of a particular accident *decreases.* The emergency plan should take into account the most likely radionuclide composition of the accidental releases which might result from the plant. However, in all cases, the plan must be flexible in order to be adaptable to the particular circumstances prevailing at the time of the accident. This general philosophy, dealing with the large range of accidents that have to be considered and the flexibility of the plan, appears in many national and international publications [2–5, 7].

When a release of radioactive materials from a nuclear facility has become uncontrolled, the implementation of remedial actions, or protective measures, involves cost, inconvenience and risk for the public. Therefore, ICRP has stated that the hazard or social cost involved in any remedial measure must be justified by the reduction of risk that will result (ICRP 26, para. 133) [2]. Thus, any intervention will only be appropriate if its social cost and risk will be less than that resulting from further exposure.

Emergency protective measures should be planned for particular circumstances and the levels of dose at which implementation of these measures are to be considered should be included in the emergency plan for any nuclear installation.

ICRP has further stated that: "The Commission's recommended limits are set at a level which is thought to be associated with a low degree of risk; thus, unless a limit were to be exceeded by a considerable amount, the risk would still be sufficiently low as not to warrant such countermeasures as would themselves involve significant risks or undue cost. It is, therefore, clear that it is not obligatory to take remedial action if a dose equivalent limit has been, or might be, exceeded". (ICRP 26, para. 135) [2].

3. PRINCIPLES FOR PLANNING INTERVENTION

During an accident at a nuclear facility the sources of exposure are, by definition, not under control and therefore the system of dose limitation established in the Agency's Basic Safety Standards for Radiation Protection [7] may not be applicable. However, the principles underlying the Basic Safety Standards can be adopted as a basis for planning intervention in the event of radiation accidents. In particular the technique of optimization can assist decision-making in the aftermath of an accident.

The principles for planning intervention in the event of an accident have been established by ICRP [5] as follows:

(a) *Serious non-stochastic effects should be avoided by the introduction of protective measures to limit individual dose to levels below the thresholds for these effects.*

(b) *The risk from stochastic effects should be limited by introducing countermeasures which achieve a positive net benefit to the individuals involved.*

This can be accomplished by comparing the reduction in individual dose, and therefore individual risk, that would follow the introduction of a countermeasure, with the increase in individual risk resulting from the introduction of that countermeasure.

(c) *The overall incidence of stochastic effects should be limited as far as reasonably practicable by reducing the collective dose equivalent.*

This source-related assessment may be carried out by cost–benefit analysis techniques and would be similar to a process of optimization in that the cost of a decrease in the health detriment in the affected population is balanced against the cost of further countermeasures" [8].

It is clear from (a) and (b) above that it is the level of individual dose which is of importance when deciding upon the introduction of a countermeasure. Although when considering (c), collective dose equivalent commitment is an appropriate parameter for decision-making, it must be recognized that the major part of the collective effective dose equivalent commitment resulting from an accident would usually be accumulated at long distances and at low levels of individual dose which it may be impracticable to avoid.

In deciding whether to ease the restrictions imposed by protective measures within a contaminated area, it will be necessary to determine whether the levels of individual dose that would subsequently be received are acceptable. This decision will depend partly upon the results of optimization studies using, for example, cost–benefit analyses as indicated in (c) above. The main inputs to this optimization will be the costs of relocation and decontamination to reduce individual doses, and the costs of health detriment in the population affected by the protective measures if normal living were resumed without either decontamination, or waiting for natural phenomena that could reduce the level of contamination.

4. ACCIDENT PHASES

For the development of radiological protection principles to be applied in emergency response planning and for the purposes of developing intervention levels, it is convenient to identify three time phases which are generally accepted as being common to all accident sequences; within each of them, different considerations apply to decision-making on off-site action. These are termed the early, intermediate and late phases, [4, 5, 9]. Although these phases cannot be represented by precise time periods and may overlap, they provide a useful framework within which to discuss the different considerations involved in emergency response planning.

The *early phase* is defined by the time period during which there is the threat of a significant release; that is, commencing from the time when the potential for off-site exposure is first recognized, and extending into the first few hours after the beginning of a release, if one occurs. The time interval between the recognition of an accident sequence and the start of the release can extend from about half an hour to about a day [4, 9] and the duration of the release may be between half an hour and several days. This timing generates difficulty in making decisions about the introduction of protective measures, 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 which will not yet have arisen. These matters are treated in detail in other Agency publications [10, 11].

The common feature which brings into the early phase both the period when there is a threat and the first few hours of release is that emergency response decisions are based on the analysis of data and predictions being provided from the nuclear installation. Thus, decisions to implement those protective measures which are appropriate and practicable during the early phase will be based primarily on information on plant conditions and the associated potential doses to individuals in the population, assessed on the basis of prior analysis of plant fault sequences.

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, wind direction and other unknowns (such as release duration and the degree to which measurements represent future plume configurations) these measurements may be of only limited value for calculating projected doses.

The *intermediate phase* covers the period which starts after the first few hours from the commencement of the release and could extend for several days or weeks. At the commencement of this phase, generally, the majority of the release will have occurred and, unless the release consisted only of noble gases, significant amounts of radioactive material may already have been deposited on the ground. There is no clear time boundary in emergency response planning between the early and the intermediate phases.

During the intermediate phase, environmental measurements of radiation levels from deposited radioactive materials as well as levels of radioactive contaminants in food, water and air will become available. The radiological characteristics of the deposited material can also be determined. Using these data, dose projections can be made for principal exposure pathways; these doses can then be compared with pre-established intervention levels as a basis for taking decisions on the implementation of protective measures.

It is also during the intermediate phase that the plant is expected to be restored to a safe condition and the protective measures, based on the environmental measurements, will be implemented. If the accident is severe, the phase may be extended in time while extra measurements are made at locations further from the plant.

The *late phase* (also referred to as the recovery phase), which is concerned with the return to normal life, may extend from weeks to several years after the accident, the duration depending upon the nature and magnitude of the release. During this phase the data obtained from environmental monitoring can be used to make decisions on returning to normal living conditions, by the simultaneous or successive lifting of the various protective measures decided during the first two phases of the accident. Alternatively, certain restrictions may need to be continued for long periods of time, affecting, for instance, agricultural production, the use of certain areas or buildings, and the consumption of certain foodstuffs (vegetable, animal or dairy products) from affected areas.

5. BIOLOGICAL EFFECTS OF SIGNIFICANCE IN ACCIDENTS

5.1. Non-stochastic effects

Non-stochastic effects can be induced in any organ or tissue, given high enough doses. The discussion here is limited to effects in those organs and tissues which are known to be most likely at risk from accidental releases from nuclear installations. Whole-body irradiation at high enough doses will cause vomiting and in addition, at higher doses, early mortality will result from bone marrow cell depletion. Inhalation of significant quantities of radioactive material will deliver high acute doses to the lung, leading to permanent impairment of lung function and even early mortality. Severe irradiation of the gastro-intestinal tract

TABLE I. LEVELS OF DOSE IN ORGANS AND TISSUES BELOW WHICH NON-STOCHASTIC EFFECTS WILL BE AVOIDED

Dose (Gy)[a]	Organ	Effect
0.1	Foetus	Teratogenesis
0.5	Whole body	Vomiting
1	Whole body	Death
3	Skin	Depilation, erythema
5	Lung	Pneumonitis
10	Lung	Death
10	Thyroid	Hypothyroidism

[a] The figures apply to absorbed dose from low LET radiation.

can lead to early mortality, but for nuclear accidents it is likely that irradiation of the bone marrow will be more limiting. Finally, non-lethal effects may occur as a result of high doses to some organs or tissues. Such effects include hypothyroidism (the dose to the thyroid will be higher than to other organs in some kinds of accident), fertility impairment, skin damage and cataracts.

Since the first of the three ICRP principles can be met by limiting doses to levels below the relevant thresholds for non-stochastic effects, data are given in Table I which have been selected to identify the levels of dose below which these effects are unlikely to occur.

For low LET radiation the dosimetric quantity, absorbed dose, is suitable for estimating the incidence of non-stochastic effects. In accidents involving release of α-emitting radioactive materials, the quantity absorbed dose is not sufficient on its own to permit assessment of the risk. The absorbed dose should be multiplied by a factor to take account of the relative biological effectiveness of acute α-irradiation for the dose ranges and types of effects that are likely to occur.

5.2. Stochastic effects

The stochastic effects that might occur are the late somatic and hereditary effects. The principal late somatic effect is the increased incidence in the irradiated population, of both fatal and non-fatal cancers, the appearance of which is likely to be spread over several decades following irradiation. Furthermore, non-fatal cancers will cause associated physical or psychological effects that can significantly reduce the quality of life. Stochastic hereditary effects may also occur following irradiation of the gonads of members of the population who are of reproductive capacity.

The linear dose–response relationship is used in practice to predict the overall incidence of stochastic effects in accident situations and the appropriate dosimetric quantity is dose equivalent. The use of the quantity effective dose equivalent has been recommended by the Commission for expressing individual risk at levels of dose encountered in normal radiation protection. At higher levels of dose, the potential incidence of non-stochastic effects invalidates the use of effective dose equivalent as a suitable quantity for expressing risks from radiation. For example, a high individual organ dose can result in non-stochastic effects, although it may correspond to an effective dose equivalent that, if it were whole-body irradiation, would not give rise to non-stochastic effects. Also, in accident situations there is the possibility of preferential irradiation of organs exhibiting high incidence of non-fatal cancer and again effective dose equivalent is not an appropriate quantity to express radiation risks.

For these reasons, the appropriate dosimetric quantity for expressing stochastic risks when preparing emergency plans is the dose equivalent in specific organs and tissues. If several organs of an individual are irradiated in an accident situation and no single organ exceeds the reference levels, then the effective dose equivalent may be calculated and at levels of H_{eff} less than 0.5 Sv, H_{eff} should be compared with the whole-body reference level.

5.3. Irradiation in utero

For irradiation in utero the median lethal dose to the foetus varies between about 1 and 3 Gy, increasing with the state of its development [5]. There is no evidence of teratogenic effects during the first few weeks of gestation for short-term exposures of less than 0.1 Gy. There should therefore be little likelihood of harm following receipt of that level of dose by the foetus in this early period. However, recent evidence [12] suggests the occurrence of the effect of serious mental retardation with a risk coefficient of 0.4 Sv^{-1} in a period of about 8–15 weeks after conception and no indication at present of a significant threshold. The risk is smaller after 15 weeks and may have a threshold, while prior to 8 weeks no such risk has been detected [5, 12].

6. PROTECTIVE MEASURES

The protective measures which are available to avoid or reduce radiation dose can be summarized as: sheltering, stable iodine administration, evacuation, relocation, control of access, decontamination of individuals, land and property, and control of distribution of foodstuffs and water. It is necessary to distinguish between evacuation and relocation with regard to accident phases. Evacuation is the urgent removal of people from an area to avoid or reduce their acute exposure, usually from the plume, or from high levels of deposited activity, and is a measure adopted when it is expected that people will return to the area concerned on a foreseeable time-scale. Relocation, on the other hand, is applied to the removal of population groups from contaminated areas to avoid chronic exposure, and when return to the area is not contemplated for some time. Conditions may develop in which some groups who have been evacuated in an emergency may be allowed to return while others may need to be relocated.

Descriptions of the risks and difficulties associated with introducing the protective measures identified above have been given by ICRP [5], by WHO [4], by the Commission of the European Communities [2], and by the IAEA [6]. They are therefore not discussed in detail here. However, it is clear that the risks, difficulties and disruption which follow the implementation of these various protective measures are widely different and depend on many factors, including the location of the site and the meteorological conditions at the time of the accident.

7. ESTABLISHMENT OF RANGES OF INDIVIDUAL DOSE

The level of dose at which a given protective measure will be introduced is influenced by the above considerations. It is not possible therefore 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, on radiation protection grounds, for each protective measure, 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 have been attempted. These two levels may be of use to national authorities when setting criteria for introducing protective measures. Judgement will be needed at the time of an accident in deciding whether or not to implement a protective measure. This judgement will be influenced by many factors involving the actual or potential release and the prevailing environmental conditions.

8. THE EARLY PHASE

Both the introduction of sheltering for a limited period of time, and, where appropriate, the administration of stable iodine, are protective measures that have been accepted by many national authorities as constituting only a small risk to the individual. Because the annual dose limits for members of the public represent a low level of risk, the introduction of such protective measures would not appear to be warranted at projected doses, liable to be received in the short term, that are of the same order of magnitude as these limits. The levels of dose below which non-stochastic effects are avoided are some two orders of magnitude above these lower levels of dose. It would seem reasonable, therefore, to set the levels of dose at which low-risk protective measures would almost certainly be justified at about one order of magnitude below those that would avoid non-stochastic effects. These considerations lead to ranges of doses of 5–50 mSv for whole body and 50–500 mSv for single organs.

Evacuation is the most disruptive of the protective measures that have been identified as applicable in this phase. Consideration of its introduction should start at dose levels significantly higher than those for the low-risk protective measures previously mentioned. Although it is difficult to justify the choice of a particular value, the level of projected dose liable to be received in the short term, below which evacuation is unlikely to be justified, will usually be about an order of magnitude greater than the annual dose limits for members of the public. The minimum objective in introducing protective measures in the early phase is the avoidance of non-stochastic effects. Therefore, evacuation should almost certainly be undertaken if the projected doses could lead to non-stochastic effects, taking into account the effectiveness of the lower risk protective measures which may already have been implemented. The resulting dose ranges are 50–500 mSv for whole body and 500–5000 mSv for single organs.

In the event of several organs or tissues being irradiated at low levels of dose, the effective dose equivalent should be calculated and compared with the whole-body dose levels.

9. THE INTERMEDIATE PHASE

The above considerations are equally valid if the introduction of the early phase protective measures is still justified in this phase. The additional protective measures that are applicable in the intermediate phase include restricting the distribution and consumption of locally produced water and foodstuffs, and relocating groups of people pending decontamination of land or buildings. The disruption associated with protective measures involving controlling food and water is much less than that associated with relocation, which would probably 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 annual dose limit for members of the public. 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 on the size and nature of the area affected. When defining radiological criteria, since 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 that dose is not going to be repeated year to year.

For both control of foodstuffs and relocation it would seem appropriate that the level of dose at which these protective measures should almost certainly be implemented should be an order of magnitude greater than the levels suggested above. The resulting upper and lower dose levels for introducing food controls are 5–50 mSv whole body and 50–500 mSv for individual organs of tissues, while for relocation only whole-body exposure is envisaged and the range is 50–500 mSv.

10. THE LATE PHASE

In the late phase the principal questions facing the decision-maker will be whether, and if so, when, normal living can be resumed in areas in which

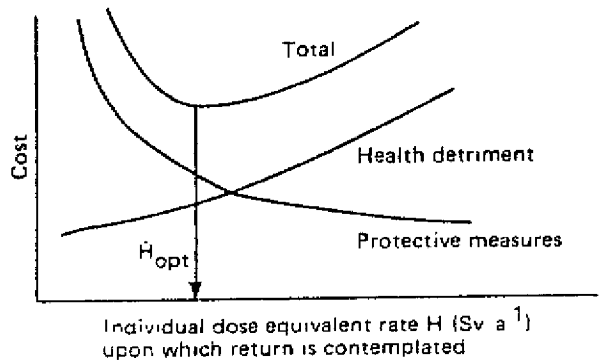

FIG. 1. Determination of the optimum dose level for withdrawal of protective measures.

protective measures have been applied. It may be that further large-scale protective measures, such as decontamination of land, will still need to be undertaken; or it may be necessary to decide to close areas and relocate the population. In making these decisions, the hazard and the social costs involved in the continued application of any protective measure must be justified by the reduction in risk that will result. The factors influencing the decision to permit a return to normal living are highly variable. For example, the nature of the activities in the area affected, the size of the population relocated, the time of the year, the ease of decontamination and the attitude of the population in returning to their homes, are some of the factors that must be weighed in the decision-making process.

The process of deciding whether to continue a protective measure, or whether, by further action, to reduce potential exposure levels, should involve a procedure rather similar to that of the optimization of radiation protection. This means that the cost of the health detriment to the population group who would be exposed, for example, upon return to the contaminated area, must be balanced against the costs of the continuation of the protective measure, or the cost of other protective measures, to reduce health detriment.

When considering the return of a population group to a previously contaminated area, the cost of the health detriment that will be received after their return increases as the level of individual dose equivalent upon which return is allowed increases. On the other hand, as the level of individual dose equivalent upon which return is allowed decreases, both the total cost of prolonging the application of the protective measure, and the cost of taking further protective measures to reduce exposure, increase. The application of cost-benefit analysis in this situation is illustrated in Fig. 1. Minimizing the total costs of the health detriment and the cost of protective measures leads to identification of the level of individual dose equivalent rate, $\dot{H}_{opt}$, at which protection is optimized.

If, as a result of this cost-benefit analysis, the optimum level of individual dose equivalent rate, $\dot{H}_{opt}$, corresponds to a greater level of individual dose equivalent rate, and therefore risk, than is considered acceptable by society, then more remedial action is required, regardless of cost. While the optimal cost value for individual radiation detriment may be calculated, this may not be the sole criterion for the return of a population to a contaminated area and further efforts to reduce the risk may be deemed justifiable. If the optimum level of individual dose equivalent rate found by this procedure is below the level of individual dose equivalent rate at which protective measures had been introduced, the residual contamination should be reduced to achieve this optimum level of dose equivalent rate before the return of the population.

The procedure of optimization described above should be applied to other areas to determine whether it is justified to reduce the contamination. The input to this optimization will involve different health detriments and different costs of measures to reduce exposure.

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