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Abstract The work described in this report has been performed as a part of the RESTRAT Project FI4P-CT95-0021a (PL 950128) co-funded by the Nuclear Fission Safety Programme of the European Commission. The RESTRAT project has the overall objective of developing generic methodologies for ranking restoration techniques as a function of contamination and site characteristics. The project includes analyses of existing remediation methodologies and contaminated sites, and is structured in the following steps:

- characterisation of relevant contaminated sites
- identification and characterisation of relevant restoration techniques
- assessment of the radiological impact
- development and application of a selection methodology for restoration options
- formulation of generic conclusions and development of a manual

The project is intended to apply to situations in which sites with nuclear installations have been contaminated with radioactive materials as a result of the operation of these installations. The areas considered for remedial measures include contaminated land areas, rivers and sediments in rivers, lakes, and sea areas.

Criteria for clean-up of contaminated land and criteria for protection of the public against chronic exposure are being developed by Advisory Groups and Task Groups within the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP). This work has been reviewed and a status as of the beginning of 1998 is given.

For illustrative purposes, the basic radiation protection principles of justification and optimisation have been applied to derive generic action levels for clean-up of residential areas contaminated with radioactive materials. These generic action levels are based upon cost-benefit analyses that include avertable doses and monetary costs of clean-up.

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1 Introduction

Within the international framework for radiation protection, human activities that involve or could involve exposure to radiation can be dealt with either as practices or as intervention. A practice is defined as [1]:

> *any human activity that introduces additional sources of exposure or exposure pathways or extends exposure to additional people or modifies the network of exposure pathways from existing sources, so as to increase the exposure or the likelihood of exposure of people or the number of people exposed*

In contrast, intervention assumes the introduction of exposures to radiation has already occurred or is presently occurring and is defined as [1]:

> *any action intended to reduce or avert exposure or the likelihood of exposure to sources which are not part of a controlled practice or which are out of control as a consequence of an accident*

Situations involving remediation of contaminated areas may fall into either of these categories, and in some cases it may not be clear which is more appropriate. For example, the clean-up of a licensed nuclear site as part of decommissioning is clearly a part of that practice, and the clean-up of contaminated areas from a major nuclear accident would clearly be intervention. However, clean-up of contamination left behind from a previously discontinued practice may be controllable by the generator and would be a practice.

The distinction between practices and intervention is fairly explicit, and can be summarised as follows. Any contaminated area would constitute a source. If this source, at the time when a decision on clean-up is being taken, is within an authorised practice, then any clean-up activities would be part of that authorised practice, and the radiological protection principles for practices would apply. If the source, *i.e.* the contaminated area, is not within an authorised practice, then any clean-up action will be classified as intervention, and the corresponding principles apply.

Contamination situations may be subdivided for convenience in considering the development and application of clean-up criteria into the following main categories or situations:

(a) residual contamination post decommissioning of existing sites (existing practices, *e.g.* decommissioning of contaminated areas and installations for the nuclear industry)

(b) residues from operations prior to regulation or under control inadequate from a present day point of view (past practices, *e.g.* contamination resulting from past uranium mining and milling operations)

(c) residual long-term contamination following accidental release of radionuclides to the environment (accidents, *e.g.* contamination of the environment due to accidents in the nuclear industry)

With these definitions, clean-up situations can readily be categorised: situations of type (a) would be part of the relevant practice, whereas those of type (b) and (c) (residues from past practices and accidents) would be intervention situations. However, for the latter cases, the status of the remaining contaminated area after any clean-up (given that clean-up will rarely remove all of the contamination) is an important consideration.

2 International work on remediation criteria

Chronic exposure situations that may need to be remediated can arise under a wide variety of circumstances, and the choice of the elements of the system of radiological protection that are appropriate for application to a specific decision on a remedial action will not always be straightforward. In some cases the principles of protection for practices would clearly apply; in some it will be the principles for intervention; but in others the choice will be ambiguous.

The International Commission on Radiological Protection published new set of general recommendations in 1990 [1]. These recommendations provide a system of radiological protection that distinguishes between two broad categories of situations: practices and interventions. Practices are human activities that increase overall exposure to radiation and, in principle, can be designed and operated to meet requirements for radiation protection that are specified in advance. Interventions are human activities intended to decrease overall exposure to radiation and apply to situations in which the source of exposure is already present when decisions on protective actions are to be taken. These situations include, for example, exposure that results from an accident or, under some circumstances, exposure from naturally occurring radionuclides, *e.g.* radon in dwellings. The basic principles of the system of radiological protection are used to set the levels of control of exposure in both practices and interventions, but are applied in different ways.

According to ICRP, *'...the primary aim of radiological protection is to provide an appropriate standard of protection for man without unduly limiting the beneficial practices giving rise to radiation exposure'* ([1], §100). More specifically, ICRP states that:

> *A system of radiological protection should aim to do more good than harm should call for protection arrangements to maximise the net benefit, and should aim to limit the inequity that may arise from a conflict of interest between individuals and society as a whole* (§14)

In 1994, IAEA formed an Advisory Group to advise the Agency on developing guidelines on criteria for clean-up of contaminated land. Consultants have further developed this work and in 1997 an IAEA TECDOC has been published [5].

In 1994, on the recommendation of the ICRP Committee 4, the Commission appointed a Task Group to provide guidance on the application of radiological protection principles for members of the public to chronic exposure situations.

Both these working groups have elaborated on the basic radiation protection principles in ICRP Publication 60. A general scheme for unified application of the principles for radiological protection in practices and interventions to clean-up situations which encompasses the principles of justification and optimisation, and, in varying degrees, requirements for limiting risks to individuals have been proposed [2, 5]. The proposed principles for a general system are as follows:

- *Justification* - The combined effect of all actions affecting risks should be to do more good than harm;
- *Optimisation* - All radiological risks should be as low as can reasonably be achieved;
- *Protection of the individual* - The inequity that may arise from a conflict of interest between individuals and that of society as a whole should be limited.

This formulation is consistent with the Commission's overall objective for radiological protection. In clean-up situations these elements of protection should be applied to determine whether to carry out remedial actions, and then to optimise such actions, subject to any constraints for protection of the individual that may be considered appropriate.

Such a general system does not invalidate the concepts of practices and intervention, but rather places them in a wider context in which they provide interpretations of the way in which the overall system applies to particular types of situation. Where situations fit well into one category or the other, this provides a valuable 'short-cut' in the form of a simpler ready-made system of protection. Where some situations do not fit well, it may be better not to persevere with the categorisation.

The work within the IAEA and ICRP working groups as a status at the beginning of 1998 is reviewed below. It should be emphasized that the work within both the ICRP and IAEA working groups is still in progress and that the preliminary recommendations may change in the final publications.

2.1 International Commission on Radiological Protection

The ICRP work on protection of the population in chronic exposure situations covers situations where there are long-term or chronic exposures that are due to human activities. Such exposure may arise from radioactive materials of either natural or artificial origin. The exposures may already be occurring or there may be the potential for exposure in the future. As an example of the former, exposure may occur due to the construction of housing on sites that contain radioactive residues from long-since discontinued mining activities. An example of the latter case is the return of former nuclear sites to a status of unrestricted use (sometimes termed 'green field status'), where future long-term exposures from residual contamination will need to be considered. Similar considerations apply to contamination, which is discovered on industrial land, which is to be re-developed, *e.g.* past radium luminising or mining activities. Another example is the potential for future off-site groundwater contamination when there is extensive contamination of land. The analysis of such future exposure may be difficult when contamination is long-lived because long-term land use is, in many cases, unpredictable. Chronic exposures may also arise in the long-term from persistent contamination following an accidental release, such as that from the accident at Chernobyl in 1986.

In 1994, on the recommendation of the ICRP Committee 4, the Commission appointed a Task Group to develop recommendations concerning:

(a) the application and withdrawal of countermeasures in exposure situations arising from the long-term presence of radioactive materials in the environment, and

(b) the management of residual exposures after the withdrawal of countermeasures.

A new Task Group was appointed at the end of 1996 to continue the work to develop protection criteria for chronic public exposure covering:

(a) situations where consideration is given to the suspension of countermeasures including situations where countermeasures were considered, but not applied,

(b) situations of decontamination and reclamation of land that had become contaminated by past practices or past accidents, and

(c) situations of unexpected high exposure to natural sources.

The major ideas in this work are presented below [2].

2.1.1 Individual- and source-related approaches

Although the main emphasis of the Commission's System of Protection is on the source, its practical application involves a pragmatic combination of source-related assessments and individual-related assessments linked to a number of defined sources. For example, in the System of Protection for practices, the optimisation of protection involves the use of collective dose (a source related concept) supplemented by the use of dose constraints (an individual-related concept linked to a defined source). The system also includes individual dose limits; these apply to the total dose from the relevant sources, and *not* to the total dose from all sources. Exposures that are outside the scope of the System of Protection for practices and the deliberate medical exposures are excluded from the individual dose limitation.

However, purely individual-related approaches and consequential criteria for the total dose incurred by individuals as a result of the exposure to all sources may be deemed necessary for a number of purposes. One purpose could be to determine whether an individual dose approaches a threshold for deterministic effects or involves a too high probability of stochastic effects; in both cases radiation protection actions would seem to be required almost mandatory. It should be noted, however, that there might be a practical problem for establishing acceptance criteria for this purpose: it may not be feasible to use total individual dose requirement through a formal regulatory system of protection. It is difficult to envisage how a source operator can control the dose delivered by other sources. Fortunately, high exposures that might approach the thresholds for deterministic effects and impose high individual risks are rare and would almost always arise from a single predominant source. Another very important purpose is to allay individual anxieties about residual exposures. Individual-related criteria should be based on total dose and *consequential* to the application of the Commission's System of Protection. They could be viewed as *complementary* to the System.

In fact, the current, fundamentally source-related, System of Protection for practices and interventions would imply a consequential criterion of an individual-related nature, namely the level of total annual individual dose that should not be of serious concern to the exposed individual. This criterion can be derived from the principles of the current System and somehow be viewed as complementary to those principles.

2.1.2 Limitation of the total annual environmental dose to individuals

The ICRP had indicated that there would be some level of dose above which "intervention will always almost be justified" under any conceivable circumstances. The Commission's current recommendations associated this level with a risk of "serious deterministic effects" and it could also have also been linked with a very high risk of stochastic effects.

There is no direct human epidemiological data on deterministic effects from chronic exposures but information has been extrapolated from experience with protracted doses incurred in the course of radio-therapeutical procedures complemented by data from animal experiments. On the basis of the available information, the Commission has estimated the lower bound of dose rate thresholds for a number of deterministic effects. They vary from over 400 mSv per year for a clinically significant depression of the blood-forming process, to somewhere above 150 mSv per year for opacities in the lens of the eye. These estimations have been reflected in international standards on continuous annual doses for which intervention should be almost always justified.

Taking account of the presumed thresholds for deterministic effects and on the basis of the current system's principles for interventions, it would be obvious that individuals under almost no conceivable circumstances should be exposed to a total annual environmental dose that could cause deterministic effects. This would mean that the annual dose should be less than *about a hundred mSv*. Although at this level of dose deterministic effects should not be expected, the risk of stochastic effects to individuals exposed at these annual dose levels will be so high that it is not generally acceptable.

2.1.3 Acceptability of chronic exposures of no serious concern

Many chronic exposure situations are natural in origin or give rise to dose levels that are similar in magnitude to those experienced in many parts of the world. In fact, the *average* annual individual effective doses from natural sources including radon, in large areas of the world, are up to the order of 10 mSv if areas with elevated exposures are taken into account. This suggests that in such situations there are few grounds for concern at these dose levels provided they cannot reasonably be reduced or avoided.

Further information on radiation levels of concern can be gained from consideration of previous recommendations from the Commission and also from internationally agreed levels for undertaking protective action against radiation exposures in various situations. In this context, the following examples are important. The ICRP action level for radon in dwellings corresponds to a dose of 3 - 10 mSv in a year for simple remedial measures, while for more severe measures (*i.e.* permanent removal of people from their homes) the action level should be at least one order of magnitude higher. The intervention level for permanent resettlement due to exposure from deposited activity in the environment from a nuclear accident has been recommended by the ICRP (and established in international standards) to be 1 Sv in a lifetime, which would correspond to an annual average dose level of about 10 - 15 mSv.

From the above discussion it appears that a total environmental dose up to about some tens of mSv per annum should not represent a serious concern to an individual. Moreover, such a dose level could represent a kind of upper bound that might be to divide situations into two "classes":

- situations with total annual individual doses above this level should trigger investigations into the feasibility of reducing doses, and
- situations with total annual individual doses below this level could, depending on the situation, be considered as a normal situation of exposure to environmental "background" radiation.

The following consequential and complementary criteria can thus be formulated:

> *a total individual environmental dose of about 10 mSv in a year is the highest that could be considered of no serious concern to individuals without further investigations, although annual doses up to this level may not be acceptable under all circumstances.*

2.1.4 Chronic exposure situations

A number of situations can be characterised on the basis of the major source of exposure giving rise to chronic exposure and it is indicated below how they can be dealt with in the context of the Commission's recommendations.

(a) *"Natural" Sources of Radiation*
In a few parts of world, building materials with high concentrations of natural radionuclides have been used over generations. Dose rates from the resulting gamma radiation sometimes exceed 100 mSv per year. It is then necessary to consider how best to apply the Commission's System of Protection. The buildings already exist and therefore the exposure situation is extant and only intervention is available.

The application of the Commission's System of Protection to radon in buildings has been dealt with in Publication 65 [4]. The Commission has emphasised that intervention should take place to protect the more highly exposed individuals in the population. The actions needed to reduce concentrations are usually fairly simple and only moderately expensive. The recommended range of annual effective dose from which an action level should be selected is 3 - 10 mSv.

(b) *Residual Environmental Sources of Radiation from Past Human Activities*
In the context of waste disposal, residues include deposits from the disposal on land of long-lived materials from previous operations such as mining and luminising works with radium compounds, and buildings that have been used for long-term storage of waste or for radium work and subsequently put to other uses. Residues have also been created by accidents in which radioactive materials have been dispersed in residential and agricultural areas.

Following a very severe nuclear reactor accident, significant quantities of long-lived radionuclides might be deposited in the environment leading to a long-term chronic exposure situation. However, such an accident would have invoked emergency countermeasures that in the case of circumstances leading to protracted incremental annual doses above around 10 mSv would have involved relocation of the affected population. In locations where countermeasures have been considered but not taken or have been taken and later withdrawn, the residual total environmental doses may well be higher than in normal situations.

If people are already living or working in a region of unusually high exposure, the first step is to consider the need for intervention. If the only form of intervention is the relocation of residents, it will usually be appropriate to accept moderately high exposures rather than to impose the social costs and disadvantages of relocation. It would then be inconsistent to prevent people from outside the affected area from moving in to take up residence or work. Guidance will be needed on return to and migration into an affected area. Return to the area can be treated as the withdrawal of a countermeasure and is then a logical part of the System of Protection for intervention, but the area should *not* be treated as a practice. This would introduce inconsistencies. The exposure of both returning and incoming populations should be regarded as being outside the scope of the System of Protection.

2.1.5 Guidance on the management of chronic exposure situations

The basis for the ICRP Task Group work on developing guidance for protection of the public against chronic exposure is the System of Protection. The System would apply to (a) controlling the *increase* in the extant doses caused by the introduction (or continuation) of *beneficial practices* and to (b) determining the *reduction* of extant doses by the introduction of *intervention* with protective actions.

Most of the situations giving rise to chronic exposure are of no concern and require no further consideration. These situations include the great majority of the locations in which people live and work and in which the exposures are due to the normal range of the environmental background radiation. Exceptionally, there are locations in which the chronic exposures due to "natural" or "artificial" environmental sources are high enough to cause concern and may call for the application of the System of Protection. There are also many applications of the System of Protection to practices or intervention that leave residual sources of chronic exposure. Once the

System of Protection has been fully applied, any further action is *not* required, because the system requires that all reasonable protection measures should already have been taken, either in the management of practices or by intervention. A total environmental dose level of about ten mSv in a year is recommended as a level below which there would normally not be a need for intervention (see Table 1).

Table 1. Existing total environmental dose levels at which intervention should be considered.

Annual environmental dose level [$mSv \cdot a^{-1}$]	Need for intervention
$>$ about ten	intervention usually needed
$<$ about ten	of no individual concern

The introduction of generic total environmental dose levels for individuals in terms of an almost always justified level for undertaking protective actions and a non-concern level for allaying individual anxieties about residual exposures does not imply, that such dose levels are automatically acceptable. The levels are meant as trigger levels for consideration of dose reductions. Consequently, if remedial actions are justified at dose levels below about ten mSv in a year, the appropriate dose reduction should be found by optimisation. At dose levels of about one hundred mSv in a year or higher intervention would almost always be justified.

2.2 International Atomic Energy Agency

The purpose of the IAEA work [5] is to set out radiological principles for use in decisions related to the clean-up of contaminated areas. More specifically, it aims to establish an approach to developing radiological criteria for clean-up and to recommend generally applicable numeric values. It is also intended that the work should provide outline guidance on how the radiological criteria can be applied to the clean-up of contaminated areas. In developing the IAEA guidance the recommendations of the ICRP and of the Basic Safety Standards from six international organisations are taken into account.

While the reference values for clean-up criteria have been developed by taking account of the need to optimise radiation protection and, as appropriate, of international dose limits and constraints, the analysis has been necessarily generic and, therefore, the values may not be appropriate in all situations. Site specific analysis could lead to criteria, implemented in terms of concentrations of specific radionuclides, which could be higher or lower than the numerical generic guidance.

The IAEA work focuses on the radiological part of decisions on clean-up. Other equally important parts of the decision making process, for example, political and social factors, are discussed but not analysed in a detailed way. The guidance is intended to apply to situations in which environmental media have been contaminated as a result of human actions. This includes such situations as accidental releases of radionuclides, previous discharge practices, uranium and other types of mining activities, and operations of nuclear sites and of industrial premises where radionuclides (or materials containing enhanced levels of naturally occurring radionuclides) have been employed. It is intended to apply to situations in which previously controlled areas are intended to be released for various uses. It is not concerned with levels of contamination within controlled areas. In relation to areas contaminated as a result of accidental releases, the guidance does not apply to the early phases of accidents where concern is with avoiding acute risks to health (the emergency phase) but rather to the later phases where the risks presented are of a chronic nature (the chronic phase or recovery phase).

2.2.1 Clean-up situations

In the past, radiation protection has been concerned primarily with establishing the conditions that should be applied to the introduction of new practices and the management of continuing practices. This has led to a well-developed system of principles for deriving numerical values including limits on releases from normally-operating facilities; levels for initiating protective actions to reduce doses; and levels to protect populations in the event of an accident. These principles and, in some cases, the resulting numerical values have been documented, for example in IAEA Safety Series No. 109 [6].

There are other situations which may need to be considered, for example, when a practice is discontinued at a particular site, when contamination from a previously discontinued practice is discovered, or when an accident occurs that leads to chronic exposures due to contamination. In these cases it is necessary to evaluate the adequacy of current and future protection of public health and the environment. Based on the evaluation, some remedial actions may be necessary, such as removal, cover and/or mixing of radioactive materials in soil, treatment of ground and surface waters, and the decontamination of structures.

Within the IAEA work [5] the term clean-up has a wider meaning than in its normal usage. Clean-up is taken to mean the measures which are carried out to reduce the exposure from existing contamination; these can be related to the contamination itself (the source) and to the exposure pathways to humans. For example, clean-up includes stabilisation of a source at a site. Measures applied to people, such as relocation of persons and access limitation are associated with clean-up but appropriate criteria are given elsewhere (*e.g.* Safety Series No. 109 [6] and Safety Series No. 115 [7]). The sources considered for clean-up include contaminated land areas, structures, rivers, lakes and sea areas. Examples of clean-up measures applied to the sources include:

- decontamination of confined areas, *e.g.* floors
- removal of the contaminated medium, *e.g.* exchange of the upper layer of soil, transport the material of a mining pile to another site, removal of sediments

Examples of clean-up measures to avoid or reduce particular exposure pathways include:

- covering the contaminated area with inactive material, *e.g.* in the case of mining piles to reduce radon emanation rates
- modifying the contaminated area, *e.g.* planting vegetation or use of synthetic covers to reduce resuspension of contaminated material

Contamination situations considered in the IAEA work are summarised in the box below [5].

CONTAMINATION SITUATIONS

Clean-up may be needed when environmental media have been contaminated as a result of a variety of human activities involving radionuclides. The activities, past and present, that may lead to contaminated areas and eventually to clean-up include amongst others:

- nuclear energy production
- mining, milling and processing of uranium ores
- enrichment and fuel fabrication
- reprocessing of spent fuel
- radioactive waste disposal, either on land or in the marine environment
- nuclear weapons production
- nuclear weapons detonations
- use of radionuclides in medicine and research
- use of sealed and unsealed sources in industry
- ore processing and mineral extraction of materials containing natural radionuclides (radium, thorium, rare earths, phosphates, oil and gas production)
- accidents

The type and extent of the contamination situation will depend on the scale of the operation, the source term, the nature of the radionuclides and the contaminated environmental media involved. This will lead to different contamination situations. They may be confined to the site of the operation or extended to the off-site area. In the latter case, the contamination situation may be caused for instance by inadequately controlled discharges, either by current operations, or by operations in the past, transportation accidents (including satellites and weapons) and major accidents with nuclear installations, causing large scale off-site contamination. Apart from the terrestrial contamination, such releases may also contaminate off-site groundwater, aquifers and river, lake and estuarine sediments. Another differentiation in contamination situations can be made by distinguishing situations resulting from ongoing and previous operations. In the latter case, the contamination can even be detected long after the operation has been ceased.

2.2.2 An alternative framework for radiation protection in clean-up situations

Clean-up situations can be fitted within the framework of practices and intervention, although this is not always entirely straightforward. A slightly more general approach based on the broader conceptual definitions of practices and intervention provided by ICRP can also be used to simplify the advice. For example, the redevelopment for public use of a site where contamination from a discontinued practice is currently within a defined and relatively inaccessible area would arguably require intervention that is constrained on equity grounds to meet criteria similar to those for practices. The same outcome could be obtained simply by designating the redevelopment to be a practice.

However, both of these approaches still imply the existence of two fundamentally different categories of situation - practices and interventions - into which every situation is required to fit, even if it does not obviously fit in either. It may be useful, at least for presentational reasons, to investigate a broader system in which the whole range of situations can more readily be accommodated, without requiring every situation to be classified as *either* a practice *or* an intervention.

This possibility is hinted at in the 'basic framework' of radiological protection given in ICRP Publication 60 [1] but only the systems of protection for practices and intervention are then developed in detail. The components of justification, optimisation and limitation in the alternative framework for radiation protection in clean-up situations as recommended by IAEA are discussed below.

Justification
Justification decisions in the context of clean-up will often be very complex, and could involve factors such as non-radiological risks and environmental effects, economic costs and benefits, and a wide range of social and political factors, as well as the radiological risks. The proper consideration of many of these factors may require expertise far beyond radiological protection. Nevertheless, consideration of justification in terms only of monetary costs of clean-up and monetary values of doses saved can provide useful information.

In particular circumstances, a constraint on residual risks may be considered to be appropriate for reasons of equity, and clean-up to at least meet the constraint would than be required. In such cases, it is possible that the clean-up may otherwise appear not to be justified. This needs to be considered carefully when decisions are made on whether to impose constraints - the perceived benefit from imposing a constraint may need to be sufficient to justify otherwise unjustified measures.

Optimisation
The word *reasonably* is clearly the key to the optimisation principle, and in a general system of protection needs to have a very broad definition (arguably even broader than in the optimisation principle of the system for practices). For example, it is not reasonable to expect significant resources to be devoted to reduce risks that are already negligible, or that could only be reduced further by means that are clearly not cost-effective, or are simply not feasible. This example is the basis for exemption and exclusion concepts.

One particular issue that may be relevant in the implementation of the optimisation principle is whether options involving restrictions on use of the land should be treated on an equal basis to those that would allow unrestricted use. In this context, sustainability may be an important factor - short-term restrictions on the use of small areas are unlikely to be of major concern, but a situation in which large areas are subject to long-term restrictions may not be sustainable.

Protection of the individual to limit inequity
The key word in the individual protection principle is *inequity*. In fact, it is arguable whether a separate principle is needed - the concept of equity (or limiting *in*equity) can be regarded simply as a further extension of the definition of reasonably in the optimisation principle. For example, *equity* requires that particular efforts be made in all circumstances to avoid individuals receiving doses high enough to cause serious deterministic health effects, but the same conclusion could be reached by saying that this is simply a reasonable thing to expect.

Actions can comply with the justification and optimisation principles whether they increase or decrease radiation risks. However, the protection of the individual principle would place particular emphasis on the responsibilities of people knowingly taking actions that are likely to increase radiological risks from sources under their control (*e.g.* by introducing new sources or modifying exposure to existing sources) in return for other benefits, such as economic profit or reduction in non-radiological risks. This emphasis is especially relevant in respect of additional risks that are imposed on individuals who are not necessarily receiving a corresponding benefit. In such cases, the additional imposed risks are controllable, and therefore it is reasonable to expect them to be controlled so that they do not substantially affect such individuals' overall risk. This argument leads to the concepts of constraining optimisation to limit inequity, and of limits on the overall imposed risks to any individual.

Considerations of equity lead one to expect that similar situations will be handled in a similar way, so that the imposed risks do not differ greatly between different situations which have most important features in common (again, this conclusion could equally well be reached from consideration of 'reasonableness'). Whereas inequity in the risk and benefit distribution associated with a particular source tends to arise from the optimisation process and may need to be limited by constraints, the potential inequity between individuals at different, but similar, sites may be expected to be reduced by optimisation, and it is the inconsistent use of constraints on optimisation that could create it. For example, if unconstrained optimisation were applied to determine clean-up levels for two similar sites, one would expect to get similar answers, but if one optimisation were to be constrained the answers could be significantly different.

2.2.3 Generic guidance on clean-up

The above discussion is summarised in Table 2 [5]. The doses quoted are additions to background. For Bands 5 and 6, however, the additional dose is large compared to average background, and so the criteria would reasonably be applied to the total dose if this is more convenient.

Table 2. Summary of recommended generic clean-up levels (action levels) in terms of annual individual doses before a justified clean-up [5].

Band No.	Ranges of annual doses	Is clean-up needed?	
		With constraint	Without constraint
Band 1	$< 10\ \mu Sv \cdot a^{-1}$	almost never	almost never
Band 2	$10 - 100\ \mu Sv \cdot a^{-1}$	sometimes	rarely
Band 3	$0.1 - 1\ mSv \cdot a^{-1}$	normally	sometimes
Band 4	$1 - 10\ mSv \cdot a^{-1}$	almost always	usually
Band 5	$10 - 100\ mSv \cdot a^{-1}$	always	almost always
Band 6	$> 100\ mSv \cdot a^{-1}$	always	always

As will be apparent from the foregoing discussion, the dose rates dividing the bands can only be approximations in view of the uncertainties involved. Nevertheless it is convenient to have single numbers to represent criteria, and considerable presentational problems may be expected if slightly different numbers are quoted in different situations.

In this case, the most significant criterion that cannot readily be linked to existing criteria is probably that *dividing Bands 4 and 5.* This represents a point above which clean-up would normally be expected to be undertaken in unconstrained situations, and therefore also represents the maximum level of residual risk that - apart from exceptional circumstances - might be considered acceptable. Therefore, situations with annual individual doses *above* this level would never be considered as normal whereas situations with annual individual doses *below* this level would in most cases - but not always - be considered as normal. In cases where the residual dose is characterised as 'normal' it would henceforth be considered 'background'.

The choice of $10\ mSv \cdot a^{-1}$ for this boundary between *normalcy* and *abnormalcy* is necessarily a judgement, but is felt to be robust in the face of a number of considerations, including:

- world-wide variation in natural background dose rates;
- action levels recommended by ICRP for radon in dwellings [4];
- doses implied by Codex Alimentarius levels of activity in foodstuffs [9]; and

- IAEA recommendations on criteria for resettlement of populations [6].

These issues are consistent with a generic criterion in the region of *10 mSv per year* [5] as a level above which some form of clean-up would normally almost always be justified.

As noted above, generic criteria such as those in Table 2 will not be appropriate in all situations. However, any perceived inconsistency in criteria may have negative effects in terms of public acceptance that could well outweigh the economic or radiological benefits to be gained by using situation-specific rather than generic criteria. Therefore, where local factors do support the use of situation-specific criteria that differ significantly from the generic ones, these factors, and the effect they have been considered to have on the criteria (including any judgements or assumptions made), should be clearly stated.

3 Application of the justification and optimisation principles

Taking into consideration only the avertable dose to the population, the doses to the workers engaged in the clean-up and the monetary costs of the cleaning operation the following factors would enter the justification/optimisation process for determining action levels for the clean-up:

- the number of people living in the contaminated area, N_{pop}
- the size of the contaminated area, A
- the monetary cost of the clean-up per unit area, c_{clean}
- the number of workers carrying out the clean-up, N_{work}
- the collective dose to the clean-up personnel, $S_{\mathrm{work}} = E_{\mathrm{work}} \cdot N_{\mathrm{work}}$
- the efficiency of the clean-up operation (fraction of activity removed), η
- the reduction factor of dose rate, $f = (1 - \eta)^{-1}$
- the equivalent monetary cost of the unit collective dose, α

In the calculations of justified clean-up levels, two different situations can be considered, namely contaminated areas from which people have not been relocated and areas from which people have been relocated. Below is given examples for non-relocated residential areas.

3.1 Justified action levels for clean-up of residential areas

The condition for a clean-up operation to be justified is that the monetary value of the avertable collective dose, ΔS, from the clean-up is larger than the sum of the monetary value of the collective dose to the clean-up workers and the cost of the clean-up operation:

$$\alpha \cdot \Delta S \geq \alpha \cdot E_{\mathrm{work}} \cdot N_{\mathrm{work}} + c_{\mathrm{clean}} \cdot A \approx c_{\mathrm{clean}} \cdot A$$

The cost of the collective dose the clean-up workers will normally be marginal compared to the other clean-up costs and therefore the first term in the above equation can be disregarded. The annual individual effective dose, E_{an}, above which clean-up is justified can be found from the following considerations.

It is assumed that the annual dose from deposited activity is proportional to the relative deposition velocity, v, to the given surface type (house, grass, soil and asphalt) as well as to the fraction, x, and to the occupancy, w, at that surface. Therefore, the dose rate reduction factor, f, can be calculated as:

$$f = \frac{\sum_i w_i \cdot v_i \cdot x_i}{\sum_i (1 - \eta_i) \cdot w_i \cdot v_i \cdot x_i}$$

The avertable collective dose over time, T, with clean-up with dose rate reduction factor, f, will determine the annual individual dose before clean-up, E_{an}, above which clean-up is justified as:

$$\alpha \cdot \Delta S = \alpha \cdot N_{\text{pop}} \cdot \frac{f-1}{f} \cdot E_{\text{an}} \cdot T \geq c_{\text{clean}} \cdot A$$

With a population density $P_{\text{pop}} = N_{\text{pop}}/A$ the value of the annual effective dose above which clean-up is justified, E_{an}, can be found to be:

$$(E_{\text{an}})_{\text{just}} = \frac{f}{f-1} \cdot \frac{c_{\text{clean}}}{\alpha \cdot P_{\text{pop}} \cdot T}$$

Figure 1 illustrates the effect of a clean-up operation which results in a reduction of the collective dose, ΔS, by a factor f.

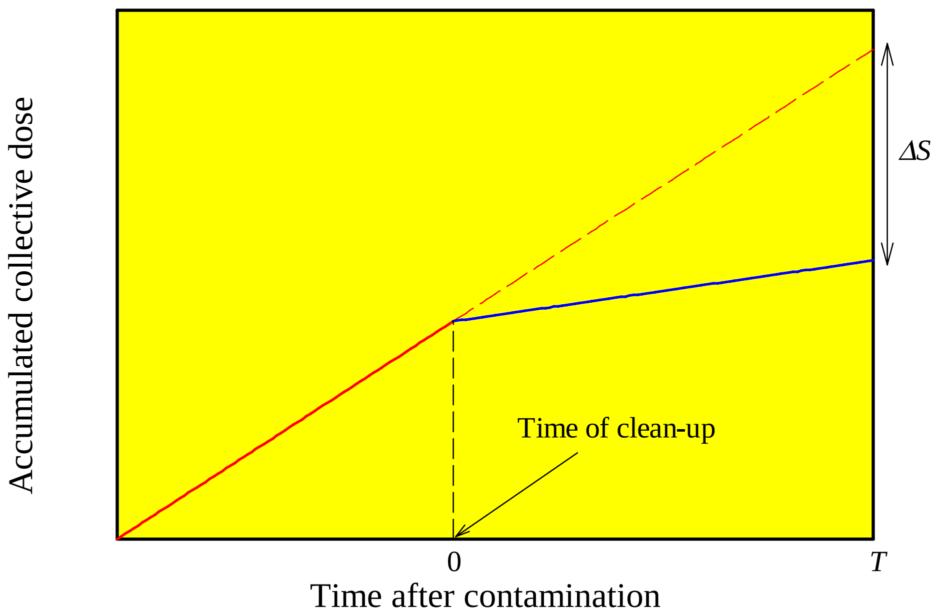

Figure 1. Avertable collective dose, ΔS, from remediation with a clean-up reduction factor, f.

Calculations of the minimum annual effective dose, E_{an}, above clean-up of urban and semi-urban areas is justified have been made with the program Crystal Ball based on different distributions of the parameters in the above equations. The results are shown in Table 3.

Table 3. Minimum justified action levels, $AL_{\min}$, in mSv·a^{-1} above which clean-up is justified based on avertable dose and monetary costs of the clean-up of urban and semi-urban areas.

Area type	Distribution	Percentiles		Mean	Median
		2.5%	97.5%		
Urban	uniform	0.2	3.2	0.9	0.6
	log-normal	0.1	1.6	0.6	0.5
Semi-urban	uniform	0.6	12	3.0	2.1
	log-normal	0.5	5.1	1.9	1.6

The justification conditions can be further elaborated upon. If it is assumed that the clean-up costs, c_{clean}, per unit area is proportional to the clean-up reduction factor, f, given as $k \cdot f$, the net benefit, $B(f)$, can be expressed as:

$$B(f) = \alpha \cdot N_{\text{pop}} \cdot \frac{f-1}{f} \cdot E_{\text{an}} \cdot T - k \cdot f \cdot A$$

Clean-up is justified if $B(f) > 0$ for any value of f. Let the population density, P_{pop}, be defined as N_{pop}/A and the dimensionless parameter u as:

$$u = \frac{\alpha}{k} \cdot \frac{P_{\text{pop}} \cdot E_{\text{an}} \cdot T}{2} = \frac{1}{2} \cdot E_{\text{an}} \cdot z$$

where $z = (\alpha/k) \cdot P_{\text{pop}} \cdot T$. Clean-up is not justified if $u < 2$. If $u > 2$, there is a range of justified reduction factors, $[f_{\min}, f_{\max}]$, given as:

$$f_{\min} = u \cdot \left(1 - \sqrt{1 - \frac{2}{u}}\right)$$

$$f_{\max} = u \cdot \left(1 + \sqrt{1 - \frac{2}{u}}\right)$$

If $u = 2$, the reduction factor, f, has only one value (2) as shown in Figure 2.

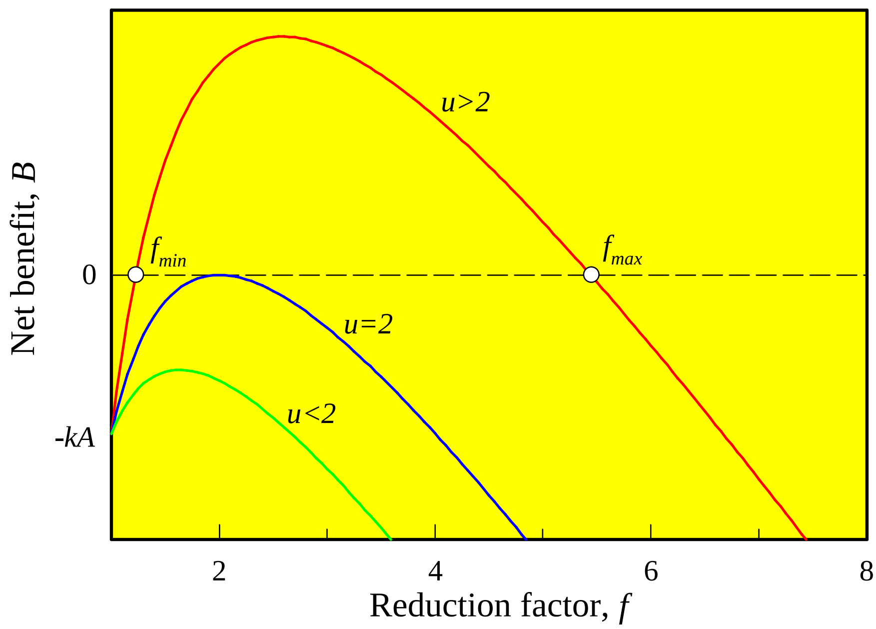

Figure 2. Net benefit of clean-up operation. The condition for the net benefit, $B(f)$, being positive is that the parameter, u, is greater or equal to 2. If $u > 2$ there is a range of justified clean-up reduction factors $[f_{\min}, f_{\max}]$. The optimised value, f_{opt}, is equal to $\sqrt{2u}$ and $f_{\min} < f_{\mathrm{opt}} < f_{\max}$.

3.2 Optimisation of clean-up reduction factors

The optimised value of the reduction factor, f_{opt}, can be found from:

$$\frac{\mathrm{d}B(f)}{\mathrm{d}f} = 0 \quad \Rightarrow \quad f_{\mathrm{opt}} = \sqrt{2u}$$

which can be rewritten as:

$$\frac{f_{\mathrm{opt}}}{\sqrt{E_{\mathrm{an}}}} = \sqrt{\frac{\alpha}{k} \cdot P_{\mathrm{pop}} \cdot T}$$

Values of $z = (\alpha/k) \cdot P_{\mathrm{pop}} \cdot T$ will be more or less independent on geography as the cost parameters α and k are similarly related to the wealth of the country. Generic values of z will probably fall in the range of 1,000 - 100,000 a·Sv^{-1}, although off-range values are possible, *e.g.* expensive operations in areas with a low population density (low z-values) or low-cost operations in areas with a high population density (high z-values).

Values of f_{opt} are shown in Figure 3 as a function of the annual dose level, E_{an}. The residual dose, E_{res}, after an optimised clean-up operation can be found from Figure 3. As $f_{\mathrm{opt}} = g(E_{\mathrm{an}})$ the residual dose can be found as the ratio $E_{\mathrm{an}}/g(E_{\mathrm{an}})$ and can also be calculated as f_{opt}/z. As an example, it appears from Figure 3 that optimised clean-up in areas with a z-value of 10,000 a·Sv^{-1} and an annual dose of 10 mSv·a^{-1} would result in a residual dose after clean-up of 1 mSv·a^{-1} ($f_{\mathrm{opt}} = 10$). In areas with a high z-value of 100,000 a·Sv^{-1} and an annual dose of 10 mSv·a^{-1}, optimised clean-up would result in a residual dose after clean-up of 0.3 mSv·a^{-1} ($f_{\mathrm{opt}} = 30$).

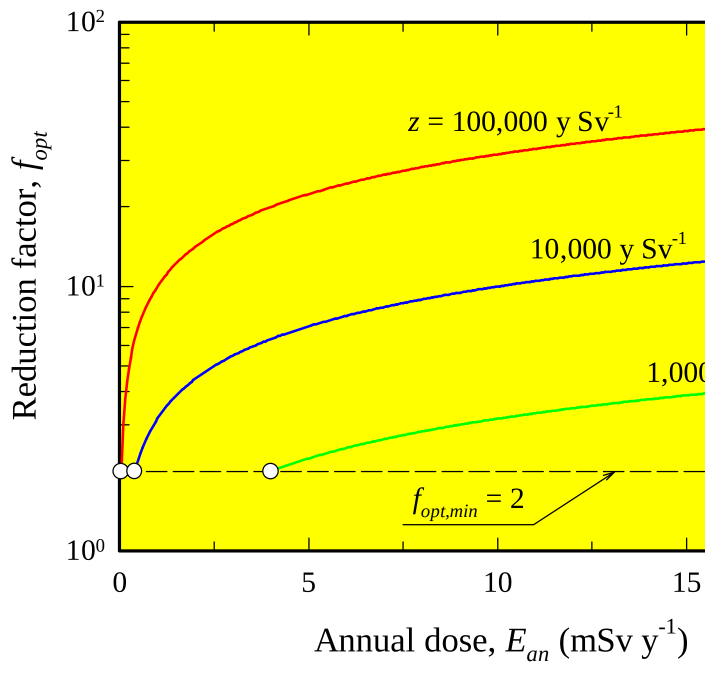

Figure 3. Optimum value of the reduction factor, $f_{\rm opt}$, for three different values of z. The minimum value of an optimised reduction factor, $f_{\rm opt,min}$, is equal to 2.

In conclusion, the generic justification calculations indicate that a minimum justified action level, $AL_{\rm min}$, in terms of annual dose before clean-up would fall in the range from a fraction of a millisievert per year to several millisievert per year. At annual dose levels of that magnitude clean-up starts to be justified (see Table 3). The optimisation calculation shows that optimised reduction factors will always be larger than 2 and proportional to the square root of the actual dose level. If the residual dose level after clean-up is much higher than a few millisieverts per year this would invoke the countermeasures appropriate for the later phases of a nuclear emergency. When assessed residual individual doses after clean-up are in the region of 10 mSv·a^{-1} or greater, corresponding to a lifetime dose of about 1 Sv, this would probably invoke permanent relocation in chronic or semi-chronic exposure situations. Consequently, areas with an annual dose level of 10 mSv·a^{-1} or greater would almost always be subject to clean-up operations.

4 Relation to Project RESTRAT

Chronic or semi-chronic exposure situations may call for clean-up measures to protect the exposed or potentially exposed populations. Such protective measures can be fitted within the framework of practices and intervention, although this is not always entirely straightforward. It has therefore been suggested by working groups within IAEA [5] and ICRP [2] to investigate a broader and more general system in which the whole range of clean-up or chronic exposure situations can more readily be accommodated.

Such a general system does not invalidate the concepts of practices and intervention, but rather places them in a wider context in which they provide interpretations of the way in which the overall system applies to particular types of situation. Where situations fit well into one category or the other, this provides a valuable 'short-cut' in the form of a simpler ready-made system of protection. Where some situations do not fit well, it may be better not to persevere with the categorisation.

This formulation is consistent with the ICRP's overall objective for radiological protection. In chronic exposure situations that need to be reduced by clean-up these elements of protection should be applied to determine whether to carry out remedial actions, and then to optimise the form and scale of remedial actions, subject to any constraints for protection of the individual that may be considered appropriate.

Generic justification calculations indicate (see Table 3) that a *minimum* justified action level in terms of annual individual dose before clean-up would fall in the range from *a fraction of a millisievert per year to several millisievert per year*. At annual dose levels of that magnitude clean-up starts to be justified. Areas with an annual dose level of 10 mSv·a^{-1} or greater would almost always be subject to clean-up operations. The choice of 10 mSv·a^{-1} is a judgement, but is felt to be robust in the face of a number of considerations, including: (a) world-wide variation in natural background dose rates, (b) action levels recommended by ICRP for radon in dwellings [4], (c) doses implied by Codex Alimentarius levels of activity in foodstuffs [9], and (d) IAEA recommendations on criteria for resettlement of populations [6].

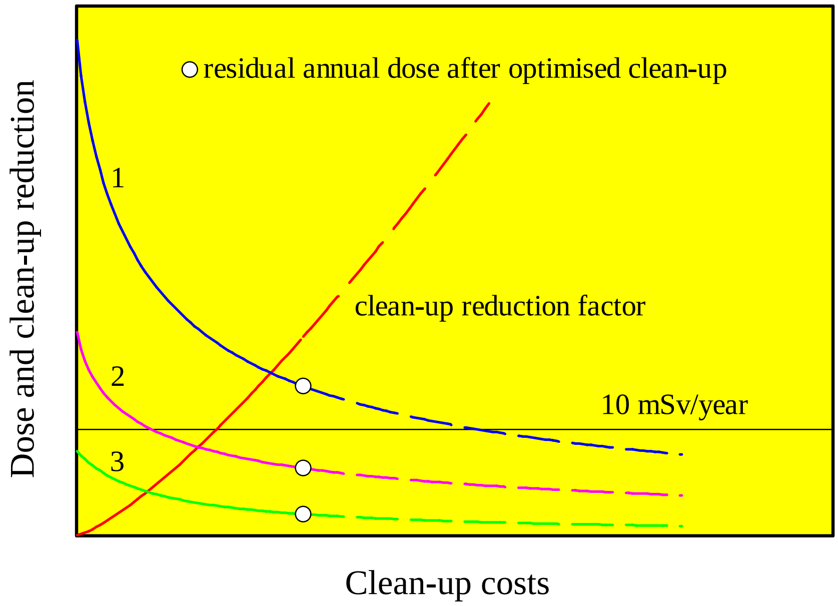

Figure 4. Clean-up of an area with three hypothetical exposure situations. In all three situations clean-up is justified and optimised based on dose reduction and costs of the clean-up. As the residual dose for situation 1 is greater than 10 mSv·a^{-1}, the acceptance of such a residual dose level will depend on the site specific conditions.

These issues are consistent with a generic criterion in the region of 10 mSv·a^{-1} as a level above which some form of clean-up would normally be expected [5]. This approach does not imply that below such a level it is never worthwhile to implement remedial actions. If it is justified such actions should always be taken, the form and scale being determined by optimisation. This is illustrated in Figure 4 for three hypothetical contamination situations.

Decisions on clean-up in chronic or semi-chronic exposure situations may well go far beyond purely radiological protection considerations. Satisfying the justification principle requires that the overall effect of the activity involved should do more good than harm, taking account of relevant radiological and non-radiological factors. The decisions can often be limited to considerations of whether or not any of the range of possible remedial actions will itself result in a net benefit. In reaching such decisions it is important to consider carefully the benefits and disadvantages because some remedial actions can significantly disrupt the exposed population.

The analysis should address both radiological and non-radiological issues. Examination of the first of these will be straightforward, in principle, since it involves only the radiation detriment to be averted and the costs associated with the remedial action (including both the direct cost of the action and costs to affected parties). Examination of the second class of issues will involve, in addition to consideration of other hazards (such as those associated with chemical contaminants), economic, and social considerations, some of which are beyond the scope of radiation protection. If it is determined that some remediation is justified on either of the above grounds then the next step is to optimise the proposed remedial action.

Situations for which remediation is not justified will fall into one of two quite different categories. The first is comprised of cases where the contamination and doses are sufficiently insignificant that no costs for remediation are justified. The other includes cases where the contamination is so extensive and severe and/or the costs are so large as to make pursuing remediation impracticable (*e.g.* situation 1 in Figure 4). In the first of these cases it will still be necessary to consider whether remediation is required to satisfy criteria for unrestricted use, and in the second to consider criteria for determining the extent to which use of the land involved should be restricted.

The individual lifetime risk of stochastic effects after remedial actions have been implemented is often of significant concern to national authorities. In this context, a lifetime is normally taken to be 70 years, and the calculation of risk should take into account the most sensitive groups, *i.e.* children, who also have the longest life expectation. In some circumstances remediation may be required to protect the current population, or may be indicated on the basis of an optimisation study that considers attributable health effects in future generations. Whilst in most cases the cost of remediation, in terms of disruption, inconvenience, etc., will be borne by the current population, it should be noted that any remedial actions taken to protect the current generation will also protect each future generation at least equally.

This is particularly the case in most situations involving very long-lived radionuclides. In such situations the collective dose to the current generation may be relatively small, but the total collective dose to future generations (due, for instance, to future contamination of ground water supplies) may be substantial and consequently have a large effect on the decision on remediation. Indeed, remediation not justified in respect of the current population may be justified by taking account of many future generations. For this reason the temporal and spatial distributions of collective dose should be carefully considered.

There are a number of theoretical bases on which a time cut-off in collective dose calculation can be postulated. Truncation where the dose rates become so low that further integration leads to essentially no further increase in collective dose would be entirely sensible, but this point can only be determined on a case-by-case basis and cannot be used as a general time cut-off. There are, however, very real practical and scientific grounds for cut-off. Long time frames create practical difficulties for protection because of the uncertainty associated with assumptions about human behaviour and the environment. This uncertainty makes such calculations increasingly difficult to justify the further they are advanced into the future. UNSCEAR apply an integration period of 500 years for nuclear power, and indicate that the collective dose integrated to infinity should not be presented as single figures in recognition of the uncertainties associated with their calculation.

Risk factors may be applied to collective dose figures in order to obtain an index of radiological detriment. Over long time-scales, these risk factors come more into question since environmental, social and medical developments may have a profound effect on the factors included in calculations of health detriments. Since it is clear that these data are not likely to be reliable in the long-term, this suggests that the weight attached to collective dose in decisions should decrease with time. Care should therefore be exercised in using collective doses relating to time periods more than a few hundred years into the future as direct indicators of the expected health detriment. In decision making, less significance should be attached to collective dose estimates relation to periods beyond 500 years into the future than to those relating to shorter time periods [10].

Clean-up criteria would generally, as indicated above, be expressed in dose, either as annual or as lifetime dose. However, these criteria may not be readily or directly measurable and the criteria may generally be converted into more readily measurable quantities, operational quantities, such as activity concentration ($Bq{\cdot}kg^{-1}$ or $Bq{\cdot}l^{-1}$), dose rate ($\mu Sv{\cdot}h^{-1}$) and surface contamination density ($Bq{\cdot}m^{-2}$) in the contaminated media.

Operational quantities correspond to avertable or residual dose levels and are derived by mathematically modelling of all the significant pathways of exposure and the projected relevant behaviour of the critical group. Such calculations require a detailed understanding of all the relevant environmental factors for the area, the reasonably possible exposure pathways by which humans may be exposed to radiation from this area, and the scenarios that describe how the site will be used after implementation of the remediation.

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Remediation of Contaminated Areas
An Overview of International Guidance

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Abstract (Max. 2000 char.)

The work described in this report has been performed as a part of the RESTRAT Project FI4P-CT95-0021a (PL 950128) co-funded by the Nuclear Fission Safety Programme of the European Commission. The RESTRAT project has the overall objective of developing generic methodologies for ranking restoration techniques as a function of contamination and site characteristics. The project includes analyses of existing remediation methodologies and contaminated sites, and is structured in the following steps:

- characterisation of relevant contaminated sites
- identification and characterisation of relevant restoration techniques
- assessment of the radiological impact
- development and application of a selection methodology for restoration options
- formulation of generic conclusions and development of a manual

The project is intended to apply to situations in which sites with nuclear installations have been contaminated with radioactive materials as a result of the operation of these installations. The areas considered for remedial measures include contaminated land areas, rivers and sediments in rivers, lakes, and sea areas.

Criteria for clean-up of contaminated land and criteria for protection of the public against chronic exposure are being developed by Advisory Groups and Task Groups within the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP). This work has been reviewed and a status as of the beginning of 1998 is given.

For illustrative purposes, the basic radiation protection principles of justification and optimisation have been applied to derive generic action levels for clean-up of residential areas contaminated with radioactive materials. These generic action levels are based upon cost-benefit analyses that include avertable doses and monetary costs of clean-up.

Descriptors INIS/EDB

CONTAMINATION; COST; COST BENEFIT ANALYSIS; DECISION MAKING; DECONTAMINATION; IAEA; ICRP; NUCLEAR FACILITIES; OPTIMIZATION; RADIATION DOSES; RADIATION PROTECTION; RECOMMENDATIONS; REMEDIAL ACTION;