholders, such as agricultural use, commercial activities, or social and cultural activities.
	* 1. **Protecting remediation workers**
11. As far as remediation workers are concerned, radiological protection aspects can be reasonably planned and exposures controlled. Remediation workers are (in most cases) managed as occupationally exposed workers and the requisites for planned occupational exposure apply, including dose constraints and dose limits. Nevertheless, the Commission recognises that the choice of the management framework for controlling remediation workers’ exposures in a contaminated area will be a case-specific decision and recommends an all-hazards or holistic approach, considering non-radiological risk in a balanced use of regulatory tools to effectively achieve protection. For instance, workers called for their skills (civil-engineering, electrician, etc.) could be involved in remediation activities even though working around ionising radiation is not a routine part of their job or typical work environment. Their exposure to radiation should be protected at the same level as members of the public. Flexibility in the implementation of specific requirements for radiation protection could be provided, commensurate with the level of exposure and adapted to the circumstances. For example: just-in-time training, adapted dose recording, or flexibility with the dose criteria since their intervention is episodical. In most cases, non-radiological risk (i.e. chemical or physical) may be the main contributor to occupational health issues.
12. As part of developing a remediation plan, the following aspects should be considered in the radiation protection programme to provide adequate remediation worker protection: identifying main exposure pathways (external and internal exposure); assessing individual doses (based on individual monitoring, site-specific measurements where work is carried out and specific conditions to avoid excessive conservatism); evaluating health and safety issues during remediation work, including the use of appropriate personal protective equipment; and, ensuring that workers are adequately trained and competent. The magnitude of the doses received will depend on many variables, such as the type of radionuclides involved, the exposure pathways (external exposure and internal exposure due to inhalation and ingestion) resulting from implementing remedial actions (including disposal of wastes), the length of exposure time, etc. Integrating radiological protection in the procedures for controlling other hazards in a more global and synergistic approach to hazard management is an important aspect to carry out (for example, personal protective equipment used during asbestos abatement can also prevent internal exposure via inhalation). Specialised training may be needed in certain areas of work.
13. Radiological protection requirements for the protection of remediation workers should be commensurate with the magnitude of radiological risk (graded approach) and included in the procedures for the control of all occupational hazards (all hazards approach).
14. In specific situations where the source(s) and exposure pathways are not adequately characterised and not completely defined, as can happen in the preliminary phases of the remediation process, it might be more appropriate to initially use reference levels for the remediation worker’s protection rather than a dose constraint or dose limits. As soon as the characterisation yields adequate information and data, dose constraints and dose limits should apply. In all cases, worker protection should be managed as deemed appropriate by the regulator. This process can be implemented through information, advice, assistance, and, where necessary, more formal requirements. Relevant information and recommendations should be communicated to them about the tasks they perform and adequate training and appropriate personal protective equipment provided.

**4.4.4. Selecting remedial actions**

1. Remediation techniques that are applied during implementation of remedial actions may aim at removing or reducing the concentration of radionuclides in soil (and other environmental compartments), disrupting exposure pathways, or reducing radionuclide bioavailability. Remediation techniques include topsoil removal, ploughing, soil washing, confinement techniques, etc. For example, removing much of the contamination at the surface will significantly reduce radionuclide uptake by plant roots, external exposure, and resuspension of radionuclides from the soil. However, such techniques might also damage terrestrial habitat. (Alexakhin, 1993; Jacob, 2001; IAEA 2006, 2012; Fesenko, 2007; Voigt, 2009)
2. The selection of a suitable technique will depend on a large variety of factors, including stakeholders’ views, the selected reference level, human and financial resources, soil types, groundwater location, protection of the environment, local culture and traditions, etc. The soil removal required in the Maralinga case study was balanced with land use restrictions to avoid environmental and cultural impacts. Remedial actions on sources were also implemented in the Swiss watch industry case study, such as removal of contaminated objects, removal of floor coverings and blasting of surface paint, which reduced the amount of waste generated.
3. Regarding contamination of aquatic ecosystems, possible actions to decrease releases into surface waters, such as the construction of dams and by-pass channels, are described in the Techa River case study. Other measures include understanding the water chemistry to reduce direct radionuclide uptake and trophic transfer of radionuclides to edible aquatic species (Mokrov, 2014; Shiskina et al., 2016).
4. Restrictive management options, such as establishing restrictions or limiting access to contaminated areas can also be applied but may have consequences on the quality of life of the local inhabitants and damage the local economy. Consequently, except where decided as part of an optimised strategy that includes input from local stakeholders, restricting access to areas of land indefinitely should not be viewed as an acceptable long-term strategy. In the Dalgety Bay case study, part of the beach where the radioactive particles of the highest activities were found was closed to the public, and the collection of fish and shellfish for human consumption was prohibited. Restrictions, such as the prohibition of fishing and consumption of water and the prohibition of the use of flood plains for pasturing cattle, were also applied in the case of the Techa River contamination. In the Maralinga case study, land use restrictions limited activities to ‘casual use’, such as transit and hunting, resulting in much lower occupancy within the boundary of the area of restricted use. After successful remediation, land use restrictions are now only limited to restricting access to burial trenches where signs have been posted to discourage intrusion.
5. The involvement of affected individuals in the implementation of the protection strategy is referred to as ‘self‑help protective actions’ (ICRP, 2020). These protective actions are more likely to be effective and achieve an expected outcome in situations where individual or community lifestyles are a significant factor in the exposures received. Both local people and authorities work together to identify possible protective actions appropriate to the local situation to reduce avoidable individual exposures. This allows the identification of self-help protective actions that affected individuals can implement. For areas contaminated by past activities, self‑help protective actions mainly consist of limiting the time spent in certain areas, no longer consuming certain locally produced foodstuffs (or reducing the amount consumed) or, in some cases, monitoring of gardens. Their effective implementation depends on individuals being aware of the situation and well informed about the implications of their actions and the associated benefits of the decisions they may make.

**4.4.5. Management of residues and waste generated by the remediation process**

1. Remediation of a contaminated area generates residual material, including radioactive waste containing radioactive and non-radioactive contaminants, both of which should be managed appropriately. This material could include tailings, mineralised rock, resins, soils, liquids, sediments, surface-contaminated objects, metal, concrete, etc. Not all the residual material generated during remediation will be contaminated such that it meets the definition of radioactive waste. Radioactive waste has a wide variety of characteristics, and precise classification schemes vary between different regulatory regimes. The IAEA document Classification of Radioactive Waste General Safety Guide No. GSG-1 (IAEA, 2009) provides a useful scheme that has six classes of waste from Exempt Waste (below concern from the radiological protection perspective) to High-Level Waste. Some residues can be recycled or reused, such as residues produced from mine processing. In the context of the Commission’s recommendations, residual materials are designated as radioactive waste that needs disposal when these materials cannot be recycled, reused or cleared from further control (ICRP, 2024).
2. The regulatory framework should provide the safe management of residues, including radioactive waste generated by remedial actions, in accordance with the overall national policy and national strategy for protection. Waste management needs to be considered alongside the selection of the protection strategy and underlying remedial actions.
3. Selection of reference levels may strongly influence the amount of waste generated during remediation. Generally, the lower the reference level, the higher the volume of waste generated. Waste generation (and its management) should be considered in the selection of the reference level.
4. The generation of radioactive waste during remediation should be reduced to the extent practicable, especially when no disposal route is available. Options that generate smaller amounts of waste should be favoured where possible, bearing in mind that although management of waste generation is an important factor in the remediation process, the overall objective is to optimise radiation protection as a whole. Therefore, in reaching decisions on waste minimisation, consideration should be given to the knock-on effects such as the availability of infrastructure to safely store waste until it can be disposed of, the implications for waste releases to the environment, the doses to workers during waste reduction activities, and so on. Moreover, waste can also be cleared from further regulatory control if it meets approved clearance criteria. The reuse or recycling of residual materials may also be considered during the development of the remedial action plan. A sustainable approach for the management of residues and waste should be applied when possible implementing reuse, recovery, and recycling of waste residues into other useful products, in an effort to move from a linear to a circular economy. This should be considered when there is a net benefit in enabling residual materials to be safely recycled or reused and when it is done within the context of optimising protection and safety.
5. Waste should be characterised to determine the appropriate transport, processing, storage and disposal methods. Characterisation is important for verification and compliance with national legal and regulatory requirements. The principal characteristics of waste that influence its management are volume, chemical and physical form, and radionuclide content. A variety of management and disposal options may be appropriate, depending on the characteristics of the waste. For example, in areas involving NORM wastes that can have large volumes with low concentrations of radionuclides or small volumes with high concertation of radionuclides, the method of disposal of wastes should be proportionate to the type and level of hazard, taking into account all types of pollutants. Some wastes could be treated as industrial or hazardous wastes and disposed of accordingly in near-surface landfills (ICRP, 2019). Tailings represent a challenge in terms of long-term management because of the large volumes generated and the presence of long- lived radionuclides, heavy metals, and chemical hazards. Relocating tailings to a more favourable site would not normally be the optimum residue management strategy because of the large volumes of waste involved. The decision on which approach to take should be optimised so as to match barrier characteristics with available site conditions (IAEA, 2021). The characterisation challenges and methods are discussed in the light of a range of case studies and other experiences in NEA (2021).
6. When a specific type of residual material cannot be cleared, recycled, or reused, it is designated as radioactive waste. Its management should follow the national policy, strategy, and legal and regulatory framework for radioactive waste management. The Commission recommends that the protection of humans and the environment should be optimised in the management of radioactive waste, with an overall goal of ensuring the well-being of individuals and their quality of life while maintaining a healthy environment. Prudence is required to ensure the decisions taken do not unduly burden current or future generations regarding disposal, also taking into account predisposal and post-disposal operations and management. Balancing the many factors necessary to optimise the radiological protection of the facilities will require prudent decisions to be made, sometimes with incomplete knowledge (e.g. the long-term environmental conditions, possible inadvertent human intrusion scenarios, etc.). Cautious but realistic assumptions should be made for the various categories of uncertainties to avoid underestimation of potential future radiological consequences of disposal facilities. Applying the ethical values of prudence and transparency is important for ensuring confidence in the calculated outcomes.
7. The involvement of stakeholders in decisions related to the management of waste generated through implementing the remedial action plan is considered valuable in gaining acceptance of the remediation project. Local residents may have concerns if residual materials are left on the site or in the area, and measures should be taken by the relevant authority to address such concerns through communication and consultation. In case the generated wastes are transferred to other areas, a dialogue should be established with the stakeholders related to the waste reception area, as part of the consultation.
	1. Implementation of the remediation action plan
8. Once the remediation plan has been decided and approved by the competent regulatory authorities, implementation of the plan will need to be initiated. Activities should be performed in accordance with the requirements established in the remediation plan in line with approved working procedures and by appropriately trained workers.
9. Management of radioactive and non-radioactive waste generated during remediation should be done in compliance with legal and regulatory requirements and should be fully documented in accordance with a robust management system (e.g. see IAEA, 2016).
10. Source, environmental and individual (for remediation workers) monitoring programmes need to be established within and around the contaminated area to ensure compliance with remediation objectives. Monitoring the area can also help to track contaminant migration from the contaminated area where remediation work is conducted to other areas. The monitoring programme should address all potential hazards, risks, and exposure pathways and should be modified, as necessary, throughout the implementation of remediation (e.g. based on characterisation and monitoring results). Monitoring data should be recorded and provided to regulatory authorities to demonstrate remediation work is being conducted in accordance with the approved remediation plan. Monitoring data can also be used for communication and consultation with stakeholders. Moreover, it is recommended to involve relevant stakeholders in the monitoring programmes of the site under remediation to build confidence and trust and to help local residents to implement their own self-help protective actions, if relevant. If, during remediation work, unexpected levels of exposure are detected, appropriate corrective actions should be taken, and the remediation plan and monitoring programme(s) should be updated as appropriate.
11. In cases where remediation cannot be implemented as planned, the remediation plan should be reviewed and updated, including the objectives of protection, if relevant. Final remediation monitoring and characterisation should be undertaken to verify whether the area has been adequately remediated and can be released for unrestricted or restricted use or if further remediation is required.
	1. Post-remediation management
12. The post‑remediation management phase of remediation addresses how the remediated area should be managed once the remediation has been completed and part or all of the site has been released from regulatory control.
13. Actions for post-remediation, such as monitoring, surveillance, and institutional control, if applicable, should be planned in advance and described in the remediation plan. If all or part of the site is released for restricted use, there may be a need for monitoring over a long timescale to ensure the level of exposure remains acceptable. Even without restriction, some level of monitoring and surveillance may be required after the remediation is completed. The extent of monitoring and surveillance should be based on the risks relating to the situation, on the associated degree of uncertainty, and on the need to verify the long-term stability of radiological conditions and other relevant conditions, based on the ethical obligation to consider the health and wellbeing of the population to be protected.
14. The results of the monitoring programmes after completion of remediation should be recorded, maintained, documented and made available. The traceability of the data along all the remediation process related to the contamination area is recommended. Dialogue with stakeholders should be maintained during the post-remediation phase. Preserving the memory of the area and the remedial actions taken contributes to the sustainability of the protection strategy.
15. Post‑remediation management includes the justification and implementation of any post‑remediation controls, and the periodic re‑evaluation of the effectiveness and robustness of the remedial actions taken. If a determination is made during re‑evaluation that the action is less effective than anticipated, additional actions may be necessary, and stakeholders will need to be fully informed and involved. Further actions could be required in the light of relevant available lessons learned from long-term post-remediation management of similar sites or the availability of new technological developments pertinent to the remediated area if justified.
16. The Commission recommends maintaining an appropriate long-term monitoring programme and transmission of the practical radiological protection culture as relevant. The aim is that the next generations also achieve a shared understanding of the process that has been done to remediate the site and its implications. Following the period of active regulatory control, it will be important to have procedures in place that will assure that the site is not forgotten. Keeping an open attitude about the role of future generations as stakeholders is the key to sustaining public trust and confidence.

1. CONCLUSIONS
2. This publication provides guidance for protection of workers, the public, and the environment from exposures resulting from areas contaminated as a result of past activities. These contaminated areas represent existing exposure situations. This publication covers areas contaminated by residual radioactive material arising from past activities that were never subject to regulatory control or that were subject to regulatory control but not in accordance with the current ICRP system of radiological protection.
3. The Commission recommends an integrated and graded approach to optimisation for the management of contaminated areas, considering prevailing circumstances. Such an approach is preferably supported by early and ongoing engagement with stakeholders. It aims to balance the resources applied to the control of both radiological and non-radiological hazards to maximise overall benefit and well-being.
4. Stakeholder engagement is important throughout the remediation process from setting reference levels and end state aims to managing the site after remediation, which could include seeking input on decisions regarding such things as site monitoring, health surveillance, and records management.
5. Even though the contaminated areas addressed in this publication are existing exposure situations, the Commission recommends that remediation workers should, in most circumstances, be considered and managed as occupationally exposed workers. Nevertheless, flexibility in the application of the Commission’s framework, using adequate regulatory and practical tools to effectively achieve the protection of remediation workers, may be required.
6. The protective strategy and remediation plan for any given contaminated area will be driven by the prevailing circumstances. For example, smaller, well-characterised areas with easily removable contaminants will generally require less time and resources to achieve remediation than complex and large contaminated areas with multiple contaminants and elevated levels of radiation. Furthermore, remedial actions can be taken to reduce either the magnitude of the dose to a representative person, the potential for that person receiving the dose, or both.
7. The reference level for public protection should be selected in the lower range of the 1 to 20 mSv per year dose band, with the objective, taking into account the prevailing circumstances, to progressively reduce exposure close to 1 mSv per year as the site situation improves. Optimisation of protection is an iterative process that is applied to both planning and implementing remediation.
8. Radiological protection of the environment, including non-human biota, is part of the ICRP’s system of protection. When humans are present within or near a contaminated area, the steps taken to protect members of the public will often provide an adequate level of protection for non-human biota. Nevertheless, an assessment of potential harm to non-human biota and their habitat should be undertaken as part of the optimisation of protection. This assessment will support decisions on remediation that are commensurate with the level of risks based on application of the Commission’s recommendations on the use of DCRLs, which are meant to protect non-human biota. Consideration should also be given to the preservation of non-human biota habitat, cultural and heritage aspects and other factors, as relevant.
9. Waste management should be considered early in, and as part of, the decision-making process for remediation of contaminated areas. The remediation process should be managed in a sustainable manner, in accordance with national policy, strategy, and legal and regulatory frameworks. The amount and nature of radioactive, hazardous, and other wastes generated during the remediation of a contaminated area, and their corresponding disposal options must be considered when making decisions about reference levels and the remediation strategy as part of an optimised, all hazards, integrated and graded approach.

# REFERENCES

Alexakhin, R.M., 1993. Countermeasures in agricultural production as an effective means of mitigating the radiological consequences of the Chernobyl accident. Sci. Total Environ. 137, 9–20.

BIOPROTA, 2015. Scales for Post-closure Assessment Scenarios (SPACE) – Addressing spatial and temporal scales for people and wildlife in long-term safety assessments. Norwegian Radiation Protection Authority, Oslo.

Brown, J.E., Alfonso, B., Avila, R., et al., 2008. The ERICA tool. J. Environ. Radioact. 99, 1371–1383.

Brown, J.E., Alfonso, B., Avila, R., Beresford, N.A., Copplestone, D., Hosseini, A., 2016. A new version of the ERICA tool to facilitate impact assessments of radioactivity on wild plants and animals. J. Environ. Radioact. 153, 141–148.

Copplestone, D., Hirth, G., Johansen, et al., 2017. Implementation of the integrated approach in different types of exposure scenarios. Ann. ICRP 47(3/4), 304–312.

Copplestone, D., Hirth, G.A., Cresswell, T., Johansen, M.P., 2020. Protection of the environment. Ann. ICRP 49(S1), 46–56.

DSA, 2020. Regulatory framework of decommissioning, legacy sites and wastes from recognition to resolution: building optimization into the process. Report of an international workshop, Tromsø, 29 October–1 November 2019. Norwegian Radiation Protection Authority, Oslo. Available at: https://dsa.no/publikasjoner/dsa-rapport-5-2020-regulatory-framework-of-decommissioning-legacy-sites-and-wastes-from-recognition-to-resolution/DSA-rapport%2005-2020%20Regulatory%20Framework%20komplett.pdf (last accessed 19 February 2024).

Fesenko, S.V., Alexakhin, R.M., Balonov, M.I., et al., 2007. An extended review of twenty years of countermeasures used in agriculture after the Chernobyl accident. Sci. Total Environ. 383, 1–24.

Griffault, L., Aubonnet, E., Brown, J., et al., 2022. Approaches to the definition of potentially exposed groups and potentially exposed populations of biota in the context of solid radioactive waste. J. Radiol. Prot. 42, 020515.

IAEA, 2006. Environmental Consequences of the Chernobyl Accident and their Remediation: Twenty Years of Experience. Radiological Assessment Reports Series No. 8. International Atomic Energy Agency, Vienna.

IAEA, 2009. Classification of Radioactive Waste. IAEA Safety Standards Series No. GSG-1. International Atomic Energy Agency, Vienna.

IAEA, 2012. Guidelines for Remediation Strategies to Reduce the Radiological Consequences of Environmental Contamination. Technical Reports Series No. 475. International Atomic Energy Agency, Vienna.

IAEA, 2016. Leadership and Management for Safety. IAEA Safety Standards Series No. GSR Part 2. International Atomic Energy Agency, Vienna.

IAEA, 2021. Management of Residues Containing Naturally Occurring Radioactive Material from Uranium Production and Other Activities. IAEA Specific Safety Guide No. SSG-60. International Atomic Energy Agency, Vienna.

IAEA, 2022. Remediation Strategy and Process for Areas Affected by Past Activities or Events. IAEA Safety Standards Series GSG-15. International Atomic Energy Agency, Vienna.

IAEA 2023. Determination of environmental remediation end states. Nuclear Energy Series No. NW-G-3.2, IAEA, Vienna

ICRP, 1983. Cost–benefit analysis in the optimisation of radiological protection. ICRP Publication 37. Ann. ICRP 10(2–3).

ICRP, 1990. Optimization and decision making in radiological protection. ICRP Publication 55. Ann. ICRP 20(1).

ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21(1–3).

ICRP, 1999. Protection of the public in situations of prolonged radiation exposure. ICRP Publication 82. Ann. ICRP 29(1–2).

ICRP, 2003. A framework for assessing the impact of ionising radiation on non-human species. ICRP Publication 91. Ann. ICRP 33(3).

ICRP, 2006a. Assessing dose of the representative person for the purpose of radiation protection of the public. ICRP Publication 101a. Ann. ICRP 36(3).

ICRP, 2006b. The optimisation of radiological protection: broadening the process. ICRP Publication 101b. Ann. ICRP 36(3).

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).

ICRP, 2008. Environmental protection – the concept and use of reference animals and plants. ICRP Publication 108. Ann. ICRP 38(4–6).

ICRP, 2014a. Protection of the environment under different exposure situations. ICRP Publication 124. Ann. ICRP 43(1).

ICRP, 2014b. Radiological protection against radon exposure. ICRP Publication 126. Ann. ICRP 43(3).

ICRP, 2016. Radiological protection from cosmic radiation in aviation. ICRP Publication 132. Ann. ICRP 45(1).

ICRP, 2018. Ethical foundations of the system of radiological protection. ICRP Publication 138. Ann. ICRP 47(1).

ICRP, 2019. Radiological protection from naturally occurring radioactive material (NORM) in industrial processes. ICRP Publication 142. Ann. ICRP 48(4).

ICRP, 2020. Radiological protection of people and the environment in the event of a large nuclear accident: update of ICRP Publications 109 and 111. ICRP Publication 146. Ann. ICRP 49(4).

ICRP, 2021. Use of dose quantities in radiological protection. ICRP Publication 147. Ann. ICRP 50(1).

ICRP, 2024. Radiological protection in surface and near-surface disposal of solid radioactive waste. Ann. ICRP, in press.

ISCORS, 2004. RESRAD-BIOTA: A tool for implementing a Graded Approach to Biota Dose Evaluation. ISCORS Technical Report 2004-02. Interagency Steering Committee on Radiation Standards, Washington, D.C.

Jacob, P., Fesenko, S., Firsakova, S.K., et al., 2001. Remediation strategies for rural territories contaminated by the Chernobyl accident. J. Environ. Radioact. 56, 51–76.

Lindborg, T., Ikonen, A., Kautsky, U., Smith, G., 2021. System understanding as a scientific foundation in radioactive waste disposal, legacy site and decommissioning programmes. J. Radiol. Prot. 41, S9–S23.

Martinez, N.E., Canoba, A., Donaher, S.E., et al., 2023. An Introduction to Ecosystem Services for Radiological Protection. Ann. ICRP52(1–2) Annex, 246–254.

Mokrov, Y., Sneve, M., 2014. Natural and Anthropogenic Treatment of Surface Water Bodies Contaminated by Radioactive Substances due to Releases from FSUE Mayak PA. International Workshop on Radioecology and Assessment Research in Support of Regulatory Supervision of Protection of the Environment and Human Health at Legacy Sites, 7–12 September 2014, Barcelona, Spain.

NEA, 2016. Strategic Considerations for the Sustainable Remediation of Nuclear Installations. NEA No. 7290. Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, Paris.

NEA, 2019. Challenges in Nuclear and Radiological Site Management: Towards a Common Regulatory Framework. NEA No.7419. Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, Paris.

NEA, 2021. Characterisation Methodology for Unconventional and Legacy Waste. NEA/RWM/R(2020)2. Nuclear Energy Agency, Organisation for Economic Co-Operation and Development, Paris.

SERA, 2017. Standards Reference Group National Standards for the Practice of Ecological Restoration in Australia. Second Edition. Society for Ecological Restoration Australasia. Available at: http://[www.seraustralasia.com](http://www.seraustralasia.com) (last accessed 19 February 2024).

Shishkina, E.A., Pryakhin, E.A., Sharagin, P.A., et al., 2019. The radiation exposure of fish in the period of the Techa river peak contamination. J. Environ. Radioact. 201, 43–55.

Shishkina, E.A., Pryakhin, I.Y., Popova, D.I., 2016. Evaluation of distribution coefficients and concentration ratios of 90Sr and 137Cs in the Techa river and the Miass river. J. Environ. Radioact. 158–159, 148–163.

United Nations, 1992. Rio Declaration on Environmental and Development. United Nations General Assembly A/CONF.151/26 (Vol. I). United Nations, New York. Available at: https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A\_CONF.151\_26\_Vol.I\_Declaration.pdf (last accessed 19 February 2024).

United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. United Nations General Assembly A/RES/70/1. United Nations, New York.

Voigt, G., Fesenko, S. (Eds.), 2009. Remediation of Contaminated Environments. Radioactivity in the Environment Series No. 14. Elsevier, Amsterdam.

WHO, 2021. Health Promotion Glossary of Terms 2021. World Health Organization, Geneva.

Yankovich, T.L., Roberts, M., Brown, J., et al., 2022. Practical application of international recommendations and safety standards in the systematic planning and implementation of remediation of sites or areas with residual radioactive material. J. Radiol. Prot. 42, 020513.

Zoetica, 2021. Biodiversity Impact Studies – Northwestern Ontario Region: Baseline Program Design. Zoetica Environmental Consulting Services, Vancouver.

1. CASE STUDIES
	* + 1. The following five case studies have been selected to represent the variety in size, complexity, radionuclides present, and remediation challenges that may be encountered. There are many other types of contaminated areas that could have been included, such as uranium mill tailing sites, nuclear weapons accident sites, and sites contaminated by unregulated industrial discharges of radioactivity. However, the following examples represent an acceptable cross section of the broad category of contaminated areas that can now be appropriately managed as existing exposure situations.
			2. It should be noted that these case studies reflect site management and cleanup decisions that, for the most part, were made before the changes to the system of radiological protection that were introduced in *Publication 103*. As a result, some of the terminology in the following descriptions is not consistent with the current system. Although not all of the elements of the current system of protection (e.g. stakeholder involvement, biota protection, application of reference levels, etc.) are present in each of the case studies, the basic principles of justification and optimisation are often applied in a manner that is broadly consistent with current ICRP Recommendations (ICRP, 2007).
	1. Stakeholder involvement in establishing radionuclide soil action levels at the Rocky Flats Plant
		1. **Background**
			1. The Rocky Flats Plant (RFP) was a U.S. Department of Energy (DOE) facility located northwest of Denver, Colorado, USA. The primary mission of the facility was the manufacture of nuclear weapons components from materials primarily plutonium, but also uranium and beryllium (Till et al., 2002). Construction of the RFP began in 1952, and its first nuclear weapons components were shipped offsite in 1953. Operations involving nuclear materials were conducted at the site from 1953 to 1989. During plant operations, materials were released through routine operations or during accidents, primarily to air, but surface water releases also occurred. Accidental releases included two fires in the plutonium finishing buildings in 1957 and 1969 and the release of plutonium contaminated soil in a drum storage area, particularly during grading operations on windy days in 1969.
			2. Estimated releases from routine operations were 4.4 GBq through stacks and vents (Voillequé, 1999a). A glove-box fire occurred in Building 771 in September 1957, resulting in the failure of the high efficiency particulate air filter (HEPA) filtration system and an estimated median release of 780 GBq of plutonium to the air through a 44-metre stack (Voillequé, 1999b). A second glove box fire occurred in Building 776 in May of 1969, resulting in the release of plutonium from roof vents over a 5-day period. The total median release from this incident was 1.4 GBq (Voillequé 1999c).
			3. The drum storage area, referred to as the 903 Pad, contained 4500 55-gallon drums containing plutonium-contaminated cutting oil and degreasing agents (Weber et al., 1998). Site personnel reported barrel corrosion and subsequent leakage onto the soil as early as 1962. By 1964, this had become a major issue, and fences were constructed to limit the spread of contamination by intruding wildlife. In 1967, the barrels were removed from the 903 Area, repackaged, and shipped offsite. However, by late 1968, there was evidence that wind action had transported plutonium-contaminated soil beyond the 903 Area. In 1969, the area was paved with asphalt to prevent further transport of plutonium-contaminated soil away from the area. Various estimates of the plutonium activity released to the soil from the leaking barrels ranged from 230 GBq to 2200 GBq. The wind-blown suspension of contaminated soil was estimated to have released 110 GBq (median value) of plutonium to the surrounding environment east of the facility. Most of the releases occurred on six days in 1968 and 1969 during high wind events, resulting in a plume of plutonium deposition in soil east of the 903 Pad and beyond the facility boundary. This plume of plutonium deposition from the 903 Pad was a primary issue for site remediation.
			4. A dose reconstruction of the site was completed in 1999, which concluded that plutonium releases into the air was the primary radionuclide and pathway of concern for public offsite radiation exposure (Rood et al., 2002).
		2. **Exposure pathways of concern**
			1. Residual contamination of 239Pu from industrial activities and from the 903 Area east of the site remained a challenging aspect of site remediation and release of the land to the public. Inhalation of suspended dust containing 239Pu is the primary exposure pathway. Offsite 239Pu concentrations east of the 2 km buffer zone were generally less than 18 Bq kg−1 and decreased rapidly with distance east of the site. Within the buffer zone concentrations were as high as 185 Bq kg−1, and, near the 903 Pad and in the industrial area, concentrations exceeded 30,000 Bq kg−1. Soil contamination above the average fallout levels in soil (2.2 Bq kg−1) extended as far as 5 km east of the 903 Pad (Rood and Grogan, 1999).
		3. **History of remedial actions**
			1. In 1996, the DOE, the Environmental Protection Agency (EPA), and the Colorado Department of Public Health and Environment (CDPHE) proposed interim radionuclide soil action levels to be used in the cleanup of the Rocky Flats site (DOE/EPA/CDPHE, 1996). The interim level for 239Pu was 9320 Bq kg−1 based on an annual dose of 0.15 mSv and 52,870 Bq kg−1 based on an annual dose of 0.85 mSv for a residential exposure scenario.
			2. As a result of public concern about the relatively high soil action levels established in October 1996 compared to cleanup levels at other sites, the Radionuclide Soil Action Level Oversight Panel (RSALOP) was formed (Till et al., 2000). The RSALOP was a group of community members with considerable experience in Rocky Flats issues. In 1998, DOE provided funds for the RSALOP to select a contractor to conduct an independent assessment and to calculate radionuclide soil actions levels (RSALs) for the RFP. The contractor was to reevaluate soil action levels based on annual dose constraints of 0.15 mSv for unrestricted use and 0.85 mSv for restricted use. Calculations were to incorporate site-specific data and use documented and reviewed computer codes. An evaluation of uncertainty was also to be included.

*A.1.4.1. Stakeholder involvement*

* + - 1. Stakeholder involvement was particularly relevant in this study because of the perceived impact the cleanup levels would have on the local communities surrounding the site. Stakeholders included the public officials, DOE personnel, and the general public. Stakeholders were kept informed of the progress and technical review of the work during the entire project through three public meetings, a technical workshop, and monthly meetings with the panel, which were also open to the public. Five peer reviewers from around the country, contracted by the RSALOP, reviewed and provided written comments on each of the five technical reports. Written comments from panel members, DOE personnel, and members of the public were also formally addressed. This process helped identify areas of concern that were not already considered and allowed those concerns to be addressed within the context of the work. The final reports reflected changes made in response to comments received from reviewers. The process of public interaction and review took place throughout the entire project and provided a valuable means for identifying issues that were critical for the public and other stakeholders.

*A.1.4.2. Estimating soil action levels*

* + - 1. Determination of RSALs employed an adaptation of the RESRAD computer program with site-specific parameters and parametric uncertainty analysis. Inhalation of suspended contaminated soil was shown to be the dominant exposure pathway, and rather than relying on default model parameters to determine the suspension rate, a site-specific value was derived from routine air sampling data within and surrounding the RFP site. Furthermore, consideration of a wildfire across the site and its impact on suspension rates was also considered. The wildfire scenario greatly impacted the doses and the model considered the probability of fire based on fire reoccurrence rates in the region. A parametric uncertainty analysis using Monte Carlo sampling was also performed, so results were presented as a probability distribution of exceeding the annual dose constraint of 0.15 mSv and 0.85 mSv for unrestricted and restricted use, respectively. Parameters considered stochastically were limited to physical transport mechanisms and soil concentrations. Exposure parameters were fixed at a deterministic value selected from the upper percentiles (i.e. 95%) from published distributions.
			2. Exposure scenarios were established through an iterative process with the RSALOP and members of the public. Six scenarios were initially considered, but final recommendations were based on an onside resident rancher family, including an adult, child, and infant, and an annual 0.15 mSv dose constraint. This scenario, along with exposure parameters (i.e. breathing rate, ingestion rates, and exposure time), were mutually agreed upon by the stakeholders. Additionally, stakeholders were asked to choose a probability level at which dose constraints would be exceeded (i.e. the confidence that the modelled doses would not exceed the dose constraint). When the modelling process and exposure parameter definitions were explained to them, they chose a 90% probability that the dose constraints would not be exceeded.
			3. Transparency was maintained throughout the project. Through the monthly meetings, stakeholders were presented with the progress of the technical aspects of the work and provided an opportunity for input. Results were presented for all the exposure scenarios, but the focus was directed toward the rancher scenario, which was shown to be the most limiting. The recommended 239Pu soil action level was 1295 Bq kg−1 for a 10% probability of exceedance of the 0.15 mSv annual dose constraint (RAC, 2000). The actual level agreed upon of 1800 Bq kg−1 was arrived at through negotiations among EPA, DOE, and other stakeholders. This level reflected the designation of the site as a wildlife refuge, reflecting consideration of minimising soil disturbance during remediation, cost, and technical feasibility.
		1. **Selected remedy**
			1. The RFP was remediated by the EPA under the Superfund program. The site was separated into two operable units (OU): 1) the 5.29 km2 Central OU that includes the industrial area; and 2) the 19.7 km2 Peripheral OU that includes the buffer area. Land within the industrial area was the most heavily contaminated and was cleaned up to the RSALs developed during the RSALOP program (239Pu soil concentration of 1800 Bq kg−1). Contamination in the buffer zone and offsite properties were below the RSALs and did not require further remediation. In 2006, the EPA determined no further cleanup was necessary. The site property has since become a wildlife refuge.
		2. **Summary**
			1. The success of the development of the RSALS was attributed to beginning the study with public involvement in mind.  The RSALOP was brought along with every phase of the technical work including model selection, scenario definition, assumptions, and parameter values. The public and stakeholders were able to understand technical aspects of the work (e.g. probability distributions) taking account of the time taken to explain and educate through monthly meetings and workshops. This process established acceptance and ownership of the RSALs developed during the program by the RSALOP and the stakeholders.
	1. Rehabilitation of the former nuclear test site at Maralinga
		1. **Background**
			1. During the 1950s, the British conducted 12 nuclear weapons tests in Australia (Symonds, 1985). These included three at the Monte Bello Islands in Western Australia (WA), two at Emu Field in South Australia (SA), and seven at Maralinga in SA. In addition to the major tests at Maralinga, approximately 600 ‘minor trials’, in several series, were carried out between 1953 and 1963. These so-called ‘minor trials’ were to investigate the explosive compression of fissile material and, later, the safety implications of fire or accidental detonation of nuclear weapons. These trials involved tens of kilograms of plutonium and several tons of uranium in chemical explosions.
		2. **Exposure pathways of concern**
			1. Various scientific surveys and assessments were conducted at these nuclear weapons test sites during the 1970s and 1980s (AIRAC, 1979, 1983). Detailed studies of the Maralinga site, carried out during the 1980s, indicated that earlier judgments and decisions about Maralinga and the need for remediation had been based on limited and deficient information (Johnson et al., 1985).
			2. Prior to the 1980s, the exposure pathway considered was external exposure due to the fallout and activation products remaining at each of the test ground-zeros. By the 1980s, the external dose rates had fallen to near-background rates, except for areas within a hundred meters of the ground-zeros, due to radioactive decay.
			3. However, the studies in the 1980s found that several tens of square kilometres were contaminated with plutonium from the ‘minor trials’ (EG&G, 1991). This contamination remained in the top few millimetres of the soil and comprised microscopic particles, presenting a potential hazard due to inhalation of dust.
			4. The studies also found that the areas immediately around where these trails had been conducted contained visible fragments and sub-millimetre particles contaminated with GBq-levels of plutonium. Due to their high levels of activity, these fragments and particles presented potential ingestion and injection hazards.
			5. While the British had buried highly contaminated material at Maralinga, the burial pits were only a few meters deep and posed a significant radiological hazard as it remained in the biologically active part of the environment.
		3. **History of remedial action**
			1. The contaminated land at Maralinga belonged to indigenous Aborigines who wished to resume ownership and use of the land. Having accepted assurances from the British government, Australia had no knowledge of the remaining problem until particles and fragments highly contaminated with uranium and plutonium/americium were discovered on and close to the surface, in large numbers over a wide area during a scientific site survey in May 1984 (Lokan, 1985).
			2. The findings from subsequent investigations were significant as it propelled the Australian Government to establish the McClelland Royal Commission into British Nuclear Tests in Australia (McClelland, 1985). The Royal Commission recommended that the Australian Government establish a Technical Assessment Group (TAG) (TAG, 1990) to advise on remediation options. The Royal Commission and subsequent political negotiations also lead to the British government providing 20 million GBP as their contribution to the estimated cost of 104 million USD, at November 1994 prices, for the rehabilitation project.
			3. At the outset, a consultative group (MARTAC 2002) was formed, made up of representatives of the Commonwealth, SA, WA and UK Governments and members of the Maralinga Tjarutja, traditional owners of land, and their legal representatives. The role of the group, which met regularly, was to serve as a forum to discuss all matters concerning test site rehabilitation. In addition, the Maralinga Indigenous people had a close involvement with the scientists from the TAG, especially through the anthropological and inhalation studies, which required their close cooperation. The role of the consultative group continued throughout the remediation program.
			4. The TAG studies included an anthropological study of the diet and lifestyle of the Maralinga Tjarutja Aboriginal community, the distribution, surface concentration and resuspension properties of the plutonium contamination, and animal studies to assess the bioavailability of the plutonium following inhalation or ingestion and its translocation from wounds. These studies provided information against which better based remediation decisions could be made.
		4. **Selected remedy (from ‘Rehabilitation of Former Nuclear Test Sites at Emu and Maralinga (Australia)’ report)**
			1. Of particular concern to the consultative group was striking a balance between restrictions on land use and soil removal, which could have a significant devastating environmental and cultural impact. To guide rehabilitation discussions, TAG (TAG, 1990) proposed that the risk of fatal cancer from a uniform chronic exposure should not exceed 1 in 10,000 by the fiftieth year. This risk value corresponded to continuous exposure to 5 mSv per year from birth. The agreed solution, arrived at in consultation with the traditional owners, minimised the soil stripping required for contamination removal. This outcome resulted in a greater area of land with some restricted use, and compensation was made to recognise the impact.
			2. An outer boundary was established for the site with permanent warning signs. This boundary enclosed all areas where annual doses for permanent occupancy would exceed the value of 5 mSv. Land use restrictions, which would limit activities to ‘casual use’, such as transit and hunting with a much lower occupancy, would apply within this boundary. Within the area of restricted use, remediation – principally through the removal and disposal of heavily contaminated soil – would be undertaken. This was to ensure, for the restricted activities envisaged, the same dose and risk limits would apply.
			3. Before the remediation of Maralinga, certain areas were found to have inhalation dose rates that were too high to be acceptable under all but the most rigorously controlled circumstances. These areas also included the highly contaminated fragments and particles and the highly contaminated objects buried in shallow pits. These areas were remediated by removal and burial at depth of contaminated surface soil and the exhumation and re-burial at depth of the contaminated objects.
			4. Some areas at the test sites at Maralinga were also contaminated with beryllium, which posed a non-radiological inhalation hazard. However, this contamination was confined to the same areas from which soil was removed. Therefore, this non-radiological contaminated was treated in the same process that treated the radiological contamination.
			5. Following the remediation all areas at Maralinga have been shown by recent dose assessments (O’Brien et al., 2011) to be well within acceptable limits for all envisaged land uses. In fact, the remediation achieved considerably better dose outcomes than were originally planned.
			6. This meant the restriction on permanent occupancy within the ‘restricted land-use’ (non-residential) boundary could be seen as a purely precautionary measure. This is because doses due to inhalation for permanent occupancy of all but a few small areas are well below the annual 1 mSv limit for members of the public.
			7. The argument for maintaining restrictions on land use at Maralinga should perhaps be seen as restricting access to the sites of the burial trenches, and thus discouraging intrusion. The restricted access also reduces the highly unpredictable (stochastic) and essentially non-assessable hazard from possible contact with any undiscovered active particles remaining in the plumes adjacent to the soil-removal areas. Accepting that land use restrictions will have to be retained essentially forever, a clear record of the history and status of the site must be preserved in libraries, archives, land titles and similar repositories. The permanent marking of burial trenches is important, together with the establishing of an open-ended periodic inspection and maintenance program for the restricted area.
			8. The traditional owners have now returned to the site and play a stewardship role. There has been a need for their culture to adapt to and include a continuing awareness of the land use restrictions and the reasons for maintaining those restrictions.
		5. **Summary**
			1. Large areas of the Australian outback were contaminated due to the explosive dispersion of plutonium in experiments carried out in conjunction with nuclear testing at Maralinga (Symonds, 1985). This contamination presented a significant inhalation risk to potential occupants.
			2. The Australian government committed to reduce the radiological hazard to enable Aboriginal traditional land use and transit of the test site area, reduce and possibly eliminate the need for control and surveillance of the sites and remove potential liabilities arising from contamination (McClelland, 1985).
			3. A consultative group was formed, made up of representatives of the Commonwealth, SA, WA and UK Governments and members of the Maralinga Tjarutja, traditional owners of land, and their legal representatives to serve as a forum to discuss all matters concerning test site rehabilitation (MARTAC, 2002). The Maralinga Tjarutja people also had a close involvement with the scientists from the TAG (TAG, 1990), especially through the anthropological and inhalation studies, which required their close cooperation.
			4. Of particular concern to the consultative group was striking a balance between restrictions on land use and soil removal, which could have a significant devastating environmental and cultural impact. The solution arrived at through this consultation minimised the soil stripping required for contamination removal and restricting occupancy on a section of the site. This translated to a reference level of 5 mSv per year from birth (corresponding to the risk of fatal cancer from a uniform chronic exposure not exceeding 1 in 10,000 by the fiftieth year) (MARTAC, 2002).
			5. The remediation project – principally through the removal and burial at depth of heavily contaminated soil and objects – began detailed planning in 1994, cost approximately 100 million AUD and was completed in 2000 (MARTAC, 2002).
			6. A recent dose assessment (O’Brian, 2011) has shown the entire area to be well within acceptable limits for all envisaged land uses. In fact, the remediation achieved considerably better dose outcomes than were originally planned. The traditional owners have now returned to the site and play a stewardship role.
	2. Remediation of radium legacies from the Swiss watch industry
		1. **Background**
			1. In June 2014, radium-contaminated waste was discovered during work carried out at a former landfill site. Following this discovery, it was reported that nearly 90 buildings, mostly localised in the Jura region of Switzerland, had been potentially contaminated with radium (Murith et al, 2016). Radium was originally used in the watchmaking industry during the 1920–1960 period for its luminescent properties before its use was abandoned for other materials. At that time, employees were working in workshops or at home, and a number of places were contaminated.
			2. The Federal Office of Public Health (FOPH), which is the radiological protection competent authority in Switzerland, proposed a plan for the management of the radium legacy in order to address the growing concerns of the population, which was approved by the Swiss government. The main objective of the plan is to ensure that no individual receives an effective dose higher than 1 mSv year−1 because of residual radium. The plan also considered the protection of the environment and the remediation workers. It consists of 4 axes:
* identification of sites where radium was used and which are therefore potentially contaminated (historical research);
* monitoring/survey of radium at the identified sites (building, surrounding garden, etc.) and, if required, dose calculation;
* implementation of a remediation plan if this is justified; and
* monitoring of former landfills that are potentially contaminated with radium waste.
	+ 1. **Selected remedy**
			1. All along the plan, stakeholder involvement is considered an important aspect of the process. Engagement and collaboration with residents (owners or renters) is required to achieve a successful remediation.
			2. The search for radium-contaminated sites involves the use of various sources of information such as archives, contacts with the watch industry and radium suppliers or other individuals. Historical research indicates that approximately 1000 sites are of concern. A dedicated databank was developed by the FOPH to record all relevant data.
			3. The screening first addressed sites that were identified by the press or reported by residents and then progressively sites identified within the historical research. The following scheme was developed to address this phase.
* Contact with the residents of the site (tenants and owners) to define the conditions for the screening (when, how long and consequences for the resident).
* Screening according to the FOPH procedure.
* Information on the results to the resident and proposal of immediate arrangements in case of significant contamination.
* If the screening value is exceeded, then additional measurements may be achieved.
* FOPH officially inform the concerned individuals and local authorities.
	+ - 1. According to ICRP *Publication 103*, FOPH needed to justify its protection strategy and to optimise radiological protection, which required defining a reference level in the 1–20 mSv year−1 dose band. When considering this choice, the Radiation Protection Ordinance (RPO) was under the revision procedure in order to transpose into the national regulation the new recommendations and international standards, namely the ICRP 2007 Recommendation (ICRP, 2007) as well as the IAEA and Euratom basic safety standards. At that time, the only regulatory value for public protection was the annual dose limit of 1 mSv year−1 for practices, as existing exposure situations were not considered in the regulations. FOPH thus decided to choose 1 mSv year−1 as a reference level for the management of radium legacies.
			2. The method for screening potentially contaminated apartments consists of measurements of the ambient dose rate at 0.1 and 1 m high on a 1m × 1m grid. When dose rate measurements are all lower than 0.1 μSv h−1 above the background, no further action is required. If one or more measurements exceed 0.1 μSv h−1, then additional measurements are performed (0.2m × 0.5m grid) and the contamination is measured with smears to evaluate the labile contamination. Based on these results, a dose assessment is performed to evaluate the maximum dose that may be received in each room. If estimated doses exceed 1 mSv year−1, remediation is justified and a remediation plan is prepared (often based on a more detailed characterisation). Remediation costs are supported by FOPH as long as the polluter cannot be identified. If the presence of radium is confirmed but estimated doses are lower than 1 mSv year−1, remediation is not justified. If owners desire to remediate the apartment for an effective dose lower than 1 mSv year−1, then they must support the costs.
			3. The company in charge of remediation submits a plan to FOPH who approves it. Radiation protection of remediation workers and the environment must be detailed and workers are considered and managed as occupationally exposed workers. The company must be authorised to perform the job, and the activity is monitored by competent authorities. Remediation waste is managed according to the regulation. In most cases, the remediation plan is specific for each site (removal of contaminated objects, removal of floor covering, blasting of surface painting, etc.).
			4. The amount of waste must be kept to a minimum. At the end of the remediation work, a final survey is performed by FOPH. Waste with a level of radioactivity below the release limit is treated as conventional waste. A provision of the RPO allows that slightly radium contaminated combustible wastes are incinerated up to a weekly activity of 2 MBq. Wastes with a higher activity are considered and managed as radioactive waste.
			5. Effective doses are estimated for any current or future occupant based on measurement results and exposure scenarios. The average cost of an indoor remediation is around 50,000 USD.
			6. For outdoor areas (mainly gardens), the ambient dose rate is measured at 1 m and 0.1 m high on a 1m × 1m grid. If the dose rate is above 0.1 μSv h−1, then soil samples are analysed by gamma spectroscopy measurements. No action is required if the activity of radium is lower than 1000 Bq kg−1. When the ground is contaminated, a characterisation is required in order to define the remediation perimeter. According to the RPO, landfill of slightly contaminated inert waste is allowed under certain conditions if the specific activity does not exceed 10,000 Bq kg−1. The average remediation cost for contaminated gardens amounts to 25, 000 USD.
		1. **Summary**
			1. As of 31 December 2018, about 20% of the 540 sites that were screened needed remediation, either indoor or outdoor.
			2. In a few cases, FOPH faced mixed pollution issues with radium-contaminated sites in areas registered as (chemically) polluted sites. These cases require coordination between FOPH and the Federal Office of the Environment in order to adequately address the issues and coordinate remedial actions.
			3. According to FOPH, the success of the radium action plan relies on good collaboration between occupants, apartment owners, FOPH, remediation companies, etc. Efforts from the various administrations are made to communicate effectively with owners and tenants to engage them in the process and to answer their questions and concerns (radiation risk, potential loss of value of properties, etc.). Results from the implementation of the Radium Action Plan are public and available. An annual meeting is organised with the stakeholders to present and discuss the progress that has been made.
			4. Whereas the Radium Action Plan was agreed upon by the Federal Government and financed for four years (2015–2019), the historical survey showed that approximately 1000 buildings could be potentially contaminated, whereas 500 to 600 were expected. On 10 April 2019, the Federal Government agreed to a 3 years’ extension of the plan (until 2022).
			5. When a residual material cannot be cleared, recycled or reused, it is designated as radioactive waste. Its management should follow the national policy framework for radioactive waste management.
			6. The involvement of stakeholders in decisions on the management of residues is essential in gaining acceptance of the remediation project.
	1. Techa River
		1. **Background**
			1. The Production Association ‘Mayak’, the first Soviet nuclear weapon enterprise constructed for the production of plutonium, located in the Chelyabinsk Region of the Urals in the Union of Soviet Socialist Republics (USSR, currently the Russian Federation), was put in operation in June 1948. A processing complex of Mayak included graphite-moderated uranium reactors to produce plutonium, radiochemical production for its isolation, chemical-metallurgical production of plutonium items. In the early 1950s, there were authorised as well as accidental releases of liquid radioactive wastes to the Techa River from Mayak. These releases caused high contamination of the riverbed and flood plains of the Techa River with a mixture of fission products, including the long-lived radionuclides 90Sr and 137Cs. In total, from 1949 until 1956, about 76 million cubic meters of radioactive material released to the environment discharge waste, with a total activity of about 115 PBq, were released to the river waters. About 95% of the radioactivity was released to the river from October 1950 until November 1951. The main contribution to the total activity of the releases was provided by the following radionuclides: 89Sr, 90Sr, 137Cs, 95Zr-95Nb, 103Ru, 106Ru, and isotopes of rare-earth elements (Akleyev et al., 2000; Shoigu, 2002; Alexakhin et al., 2004; Akleyev, 2016; Degteva et al., 2016). Releases into the Techa River resulted in its contamination through entire length (area of about 240 km), as well as contamination of part of the Iset River where the Techa River inflows.
			2. A large amount of radionuclides was deposited in the river bottom, and later on it became a source of secondary contamination of river water. Spring floods, particularly those of 1951, were the main factor causing a massive radioactive contamination of the Techa River flood plains and banks. The heaviest radioactive contamination of the river water, flood plain, area outside the flood plain, as well as of agricultural products occurred in the upper reaches of the Techa, including the Metlinsky pond. In 1951 contamination of soil in village Metlino, the first village on the river (7 km downstream from the release site), reached 100 kBq kg−1, plant and animal products – 1–1000 kBq kg−1. The exposure rate on the banks of the Techa river and pond in Metlino was 1.5–2.0 mGy h−1 on average. Until the end of 1952, 95Zr and 95Nb provided a significant contribution to the external exposure, after which the external exposure was determined by long-lived 137Cs. In 1953–1956 in some settlements the exposure rate measurements on the streets and backyards at different distances from the water's edge were carried out. According to those results the exposure rate greatly decreased with distance from the water's edge, especially during the first 100 meters by about two orders of magnitude. This clearly shows that the distribution of the exposure rate on the banks of the Techa River and in the territory of settlements was extremely uneven. Downstream the village of Muslyumovo (78 km from the release site), the radioactive contamination of the flood plain is also highly inhomogeneous. The density of 90Sr contamination in the flood plain ranges from 30 to 6100 kBq m−2, 137Cs – 30–5600 kBq m−2.
		2. **Exposure pathways of concern**
			1. High specific activity of radionuclides in the river water, used generally as drinking water, and local products including fish caused rather intensive internal exposure of the population. Another essential exposure pathway for those inhabitants was external irradiation from contamination of the area, mainly the flood plain (especially near the river mouth). Overall, external exposure of the population was rather high along the entire river length. Living under external and internal irradiation required the applications of measures on radiation protection of the inhabitants.
		3. **History of remedial actions**

*A.4.3.1. Driving factors for remediation*

* + - 1. Studies of radiation conditions in the Techa River basin began in July 1951. At the same time the first medical dosimetric examinations of the population of Metlino neighboring to the place of release were conducted. In the next years, these examinations were repeated and extended to the other villages. In 1953, it became clear, that the state of health of the population is worsened, the chronic radiation sickness was detected in the part of the inhabitants. Accounting for the results of medical dosimetric examinations, the authority recommended to relocate the Techa River inhabitants living near to the place of release. Thus, in the absence of clear radiological-safety criteria during that time for the resettling justification, the medical recommendations were naturally utilised. Thus, the medical recommendations were the driving factor for initiating further remedial actions.

*A.4.3.2. Non-radiological factors*

* + - 1. Non-radiological factors were not taken into account.

*A.4.3.3. Stakeholder involvement*

* + - 1. It is important to stress that the residents living in the territories affected by radioactive exposure resulted from releases to the Techa River were neither notified about radiation conditions nor involved in the process of discussing possible counter measures to be applied. The process of elaborating of making decision regarding selection of types and forms of countermeasures was done in the 1950s without involvement of stakeholders. As well information on radiological conditions and doses to the residents was not reported by mass media until the end of the 1980s. The serious concerns of the population were not also observed until these years. In early 1990s, the recovery of the Chernobyl nuclear power plant accident has evolved the interest to the effects of the Urals region contamination. The Law was adopted to give effect of ‘Chernobyl’ Law for the Urals population. The Russian State Program was elaborated and implemented to provide justified radiation rehabilitation in Urals region up to 1995 and later on. Basic goals of those programs include:
* localisation of radioactive waste and prevention of radioactive contamination due to Mayak operation;
* ecological rehabilitation of contaminated lands;
* development of monitoring system for ecological radiation situation;
* improvement of the public medical assistance; and
* development of social and industrial infrastructure.

*A.4.3.4. Protection of environment*

* + - 1. The initial (1950–1952) radioactive contamination of local fish species in the Techa River reached 1–10 MBq kg−1 of total beta-activity near Metlino and declined to 10 kBq kg−1 towards the Techa River mouth (Lemberg et al., 1951; Alexakhin et al., 2004). The radionuclide activity concentrations as well as exposure doses to biological objects noticeably decreased with distance from the release site. The short-lived 103,106Ru, 95Zr, 95Nb and 89Sr were the main contributors to the river ecosystem exposure until October 1951 (Shishkina et al., 2019). Dose rates in fish were formed mainly due to internal exposure. Radioactive contamination of local fish reached and could reach 200 mGy day−1 and 40 mGy day−1 upstream and downstream, respectively. In subsequent years up to 1952, 144Ce (T1/2 = 285 days), 90Sr and 137Cs (T1/2 are about 30 years for the last two radionuclides) became the main dose-forming radionuclides. Dose rates in fish could reach 170 mGy day−1 and 30 mGy day−1 upstream and downstream, respectively. Contribution of external exposure was comparable to the internal one for the bottom fish of the upper reaches, where significant fraction of 144Ce and 137Cs was deposited. The presence of long-lived 90Sr and 137Cs in river and near-river ecosystems had caused a long-term existence of contaminated ecosystems and long-term exposure of biological objects. The current dose rates for fish inhabiting the Techa River (3×10−6–0.15 mGy day−1, depend on the distance along the stream) (Shishkina et al., 2016). Radiation doses to other aquatic organisms, such as molluscs and macrophytes exceeded the fish doses by a factor of 2 and 3, respectively. Radiation exposure effects on ichthyofauna in terms of growth rate was described in two studies performed in summer 1950 and 1952 (Lemberg et al., 1951; Marey et al., 1952). The first study shows the tendency to an increase in fish growth rate. The second study shows no radiation induced changes for most of fish species despite of the fact that the dose rates in the upper reaches of the river were about 70 mGy day−1 (Shishkina et al., 2019). Only the bottom-dwelling fish (such as gudgeon) demonstrated a slight slowdown in growth rate (Marey et al., 1952) with an increase in the radionuclide activity concentrations in water and sediments. Unfortunately, there is no other information about radiation exposure effects on non-human biota in the Techa River during the early 1950s. It is likely that radiobiological effects did take place in that period but they were not investigated. But nonetheless, studies on the Techa River system in 2008–2015 (after 2 half-life periods of 90Sr and 137Cs) discovered the radiation-induced increase in the frequency of erythrocytes with micronuclei and increase in DNA breaks using the comet-assay for bottom-dwelling roach (Pryakhin et al., 2012; Styazhkina et al., 2012, 2015). They have also demonstrated that chronic exposure at a dose rate of 0.11 mGy day−1 reduces the adaptive capacity of fish, i.e. stress led to ineffective erythropoiesis (Tryapitsina et al., 2017). In 1950–1951, the absorbed doses to aquatic organisms in the Techa River were on average 100–300 times higher than those to humans (Alexakhin et al., 2004). However, protection of non-human biota did not play any role in remediation process.
		1. **Selected remedy**
			1. The basic practical measures applied since 1951 to minimise the Techa River discharge effects of releases from the Techa River on exposure to the public were developed in two directions:
* improvements of technology to decrease releases into the environment; and
* interventions in the resident activities to decrease or prevent further exposure to the population.
	+ - 1. By the end of 1951, the termination of releases of high-level wastes into the river allowed for considerable reduction of the specific activity of the river water. To separate the most heavily contaminated lands from the rest of the territory, dams No. 10, constructed in 1956, and No. 11, constructed in 1964, cut off the swampy upper reaches. In addition, by-pass canals were built. The hydro engineering measures allowed for significant reduction of the entry of activity into the Techa River, but did not completely eliminate it.
			2. To minimise the exposure of local residents to the contaminated river, a number of complex measures were taken, including resettlement of the population, establishment of a sanitary zone for residents who continued to live in the riverside villages, digging of wells, and the construction of water-supply facilities. Evacuations of residents from the most highly contaminated villages were conducted in 1954–1960. About 7500 people, i.e. 30% of the total riverside population, were moved from the Techa River banks. However, the delay in the implementation of this measure made it rather ineffective since the residents had already received major doses from both internal and external exposure by the time of evacuations.
			3. However, all applied countermeasures were realised too late to prevent public exposure from the initial intensive release. The 1950–1951 radioactive releases have practically resulted in the whole activity accumulated in the river system, though it was significantly decreased to the present time due to the radionuclide decay and natural decontamination, as well as they provided more than 90% exposure doses to local inhabitants within the whole period and including resettled residents. During two years of the Mayak operation, the radioactive releases have caused all the consequent problems.
			4. It is important to stress that the long-term suppression of official information on the radioactive contamination of the river also contributed to violations of the health-protection regulations by the public. It should be noted that lack of information was unfavourably affecting the population’s trust in local and federal authorities and the decisions they made. The restriction on the use of river water and especially the resettlements of the population caused changes in the habitual way of life and production activity patterns and brought about a persistent psychological distress.
			5. The economic consequences of radioactive contamination of the Techa River for agriculture are undoubtedly determined by a necessary intervention of persons in the society life responsible to restrict irradiation of the local population, including: 1) imposing ban on the economic use of natural resources within the flood plain agricultural lands; and 2) liquidation of settlements and there located farms, evacuation of people from the riverside area.
		1. **Present conditions**
			1. It is worth noting that so far powerful sources of secondary radioactive contamination determined radiation conditions on the Techa River. The principal sources of contamination are the cascade of water reservoirs, the by-pass canals, the swamps, and the flood plains in the upper reaches of the Techa River. In spite of the essential restrictive measures, the population is still using parts of contaminated flood plains for agricultural production. The main foodstuff that contributes to 90Sr and 137Cs body intakes for residents of riverside villages is milk produced on private farms.
			2. Until the beginning of the 2000s, Muslyumovo was the Techa riverside non-evacuated settlement closest to the Mayak with highest levels of environmental contamination. The average annual effective dose in Muslyumovo in the 1990s was by a factor of five below 1 mSv. The doses were kept low because of major restrictions including 1) prohibition of fishing in the Techa River and consumption of river water; and 2) prohibition of the use of flood plains for pasturing meat and dairy cattle. However, a large hypothetical intake of contaminated foodstuffs may increase the total effective dose of the critical group to more than 1 mSv (Balonov et al., 2007). In 2006, a decision on relocation of Muslyumovo residents was made jointly by Rosatom State Corporation and the Government of the Chelyabinsk Region. The relocation was completed in 2012.
			3. At present, an epidemiological study is underway on a cohort of about 30,000 Techa River residents. As part of this study, individual doses from external and internal exposure were reconstructed for each member of the cohort. According to the deterministic version of the dosimetric system TRDS-2016D, the average individual dose to the red bone marrow for members of this cohort was 0.35 Gy, and the maximum value was 7.9 Gy (Degteva et al., 2019).
		2. **Summary**
			1. One of the reasons for a heavy radiation situation occurred on the Techa River in the early period of the nuclear industry development in the USSR was a lack of legitimated sanitary and ecological regulations for permissible levels for discharges of radioactive material to the environment. An unrestrained race of plutonium production, strict confidentiality regime, non-involvement of stakeholders, lack of radioecological knowledge and insufficient radiation control of the environment in the vicinity of Mayak caused a delay in understanding of the problems and delay in making governmental decisions aimed at reducing waste disposals and limiting exposure of the population.
	1. Radium contamination at Dalgety Bay, Scotland
		1. **Background**
			1. Dalgety Bay is an area located on the north bank of the Firth of Forth estuary in Scotland. It comprises an estuarine bay and the adjacent land stretching along approximately 1 km of coastline, which was used by the UK Ministry of Defence as an airfield and aircraft servicing base between 1917 and 1959. During this time, radium was commonly used in paint to luminise aircraft components, such as dials and switches, allowing them to be visible in the dark. Activities at the airfield are known to have included the luminising and servicing of aircraft components using paint containing radium, as well as the incineration and disposal of solid wastes from the dismantling of retired aircraft. Today, the land is host to Dalgety Bay town of approximately 10,000 people, with various public amenities along the coastline. Radium contamination, in the form of discrete particles, was first discovered on the beach at Dalgety Bay in 1990, resulting in episodic monitoring and assessment of the site until 2011, when the detection of particles in greater numbers and of higher activities prompted more detailed investigation.
			2. The Scottish Environment Protection Agency (SEPA) is responsible for the identification, characterisation, and regulation of remediation of land affected by radioactive contamination in Scotland. Scottish Government Statutory Guidance to SEPA states for land to be considered as radioactively contaminated land (RCL) where exposures are not certain to occur (i.e. heterogeneous contamination, such as discrete particles), exposures must meet the following criteria.
* A potential effective dose greater than 100 mSv or contact with the contamination would result in a dose rate to the skin greater than 10 Gy h−1, irrespective of the probability of the dose being received. If these criteria are not met.
* A potential effective dose greater than 3 mSv, or a potential equivalent dose to the lens of the eye greater than 15 mSv, or a potential equivalent dose to the skin greater than 50 mSv, considering the probability of the dose being received.
	+ - 1. SEPA has the responsibility to carry out an appropriate scientific and technical assessment of land affected by radioactive contamination to determine if it meets the RCL criteria. For exposures not certain to occur, if either of the above criteria are met, SEPA has the additional responsibility for identifying and notifying those who are to bear responsibility for the remediation, termed the Appropriate Person(s).
			2. The aim of this case study is to provide an example of an approach taken to address an existing exposure situation involving public exposures not certain to occur due to contamination from a past practice. This case study describes the more detailed investigation initiated by SEPA in 2011, which involved a significant programme of work to characterise the site, assess the potential public exposures against the RCL criteria, identify the appropriate person(s), and instigate a remediation plan to deliver a sustainable solution for Dalgety Bay.
		1. **Exposure pathways of concern**
			1. Radiological monitoring and particle recovery was undertaken to estimate particle numbers, activities, and distribution within the environment. Several thousand particles were removed from the beach that contained 226Ra and its daughter radionuclides, with activities ranging from ~1 kBq to ~76 MBq. Physical attributes were also wide ranging, with some similar in size to a grain of sand up to relatively large lumps of a few centimetres in diameter or more, as well as identifiable aircraft components. The population of particles was heterogeneously distributed with some detected on the surface of the beach, and others at varying depths in the sediment (Dale, 2013).
			2. A survey of the habits of members of the public was commissioned to identify the potential exposure pathways and assist in determining the probability of exposure. Interviews with members of the public and the recording of observations provided data on the activities being undertaken in the area, where they were taking place, and for what length of time. Activities were recorded on the coastline and on the beach, with the main activities being walking, dog walking, sailing, cycling, and bird watching (Clyne, 2013).
			3. Due to the particle activities and the habits observed, potential public exposures were assessed for skin contact, inadvertent ingestion, inhalation, and external exposure. The main exposure pathways of concern were skin contact and inadvertent ingestion; inhalation and external exposure did not exceed the RCL criteria at the time of assessment.
			4. For assessing potential ingestion doses, an in-vitro solubility study was commissioned to estimate the amount of radioactivity that could be released into the gastrointestinal tract and hence be available for absorption. Using simulated stomach and small intestine fluids, a sample of 60 particles were digested and the activity in the fluids measured by gamma spectrometry. The study demonstrated that the solubility of the particles varies greatly, ranging from less than 1% to 35% for 226Ra (Tyler, 2013). Using a mean value of 7.59%, particles of 100kBq 226Ra could deliver a committed effective dose greater than 100 mSv to the 3-month and 1-year ICRP age groups. As particles ≥ 100 kBq 226Ra have been found on the beach, the first RCL criteria has been met.
			5. For assessing potential skin doses, studies were commissioned to model and measure the potential dose rates from 226Ra particles over a skin area of 1 cm2 and at a skin thickness of 70 µm, as recommended by the ICRP. Based on this work, particles with 226Ra activities ≥ 10 MBq could deliver dose rates to the skin that exceed the RCL criteria of 10 Gy h−1 (Charles, 2010). Only two particles have been found on the beach with activities ≥ 10 MBq but, given the first RCL criteria is irrespective of the probability of the dose being received, it has again been met.
			6. The probability of members of the public encountering a particle was assessed using the site-specific data on the habits observed and the number of particles found in the environment, as well as assumptions for other parameters such as the area of skin uncovered and breathing rates. The probability of any member of the public encountering a particle that could realistically cause harm was assessed to be ~1 in 700,000 per year for inadvertent ingestion and ~1 in 300 per year for skin contact, with a total probability for all exposure pathways of ~1 in 200 per year (Dale, 2013).
		2. **Remedial actions**
			1. Public Health England (PHE) (now known as the UK Health Security Agency) is the UK’s authority on health protection, including providing radiological protection advice. To inform the remediation at Dalgety Bay, PHE provided risk-based advice in the form of remediation criteria, which were designed firstly to avoid tissue reactions or unacceptably high stochastic risks from higher activity particles, and secondly to ensure the approach taken to lower activity particles is optimised. The advice comprised two remediation criteria summarised as follows.
* Criterion 1: All efforts should be made to ensure that objects that could give rise to a committed effective dose of 100 mSv to an individual, regardless of object size, or an external dose of 1 Gy h−1, averaged over an area of 1 cm2 skin at a depth of 70 µm, are either removed or isolated so that there is no credible current or future mechanism for exposure. In terms of activity, a criterion for the 226Ra activity content for any single object of 20–40 kBq detected in recovered material is recommended as a cautious indicative value corresponding to a committed effective dose of 100 mSv to an individual. Additionally, a criterion for the 226Ra activity content for any single object of 1–2 MBq detected in recovered material is recommended as an indicative value corresponding to the 1 Gy h−1 criterion.
* Criterion 2: Contaminated objects remaining after application of Criterion 1 should be either removed or isolated so that the current or future probability of an individual receiving 1 mSv committed effective dose is less than 10−6 per year. In addressing this criterion, optimisation should be carried out so that increasing weight is given to management options that remove or isolate objects of increasingly high activity. In terms of activity, it is recommended that a 226Ra activity content for an object of 1 kBq is adopted as an indicative value corresponding to a committed effective dose of 1 mSv to an individual.
	+ - 1. A comprehensive study of the history of Dalgety Bay was undertaken to establish the source of the contamination and identify those who were to bear responsibility for the remediation. A wide variety of resources were used including historical maps and aerial photographs of the area, records of landownership, witness accounts and records of the activities undertaken on the site, as well as geotechnical data from site investigations undertaken by the UK Ministry of Defence. The study established the contamination originated from the activities undertaken on the site when it was operated as an airfield and servicing base, and the UK Ministry of Defence caused, or knowingly permitted, the contamination to be deposited in, on, or under the land. The geotechnical data revealed the contamination was deposited prior to 1959, some of which has since been disturbed by coastal erosion, allowing some of the contamination to be released onto the beach and mobilised through coastal processes. The study concluded the UK Ministry of Defence to be the sole Appropriate Person to bear responsibility for the remediation of the site (Patton, 2013). In response, the UK Ministry of Defence agreed to undertake the remediation on a voluntary basis, without accepting liability, meaning that formal regulatory enforcement was not required.
		1. **Selected remedy**
			1. The UK Ministry of Defence, and appointed contractors, developed and implemented a remediation plan for the site to address the contamination present on the beach, as well as the contamination present within the adjacent land. To address the contamination on the beach, the plan involved the removal of beach material followed by screening to remove particles in accordance with the remediation criteria. To address the contamination within the land, the screened material was returned to the beach, covered with a geotextile membrane, and finished with rock armour to prevent any residual contamination still within the land from being eroded and deposited on the beach. Together, these remedial actions aimed to ensure the public are protected, both now and in the future.
			2. Following completion of the remediation plan in 2023, the UK Ministry of Defence, and appointed contractors, are undertaking verification monitoring for two years to demonstrate its efficacy. After the two years, assuming the verification is successful, SEPA will periodically undertake reassurance monitoring of the beach at a frequency and duration yet to be determined, and the local government authority will take responsibility for maintaining the integrity of the rock armour.
			3. The process of delivering a sustainable solution for Dalgety Bay required ongoing stakeholder involvement. Continuous engagement with the UK Ministry of Defence meant that remediation was taken forward on a voluntary basis, rather than through regulatory enforcement. Regular participation in the Dalgety Bay Community Council meetings kept the local community updated and given them the opportunity to ask questions. Wider engagement was achieved through various group meetings, such as the Dalgety Bay Forum, allowing for communication between national and local government, public agencies, the UK Ministry of Defence, the current landowner and occupier, and the local community.
			4. Additionally, it is worthy to note that SEPA did not act unilaterally in addressing the contamination at Dalgety Bay. An advisory group was formed to provide SEPA with independent scientific advice, comprising experts with knowledge in areas such as radiation detection, coastal processes, and statistics. As the UK’s authority on health protection, PHE provided advice to the Scottish Government (Brown, 2012), as did the UK Government Committee on Medical Aspects of Radiation in the Environment (COMARE, 2014). Expert engagement was important in ensuring the decisions made for Dalgety Bay were founded on the best available data and information.
			5. Following the initial discovery of the contamination, various public protection measures were introduced by the relevant authorities whilst the work to characterise, assess, and remediate the site was progressed. Initially, these measures included monitoring of the beach with any detected particles removed, as well as issuing general public health advice. As understanding of the site improved, part of the beach where the radioactive particles of the highest activities were found was closed to the public, and the collection of fish and shellfish for human consumption was prohibited.
			6. In 2023, the Dalgety Bay remediation work was completed and, alongside the post-remediation verification monitoring followed by the reassurance monitoring and agreed maintenance, the public will be able to enjoy access again to the site for the first time since 2011.
		2. **Summary**

This case study has provided an example of an approach taken to address an existing exposure situation involving public exposures not certain to occur due to contamination from a past practice. The programme of work to characterise the site, assess the potential public exposures against the RCL criteria, identify the appropriate person, and instigate a remediation plan has been described, as well as highlighting the importance of continuous stakeholder involvement. After successful completion of the remediation plan, the public will once again have unrestricted access to their local amenities.

* 1. References

AIRAC, 1979. Radiological safety and future land use at the Maralinga atomic weapons test range. Report No. 4. Australian Government Publishing Service, Canberra.

AIRAC, 1983. British nuclear tests in Australia—a review of operational safety measures and of possible after-effects. Report No. 9. Australian Government Publishing Service, Canberra.

Akleyev, A.V., Kostyuchenko, V.A., Peremyslova, L.M., Baturin, V.A., Popova, I.Y., 2000. Radioecological impacts of the Techa River contamination. Health Phys. 79, 36–47.

Akleyev, A.V. (Ed.), 2016. Consequences of radioactive contamination of the Techa River. Kniga, Chelyabinsk.

Alexakhin, R.M., Buldakov, L.A., Gubanov, V.A., 2004. Large radiation accidents: Consequences and protective countermeasures. IzdAt Publisher, Moscow.

Balonov, M.I., Bruk, G.Y., Golikov, V.Y., et al., 2007. Assessment of current exposure of the population living in the Techa River basin from radioactive releases of the Mayak facility. Health Phys. 92. 134–147.

Brown, J., Oatway, W., 2012. Scoping Health Risk Assessment for Beach Users at Dalgety Bay to Support Advice to Scottish Government Given in February 2012. Health Protection Agency, Health Protection Agency.

Charles, M.W., Gow, C., 2010. Skin dose from Dalgety Bay Ra-226 contamination: Dose rate measurements for ten selected samples. University of Birmingham, Birmingham.

Clyne, F.J., Garrod, C.J., Ly, V.E., 2013. Radiological Habits Survey: Dalgety Bay, 2012. Environment Report RL 13/13. Scottish Environment Protection Agency, Stirling.

COMARE, 2014. Committee on Medical Aspects of Radiation in the Environment: Fifteenth Report – Radium contamination in the area around Dalgety Bay. Committee on Medical Aspects of Radiation in the Environment, Chilton.

Dale, P., 2013. Dalgety Bay Radioactive Contaminated Land Risk Assessment. Scottish Environment Protection Agency, Stirling.

Degteva, M.O., Shagina, N.B., Vorobiova, M.I., Shishkina, E.A., Tolstykh, E.I., Akleyev, A.V., 2016. Contemporary understanding of radioactive contamination of the Techa River in 1949-1956. Radiat. Biol. Radioecol. 56, 523–534.

Degteva, M.O., Napier, B.A., Tolstykh, E.I., 2019. Enhancements in the Techa River Dosimetry System: TRDS-2016D code for reconstruction of deterministic estimates of dose from environmental exposures. Health Phys. 117, 378–387.

DOE/EPA/CDPHE, 1996. Action Levels for Radionuclides in Soils for the Rocky Flats Cleanup Agreement. U.S. Department of Energy, Washington, DC, U.S. Environmental Protection Agency, Washington, DC, and Colorado Department of Public Health and the Environment, South Denver, CO.

EG&G, 1991, Energy Measurements: An aerial radiological survey of Maralinga and Emu, South Australia. Technical Assessment Group Study Program Reports, vol. 1. Australian Government Publishing Service, Canberra.

ICRP, 2007. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).

Johnson, P.N., Lokan, K.L., Richardson, C.K., Williams, G.A., 1985. Plutonium contamination in the Maralinga Tjarutja Lands. Report ARL/TR085. Australian Radiation Laboratory, Yallambie.

Lemberg, V.K., Antipina, I.V., 2004. Report on investigation of radioactive pollution of the area of Metlino Village, 1951. Radiat. Saf. Prob. 3, 61–71.

Lokan, K.H. (ed.), 1985, Residual radioactive contamination at Maralinga and Emu. ARL Report TR070. Australian Radiation Laboratory, Yallambie.

Marey, A.N., Ilyin, D.I., Kardeeva, A.A., et al., 2009. Influence of industrial releases from Mendeleev factory into the Techa River on the sanitary life conditions and health of riverside residents: Report. 1952. Radiat. Saf. Probl. 2, 93–109.

MARTAC, 2002, Rehabilitation of Former Nuclear Test Sites at Emu and Maralinga (Australia). Commonwealth of Australia, Canberra.

McClelland, J.R., 1985. The report of the Royal Commission into British Nuclear Tests in Australia. Australian Government Publishing Service, Canberra.

Murith, C., Baechler, S., Estier, S., Palacios-Grusion, M., 2016. Remediation of Radium Legacies from the Swiss Watch Industry. Radiat. Prot. Dosimetry 173, 245–251.

O’Brian, R., Carpenter, J., Grzechnik, M., Long, S., Green, L., 2011. Maralinga and Oak Valley Dose Assessment – 2011. Technical Report 158. Australian Radiation Protection and Nuclear Safety Agency, Yallambie.

Patton, N., 2013. Dalgety Bay Appropriate Person Report. Scottish Environment Protection Agency, Stirling.

Pryakhin, E.A., Tryapitsina, G.A., Styazhkina, E.V., Shaposhnikova, I.A., Osipov, D.I., Akleev, A.B., 2012. Assessment of erythrocytes pathology level in peripheral blood in roach (Rutilus rutilus L.) from reservoirs with different levels of radioactive contamination. Radiat. Biol. Radioecol. 52, 616–624.

RAC, 2000. Task 5: Independent Calculation, Radionuclide Soil Action Level Oversite Panel. 16-RSALOP-RSAL-1999-Final. Risk Assessment Corporation, Neeses, SC.

Rood, A.S., Grogan, H.A., Till, J.E., 2002. A Model for a Comprehensive Evaluation of Plutonium Released to the Air from the Rocky Flats Plant, 1953–1989. Health Phys. 82, 182–212.

Rood, A.S., Grogan, H.A., 1999. Estimated Exposure and Lifetime Cancer Incidence Risk from 903 Area Plutonium Releases at the Rocky Flats Plant. 01-CDPHE-RFP-1998-Final. Radiological Assessments Corporation, Neeses, SC.

Shishkina, E.A., Pryakhin, E.A., Popova, I.Y., et al., 2016. Evaluation of distribution coefficients and concentration ratios of 90Sr and 137Cs in the Techa River and the Miass River. J. Environ. Radioact. 158–159, 148–163.

Shishkina, E.A., Pryakhin, E.A., Sharagin, P.A., et al., 2019. The radiation exposure of fish in the period of the Techa river peak contamination. J. Environ. Radioact. 201, 43–55.

Shoigu, S.K. (Ed.), 2002. Consequences of anthropogenic radiation impact and problems of the Ural region rehabilitation. Komtekhprint, Moscow.

Styazhkina, E.V., Obvintseva, N.A., Shaposhnikova, I.A., Tryapitsina, G.A., Stukalov, P.M., PStyazhkinaryakhin, E.A., 2012. Analysis of DNA damage/repair level in Rutilus rutilus L. from reservoirs of the Techa River cascade with different levels of radioactive pollution. Radiat. Biol. Radioecol. 52, 198–206.

Styazhkina, E.V., Shaposhnikova, I.A., Osipov, D.I., Pryakhin, E.A., 2015. Evaluation of the nuclear DNA of roach’ peripheral blood cells from the Techa River with comet assay. Bulletin of Chelyabinsk State University 376, 84–88.

Symonds, J.L., 1985. A history of British Atomic Tests in Australia. Department of Resources and Energy, Canberra.

TAG, 1990. Rehabilitation of former nuclear test sites in Australia. Department of Primary Industries and Energy, Canberra.

Till, J.E., Meyer, K.R., Aannenson, J.W., et al., 2000. Technical Project Summary; Radionuclide Soil Action Level Oversight Panel. 1-RSALOP-RSAL-2000-Final. Risk Assessment Corporation, Neeses, SC.

Till, J.E., Rood, A.S., Voilleque, P.G., et al., 2002. Risks to the Public from Historical Releases of Radionuclides and Chemicals at the Rocky Flats Environmental Technology Site. J. Expo. Anal. Environ. Epidemiol. 12, 355–372.

Tryapitsina, G.A., Osipov, D.I., Yegoreichenkov, E.A., et al., 2017. Assessment of erythropoiesis status in roach (Rutilus rutilus) of the radioactively contaminated Techa River. Radiats. Biol. Radioecol. 57, 98–107.

Tyler, A.N., Dale, P., Copplestone, D., et al., 2013. The radium legacy: Contaminated land and the committed effective dose from the ingestion of radium contaminated materials. Environ. Int. 59, 449–455.

Voillequé, P.G., 1999a. Review of Routine Releases of Plutonium in Airborne Effluents at Rocky Flats. 06-CDPHE-RFP-1998-Final. Radiological Assessments Corporation, Neeses, SC.

Voillequé, P.G., 1999b. Estimated Airborne Releases of Plutonium during the 1957 Fire in Building 71. 10-CDPHE-RFP-1999-Final. Radiological Assessments Corporation, Neeses, SC.

Voillequé, P.G., 1999c. Estimated Airborne Releases of Plutonium during the 1969 Fire in Building 776-777. 09-CDPHE-RFP-1999-Final. Radiological Assessments Corporation, Neeses, SC.

Weber, J.M., Rood, A.S., Meyer, H.R., 1998. Development of the Rocky Flats Plant 903 Area Plutonium Source Term. 08-CDPHE-RFP-1998 (Rev. 1). Radiological Assessments Corporation, Neeses, SC.

GLOSSARY

Integrated approach

the term integrated approach in this report means that remedial actions should be taken to ensure both the protection of people and the environment. The radiological and non‑radiological impacts on the environment from remedial actions that are intended to reduce public exposure should be considered in order to determine the overall benefits gained from the remediation.

All hazards approach

the term all hazards approach in this report means that radiological and non‑radiological hazards should be considered together while defining the best protection strategy. The options being considered should seek an overall balance of risks and benefits for the protection of people and the environment, now and in the future.

Remediation

remediation is defined as the process to reduce radiation exposure, or to reduce the probability of such exposures being received, through actions to remove the contamination (decontamination) or to modify the exposure pathways.

Exposures not certain to occur

Exposures not certain to occur, as used in this report, means those exposures arising from contaminated areas over the medium and long term that are not expected to be delivered with certainty. These exposures may result from a sequence of events of a probabilistic nature, such as potential transport or exposure pathways, or they may be due to special characteristics of the source (for example, cases of heterogeneous contamination) that could lead in the future to higher exposures and that should also be assessed to define an appropriate remediation process.

ACKNOWLEDGEMENTS

ICRP Task Group 98 was established in November 2014 to develop a report that describes and clarifies the application of the Commission’s Recommendations on radiological protection of workers, the public, and environment in contaminated areas where radioactivity is present because of past activities, excluding exposures in the post-accidental phase after a nuclear emergency.

ICRP thanks all those involved in the development of this publication for their hard work and dedication over many years.

**Task Group 98 members *(2014****–****present)***

|  |  |  |
| --- | --- | --- |
| M. Boyd (Chair) | S. Long  | G. Smith  |
| A. Canoba (Vice-chair) | C. McGuire  | M. Sneve  |
| L. Vaillant (Secretary) | A. Rood  | T. Yankovich  |
| E. Lazo  | S. Shinkarev  | H. Yasuda  |

**Task Group 98 technical secretary**

A. Ethier

**Committee 4 critical reviewers**

|  |  |  |
| --- | --- | --- |
| E. Gallego | A. Nisbet | H. Yoshida |

**Main Commission Critical Reviewers**

|  |  |  |
| --- | --- | --- |
| M. Kai | S. Romanov |  |

**Editorial members**

C.H. Clement (Scientific Secretary and *Annals of the ICRP* Editor-in-Chief)

T. Yasumune (Assistant Scientific Secretary and *Annals of the ICRP* Associate Editor) *(2022–2024)*

K. Nakamura (Assistant Scientific Secretary and *Annals of the ICRP* Associate Editor) *(2024–)*

**Committee 4 members during preparation of this publication**

*(2013–2017)*

|  |  |  |
| --- | --- | --- |
| D.A. Cool (Chair) | M. Doruff | A. Nisbet |
| K.W. Cho (Vice-Chair) | E. Gallego | D. Oughton |
| J-F. Lecomte (Secretary) | T. Homma | T. Pather |
| F. Bochud | M. Kai | S. Shinkarev |
| M. Boyd | S. Liu | J. Takala |
| A. Canoba | A. McGarry |  |

*(2017–2021)*

|  |  |  |
| --- | --- | --- |
| D.A. Cool (Chair) | A. Canoba | Y. Mao |
| K.A. Higley (Vice-Chair) | D. Copplestone | N. Martinez |
| J-F. Lecomte (Secretary) | E. Gallego | A. Nisbet |
| N. Ban | G. Hirth | T. Schneider |
| F. Bochud | T. Homma | S. Shinkarev |
| M. Boyd | C. Koch | J. Takala |

*(2021–2025)*

|  |  |  |
| --- | --- | --- |
| T. Schneider (Chair) | Y. Billarand  | A. Mayall |
| N. Martinez (Vice-Chair) | A. Canoba | A. Nisbet |
| J. Garnier-Laplace (Secretary) | E. Gallego | S. Shinkarev |
| J. Burtt | D. Giuffrida | J. Takala |
| M. Baek | C.B. Koch | H. Yoshida |
| N. Ban | Y. Mao | F. Zölzer |

**Committee 4 emeritus members**

|  |  |  |
| --- | --- | --- |
| J-F. Lecomte |  |  |

**Main Commission members at the time of approval of this publication**

Chair: W. Rühm, *Germany*

Vice-Chair: S. Bouffler, *UK*

Scientific Secretary: C.H. Clement, *Canada*; *sci.sec@icrp.org\**

K.E. Applegate, *USA* D. Laurier, *France* **Emeritus members**

F. Bochud, *Switzerland* S. Liu, *China*  R.H. Clarke, *UK*

K.W. Cho, *Korea* S. Romanov, *Russia*  C. Cousins, *UK*

G. Hirth, *Australia* T. Schneider, *France* J. Lochard, *France*

M. Kai, *Japan* A. Wojcik, *Sweden* F.A. Mettler Jr, *USA*

 R.J. Pentreath, *UK*

 R.J. Preston, *USA*

C. Streffer, *Germany*

 E. Vañó, *Spain*

\*Although formally not a Main Commission member since 1988, the Scientific Secretary is an integral part of the Main Commission.

1. The referenced case studies were prior to *Publication 103*, so the concept of reference level was not applied. [↑](#footnote-ref-2)
2. Action level: a measurable quantity (e.g. dose rate or activity concentration) above which remedial actions or protective actions should be carried out in existing exposure or emergency exposure situations. (http://icrpaedia.org/ICRP\_Glossary). [↑](#footnote-ref-3)
3. Low dose: a qualitative term to mean relatively low level of dose, typically refers to doses lower than 100 mSv (or 100 mGy for low linear energy transfer radiation) based on knowledge of radiation effects (UNSCEAR, 2012). [↑](#footnote-ref-4)
4. Well-being: Is a positive state experienced by individuals and societies. Similar to health, it is a resource for daily life and is determined by social, economic and environmental conditions (WHO, 2021). [↑](#footnote-ref-5)