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Purposes of planning for radiation accidents

Safety analyses of nuclear installations usually identify and describe a wide range of potential accident sequences leading to exposure of the public. The predicted frequency of these accidents usually decreases as the magnitude of the corresponding releases increases.

Emergency plans should be designed to deal with an appropriately wide range of possible accidents. However, it would be a misallocation of resources to prepare detailed emergency plans and procedures for dealing with hypothetical accidents having extremely low probability of occurrence, even if the associated potential consequences may be very high. Therefore, such worst-case scenarios will not be covered in this report, although their consideration may be useful for other applications such as the characterization of the overall risk associated with a nuclear installation, for the purposes of siting and risk assessment.

The choice of the upper end of the frequency range of potential accident sequences on which to base emergency plans should therefore be an appropriate compromise between the requirement to protect the potentially exposed population (which would imply consideration, for planning purposes, of severe accidents) and that of practicability of emergency countermeasures (which would imply avoidance of committing disproportionately large amounts of resources to cope with very unlikely events). This threshold is frequently associated with accident sequences (called "reference accidents" in this report) which historically have had frequencies of occurrence in the range 10^{-4}–10^{-3} per year. The more modern designs of nuclear reactor have lower frequencies for the same magnitude of release *(4)* but emergency plans still consider the same order of release for preparatory planning.

Characteristics of Releases from Nuclear Installations

The majority of accidents requiring an off-site response will involve at some stage the potential or actual release of radioactive materials to the atmosphere. As emphasized in the Introduction, this report is primarily concerned with the consequences of these atmospheric releases.

The probability of occurrence, magnitude and isotopic composition of an accidental release will vary depending on the type of nuclear facility and the severity of the accident. In the preparation of emergency plans, different source terms are considered, each being defined by the quantities of the different radionuclides liable to be released, their physicochemical form, the amount of time available before the release commences, and the expected duration of the release. These time factors are very important and may be decisive in the selection of the most effective and practicable protective measures to reduce the potential health consequences to the public.

The interval between the recognition of the start of an accident sequence having the potential for off-site consequences and the emergence of radioactive material into the atmosphere is important. If it is very short, only limited off-site action may be feasible before the release actually starts; this is improbable at large nuclear facilities with elaborate safety systems. In most cases there will be a delay before the uncontrolled release occurs, which may vary from about half an hour to one day or more *(5)*.

The duration of release also has important off-site consequences and may last from a fraction of an hour to several days *(1,5)*. Within this period there may be irregular and unpredictable peaks in the release rate. During the course of prolonged releases, changes may occur in the meteorological conditions, such as atmospheric stability, wind direction and velocity, or the presence and degree of precipitation. All these factors may modify the concentration of the dispersed radionuclides. For example, a change in meteorological conditions may well decrease the concentration, thus reducing the individual doses received, but may lead to population groups becoming involved who were not identified in the earlier stages.

At the stage of decision-making on emergency planning, it is for national regulatory authorities to decide on the level of consequences and the probability of occurrence that they are prepared to adopt in the definition of the reference accident. They would generally require that there exists a significant discontinuity in the probability–consequence relationship, so that more severe but very unlikely accidents can be discounted for emergency planning purposes.

The data and value ranges presented in the examples result from a review of a number of safety assessments carried out by competent authorities in several countries *(4,6–11)*. Table 1 shows the orders of magnitude of the release of the groups of radionuclides which are most relevant in the case of a reference accident in a light-water-cooled reactor producing 1000 MW of electricity per year. The possible range of radiological consequences associated with these typical releases depends on the distance to the nearest population group and on meteorological conditions. Orders of magnitude of individual doses are shown in Table 2 for the more important exposure pathways during the early phase of a release, namely the whole-body dose by external irradiation due to exposure to the airborne plume, the dose to the thyroid of children by inhalation of radioiodine from the cloud, and the dose to the lung by inhalation of radioactive aerosols. These doses are given merely to offer public health authorities an idea of the order of magnitude of individual doses liable to arise in the event of a nuclear emergency severe enough to activate the emergency plan. They should *not* be regarded as definitive for a particular nuclear plant at a given location.

Table 1. Example of a range of atmospheric releases from a reference accident

Range of annual probabilities	Total activity release (Bq)	Activity (Bq) associated with:		
		noble gases	iodine	other radionuclides (Ru, Cs)
10^{-4}–10^{-3}	10^{16}–10^{17}	~ 10^{16}–10^{17}	10^{13}–10^{14}	10^{13}–10^{14}

Table 2. Example of a range of radiation exposures from a reference accident

Type of dose (Sv)	Distance from the point of release		
	1 km	3 km	10 km
Whole-body (external irradiation)	10^{-2}–10^{-1}	5×10^{-3}–5×10^{-2}	10^{-3}–10^{-2}
Thyroid (inhalation)	10^{-1}–1	10^{-2}–10^{-1}	10^{-3}–10^{-2}
Lung[a] (inhalation)	10^{-2}–1	10^{-3}–10^{-1}	10^{-4}–10^{-2}

[a] The lung dose values depend heavily on the radioisotopic composition of the "other" nuclides released

Source: **Kelly, G.N. et al.** *(12)* and **Charles, D. & Kelly, G.N.** *(13)*.

Time Phases

For the purposes of developing intervention levels three phases of an accident have been identified, which are generally accepted as being common to all accident sequences *(1,3)* — the early, intermediate and late (or recovery) phases. Although these phases cannot be represented by precise periods, and may overlap, they provide a useful framework within which the radiological criteria were established in the last report *(1)*.

Early phase

The early phase is defined by the period when there is the threat of a serious release, i.e. from the time when the potential for off-site exposure is recognized to the first few hours after the beginning of a release, if a release occurs. The interval between the recognition of an accident sequence and the start of the release can be from less than half an hour to about a day *(1,5)* and the duration of the release may be between half an hour and several days. This variation in timing renders difficult decisions about the introduction of countermeasures, since there will be a need to forecast the future course of the accident and thus to predict doses and potential reductions of dose for situations that will not have arisen.

The feature common to both the warning period and the first few hours of release is that operational decisions are based on analysis of data from the nuclear installation itself and existing meteorological conditions. Thus decisions to implement countermeasures during the early phase will be based primarily on plant conditions and the associated potential doses to individuals in the population, assessed on the basis of prior analysis of plant fault sequences and probable meteorological patterns.

Some environmental measurements of off-site exposure rates and airborne concentrations from the plume may become available in this phase. Because of potential changes in release rate, meteorological conditions and wind direction, and in other unknown factors such as duration of release and the degree to which measurements represent future plume configurations, such measurements will be of minimal value for calculating projected doses.

Intermediate phase

The intermediate phase covers the period from the first few hours after the start of the release to one or more days. It is assumed that the majority of the release will have occurred at the beginning of this phase and significant amounts of radioactive material may already have been deposited on the ground, unless the release consisted only of noble gases. As previously stated, there is no clear boundary in emergency planning between the first and second phases.

It is during the intermediate phase that measurements of radioactivity in food, water and air, as well as radiation levels from deposited radioactive materials, will become available. The radiological characteristics of the deposited material will also be determined. Based on these data, dose projections can be made for principal exposure pathways, and these doses compared to pre-established intervention levels, so that decisions on the implementation of countermeasures can be made.

The intermediate phase ends when all the countermeasures based on environmental measurements have been implemented. If the accident is severe, the phase may be prolonged while extra measurements are made at locations further from the plant.

During the intermediate phase it would be expected that a group of experts would be formed from representatives of both the local and national authorities to advise on radiological protection of the public *(3)*. The responsibility for deciding on countermeasures involving the public may, in this phase, transfer from the operator who had such responsibility in the early phase to a government representative, who would be advised by the experts.

Recovery phase
The late or recovery phase is concerned with the return to normal living conditions. It may extend from some weeks to several years after the accident, the duration depending on the nature and magnitude of the release. During this phase the data obtained from environmental monitoring can be used to make the decision to return to normal living conditions, by the simultaneous or successive lifting of the various countermeasures decided during the first two phases of the accident. Alternatively, the decision could also be made to continue certain restrictions for long periods of time, with consequences for such aspects as agricultural production, occupation of certain areas or buildings, and the consumption of certain foodstuffs.

The withdrawal of countermeasures in the recovery phase will be based on analyses of actual cost, risk, benefit and societal impact of any residual contamination following decontamination, natural decay and weathering, and thus no predetermined levels have been provided for the withdrawal of countermeasures.

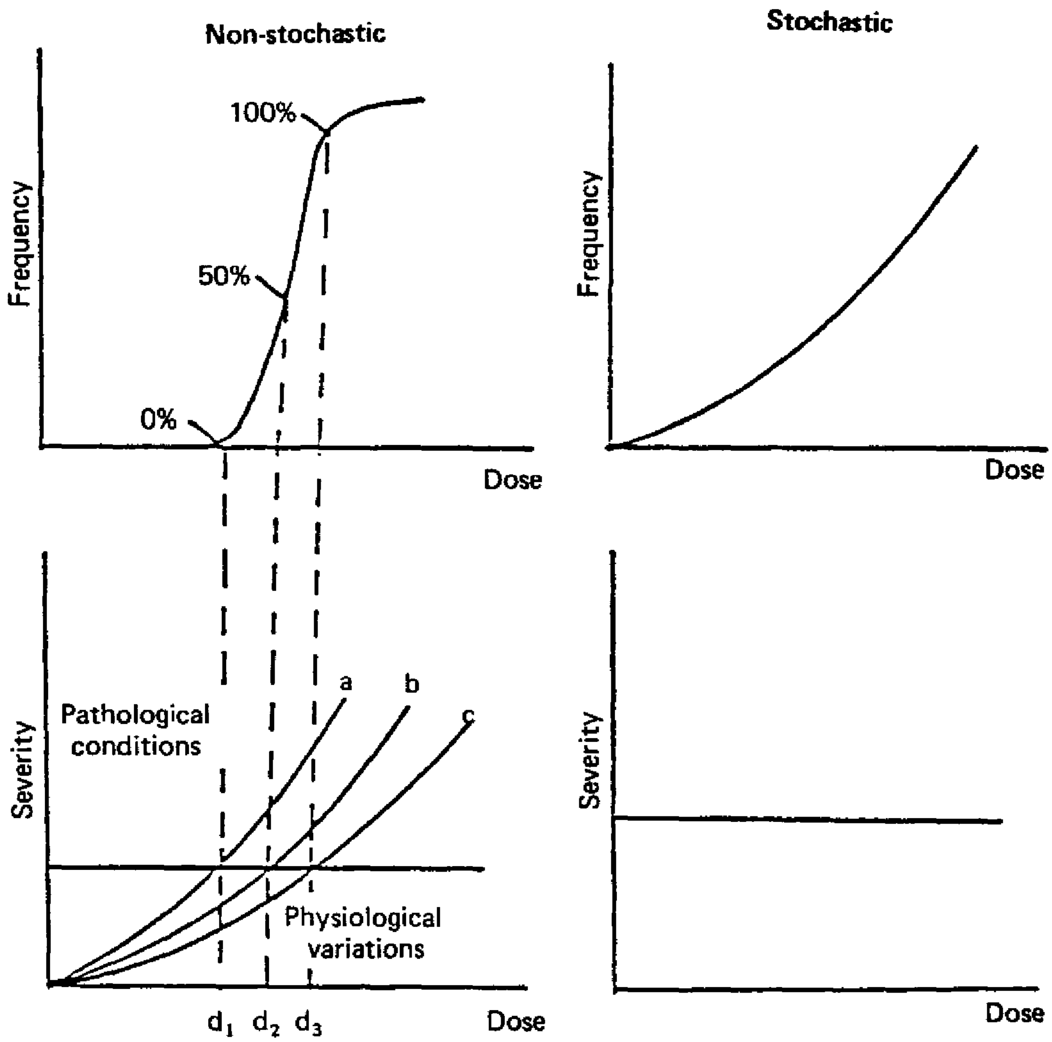
Health Effects

The previous report *(1)* described in detail the non-stochastic and stochastic effects, and only a brief summary is given here. The difference between non-stochastic and stochastic effects is illustrated in Fig. 1, which is based on an ICRP task group report *(14)*. Non-stochastic effects in individuals usually become more severe with increasing dose. In populations, an increase in dose may also result in increased frequency. Since the mechanisms of non-stochastic effects include cell death, and other effects may in themselves be observable at incipient stages, delineation of the dose–response relationship for any given type of non-stochastic effect depends on the stage and severity at which the effect is recognized. Fig. 1 shows how the frequency and severity of a non-stochastic effect, defined as a pathological condition, increase as a function of dose in a population of individuals of varying susceptibilities. The severity of the effect increases most steeply in those who are of greatest susceptibility (curve a), reaching the threshold of clinical detectability at a lower dose than in less susceptible subgroups (curves b and c). The range of doses over which the different subgroups cross the same threshold of detectability is reflected in the upper curve, which shows the frequency of the pathological condition in the population, and which reaches 100% only at that dose which is sufficient to exceed the defined threshold of severity in all members of the population.

For stochastic effects, as also illustrated in Fig. 1, the severity of the effect is independent of dose, and only the predicted frequency of the effect increases with increasing dose, without threshold.

Non-stochastic effects
The main interest in emergency planning is the identification of the dose levels below which non-stochastic effects are not likely to occur in a normal population. Non-stochastic effects can be induced in any organ or tissue given high enough doses. The discussion here is limited to effects in those

Fig. 1 Characteristic differences in dose-effect relationship between non-stochastic and stochastic effects



organs and tissues that are known to be most at risk from accidental releases from nuclear installations.

Whole-body irradiation at high enough doses will cause nausea, vomiting and diarrhoea; at even higher doses, early mortality will result from bone marrow cell depletion. Inhalation of large quantities of radioactive material will deliver high acute doses to the lung, leading to permanent impairment of lung function and even early mortality. Although severe irradiation of the gastrointestinal tract can also lead to early mortality, in nuclear accidents it is likely that irradiation of the bone marrow will be more important. Furthermore, at sufficiently high doses to the thyroid, non-stochastic effects may occur which may occasionally lead to death. Other non-lethal effects include impairment of fertility, skin damage and cataracts, but these are all less significant than those mentioned above. In addition, it should be emphasized that single-organ irradiation is most unlikely to occur in a nuclear accident, and that irradiation of several organs and tissues will be the most common type of exposure.

In the event of external irradiation *in utero*, the classic effects of sufficiently high doses on the developing fetus are gross congenital malformations, mental and growth retardation and death. For internal irradiation, differences in cellular metabolism may lead to different levels of risk. For example, the fetal thyroid is only at risk to ingested radioiodine when it is sufficiently developed to accumulate iodine.

Table 3 gives the levels of dose below which non-stochastic effects are not likely to occur in a normal population. It shows that, except for the fetus, the severe diseases and early deaths are related to high doses; accidents leading to such high doses will occur very infrequently.

Table 3. Levels of dose below which acute non-stochastic effects are unlikely to occur in a normal population

Dose (Gy)	Organ	Effect
0.1	fetus	teratogenesis
0.5	whole body	vomiting
1	whole body	early death
3	gonads	sterility
3	skin	depilation, erythema
5	lens	cataract
5	lung	pneumonitis
10	lung	early death
10	thyroid	hypothyroidism

Stochastic effects
The stochastic effects following irradiation are either late somatic or genetic. The late somatic effect of primary concern is the increased incidence of fatal and non-fatal cancers in the irradiated population. The appearance of these cancers is usually delayed and may be spread over several decades. These late somatic effects include cancers for which the cure rate is low (lung, leukaemia) and others for which the cure rate is high (skin, thyroid). However, any cancer causes psychological effects that can significantly reduce the quality of life. There is a risk that serious hereditary disease may occur in subsequent generations following irrradiation of the gonads.

Risk factors for stochastic effects are given in the previous WHO report *(1)*. These risk factors are values averaged over all ages and for both sexes of a normal population. It should be recognized that these risk factors are based on the assumption of a linear dose–response curve without threshold, and consider only fatal cancers. For specific organs these factors may vary substantially with age, sex and other variables; consequently, they may lead to overestimation or underestimation of the risk. However, as they do not take into account the non-fatal cancers, such as thyroid and skin cancers, they may underestimate the total risk of cancers of some specific organs or tissues. These risk factors should therefore be considered as approximate values, and used as such.

Psychological effects
In addition to the predicted physical health consequences of irradiation, considerable psychological effects may constitute a significant public health problem. In contrast to the health effects previously described, the level of anxiety generated by possible exposure is not related to the level of exposure. Psychological stress may well be exhibited where radiation is low or insignificant. Psychological effects can be attributed to:

— the association of nuclear accidents with the explosion of a nuclear bomb;

— the inability of the human senses to detect ionizing radiation;

— inadequate and often conflicting information concerning the accident.

Recognition of this potential problem, and planning to deal with it, is an essential component of emergency preparedness.

Countermeasures and Objectives of Emergency Planning

Emergency measures designed to reduce adverse health effects are of two types: those that reduce the radiation exposure (protective measures) and those that reduce the health consequences of accidental exposure (medical care). The potential protective measures that could be implemented are:

— sheltering

— stable iodine administration

— control of access to the affected area

— evacuation
— relocation
— control of food and water supplies
— personal decontamination
— decontamination of areas.

The implementation of one or more of these measures depends not only on the nature of the accident, and its time phase, but also on specific local conditions such as population size and climatic and meteorological conditions. As a general principle, it is reasonable only to implement those protective measures whose social cost and risk will be less than that incurred by the radiation exposure.

Sheltering

A significant reduction in whole-body and skin doses due to external irradiation can be achieved by remaining indoors during the early phase. A substantial reduction in inhalation dose, affecting thyroid and lung, can also be achieved by closing windows, doors and other openings and switching off any ventilation systems. The shielding dose reduction factor provided by buildings can vary from 0.2–0.8 in the plume to 0.08–0.4 from deposition *(1)*. Appropriate ventilation control can result in a reduction of inhalation dose by about a factor of 10.

The risk and harm resulting from short-term sheltering are low. Unplanned long-term sheltering can lead to social, medical and psychological problems.

Stable iodine administration

The administration of stable iodine compounds is effective in reducing the uptake of radioiodine by the thyroid gland. It is most effective when ingested prior to or at the time of exposure, and rapidly loses efficacy if administered a few hours after exposure. Consequently, it is necessary to ingest the stable iodine as soon as possible when a significant radioiodine release is predicted.

The recommended dosage of stable iodine compounds (KI or KIO_3) is 100 mg iodine equivalent daily for those over 1 year of age, and 50 mg iodine equivalent daily for infants. Undesirable but relatively minor side effects may occur in a very small proportion of people. In many circumstances it is unrealistic to attempt to distribute stable iodine to the population at risk once the accident has occurred; prior distribution is recommended either to individual dwellings or to focal points from which the iodine can be made available within a short time.

Control of access

Controlling the movement of people to and from the area affected by the accident will reduce the number exposed and facilitate emergency operations. Difficulties may arise if this countermeasure is maintained, as population groups may be anxious to move from or to return to their homes, to tend to domestic animals, or to salvage goods or products from the closed areas. With adequate control, the risk of traffic accidents should be minimal.

Evacuation

Evacuation is effective against external and internal exposure, but is a very disruptive measure and most difficult to implement. This is particularly true when large populations are involved. It should therefore be applied only when absolutely necessary to avoid short-term accumulation of doses leading to non-stochastic effects, and as far as possible to small population groups in the vicinity of the nuclear facility. It should be remembered that evacuation requires time to implement and will probably be most effective either if there is sufficient warning before a release or if it is used to avoid exposure to deposited radionuclides during the intermediate phase. Any emergency plan should take into account the private exodus of people from both affected and unaffected areas so as to minimize the disruptive effect. Although the social and economic costs of evacuation may be high, the risks to health are considered to be relatively small and will primarily result from traffic accidents.

Relocation

Relocation is implemented to avoid long-term high doses from the ground deposition of radionuclides, usually after the release has ended. It is less urgent than evacuation, and may be either short- or long-term. It is expensive, and depends on the availability of an appropriate reception area. The stress involved in relocation should not be underestimated.

Control of food and water supplies

Food control may entail destroying contaminated foodstuffs or restricting or banning their consumption, delaying their consumption by converting them to other products (e.g. milk to cheese), or storing them until the activity decreases to an acceptable level.

Control of water supplies usually means prohibiting the use of water from a contaminated source for any purpose.

Such measures may cause other problems in areas where there is already a shortage of food and/or water.

Personal decontamination

Personal decontamination should be undertaken only where there is evidence or a strong suspicion of body surface contamination. In general, domestic showers are adequate for decontaminating the skin, and most contamination of clothing can be removed by laundering.

Medical assistance may be required if there are contaminated injuries or where contamination cannot be removed by repeated washing. The only risk from personal decontamination is that of spreading radioactivity to previously uncontaminated areas.

Decontamination of areas
This protective measure involves the removal of contamination from the affected area to another location where it will be less hazardous. It may consist of washing, vacuum cleaning surfaces, ploughing agricultural land, or removing surface layers of soil. These measures are effective in reducing external radiation from deposited radioactivity and in restricting internal doses from the inhalation of resuspended radionuclides. The risk is to those who are exposed in performing the procedures.

The applicability of protective measures during various phases of the accident is shown in Table 4.

Table 4. Range of applicability of various countermeasures

Countermeasure	Phase		
	early	intermediate	late
Sheltering	+	±	—
Radioprotective prophylaxis	+	±	—
Respiratory protection	+	—	—
Body protection	±	±	—
Evacuation	+	+	—
Personal decontamination	±	±	±
Relocation	—	+	±
Control of access	±	+	±
Food control	—	+	+
Decontamination of areas	—	±	+

+ = Applicable and possibly essential
± = Applicable
— = Not applicable or of limited application

Source: **International Atomic Energy Agency** *(5)*.

Guidance on Dose Value for the Introduction of Protective Measures

The principles for protection are identified in the Introduction to this book as:

— avoidance, if possible, of non-stochastic effects in individuals;

— limitation of individual stochastic risks by balancing the risk and cost of countermeasures against the risk and cost of further exposure;

— limiting the residual health detriment in the affected population.

The individual exposure should be as low as reasonably achievable, taking into account the risk of exposure and the risk associated with the countermeasures.

The decision to implement a protective measure, particularly in the early and intermediate phases, must be made on the basis of the risk to the potentially exposed individual, and the dosimetric quantity used must, therefore, express this risk. The quantity "effective dose equivalent" has been recommended *(1, 15)* for expressing the risk to individual members of the public during normal operation; this cannot, however, be applied to non-stochastic effects following accidents, since the risk coefficients and their associated weighting factors are based on fatal cancer incidence and serious hereditary defects with the assumption of proportionality between dose and risk. Therefore, the quantity that should be used to evaluate the non-stochastic effects will be the *absorbed dose*. In most accidents, the primary exposure of the public will be from beta- and gamma-radiation, and *dose equivalent* may be considered the suitable dosimetric quantity for expressing the stochastic risk to the individual.

Where an intake of radioactive material occurs at levels at which non-stochastic effects cannot occur, the individual *committed dose equivalent* is generally an accepted quantity to be applied to members of the general public. Other dosimetric quantities, such as the *collective dose*, will be of interest in decision-making during the late phase as part of an input to the general process of cost–benefit analysis.

Establishment of ranges of individual dose

It is clear that the risks, difficulties and disruption that follow the implementation of the various protective measures are widely different and thus the level of dose at which a given protective measure will be introduced is influenced by such considerations as well as by other site-specific factors. For these reasons, it is not possible to set one generally applicable intervention level at which a particular action would always be required. On the other hand it should be possible to define for each protective measure, on radiation protection grounds, a lower level of dose below which the introduction of the protective measure would not be warranted, and an upper level of dose for which its implementation should almost certainly be attempted. These two levels may be of guidance to national authorities when setting criteria for introducing protective measures.

The early phase

The introduction of sheltering for a limited period of time and, where appropriate, the administration of stable iodine, are countermeasures that have been accepted by many national authorities as constituting only a small risk to the individual. On radiological protection grounds the introduction of such countermeasures would not appear to be warranted at projected doses, liable to be received in the short term, that are below the dose limits recommended for members of the public in any one year (5 mSv). It would seem reasonable that the levels of dose at which these countermeasures would almost certainly be justified be set an order of magnitude higher.

Evacuation is the most disruptive of the countermeasures that have been identified as applicable in this phase. Consideration of its introduction should start at dose levels significantly higher than those for the countermeasures mentioned above. Although it is difficult to justify choice of a particular value, the level of projected dose liable to be received in the short term, below which evacuation would not be justified, is likely to be about an order of magnitude greater than the dose limits for members of the public in any one year. The overriding aim in introducing countermeasures in the early phase is avoidance of non-stochastic effects. Therefore, evacuation should certainly be undertaken if the projected doses are liable to exceed those above which non-stochastic effects may occur. The resulting most restrictive upper and lower dose levels for the most common protective measures applicable in the early phase are shown in Table 5.

Table 5. Dose levels for early-phase protective measures as developed by ICRP

Protective measure	Dose (mGy)	
	Whole body	Lung,[a] thyroid and any single organ preferentially irradiated
Sheltering and stable iodine administration	5-50	50-500
Evacuation	50-500	500-5000

[a] In the event of high-dose alpha-irradiation of the lung, the numerical values of the absorbed dose will be multiplied by a factor of 10, reflecting the relative biological effectiveness

Source. **International Commission on Radiological Protection** *(3)*

The intermediate phase

The additional countermeasures applicable in the intermediate phase include restricting the distribution and consumption of locally produced water and fresh food and relocating groups of people pending decontamination of land or buildings. The disruption associated with countermeasures involving controlling food and water may be much less than that associated with relocation, which would be likely to be introduced to avert a higher level of projected dose. In general, there should be little penalty in not distributing fresh food, including milk. It may be appropriate to control the distribution and consumption of fresh foods if the projected committed dose equivalent within the first year would otherwise exceed the dose limit for members of the public in any one year. However, under certain conditions, such as the unavailability of alternative supplies, it may be appropriate to allow a higher level of dose. The dose levels at which relocation would be considered depend largely on the size of the population affected.

When defining radiological criteria, one may consider that the annual dose equivalent limits for members of the public are clearly set at a low level of risk; the levels at which relocation would be considered should be significantly higher, and a factor of 10 seems appropriate. The time over which the contamination persists will affect decision-making; for example, it may be acceptable to allow people to receive higher doses in the first year after an accident if the annual projected dose is expected to decrease rapidly. In addition, the national interest may dictate that an industrial activity be continued in a contaminated area where the dose to essential personnel exceeds the annual occupational dose limit (50 mSv).

For both control of foodstuffs and relocation of population groups, the level of dose at which these protective measures should certainly be implemented should be an order of magnitude greater than the levels suggested for considering their possible introduction.

The resulting upper and lower dose levels for protective measures applicable in the intermediate phase are shown in Table 6. As with the protective measures applicable in the early phase, national authorities should give special consideration to the implications of irradiation of pregnant women and other special groups.

Table 6. Doses for intermediate-phase protective measures as developed by ICRP

Protective measure	Dose (mSv or mGy) committed in the first year	
	Whole body	Individual organs preferentially irradiated
Control of foodstuffs and water	5–50	50–500
Relocation	50–500	not anticipated

Source: **International Commission on Radiological Protection** *(3)*

It will need to be decided at the time of an accident whether or not to implement an appropriate protective measure. This decision will be influenced by many factors involving the actual or potential release and the prevailing environmental and other conditions.

The above principles form the basis on which appropriate national authorities can specify levels at which emergency action would be implemented. In some cases all the quantitative data necessary to determine the balance of risk may not be available. Under these circumstances some general guidance on dose levels for the implementation of protective measures may be useful. Because of differences between various sites and countries the particular levels may vary; it can easily be proved in specific cases that a risk–benefit analysis could lead to other values for the introduction of any given countermeasure.

The recovery phase

As indicated previously it is neither feasible nor necessary to provide predetermined dose levels for the withdrawal of protective measures in the late phase, since this will be based on analyses of actual cost/risk, of the residual contamination, and of the benefit to and impact on society of the maintenance of the protective measures introduced.