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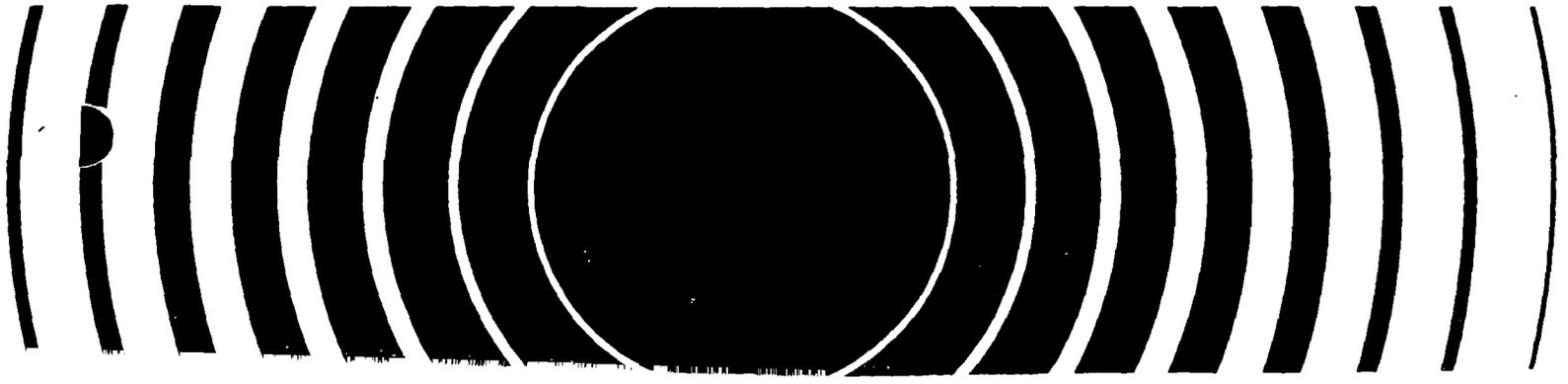
Manual of Protective Action Guides and Protective Actions for Nuclear Incidents



MANUAL OF PROTECTIVE ACTION GUIDES AND PROTECTIVE ACTIONS FOR NUCLEAR INCIDENTS

Office of Radiation Programs
United States Environmental Protection Agency
Washington, DC 20460

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PREFACE

Public officials are charged with the responsibility to protect the health of the public during hazardous situations. The purpose of this Manual is to assist these officials in establishing emergency response plans, and in making decisions during a nuclear accident. It provides radiological protection guidance for responding to nuclear incidents or radiological emergencies and procedures for their implementation.

In conformance with regulations on radiological emergency planning and preparedness issued by the Federal Emergency Management Agency (47FR10758, March 11, 1982), the Environmental Protection Agency's responsibilities include, among others, (1) to establish Protective Action Guides (PAGs), (2) to prepare guidance on implementing PAGs, including recommendations on protective actions, (3) to develop and promulgate guidance to State and local governments on the preparation of emergency response plans, and (4) to develop, implement, and present training programs for State and local officials on PAGs and protective actions, radiation dose assessment, and decision making. This document is intended to respond to the first two of these responsibilities.

The Manual is organized to provide first, a general discussion of Protective Action Guides (PAGs) and their use in planning for protective actions to safeguard the public. The Manual then provides PAGs for specific exposure pathways and associated time periods. This is followed by guidance for their implementation. In addition, appendices describe the rationale for the choice of the numerical values of the PAGs.

This revised Manual supercedes the 1980 edition. Previously issued Appendix D "Technical Bases for Dose Projection Methods" has been deleted, and the relevant portions have been incorporated into Chapter 5. PAGs for ingestion of food and water and radiation protection guidance for recovery will be incorporated at a later date. The chapters and appendices which will address these are reserved. When they are completed, this Manual will be reissued.

These PAGs are published on an interim basis in order to provide timely guidance to officials who are charged with developing emergency response plans. After some experience is gained in application of these recommendations, they will be reexamined and final guidance issued. Users of this Manual are encouraged to provide comments and suggestions for improving its contents. Comments should be sent to Joe E. Logsdon, Guides and Criteria Branch, Criteria and Standards Division, Office of Radiation Programs, US Environmental Protection Agency, Washington, DC 20460.

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Richard J. Guimond, Director Date
Office of Radiation Programs

CHAPTER 1

Overview

1.0 Introduction

Public officials are charged to protect the health of the public during hazardous situations. In discharging this responsibility, they will usually be faced with decisions that must be made in a short period of time. A number of factors influencing the choice of protective actions will exist, but the decision may be complex, and all of the information needed to make the optimum choice will usually not be immediately available. In situations where a public official must rapidly, make decisions it is helpful if the complexity of the decisions needed can be reduced during the accident response planning phase.

The Environmental Protection Agency has developed this Manual in order to assist public officials in their decisionmaking process for nuclear accidents. The Manual provides radiological protection criteria for responding to nuclear incidents or radiological emergencies and procedures for their implementation. These recommendations are for the use of those at the national, State, and local government levels with responsibility for emergency response planning. In the context of this Manual, a nuclear incident is defined as an event or a series of events leading to the release, or potential release, into the environment of radioactive materials in sufficient quantity to warrant consideration of protective actions. (The terms "incident" and "accident" have the same meaning in the context of this Manual.) A radiological emergency may result from an incident at a facility that is or is not part of the nuclear fuel cycle, or from the transportation of radioactive materials. This radiation protection guidance is intended to apply to all radiological emergency response situations, other than nuclear war.

The decision to require members of the public to take an action to protect themselves from radiation from a nuclear incident involves a

complex judgment in which the risk avoided by the protective action must be weighed against the risks and costs involved in taking the action. Furthermore, the decision may have to be made under emergency conditions, with little or no detailed information available. Therefore, considerable planning is necessary to reduce to a manageable level the types of decisions required to effectively protect the public.

The objective of emergency planning is to simplify the choice of possible responses so that judgments are required only for viable alternatives when an emergency occurs. During the planning process it is possible to make some value judgments and determine which responses are not required, which decisions can be made on the basis of prior judgments, and which judgments must be made during an actual emergency. From this exercise, it is then possible to devise operational plans which can be used to respond to the spectrum of hazardous situations which may develop.

The main contribution to the protection of the public from abnormal releases from a nuclear facility is provided by site selection, design, quality assurance in construction, the engineered safety systems of the installation, and the competence of staff in its safe operation and maintenance. These measures can reduce both the probability of an accident and the magnitude of potential consequences. Despite these measures, the occurrence of accidents cannot be excluded. Accordingly, emergency response planning to mitigate the consequences of an accident is a necessary supplementary level of protection.

In an accident, the source of exposure is, by definition, not under control and the exposure of members of the public can only be limited by some form of intervention which will disrupt normal living. Such intervention is termed protective action. A Protective Action Guide (PAG) is the projected dose to standard man, or other defined individual, from an accidental release of radioactive material at which a specific protective action to reduce (or avoid) that dose is warranted. The objective of this manual is to provide such PAGs for the principal protective actions available to responsible public officials during a nuclear accident, and to provide guidance for their use.

1.1 Accident Phases and Protective Actions

It is convenient to identify three time phases which are generally accepted as being common to all accident sequences; within each, different considerations apply most to protective actions. These are termed the early, intermediate and late phases. Although these phases cannot be represented by precise periods and may overlap, they provide a useful framework for the considerations involved in emergency response planning.

The early phase (also referred to as the emergency phase) is the period at the beginning of a nuclear accident when immediate decisions for effective use of protective actions are required and these must therefore be based primarily on predictions of radiological conditions in the environment from the condition of the source. This phase may last from hours to days.

The intermediate phase is the period beginning after the the accident source and releases have been brought under control and reliable environmental measurements are available for use as a basis for decisions on additional protective actions. It extends until these protective actions are terminated. This phase may overlap the early and later phase and may last from weeks to many months.

The late phase (also referred to as the recovery phase) is the period beginning when recovery action designed to reduce radiation levels to permanently acceptable levels are commenced, and ending when all recovery actions have been completed. This period may extend from months to years.

The protective actions available to avoid or reduce radiation dose can be categorized as a function of exposure pathway and accident phase, as shown in Table 1-1. Sheltering (supplemented by bathing and changes of clothing), administration of stable iodine and evacuation are the principal protective actions for use during the early phase to protect the public from exposure to direct radiation and inhalation from an airborne plume. Some protective actions are not addressed by these PAGs. Although

TABLE 1-1. EXPOSURE PATHWAYS, ACCIDENT PHASES, AND PROTECTIVE ACTIONS.

POTENTIAL EXPOSURE PATHWAYS AND ACCIDENT PHASES		PROTECTIVE ACTIONS
1. External radiation from facility	*Early*	Sheltering Evacuation Control of access
2. External radiation from plume		Sheltering Evacuation Control of access
3. Inhalation of activity in plume		Sheltering Administration of stable iodine Evacuation Control of access
4. Contamination of skin and clothes		Sheltering Evacuation Decontamination of persons
5. External radiation from ground deposition of activity	*Intermediate*	Evacuation Relocation Decontamination of land and property
6. Inhalation of resuspended activity	*Late*	Relocation Decontamination of land and property
7. Ingestion of contaminated food and water		Food and water controls

Note: The use of stored animal feed to limit the uptake of radionuclides by domestic animals in the food chain can be applicable in any of the phases.

the use of simple, ad hoc respiratory protection may be applicable for supplementary protection in some circumstances, this protective action is primarily for use by emergency workers. The control of access to areas is also a protective action whose introduction is coupled to a decision to implement one of the early or intermediate phase protective actions and is not discussed separately.

Relocation and decontamination are the principal protective actions for protection of the public from whole body external exposure due to deposited material and from inhalation of any resuspended radioactive particulate materials during the intermediate and late phases. It is assumed that decisions will be made during the intermediate phase concerning whether relocated areas will be decontaminated and reoccupied, or condemned and the occupants permanently relocated. The second major type of protective action during the intermediate phase encompasses restrictions on the use of contaminated food and water. This protective action, in particular, may overlap earlier and later phases.

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 high-level, short-term exposure, usually from the plume or deposited activity. Relocation, on the other hand, is the removal or continued exclusion of people from contaminated areas to avoid chronic radiation exposure. Conditions may develop in which some groups who have been evacuated in an emergency may be allowed to return based on the relocation PAGs, while others may be converted to relocation status.

1.2 Basis for Selecting PAG Values

The PAGs in this manual incorporate the concepts and guidance contained in Federal Radiation Council (FRC) Reports 5 and 7 (FR-64 and FR-65). One of these is that the decision to implement protective actions should be based on the projected dose that would be received if the protective actions were not implemented. However, since these reports were issued, considerable additional guidance as been developed on the

subject of emergency response (IC-84, IA-89). EPA considered the following four principles in establishing values for PAGs:

1. Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which they are not likely to occur) should be avoided.

2. The risk of delayed effects on health (primarily cancer and genetic effects for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health under emergency conditions, and are reasonable achievable.

3. PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health avoidable at acceptable cost should be carried out.

4. Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.

The above principles apply to the selection of any PAG. Similar principles have been proposed for use by the international community (IA-89). Appendices C and F demonstrate their application to the selection of PAGs for evacuation and relocation. Although in establishing PAGs it is necessary to consider a range of source terms to estimate the variability of cost associated with their implementation, the PAGs are chosen so as to be independent of the magnitude or type of accidental release.

1.3 Planning

The planning elements for developing radiological emergency response plans for accidents at nuclear power facilities are provided in NUREG-0654 (NU-80), which references the PAGs in this Manual as the basis for

emergency response. NUREG-0396 (NU-78) provides guidance on time frames for response, the types of releases to be considered, and emergency planning zones (EPZ). The size and shape of the recommended EPZs were only partially based on consideration of the numerical values of the PAGs. A principle basis was that the planning zone for evacuation and sheltering should be large enough to encompass all of rural areas and the various organizations needed for emergency response. Experience gained in exercises is then expected to provide an adequate basis for expanding response to an actual incident to larger areas if needed. It was also noted that the 10-mile radius EPZ for evacuation is large enough to avoid exceeding the evacuation PAGs at its boundary for low-consequence, core-melt accidents and to avoid early fatalities for high-consequence, core-melt accidents. The 50-mile EPZ for ingestion pathways was selected to account for the proportionately higher doses via ingestion compared to inhalation and whole body external exposure pathways.

1.4 Implementation of PAGs

The sequence of events during the early phase includes notification of responsible authorities, evaluation of potential offsite consequences, recommendations for action, and protection of the public. In the early phase of response, the time available to implement protective action will probably be quite limited.

Immediately upon becoming aware that an incident has occurred that may result in exposure of the offsite population, responsible authorities will make a preliminary evaluation to determine the nature and potential magnitude of the incident. This evaluation, if possible, will determine potential exposure pathways, population at risk, and projected doses. At this time, projected doses may be estimated from releases anticipated for the particular circumstances types of the nuclear incident or from monitoring data at the point of radionuclide release. The incident evaluation and recommendations are then presented to emergency response authorities for action. In the absence of recommendations from the nuclear facility operator for protective actions in specific areas, the emergency plan will provide for protective action in predesignated areas.

Contrary to the situation during the early phase, dose projections used to support protective action decisions during the intermediate and late phases will be based on measurements of environmental radioactivity and dose models. Following relocation of the public from affected areas to protect them from exposure to deposited materials, it will also be necessary to compile radiological and cost of decontamination data to form the basis for radiation protection decisions for recovery.

The following chapters provide guidance on the projected doses at which specific protective actions should be implemented and the corresponding implementation procedures.

REFERENCES

FE-85 FEDERAL EMERGENCY MANAGEMENT AGENCY. Federal Policy on Distribution of Potassium Iodide around Nuclear Power Sites for Use as a Thyroidal Blocking Agent. Federal Register 50-142, p. 30256, July 24, 1985.

FR-64 FEDERAL RADIATION COUNCIL. Radiation Protection Guidance for Federal Agencies. Federal Register, Volume 29, pp. 12056-7, August 22, 1965.

FR-65 FEDERAL RADIATION COUNCIL. Radiation Protection Guidance for Federal Agencies. Federal Register, Volume 30, pp. 6953-5, May 22, 1965.

IA-89 INTERNATIONAL ATOMIC ENERGY AGENCY. Principles for Establishing Intervention Levels for the Protection of the Public in the Event of a Nuclear Accident or Radiological Emergency. Safety Series No. 72, revision 1, in press. International Atomic Energy Agency, Vienna, Austria.

IC-84 INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Protection of the Public in the Event of Major Radiation Accidents: Principles for Planning, ICRP Publication 40, Pergamon Press, Oxford, England, 1984.

NU-78 NUCLEAR REGULATORY COMMISSION. Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants. (1978). U.S. Nuclear Regulatory Commission, Washington, D. C. 20555.

NU-80 NUCLEAR REGULATORY COMMISSION. Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants. (1980). U.S. Nuclear Regulatory Commission, Washington, D. C. 20555.

CHAPTER 2

Protective Action Guides for the Early Phase

2.1 Introduction

Rapid action may be needed to protect the public following an accident involving a large release of radioactive material to the atmosphere. This chapter identifies the levels of exposure to radiation at which such prompt protective action should be initiated. These are set forth as Protective Action Guides (PAGs) for the general population. Limits for exposure of emergency workers during such an accident are also provided. These guides and limits apply to any type of nuclear accident or other incident that can result in exposure of the public to an airborne plume of radioactive materials.

PAGs are expressed in terms of the projected doses above which specified protective actions are warranted. In the case of an airborne plume, the relevant protective actions are evacuation or sheltering. These may be supplemented in special cases by washing and changing clothing and by using stable iodine to block uptake by the thyroid.

The PAGs should be considered mandatory only for planning purposes: for example, in developing radiological emergency response plans. Under accident situations, because of unanticipated local conditions and constraints, professional judgment will be required in their application. Situations can be envisaged, for example, in which a nuclear accident occurs at a time when other competing emergency conditions would make evacuation impracticable. Conversely, under some conditions evacuation of some areas may be quite practicable at projected doses below the PAGs. These situations require judgments by those responsible for protective action decisions at the time of the accident. A discussion of the implementation of these PAGs is provided in Chapter 5.

The period addressed by this guidance is denoted the "early phase." This is somewhat arbitrarily defined as the period from initiation of an atmospheric release until four days after the event occurs, at which time protective actions based on PAGs for relocation are assumed to be implemented. Furthermore, after the initial emergency has passed, workers are expected to be governed by the Federal guidance for normal work situations. The PAGs for members of the public and limits for emergency workers specified in this chapter, therefore, refer only to doses incurred during the early phase. These may include whole-body external beta and gamma dose from direct exposure to the airborne plume, exposure to beta and gamma radiation from deposited materials, and the dose to internal organs from direct inhalation of radioactive material from the plume.

Individuals exposed to a plume may also be exposed to deposited material over longer periods of time via ingestion, direct external exposure, and inhalation pathways. Because it is usually not practicable, at the time of an accident, to project the long-term doses that might occur after plume passage, and because different protective actions may be appropriate, these are not included in the dose specified in these PAGs.

The former Federal Radiation Council (FRC), in a series of recommendations issued in the 1960's, introduced the concept of PAGs and issued guides for avoidance of exposure due to ingestion of strontium-89, strontium-90, cesium-137, and iodine-131. These guides were developed for the case of worldwide atmospheric fallout from weapons testing, and were appropriate for application to food products that were contaminated as a result of such atmospheric releases. That is, they were not developed for application to protective actions relevant to prompt exposure to a plume from a nuclear accident. The guidance in this chapter thus does not supersede this previous FRC guidance, but provides new guidance for different exposure pathways and situations.

2.2 Exposure Pathways and the Population Affected

The most immediate exposure pathway from an accidental airborne release of radioactive material is direct exposure to an overhead plume of

radioactive material carried by prevailing winds. The detailed content of such a plume will depend on the source involved and conditions of the accident. In the case of an accident at a nuclear power reactor, it will most commonly contain radioactive noble gases, radioiodines, and radioactive particulate materials. These materials emit gamma radiation, which is not significantly absorbed by air and can expose people nearby as the plume passes.

An additional exposure pathway occurs when people are directly immersed in the radioactive plume, in which case radioactivity is inhaled and the skin and clothes become contaminated. When this occurs, internal body organs as well as the skin will be exposed through proximity to radioactive materials. Although beta radiation from materials deposited on the skin and clothing could be significant, generally it will be less important than radioactive material taken into the body through inhalation. This is especially true if early protective actions include washing exposed skin and changing clothing. Inhaled radioactive particulate materials, depending on their solubility in body fluids, will remain in the lungs or move via the bloodstream to other organs. Some radionuclides, once in the bloodstream, are concentrated in a single body organ, with only small amounts going to other organs. For example, if radioiodines are inhaled into the lungs, they move rapidly through the bloodstream to the thyroid gland, where most of the dose is delivered.

As the passage of a typical radioactive plume progresses, some radioiodines and radioactive particulate materials will settle out onto the ground and other surfaces. People present after the plume has passed will receive whole-body exposure from beta and gamma radiation emitted from these deposited materials. If the proportion of radioiodines or particulate materials contained in a release is large compared to the noble gases, this exposure pathway can be more significant than direct exposure to gamma radiation from the passing plume.

These PAGs are intended for general use to protect all of the individuals in an exposed population. However, there are some population groups that are at markedly different levels of risk from some protective

actions--particularly evacuation. To avoid social and family disruption and the complexity of implementing different PAGs for different groups in a population under emergency conditions, the PAGs are intended to be applied equally to most members of the population. Optional, higher values are, however, appropriate for a few groups for whom the risk associated with evacuation is exceptionally high (e.g., infirm persons). These higher levels are provided to assure that the risk associated with evacuation of these groups will not exceed the radiation risk avoided by evacuation.

Prisoners are a special group who are not at higher risk from evacuation, but due to the potential for escapes during or following their evacuation, the population may be at greater risk. States may wish to consider extra security to eliminate this risk as well as the protection factor from sheltering in prisons.

It should also be recognized that the risk from evacuation could be higher than normal if carried out under hazardous environmental conditions. Examples of these conditions are: severe weather, flood, earthquake, or the existence of a competing disaster. Higher dose levels may be justified for continued sheltering under these conditions.

2.3 The Protective Action Guides

The PAGs for the early phase are summarized in Table 2-1[1]. They are expressed in terms of effective dose, with supplementary guides for dose to the thyroid and skin. The basis for these values is given in detail in Appendix C. In summary, these analyses indicate that evacuation of the public is not justified unless the projected dose to individuals receiving the largest exposure at the outer edge of the evacuation zone is at least one rem. This conclusion is based primarily on consideration of

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[1] This more complete guidance updates and replaces previous values, expressed in terms of whole-body dose equivalent from external gamma exposure and thyroid dose equivalent from inhalation of radioactive iodines, that were recommended in the 1980 edition of this document.

Table 2-1 PAGs for the Early Phase of a Nuclear Incident

Protective Action	PAG (projected dose)[a]	Comments
Shelter; wash and change clothes, if immersed in plume.	<1 rem	There is no dose below which these protective actions are not recommended. Local planners and decision makers must consider other factors, such as boundaries of designated planning areas, the need for rapid communication with the public, risks associated with sheltering, and the extent of local contamination from the plume.
Evacuate the general population.[c]	1 rem	Special groups[b] may remain sheltered.
Evacuate special groups.[c]	5 rems	Higher doses may be permissible under some circumstances.[d]

[a] The PAGs are expressed in terms of the projected committed effective dose equivalent from exposure to the plume and deposited materials during the first 4 days. Projected committed dose equivalents to the thyroid and to the skin may be 5 and 50 times larger, respectively. In cases where sheltering and/or evacuation will not prevent thyroid doses from exceeding 25 rems, stable iodine may be used (subject to approval by State medical officials) to block the uptake of radioiodines by the thyroid.

[b] Special groups (e.g., infirm persons) are those for which evacuation creates a higher than normal risk.

[c] Under hazardous weather conditions or in the event of a competing disaster, the general population may remain sheltered at projected doses up to 5 rems, and special groups up to 10 rems. Evacuation should not be carried out in any special circumstance for which the health risk from the action would exceed the health risk to be avoided.

[d] PAGs for evacuation are based in part on the assumption that sheltering will reduce dose from the plume by approximately a factor of two. The emergency planning process may identify structures with significantly different dose reduction factors, which would justify their use for sheltering at higher or lower projected doses.

the magnitudes of the risks of cancer and of effects on the unborn from the radiation dose that is avoided by such evacuation. The analyses also show that, at this radiation dose, the ratio of the cost of evacuation to the risk avoided falls within the range of values commonly placed on avoiding risk to public health. Because of the higher risk associated with evacuation of some groups in the population (e.g. infirm persons and prisoners), projected doses up to 5 rems were judged permissible in order to provide reasonable assurance that the risk associated with their evacuation would be justified. Under unusually hazardous environmental conditions, or in the event of a competing disaster, projected doses of up to 5 rems to the general population and up to 10 rems to special groups are judged to be justified. (At these levels, attendants for special groups would still not exceed acceptable levels for emergency workers.)

Effective dose considers only the risk of fatal cancer from irradiation of organs within the body, and does not include dose to skin. Since the thyroid is at disproportionately high risk for induction of nonfatal cancers and nodules by radiation compared to other internal organs, supplementary guides are provided to limit dose to the thyroid to five times the PAG for effective dose to reduce the risk of these effects. Supplementary guidance is also provided to limit dose to skin to 50 times the numerical value of the PAG for effective dose to protect against the risk of skin cancer, which is not accounted for by effective dose.

Low-risk, low-cost protective actions such as sheltering, washing, and changing clothes are recommended at projected dose levels below 1 rem, the PAG for evacuating most members of the public under normal environmental conditions. Because of the unknown, but assumed very low, cost and risk associated with short duration (a few hours) sheltering, and because of the associated enhanced capability for response officials to communicate with sheltered populations, no PAG is established below which sheltering is not recommended. The choice of the lower bound of projected dose at which to order sheltering is left to the judgment of planners and implementers of emergency response, based on conditions at the location

and time of an accident. Normally, this choice will be strongly influenced by the principle that exposure to radiation should be maintained as low as reasonably achievable. As a reference level for a lower bound, it may be useful to note that most planned releases of radioactive materials from individual sources are limited in the United States in such a manner as to assure that annual doses greater than 25 mrem will not occur. Further, international recommendations limit chronic annual dose from all sources combined to 0.1 rem. Temporary sheltering may also be indicated as a minimum response for projected doses higher than the evacuation PAG for situations where evacuation cannot be carried out prior to plume arrival, if the dose during evacuation is projected to exceed that under sheltering.

Washing and changing of clothing is recommended primarily to provide protection from beta radiation from materials deposited on the skin or clothing. Calculations indicate that dose to skin should not be a controlling pathway if these actions take place within 12 hours after exposure. However, it is good radiation protection practice to recommend these actions to all persons exposed to the plume as soon as practical.

Evacuation of most individuals is recommended, under normal environmental conditions, at a projected dose of 1 rem. In the case of special population groups for which the risk associated with evacuation is higher than normal (e.g., infirm persons or prison populations), evacuation is not recommended until the projected dose is 5 rems. However, if environmental conditions are severe, so that the risk of evacuation is much higher than normal, evacuation of the general population may be deferred until the projected dose is as high as 5 rems. Since special groups also experience additional risk from evacuation during hazardous environmental conditions, their evacuation may be deferred until the projected dose is as high as 10 rems. However, in situations where it is impracticable to apply the different PAG for persons at high risk, a 1 rem PAG for evacuation under normal environmental conditions, or up to 5 rems under hazardous environmental conditions, may be applied to the entire population.

The PAGs governing evacuation are based in part on the assumption that short-term sheltering (two hours or less) will usually reduce dose from a plume by a factor of about two. Evacuation from specific structures (or types of structures) for which the dose reduction factor for sheltering is different may be appropriate at higher or lower projected doses. For example, large institutional structures, such as hospitals and prisons, are typically expected to provide a protection factor of about four. Sheltering in such facilities for protection from short duration plumes would be justified at projected doses up to 10 rems under normal environmental conditions and up to 20 rems under hazardous environmental conditions.

The use of stable iodine to protect against uptake of inhaled radioiodine by the thyroid is recognized as an effective alternative to evacuation for situations involving radioiodine releases where evacuation cannot be implemented. If the administration of stable iodine is included in an emergency response plan, its use should be considered for any radioiodine exposure situation in which the committed thyroid dose is projected to be 25 rems or greater.

The PAGs do not imply an acceptable level of risk for normal (nonemergency) conditions. Furthermore, under emergency conditions, in addition to the protective actions specifically identified for application of the PAGs, any other reasonable measures available should be taken to minimize radiation exposure of the general public and of emergency workers. These PAGs are also not intended for use as criteria for the ingestion of contaminated food or water, or for return to an area contaminated by radioactivity. Separate guidance is provided for these situations in Chapters 3 and 4.

2.4 Dose Projection

The PAGs are expressed in terms of projected dose. However, in the early phase of an accident, parameters other than projected dose may frequently provide a more appropriate basis for decisions to implement protective actions. In a rapidly unfolding accident situation it will

usually be impractical to directly estimate the projected dose soon enough. For such cases, provision should be made for decisions to be made on the basis of specific conditions at the source of a possible release that are relatable to anticipated offsite doses. Nuclear power plant emergency response plans should therefore include Emergency Action Levels (EALs) which indicate in-plant conditions that will trigger notification of and recommendations to offsite officials to implement prompt sheltering or evacuation in specified areas in the absence of information on actual releases or environmental measurements. Later, when these data become available, dose projections based on measurements may be used as a basis for implementing further action based on the PAGs.

The projected dose should include only contributions from exposures and intakes during the early phase of an emergency. Doses incurred prior to the protective action under consideration should not normally be included. However, in those rare cases where individuals might exceed 50 rems (the assumed threshold for acute effects) these doses should be included, to the extent that they can be projected. Similarly, doses that might be received following the early phase should not be included for decisions on whether or not to evacuate or shelter. Such doses, which may occur from food pathways, long-term radiation exposure to deposited radioactive materials, or long-term inhalation of resuspended materials, are chronic exposures for which neither emergency evacuation nor sheltering are appropriate protective actions. Separate PAGs relate the appropriate protective action decisions to those exposure pathways.

In practical applications, dose projection will usually begin at the time the condition on which the projection is based occurs. For rare situations where significant time will elapse before the earliest possible implementation of protective actions, the projected dose for comparison to the PAG should be that beginning at the earliest time that protective actions could be implemented.

2.5 Emergency Worker Limits

The PAGs for protection of the general population and dose limits for emergency workers are derived under different assumptions. PAGs consider

primarily the risk to individuals from exposure to radiation and the risk and costs associated with the protective actions themselves. On the other hand, emergency workers may receive exposure in order to assure protection of the population and of valuable property. These exposures will be justified if the individual risks are acceptability low, and the risks or costs avoided by their actions outweigh the risks to which they are subjected. Examples of emergency worker occupations are law enforcement, fire fighting, civil defense, traffic control, health services, environmental monitoring, transportation services, and animal care. Similarly, some workers at utility, industrial, and institutional facilities, and at farms, must control releases and/or protect property, as well as protect employees and others during an emergency.

Dose limits for emergency workers are summarized in Table 2-2. Radiation exposure of emergency workers should normally be limited by the Federal Radiation Protection Guidance for occupational exposure. This guidance provides an upper bound of five rems committed effective dose equivalent per year. In addition, in order to satisfy the provisions of this guidance for protection of minors and the unborn, emergency work during nuclear accidents should be limited to nonpregnant adults.

There are some emergency situations, however, for which higher exposures may be justified. Justification of any such exposure must include the presence of conditions that prevent the rotation of workers or other commonly-used dose reduction methods. The dose resulting from such emergency exposures should be limited to 10 rems for protecting property, and to 25 rems for life saving activities and the prevention of high risks to populations. In the context of this guidance, high risks to populations means situations in which the collective dose avoided by the emergency operation is significantly larger than that incurred by the emergency workers involved.

Situations may also rarely occur in which a dose in excess of 25 rems for emergency exposure would be unavoidable in order to carry out a lifesaving operation or to avoid large risks to populations. It is not possible to prejudge the risk that one should be allowed to take to

Table 2-2 Dose Limits for Emergency Workers

Dose limit[a]	Activity	Condition
5 rems	all activities	Use rotation of workers or other common radiation protection methods to maintain doses as low as practicable.
10 rems	protecting property	Lower dose not practicable.
25 rems	life saving or preventing high risk to populations	Lower dose not practicable.
>25 rems	lifesaving or preventing high risk to populations	Only on a voluntary basis to persons fully aware of the risks involved.

[a] Committed effective dose equivalent to nonpregnant adults from exposure during an emergency situation. In addition to the limitation on effective dose equivalent, emergency workers should not exceed 15 rems to the lens of the eye, or 50 rems to any other organ, tissue (including the skin), or extremity of the body.

save the lives of others. However, persons undertaking any emergency operation in which the dose will exceed 25 rems to the whole body should do so only on a voluntary basis and with full awareness of the risks involved, including the numerical levels of dose at which acute effects of radiation will be incurred and numerical estimates of the risk of delayed effects.

Tables 2-3 and 2-4 provide some general information that may be useful in advising emergency workers of risks of acute and delayed health effects associated with large doses of radiation. Table 2-3 presents the estimated risks of fatalities and moderately severe prodromal (forewarning) effects that are likely to occur shortly after exposure to a wide range of whole-body radiation doses. Estimated average cancer mortality risks for emergency

Table 2-3 Acute Health Effects Associated with Whole-Body Absorbed Doses (see Appendix C)

Absorbed dose (rem)	Fatalities (percent)	Absorbed dose (rads)	Prodromal effects (percent affected)
<140	a	<50	a
140	5	50	2
200	15	100	15
300	50	150	50
400	85	200	85
460	95	250	98

[a] The risk of fatality below 140 rems and of prodromal effects below 50 rems is indeterminate.

Table 2-4 Average Cancer Risk to Emergency Workers Receiving 25 Rems Whole-Body Dose (see Appendix C)

Age of the emergency worker (years)	Approximate risk of premature death (deaths per 1,000 persons exposed)	Average years of life lost if premature death occurs (years)
20 to 30	9.1	24
30 to 40	7.2	19
40 to 50	5.3	15
50 to 60	3.5	11

workers corresponding to a whole-body dose of 25 rems are given in Table 2-4, as a function of age at the time of exposure. To approximately estimate average cancer mortality for lifesaving missions at higher doses (up to a few hundred rems), the values in Table 2-4 may be increased linearly. For example, if the dose is increased three-fold to 75 rems, the projected incidence of fatal cancer over the ensuing lifetimes of workers exposed at age 25 would be about 27 per 1000 persons exposed. These values were calculated using a life

table analysis that assumes the period of risk continues for the duration of the worker's lifetime. Somewhat smaller risks of serious genetic effects (if gonadal tissue is exposed) and of nonfatal cancer would also be incurred.

Many emergency workers will have little or no health physics training, so dose minimization through use of protective equipment cannot always be assumed. However, the use of respiratory protective equipment can reduce dose from inhalation, and clothing can reduce beta dose. Stable iodine may also be appropriate for blocking thyroid uptake of radioiodine in personnel involved in emergency actions where atmospheric releases include radioiodine. The issuance of stable iodine must be carried out in accordance with State medical procedures, and planning is required to ensure its availability and proper use.

CHAPTER 3

Protective Action Guides for the Intermediate Phase (Food and Water)

(reserved)

CHAPTER 4

Protective Action Guides for the Intermediate Phase (Deposited Radioactive Materials)

4.1 Introduction

Following a nuclear accident it may be necessary to temporarily relocate the public from areas where extensive deposition of radioactive materials has occurred until decontamination has taken place. This chapter identifies the levels of radiation exposure which indicate when relocation from contaminated property is warranted.

The period addressed by this guidance is denoted as the "intermediate phase." This is arbitrarily defined as the period beginning after the accident source and releases have been brought under control and environmental measurements are available for use as a basis for decisions on protective actions and extending until these protective actions are terminated. This phase may overlap the early phase and may last from weeks to many months. For the purpose of dose projection, it is assumed to last for one year. Prior to this period protective actions will have been taken based upon the PAGs for the early phase (Chapter 2). It is assumed that decisions will be made during the intermediate phase concerning whether particular areas or properties from which persons have been relocated will be decontaminated and reoccupied, or condemned and the occupants permanently relocated. These actions will be carried out during the late or "recovery" phase.

Although these Protective Action Guides (PAGs) were developed based on expected releases of radioactive materials characteristic of reactor accidents, they may be applied to any type of nuclear accident or other incident that can result in long-term exposure of the public to deposited radioactivity.

PAGs are expressed in terms of the projected doses above which specified protective actions are warranted. In the case of deposited radioactivity, the major relevant protective action is relocation. Persons not relocated (from less contaminated areas) may reduce their dose through the application of simple decontamination techniques and by spending more time than usual in low exposure rate areas (e.g., indoors).

The PAGs should be considered mandatory only for planning purposes: for example, in developing radiological emergency response plans. Under accident situations, because of unanticipated local conditions and constraints, professional judgment by responsible officials will be required in their application. Situations can be envisaged, where contamination from a nuclear accident occurs at a site or time in which relocation of the public, based on the recommended PAGs, would be impracticable. Conversely, under some conditions, relocation may be quite practicable at projected doses below the PAGs. These situations require judgments by those responsible for protective action decisions at the time of the accident. A discussion of the implementation of these PAGs is provided in Chapter 7.

The PAGs for relocation specified in this chapter refer only to estimates of doses due to exposure during the intermediate phase. These may include external exposure to radiation from deposited radioactivity and inhalation of resuspended radioactive materials. Protective Action Guides for ingestion exposure pathways, which also apply during the intermediate phase, are discussed separately in Chapter 3.

Individuals who live in areas contaminated by materials deposited from an airborne plume may be exposed to radiation from these materials over the entire time that they live in the area. This would be the case for those who are not relocated as well as for persons who return following relocation. Because it is usually not practicable, at the time of a decision to relocate, to calculate the doses that might be incurred from exposure beyond one year, and because different protective actions may be appropriate over such longer periods of time, these doses are not included in the dose specified in the PAGs for relocation.

4.1.1 Exposure Pathways

The principal pathways for exposure of the public occupying locations contaminated by deposited radioactivity are expected to be exposure of the whole body to external gamma radiation from deposited radioactive materials (groundshine) and internal exposure from the inhalation of resuspended materials. For reactor accidents, external gamma radiation is expected to be the dominant source.

In most cases relocation decisions will be based on doses from the above pathways. However, in rare cases where withdrawal of contaminated food or drinking water from public consumption would itself create a risk to health, dose from the ingestion pathway should also be included. In this case, the projected committed effective dose from ingestion of food and water should be added to the dose from the above exposure pathways in making relocation decisions. (PAGs related specifically to the withdrawal of contaminated food and water from use are discussed in Chapter 3).

Other potentially significant exposure pathways include exposure to beta radiation from surface contamination and direct ingestion of contaminated soil. These pathways are not expected to be controlling for reactor accidents (EP-88).

4.1.2 The Population Affected

The PAGs for relocation are intended for use in establishing the boundary of a restricted zone within an area that has been subjected to deposition of radioactive materials. During their development, consideration was given to the higher risk of effects on health to children and fetuses from radiation dose and the higher risk to some other population groups from relocation. To avoid the complexity of implementing separate PAGs for individual members of the population, the relocation PAG is established at a level that will provide adequate protection for all relocated individuals.

Persons residing in contaminated areas outside the restricted zone will be at some risk from radiation dose. Therefore, guidance on the reduction of

dose during the first year to residents outside this zone is also provided. Due to the high cost of relocation, it is more practical to reduce dose in this population group by the early application of simple, low-impact, protective actions other than by relocation.

4.2 The Protective Action Guides for Deposited Radioactivity

PAGs for protection from deposited radioactivity during the intermediate phase are summarized in Table 4-1. The basis for these values is presented in detail in Appendix F. In summary, relocation is warranted

when the projected sum of dose from external gamma radiation and the committed effective dose from inhalation of resuspended radionuclides exceeds 2 rems in the first year. Relocation to avoid exposure of the skin to beta radiation is warranted at 50 times the numerical value of the relocation PAG for effective dose.

Persons who are not relocated, i.e., those in areas that received relatively small amounts of deposited radioactive material, should reduce their exposure by the application of other measures. Possible dose reduction techniques range from the simple processes of scrubbing and/or flushing surfaces, soaking or plowing of soil, removal and disposal of small spots of soil found to be highly contaminated (e.g., from settlement of water), and spending more time than usual in lower exposure rate areas (e.g., indoors), to the difficult and time-consuming processes of removal, disposal, and replacement of contaminated surfaces. It is anticipated that simple processes will be most appropriate for early application. Many can be carried out by residents themselves with support from response officials for assessment of the levels of contamination, guidance on appropriate actions, and disposal of contaminated materials. Due to the relatively low cost and risk associated with these protective actions, no dose level is established below which they are not recommended. It is, however, recommended that response officials concentrate their initial efforts in areas where the projected dose from the first year of exposure exceeds 0.5 rems. In addition, first priority should be given to residences of pregnant women.

Table 4-1 Protective Action Guides for Exposure to Deposited Radioactivity during the Intermediate Phase of a Nuclear Incident

Protective Action	PAG (projected dose)[a]	Comments
Apply simple dose reduction techniques.[b]	<2 rems	There is no dose below which these protective actions are not recommended. Early efforts should reduce the highest exposure rates, with priority given to residences of pregnant women.
Relocate the general population.[c]	≥2 rems	Beta dose to skin may be up to 50 times higher.

[a] Dose refers to the projected sum of effective dose equivalent from the external gamma radiation and the committed effective dose equivalent from inhalation of resuspended materials, during the first year. Projected dose means the dose that would be received in the absence of shielding from structures or the application of dose reduction techniques.

[b] Simple dose reduction techniques include scrubbing and/or flushing hard surfaces, soaking or plowing soil, minor removal of soil from spots where radioactive materials have concentrated, and spending more time than usual indoors or in other low exposure rate areas.

[c] Persons previously evacuated from areas outside the relocation zone defined by this PAG may return to occupy their residences. Cases involving relocation of persons at high risk from such action (e.g., patients under intensive care), should be evaluated individually

4.2.1 Longer Term Objectives of the Protective Action Guides

It is an objective of these PAGs to assure that 1) doses in any single year after the first will not exceed 0.5 rems, and 2) the cumulative dose over the next 50 years will not exceed 5 rems. For reactor accidents, the above PAG of 2 rems projected dose in the first year is expected to meet both of those objectives. Decontamination of areas outside the restricted area may be required during the first year to meet these objectives for other types of accidents. For situations where it is impractical to meet these objectives though decontamination, consideration should be given to relocation at a lower projected first year dose than that specified by the relocation PAG.

After the population has been protected in accordance with the PAGs for relocation, return for occupancy of previously restricted areas should be governed on the basis of Recovery Criteria as presented in Chapter 8.

Projected dose considers exposure rate reduction from radioactive decay and, generally, weathering. When one also considers the anticipated effects of shielding from partial occupancy in homes and other structures, persons who are not relocated should receive a dose substantially less than the projected dose. For commonly assumed reactor source terms, we estimate that 2 rems projected dose in the first year will be reduced to about 1.2 rems by these factors as shown in Table 4-2. The application of simple decontamination techniques shortly after the accident can be assumed to provide a further 30 percent or more reduction, so that the maximum first year dose to persons who are not relocated is expected to be less than one rem. Taking account of decay rates assumed to be associated with releases from nuclear power plant accidents (SN-82) and shielding from partial occupancy and weathering, a projected dose of 2 rems in the first year is likely to amount to 0.5 rems or less in the second year and 5 rems or less in 50 years. The application of simple dose reduction techniques would reduce these doses further. Results of calculations supporting these projections are summarized in Table 4-2.

Table 4-2 Estimated maximum dose to persons not relocated[a]

Accident Category	Dose (rem)					
	No applied dose reduction[b]			Early simple dose reduction[c]		
	Year 1	Year 2	50 years	Year 1	Year 2	50 years
SST-1	1.2	0.5	5.0	0.9	0.35	3.5
SST-2	1.2	0.34	3.9	0.9	0.24	2.7
SST-3	1.2	0.20	3.3	0.9	0.14	2.3

[a]Applies to fuel-melt reactor accidents.

[b]Based on relocation at a projected dose of 2 rems in the first year and 40 percent dose reduction to nonrelocated persons from normal, partial occupancy in structures. No dose reduction is assumed from decontamination, shielding, or special limitations on time spent in high exposure rate areas.

[c]The projected dose is assumed to be reduced 30 percent by the application of simple dose reduction techniques during the first month. If these techniques are completed later in the first year, the first year dose will be greater.

4.2.2 Applying the Protective Action Guides for Relocation

Establishing the boundary of a restricted zone may result in three different types of actions:

a. Persons who, based on the PAGs for the early phase of a nuclear accident (Chapter 2), have already been evacuated from an area which is now designated as a restricted zone must be converted to relocation status.

b. Persons not previously evacuated who reside inside the restricted zone must relocate.

c. Persons who normally reside outside the restricted zone, but were previously evacuated, may return. A gradual return is recommended, as discussed in Chapter 7.

Small adjustments in the boundary of the restricted zone from that given by the PAG may be justified on the basis of difficulty or ease of implementation. For example, the use of a convenient natural boundary could be justification for adjustment of the restricted zone. However, such decisions should be supported by demonstration that exposure rates to persons not relocated can be promptly reduced by methods other than relocation to meet the PAG, as well as the longer term dose objectives addressed in Section 4.1.1.

Reactor accidents involving releases of major portions of the core inventory under adverse atmospheric conditions can be postulated for which large areas would have to be restricted under these PAGs. As the affected land area increases, they will become more difficult and costly to implement, especially in densely populated areas. For situations where implementation becomes impracticable or impossible, informed judgment must be exercised to assure priority of protection for individuals in areas having the highest exposure rates. In such situations, the first priority for any area should be to reduce dose to pregnant women.

4.3 Exposure Limits for Persons Reentering the Restricted Zone

Individuals who are permitted to reenter a restricted zone to work, or for other justified reasons, will require protection from radiation. Such individuals should enter the restricted zone under controlled conditions in accordance with dose limitations and other procedures for control of occupationally-exposed workers (EP-87). Ongoing doses received by these individuals from living in a contaminated area outside the restricted zone should be included as part of the dose limitation applicable to workers. However, dose received previously from the plume and associated groundshine, during the early phase of the nuclear incident, need not be considered unless it is significant with respect to the higher occupational dose limits for health effects other than cancer and genetic effects (i.e., the limits for nonstochastic effects).

REFERENCES

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CHAPTER 5

Implementing the Protective Action Guides for the Early Phase

5.1 Introduction

This chapter provides guidance for implementing the Protective Action Guides (PAGs) set forth in Chapter 2. The main objectives are to provide guidance for estimating doses from exposure to an airborne plume, and for choosing and implementing protective actions.

Due to the wide variety of types of nuclear facilities and releases that could occur, it is not practical to provide general implementing guidance for all situations. The guidance in this chapter applies primarily to accidents at nuclear power plants. In some situations it may also be applied to accidental releases from other nuclear facilities. In most cases, however, specific implementation procedures for incidents at nuclear facilities other than nuclear power plants will have to be developed by planners on a case-by-case basis.

Following an incident which has the potential for an atmospheric release of radioactive material, the responsible authorities (State and/or local) will need to decide whether protective actions are needed and, if so, where and when they should be implemented. These decisions will be based primarily on (a) the potential for releases, and (b) projected doses as a function of time at various locations in the environment.

5.2 Initial Response and Sequence of Subsequent Actions

In the case of an atmospheric release, the protective actions which may be required are those which protect the population from inhalation of radioactive materials in the plume, from exposure to gamma radiation from

the plume, and from short-term exposure to radioactive materials deposited on the ground. It may also be necessary to consider protective action to avoid doses from deposition of radioactive material on the skin and clothing.

The time of exposure to a plume can be divided into two periods: (a) the period immediately following the incident, when little or no environmental data are available to confirm the magnitude of releases, and (b) the subsequent period, when environmental levels are known.

During the first period, speed in completing such actions as sheltering, evacuating, and control of access may be critical to minimize exposure. Environmental measurements made during this period may have little meaning because of uncertainty concerning the location of the plume when the measurements are made or uncertainty about changes in the releases from the facility, due to changes in pressure and radionuclide concentrations within the structures from which the plume is being released. Therefore, it is advisable to initiate early protective actions in a predetermined manner that is related to plant conditions. This will normally be carried out through recommendations provided by the facility operator. During the second period, when environmental levels are known, these actions can be adjusted as necessary.

For incidents involving release to the atmosphere, the following sequence of actions is suggested:

1. Notification of State and/or local authorities by the facility operator that an incident has occurred with the potential to cause offsite doses that exceed normal limits. This should be provided as soon as possible, following the incident, and prior to the release, if possible. (NRC regulations require such notification within 15 minutes of declaring an emergency.)

2. Immediate evacuation (and/or sheltering) of populations in predesignated areas without waiting for release rate or environmental measurements.

3. Monitoring of release rates, plant conditions, environmental concentrations, and exposure rates.

4. Calculation of the plume centerline dose rates and projected doses at various distances downwind from the release point.

5. Implementation of protective actions in additional areas if indicated. (Withdrawal of protective actions from areas where they have already been implemented is usually not advisable during the early phase because of the potential for changing conditions.)

6. Continuation of adjustments as more data become available.

5.2.1 Notification

The first indication that a nuclear incident has occurred should come to State and/or local authorities from the facility operator. Notification by a nuclear power facility of State and local response organizations should include recommendations, based on plant conditions, for early evacuation and sheltering in predesignated areas. An early estimate of the projected dose to the population at the site boundary and at more distant locations, along with estimated time frames, should be made as soon as release data become available. Emergency response planners should make arrangements with the facility operator to assure that this information will be made available on a timely basis and that dose projections will be provided in units that can be directly compared to the PAGs.

5.2.2 Immediate Protective Action

The Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans (NR-78) recommends that States designate an emergency planning zone (EPZ) for protective action for plume exposure out to about 10 miles from a nuclear power facility. Within this zone, areas should be predesignated for immediate response,

based on specified plant conditions, prior to the availability of information on quantities of radioactive materials released. These should consist of a circular (or, depending on local topography, other appropriately shaped) area centered on the facility and extending outward for 2 to 3 miles, with additional areas, in the downwind direction at the time of the incident, to distances determined by the potential magnitude of the release, and of an angular spread determined by meteorological conditions. An angular spread of 90 degrees (4 sectors) will usually be adequate for this immediate response. The remaining area within the EPZ should be placed on alert, pending more information.

The predesignated areas for immediate protective action may be reserved for use only in situations where the facility operator cannot provide an immediate reliable estimate of projected dose based on actual releases. If the facility operator is able to provide reliable and prompt offsite dose projections, then these may be used to determine the area for immediate protective action, in lieu of using a predesignated area.

This will be possible when the facility operator can estimate the potential offsite dose based on information in the control room, using relationships developed during planning that relate abnormal plant conditions and meteorological conditions to potential offsite doses. After the release starts and the release rate is measurable and/or when plant conditions or measurements can be used to estimate the characteristics of the release and the release rate as a function of time, then these factors, along with meteorological stability conditions, windspeed, and wind direction, can be used to estimate integrated concentrations of radioactive contamination as a function of location downwind. Although such projections are useful for initiating protective action, the accuracy of these methods for estimating projected dose is necessarily poor because of unknown factors and uncertainty related to input data. For this reason, follow-up measurements in the environment will almost always be required.

When further information or forecasts on wind direction and meteorology become available, decisions for protective action in additional areas can be made. With dependable and stable meteorological and wind direction information, it may be possible to reduce the angular spread of the area in which additional protective action is taken. However, if the wind direction is variable or uncertain, the start of the release is delayed, the release is large, the duration is long, or the atmosphere is very unstable, the angular spread of the evacuated area may have to be increased, and possibly extended to a complete circle. The importance of current information on and forecasts of wind direction cannot be overemphasized.

5.3 The Establishment of Exposure Patterns

During and immediately following the early response to protect the population close to a facility, detailed environmental measurements are not possible, and calculations based on minimal measurements must be used to project doses. These projections are needed to determine whether protective action should be implemented in additional areas during the early phase. Because of the short time frame involved (4 days), if lower concentrations or exposure rates are projected than were initially predicted (usually on the basis of plant conditions alone), existing protective action should not be terminated. Such decisions should be based on the PAGs for relocation (Chapter 4).

Exposure rates or concentrations measured in the plume at a few selected locations may be used to estimate the pattern of the exposed area in a variety of ways. A simple, but crude, method is to measure the plume centerline exposure rate[1] at ground level at a known distance downwind of the release point and then to calculate exposure rates at other downwind locations by assuming that the plume centerline exposure

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[1] The centerline exposure rate can be determined by traversing the plume at a point sufficiently far downwind that it has stabilized (usually more than one mile from the site) while taking continuous exposure rate measurements, preferably from a helicopter or other small aircraft.

rate is a known function of the inverse of the distance from the release point.[2]

The following relationship can be used for this calculation:

$$D_2 = D_1 [R_1 / R_2]^x,$$

where D_1 = exposure rate at distance R_1,
D_2 = exposure rate at distance R_2, and
x = a constant, which depends on the stability class.

For average meteorological conditions, this relationship can be used to develop a pattern of estimated exposure rates by assuming that $x = 1.5$ and that the exposure rate calculated for the plume centerline would exist at all points equidistant from the source in the general downwind direction.[3] To use this method, one must be sure that the exposure rate measurement is taken at or near the plume centerline. Another method useful for estimating exposure rate patterns for flat terrain is to use a series of previously-prepared isopleths for standard meteorological conditions which are calculated using more sophisticated models.[4]

Computer modeling is now extensively used to estimate exposure rate patterns. A variety of computer software has been developed which will yield real-time isodose lines from projected (or actual) releases as well as from offsite measurements. This is the preferred method for estimating exposure patterns, because of the ease of performing

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[2] This may not always be a valid assumption. In the case of an elevated plume, for example, the ground level exposure rate at a near point may be less than at a location farther downwind.

[3] This value applies to meteorological stability classes C and D. If the meteorological stability condition is known, more accuracy can be achieved by using the values $x = 2$ for stability classes A and B; and $x = 1$ for classes E and F.

[4] Since meteorological stability class and the windspeed at the time of the release affect the shape of such isopleths, several sets of curves are needed in association with a corresponding map. By the application of simple multipliers, these isopleths may be used to estimate exposure rates over a wide area based on measurements at specific locations.

sophisticated calculations, as well as the ability to rapidly process large amounts of data and to simulate results for a wide variety of release and meteorological scenarios.

5.4 Dose Projection

The PAGs set forth in Chapter 2 are specified in terms of the effective dose equivalent. This dose includes that due to external gamma exposure of the whole body, as well as the committed effective dose equivalent from inhaled radionuclides. Guidance is also provided for the thyroid and skin in terms of the dose equivalent to these organs. Methods for estimating projected doses in each of these units, based on the exposure pattern, are discussed below. These require knowledge of or assumptions for the duration of exposure and the relation, for each radioisotope, between exposure and dose.

5.4.1 Duration of Exposure

The projected dose (or projected committed dose in the case of inhaled radionuclides) for comparison to the PAGs is calculated for exposure during the early phase of an emergency, normally defined as the first four days following the start of a release. In the case of a short duration release, this will encompass the entire period of exposure to the plume and exposure to deposited material for the first four days (deposition on skin and clothing is limited to 12 hours).

Doses that are incurred before the start of the release for which protective action is being considered should not normally be included in evaluating the need for protective action. Likewise, radiation doses that may be incurred at later times should not be included. These doses, which may occur through ingestion pathways or long-term exposure to deposited radioactive materials, take place over a different, longer time period. Protective action for such exposure is based on guidance addressed in other chapters.

The projected dose from a plume is proportional to the time-integrated concentration of radioactivity in the plume at each

location. This concentration will depend on both the rate of release and meteorological conditions. Release rates will vary with time, and this time-dependence cannot usually be predicted accurately. In the absence of more specific information, the release rate is therefore usually assumed to be constant.

The only remaining factor is then the duration of the plume at a particular location. Plume exposure will start at a particular location when the plume arrives and end when the plume is no longer present, due either to an end to the release, or a change in wind direction.

Prediction of time frames for releases is difficult because of the wide range associated with the potential spectrum of accidents. Therefore, planners should consider the possible time periods between an initiating event and arrival of a plume and the duration of releases in relation to the time needed to implement protective actions. Analyses (NR-75) have shown that some reactor incidents may take several days to develop to the point of a release, while others may begin as early as one-half hour after an initiating event. Furthermore, the duration of a release may range from less than one hour to several days, with the major portion of the release usually occurring within the first day. In addition, significant plume travel times are associated with the most adverse meteorological conditions (low windspeeds and stable atmospheric conditions), which may result in large exposures far from the site. For example, under such adverse conditions, two hours or more might be required for a plume to travel five miles. For equivalent release characteristics, higher windspeeds (which produce shorter travel times and provide more dispersion) result in individual exposures less than those under lower windspeeds. Planning information on time frames for releases from nuclear power facilities may be found in Reference NR-78.

Since a change in wind direction will also affect the duration of exposure, it is very important that arrangements be made for the State or local weather forecast center to provide information on current meteorological and wind conditions and predicted wind direction persistence during an incident, in addition to information received from

the facility operator. If neither a wind change nor the time to the end of the release can be predicted, the period of exposure should be conservatively assumed to be equal to the 99 percent probable maximum duration of wind direction persistence at the site. Historical data on wind direction persistence as a function of atmospheric stability class for nuclear power plant sites are available in the Final Safety Analysis Reports prepared by facility operators.

5.4.2 Dose Conversion Factors

This section provides dose conversion factors (DCFs) and derived response levels (DRLs) for those radionuclides important for accidents at nuclear power plants. These are supplemented by an example to demonstrate their application. The DCFs are useful where multiple radionuclides are involved, because the total dose from a single exposure pathway will be the sum of the doses calculated for each radionuclide. The DRLs are useful for releases consisting primarily of a single nuclide, in which case the DRL can be compared directly to the measured or calculated concentration. (DRLs can be used for multiple radionuclides by summing the ratios of the environmental concentration of each nuclide to its respective DRL. To meet the PAG, this sum must be equal to or less than unity.)

Table 5-1 provides DCFs and DRLs for external exposure to gamma and beta radiation due to immersion in contaminated air.[5] The values for gamma radiation will provide conservative estimates for exposure to an overhead plume under most realistic conditions. They are derived under the assumption that the plume is correctly approximated by a semi-infinite source.

The beta dose to skin from immersion is considered only for the noble gases. For other radionuclides, the beta skin dose is

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[5] The exposure from gamma radiation in air is not numerically equal to effective dose equivalent, because of attenuation of gamma radiation in the body. An approximation, valid for radionuclides from typical reactor accidents, is that the numerical value of the effective dose equivalent is about 0.7 times the numerical value of the exposure in air. Dose conversion factors in this section take these differences into account.

Table 5-1 Dose Conversion Factors (DCF) and Derived Response Levels (DRL) for External Exposure due to Immersion in Contaminated Air

Radionuclide[a]	Whole body gamma dose		Beta dose to skin	
	DCF[b] $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[c] $\mu\text{Ci-h/cm}^3$	DCF[d] $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[e] $\mu\text{Ci-h/cm}^3$
Kr-85	1.2E 0	8.3E-1	1.7E+2	2.9E-1
Kr-85m	8.4E+1	1.2E-2	1.8E+2	2.8E-1
Kr-87	4.8E+2	2.1E-3	1.2E+3	4.2E-2
Kr-88	1.2E+3	8.3E-4	2.8E+2	1.8E-1
Zr-95	4.1E+2	2.4E-3		
Ru-103	2.6E+2	3.9E-3		
Ru/Rh-106	2.4E-1	4.1E 0		
Te/I-132	1.1E+2	8.9E-3		
I-131	2.0E+2	5.0E-3		
I-132	1.3E+3	7.9E-4		
I-133	3.3E+2	3.1E-3		
I-135	9.0E+2	1.1E-3		
Xe-133	1.8E+1	5.6E-2	3.5E+1	1.4E 0
Xe-135	1.3E+2	7.7E-3	2.3E+2	2.2E-1
Cs-134	8.6E+2	1.2E-3		
Cs/Ba-137	7.1E-1	1.4E 0		
Ba-140	1.0E+2	1.0E-2		
Ce-144	9.2E 0	1.1E-1		
Np-239	8.6E+1	1.2E-2		

[a] Data from NUREG/CR-1918, Kocher (KO-81), pp. 163-205.
[b] Effective dose equivalent per unit exposure.
[c] Assumes a PAG of 1 rem.
[d] Dose equivalent per unit exposure.
[e] Assumes a PAG of 50 rems.

insignificant in comparison to the committed effective dose from inhalation. Even though the beta dose exceeds the gamma dose in the case of the noble gases, it is usually not controlling, because the guide for dose to skin is 50 times the PAG for exposure of the whole body. Kr-85 is an exception, because the beta dose exceeds the gamma dose by a factor of about 140. This radionuclide is not dominant for reactor accidents, however, because the inventory of Kr-85m normally exceeds that of Kr-85 by a factor of about 40.

Table 5-2 provides DCFs and DRLs for dose due to inhalation and for dose to skin from radionuclides deposited on skin and clothing. DCFs and DRLs are also provided for dose to the thyroid due to inhalation of radioiodines. For protective action decisions, it is necessary to consider the effective dose (to the whole body) and dose to thyroid and skin individually.

The effect of varying dose per unit intake and breathing rate with respect to age were analyzed, and the dose conversion factors tabulated in Table 5-2 are those that yield the greatest dose per unit concentration in air. These dose conversion factors are based on the assumption that the radionuclides are in oxide form (class Y), except for iodine (elemental), and that the particle size is one micron. For other chemical forms of practical interest the doses will differ, but in general only by a small factor (IA-86). If the solubility class or particle size is known or can be predicted, the inhalation dose conversion factors should be adjusted as appropriate.

It is not practical to determine dose to skin by measurement of the beta exposure rate near the skin surface. Such doses are determined more practically through calculations based on time-integrated air concentration, an assumed deposition velocity, and an assumed time period between deposition and skin decontamination. For purposes of calculating the DRLs, a deposition velocity of 1 cm/sec and an exposure time before decontamination of 12 hours were assumed. If other values are more appropriate, the tabulated DRLs can be scaled accordingly.

Table 5-2 Dose Conversion Factors (DCF) and Derived Response Levels (DRL) for Doses due to Inhalation and from Material Deposited on Skin and Clothing

Radionuclide[a]	Inhalation doses[b]				Beta dose	
	Effective dose		Thyroid		Skin	
	DCF $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[c] μCi-h/cm^3	DCF $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[d] μCi-h/cm^3	DCF $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[e] μCi-h/cm^3
Sr-89	9.1E+3	1.1E-4			1.9E+5	2.6E-4
Sr-90	2.2E+5	4.5E-6			1.9E+5	2.6E-4
Zr-95	2.6E+4	3.8E-5			1.5E+5	3.3E-4
Ru-103	1.1E+4	9.1E-5			1.2E+5	4.2E-4
Ru/Rh-106	6.0E+5	1.7E-6			1.9E+5	2.6E-4
Te/I-132	1.3E+4	7.7E-5	3.3E+5	1.5E-5	2.0E+5	2.5E-4
I-131	5.1E+4	2.0E-5	1.7E+6	3.0E-6	5.5E+5	9.1E-5
I-132	4.9E+2	2.0E-3	9.1E+3	5.5E-4	1.6E+5	3.1E-4
I-133	8.5E+3	1.2E-4	2.6E+5	1.9E-5	5.1E+5	9.8E-5
I-135	1.7E+3	5.9E-4	4.3E+4	1.2E-4	3.3E+5	1.5E-4
Cs-134	4.3E+4	2.3E-5			1.2E+5	4.2E-4
Cs/Ba-137	2.6E+4	3.8E-5			2.4E+5	2.1E-4
Ba-140	4.3E+3	2.3E-4			1.9E+5	2.6E-4
Ce-144	4.3E+5	2.3E-6			2.9E+5	1.7E-4
Np-239	3.3E+3	3.0E-4			1.3E+5	3.8E-4
Pu-238	2.6E+8	3.8E-9				
Pu-239	2.6E+8	3.8E-9				
Pu-240	2.6E+8	3.8E-9				
Pu-241	4.3E+6	2.3E-7				
Am-241	4.3E+8	2.3E-9				
Cm-242	2.2E+7	4.5E-8				
Cm-244	2.2E+8	4.5E-9				

[a] Data for all elements except I and Te are from Table XX, IAEA Safety Series 81 (IA-86). The data for I and Te are from NRPB R-162 (GR-85).

[b] The DCFs and DRLs are based on the age groups that would receive the greatest dose.

[c] Assumes a PAG of 1 rem.

[d] Assumes a PAG of 5 rems.

[e] Assumes a PAG of 50 rems, a deposition velocity of 0.01 m/s, and an exposure period of 12 hours after deposition. Data are from IAEA Safety Series 81 Table XII (IA-86).

DCFs and DRLs for beta dose to skin are not provided in Table 5-2 for the transuranic alpha emitters because skin dose from these radionuclides is insignificant compared to from inhalation, and thus would not affect decisions on evacuation. It should be noted that, even in situations where the beta skin dose might exceed 50 rems, evacuation would not usually be the appropriate protective action, because skin decontamination and clothing changes are easily available and effective protective actions.

Table 5-3 provides DCFs and DRLs for 4-day exposure to gamma radiation from selected radionuclides following deposition on the ground from a plume. The deposition velocity (assumed to be 1 cm/s) could vary widely, depending on meteorological (primarily precipitation) conditions. Decision makers are cautioned to pay particular attention to actual measurements of gamma exposure from deposited materials in situations where precipitation occurs during plume passage. The tabulated values include consideration of the dose contributed by short-lived daughters over the assumed 4-day period of exposure.

The above tables provide DCFs and DRLs for individual exposure pathways. Since these quantities are all expressed in terms of the integrated air concentration, they can be conveniently summed over the three major exposure pathways (plume gamma, plume inhalation, and gamma exposure to deposited materials) for the early phase to obtain a composite DRL for each radionuclide. These are tabulated in Table 5-4. (Since, in the case of exposure of the skin and thyroid, only one pathway is significant for each, the DCFs and DRLs for these organs are identical to those in Tables 5-1 and 5-2 for the thyroid and skin.) Table 5.4 summarizes all the factors necessary to evaluate the significance of environmental concentrations during the early phase of an accident.

To apply the data in Table 5-4, one may use either the DCFs or DRLs. The DCFs are used by calculating the projected composite dose for each radionuclide, summing these doses, and comparing them to the PAG. The DRLs may be used by summing the ratios of the concentration of each

Table 5-3 Dose Conversion Factors (DCF) and Derived Response Levels (DRL) for 4-Day Exposure to Gamma Radiation from Deposited Radionuclides

Radionuclide[a]	DCF[b] $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL[b,c] $\mu\text{Ci-h/cm}^3$
Zr-95	2.8E+4	3.5E-5
Nb-95	2.7E+4	3.7E-5
Ru-103	1.8E+4	5.7E-5
Ru/Rh-106	7.6E+3	1.3E-4
Te/I-132	7.6E+3	1.3E-4
I-131	1.4E+4	7.1E-5
I-132	2.9E+3	3.4E-4
I-133	7.1E+3	1.4E-4
I-135	5.1E+3	2.0E-4
Cs-134	5.9E+4	1.7E-5
Cs/Ba-137	2.1E+4	4.7E-5
Ba-140	5.1E+4	2.0E-5
Ce-144	2.1E+3	4.9E-4
Np-239	3.8E3	2.6E-4

[a] Data are from Table IX, page 56, IAEA Safety Series 81 (IA-86).
[b] Assumes a deposition velocity of 1 cm/sec, and that all activity is deposited at approximately the time of the incident.
[c] Assumes a PAG of 1 rem.

Table 5-4 Dose Conversion Factors (DCF) and Derived Response Levels (DRL) for Combined Exposure Pathways during the Early Phase of a Nuclear Incident

Radionuclide	Composite[a]	Composite[b]	Thyroid	Thyroid[c]	Skin	Skin[d]
	DCF $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL $\mu\text{Ci-h/cm}^3$	DCF $\frac{\text{rem}}{\mu\text{Ci-h/cm}^3}$	DRL $\mu\text{Ci-h/cm}^3$	DCF $\frac{\text{rad}}{\mu\text{Ci-h/cm}^3}$	DRL $\mu\text{Ci-h/cm}^3$
Kr-85	1.2E 0	8.3E-1			1.7E+2	2.9E-1
Kr-85m	8.4E+1	1.2E-2			1.8E+2	2.8E-1
Kr-87	4.8E+2	2.1E-3			1.2E+3	4.2E-2
Kr-88	1.2E+3	8.3E-4			2.8E+2	1.8E-1
Sr-89	9.1E+3	1.1E-4			1.9E+5	2.6E-4
Sr-90	2.2E+5	4.5E-6			1.9E+5	2.6E-4
Zr-95	5.4E+4	1.9E-5			1.5E+5	3.3E-4
Ru-103	2.9E+4	3.4E-5			1.2E+5	4.1E-4
Ru/Rh-106	6.1E+5	1.6E-6			1.9E+5	2.6E-4
Te/I-132	2.1E+4	4.8E-5	3.3E+5	1.5E-5	2.0E+5	2.5E-4
I-131	6.5E+4	1.5E-5	1.7E+6	3.0E-6	5.5E+5	9.1E-5
I-132	4.7E+3	2.1E-4	9.1E+3	5.5E-4	1.6E+5	3.1E-4
I-133	1.6E+4	6.3E-5	2.6E+5	1.9E-5	5.1E+5	9.8E-5
I-135	7.7E+3	1.3E-4	4.3E+4	1.2E-4	3.3E+5	1.5E-4
Xe-133	1.8E+1	5.6E-2			3.5E+1	1.4E 0
Xe-135	1.3E+2	7.7E-3			2.3E+2	2.2E-1
Cs-134	1.0E+5	1.0E-5			1.2E+5	4.2E-4
Cs/Ba-137	4.7E+4	2.1E-5			2.4E+5	2.1E-4
Ba-140	5.5E+4	1.8E-5			1.9E+5	2.6E-4
Ce-144	4.3E+5	2.3E-6			2.9E+3	1.7E-4
Np-239	7.2E+3	1.4E-4			1.3E+5	3.8E-4
Pu-238	2.6E+8	3.8E-9				
Pu-239	2.6E+8	3.8E-9				
Pu-240	2.6E+8	3.8E-9				
Pu-241	4.3E+6	2.3E-7				
Am-241	4.3E+8	2.3E-9				
Cm-242	2.2E+7	4.5E-8				
Cm-244	2.2E+8	4.5E-9				

[a] Sum of DCFs for gamma and inhalation from the plume, and gamma from deposition. Dose is expressed in terms of the committed effective dose equivalent.
[b] For a PAG of 1 rem.
[c] For a PAG of 5 rems.
[d] For a PAG of 50 rems.

radionuclide to its corresponding DRL. If the sum of the ratios exceeds unity, the appropriate protective action should be initiated.

The following example demonstrates the use of the data in Table 5-4 for a simple analysis involving three radionuclides.

EXAMPLE:

Based on source term and meteorological considerations, it is assumed that the worst probable accident at an industrial facility is a fire that could disperse radioactive material into the atmosphere, yielding a time-integrated concentration of radionuclides at a nearby populated area, as follows:

Radionuclide	uCi-h/cm^3
Zr-95	2E-6
Cs-134	4E-8
I-131	1.2E-5

We examine whether evacuation is warranted at these levels, based on PAGs of 1 rem for effective dose to the whole body, 5 rems for dose to the thyroid, and 50 rems for dose to skin. We use the DCFs in Table 5-4 and the following equation:

$$H_E = \sum_{1}^{n} D_n$$

where H_E = effective dose (rem),
D_n = DCF_n x C_n; where, for radionuclide n,
DCF_n = dose conversion factor, and
C_n = environmental concentration.

For effective dose:

(2 E-6 x 5.4E+4) + (4E-8 x 1.0 E+5) + (1.2E-5 x 6.5E+4) = 0.89 rem.

For dose to the thyroid:

1.2E-5 x 1.7E+6 = 20.4 rems.

For dose to the skin:

(2E-6 x 1.5E+5) + (4E-8 x 1.2E+5) + (1.2E-5 x 5.5E+5) = 6.9 rems.

The results of these calculations show that, at the location for which these time-integrated concentrations are specified, the committed dose equivalent to the thyroid from inhalation would be about four times the PAG for dose to thyroid, thus justifying evacuation. Using meteorological dilution factors, one could calculate the additional distance to which evacuation would be justified to avoid exceeding the PAG for thyroid dose.

The process for using the DRLs from Table 5-4 is as follows:

$$\sum_{1}^{n} \frac{C_n}{DRL_n} \quad 1$$

where DRL_n is the derived response level for radionuclide n, and C_n is defined above.

For effective dose:

$$\frac{2\ E\text{-}6}{1.9\ E\text{-}5} + \frac{4\ E\text{-}8}{1\ E\text{-}5} + \frac{1.2\ E\text{-}5}{1.5\ E\text{-}5} = 0.9$$

For the dose to thyroid:

$$\frac{1.2\ E\text{-}5}{3.0\ E\text{-}6} = 4$$

For the dose to skin:

$$\frac{2\ E\text{-}6}{3.3\ E\text{-}4} + \frac{4\ E\text{-}8}{4.2\ E\text{-}4} + \frac{1.2\ E\text{-}5}{9.1\ E\text{-}5} = 0.13$$

It is apparent that these calculations yield the same conclusions.

5.4.3 Relative Importance of Exposure Pathways

Many emergency response plans have already been developed using previously-recommended PAGs that apply to the dose equivalent to the whole body from direct (gamma) radiation from the plume and to the thyroid from inhalation of radioiodines. Those PAGs were 1 to 5 rems to the whole body and 5 to 25 rems to the thyroid. For response to nuclear

power plant accidents, they provide public protection comparable to that provided by the PAGs based on effective dose equivalent and dose equivalent to the thyroid and skin now recommended. This is demonstrated in Table 5-5, which shows comparative doses for nuclear power plant fuel-melt accident sequences having a wide range of magnitudes.

Thyroid dose, skin dose, and effective dose to the whole body from the three major plume exposure pathways were calculated for radionuclide mixes postulated for three nuclear power plant accident sequences, using the dose conversion factors in Table 5-4. The doses were then normalized for each accident so that they represent a location in the environment where the controlling dose (effective, thyroid, or skin) would be equal to the corresponding current PAG. The calculated direct radioactive dose from external gamma radiation from the plume, based on data in Table 5-1, is shown in the last column.

Table 5-5 Comparison of Projected Doses for Various Accident Scenarios

Accident category[a]	Effective dose equivalent[b] (rem)	Skin dose equivalent (rem)	Thyroid dose equivalent (rem)	Direct radiation dose equivalent (rem)
SST-1	0.6	6	5[c]	0.03
SST-2	0.8	3	5[c]	0.33
SST-3	0.4	7	5[c]	0.03

[a] See NUREG/CR-2239(SN-82) for a description of these accident scenarios.

[b] The dose is the the sum of doses from 4-day exposure to direct radiation from and inhalation of the plume, and from deposited materials.

[c] Doses are normalized so that the relevant projected dose is equal to the limiting PAG.

Based on the results shown in Table 5-5, the following conclusions are apparent for the accident sequences analyzed:

1. The current PAG for thyroid dose is controlling for all three accident categories. For the SST-2 category, effective dose approaches being controlling.

2. Application of the full range of the previous PAG (5-25 rems) for thyroid would provide the same or less protection, depending on the choice of level within the range.

3. Skin doses will not be controlling for any of the accident sequences (if bathing and change of clothing is completed within 12 hours of plume passage, as assumed).

4. Gamma dose from direct exposure to the plume is small compared to the effective dose from the three major exposure pathways combined.

5.5 Protective Actions

This section provides guidance for implementing the principal protective actions available for protection against an airborne plume, sheltering and evacuation. Sheltering means the use of the closest available structure which will provide protection from exposure to an airborne plume, and evacuation means the transfer of individuals away from the path of the plume.

Sheltering and evacuation provide different levels of dose reduction for the principal exposure pathways (inhalation of radioactive material, and direct gamma exposure from the plume on from material deposited on surfaces.) The effectiveness of evacuation depends primarily on how rapidly it can be implemented in relation to the arrival of radioactive material at a given location. Sheltering, which in most cases should be almost immediately implementable, varies in usefulness depending upon the type of shelter available and the duration of the plume passage.

Studies have been conducted to evaluate shelter (EP-78a) and evacuation (HA-75) as protective actions. Reference EP-78b suggests one method for evaluating and comparing the benefits of these two actions. This requires collecting planning information before and data following an incident, and using calculations and graphical means to evaluate whether evacuation, sheltering, or a combination of sheltering followed by evacuation should be recommended at different locations. Because of the many interacting variables, the user is forced to choose between making decisions during the planning phase, based on assumed data that may be grossly inaccurate, or using a time-consuming more comprehensive process after the incident when data may be available. In the former situation, the decision may not have a sound basis, whereas in the latter, the decision may come too late to be useful.

The recommended approach is to use planning information for making early decisions. The planned response should then be modified following the incident only if timely detailed information is available to support such modifications.

The planner should first compile the necessary information about the emergency planning zone (EPZ) around the facility. This should include identifying the population distribution, the sheltering effectiveness of residences and other structures, institutions containing population groups that require special consideration, evacuation routes, logical boundaries for evacuation zones, transportation systems, communications systems, and special problem areas. In addition, the planner should identify the information that may be available following an incident, such as environmental monitoring data, meteorological conditions, and plant conditions. The planner should identify key data or information that would justify specific protective actions. The evaluation and planning should also include the selection of institutions where persons should be provided with stable iodine for thyroid protection in situations where radioiodine inhalation is projected.

The following sections discuss key factors which affect the choice between evacuation and sheltering.

5.5.1 Evacuation

The primary objective of evacuation is to avoid exposure to airborne or deposited radioactive material by moving individuals away from the path of the plume. Accordingly, evacuation, if accomplished soon enough, can be 100 percent effective in avoiding exposure. If, however, evacuation coincides with or follows plume passage, the reduction of exposure will be only partial. Since, in the absence of evacuation, sheltering will be implemented at any location where significant exposure is possible, the maximum dose avoided by evacuation will be the dose not avoidable by sheltering. Accordingly, if an evacuation is carried out improperly and direct exposure to the plume occurs during evacuation itself, the dose could be greater than if sheltering were continued.

Some general conclusions regarding evacuation (HA-75) which may be useful for planning purposes are summarized below:

1. Advanced planning is essential to identify potential problems that may occur in an evacuation.

2. Most evacuees use their own personal transportation.

3. Most evacuees assume the responsibility of acquiring food and shelter for themselves.

4. Evacuation costs are highly location-dependent and usually will not be a deterrent to carrying out an evacuation.

5. Neither panic nor hysteria has been observed when evacuation of large areas is managed by public officials.

6. Large or small population groups can be evacuated effectively with minimal risk of injury or death.

7. The risk of injury or death to individual evacuees does not change as a function of the number of persons evacuated, and can

be conservatively estimated using National Highway Safety Council statistics for motor vehicle accidents (subjective information suggests that the risks will be lower).

Evacuation of the elderly, the handicapped, and inhabitants of medical and penal institutions presents special problems. When sheltering can provide adequate protection, this will often be the protective action of choice. However, if the general public is evacuated and those in institutions are sheltered, there is a risk that attendants at these institutions may leave and make later evacuation of institutionalized persons difficult because of a lack of attendants. Conversely, if evacuation of institutions is attempted during evacuation of the public, traffic conditions may cause unacceptable delays. If evacuation of institutions is attempted before evacuating the public, increased risk to the public from a delayed evacuation could occur, unless the incident is very slow in developing to the point of an atmospheric release. The potential risk to society of evacuating dangerous criminals from prison at relatively low projected doses should also be considered.

Because of the above difficulties, medical and penal institutions located within the EPZ should be evaluated to determine whether there are any logical categories of persons that should be evacuated after the public (or, when time permits, before).

5.5.2 Sheltering

Sheltering refers here to the use of readily available nearby structures for protection from exposure to an airborne plume.

As with evacuation, delay in taking shelter during plume passage will reduce the protection from exposure to radiation. The degree of protection provided by structures is governed by attenuation of radiation by structural components (the mass of walls, ceilings, etc.) and by outside/inside air-exchange rates. These two protective characteristics are considered separately.

The protection factor may be characterized by a dose reduction factor (DRF), defined as:

$$DRF = \frac{\text{dose with protective action}}{\text{dose without protective action}}.$$

The shielding characteristics of most structures for gamma radiation can be categorized based on whether they are "small" or "large." Small structures are primarily single-family dwellings, and large structures include office, apartment, industrial, and commercial buildings. The typical attenuation factors given in Table 5-6 show the importance of the type of structure for protection from direct radiation (EP-78a). If the structure is a wood frame house without a basement, then sheltering from gamma radiation would provide a DRF of 0.9; i.e., only 10 percent of the dose would be avoided. The DRFs shown in Table 5-6 are initial values prior to infiltration and therefore apply to short duration plumes. The values will increase with increasing time of exposure to a plume because of the increasing importance of inside-outside air exchange. However, this reduction in efficiency is not dramatic for gamma radiation because most of the dose arises from outside, not from the small volume of contaminated air inside a shelter. Therefore, most shelters will retain their efficiency as shields against gamma radiation, even if the concentration inside equals the concentration outside.

Table 5-6 Representative Dose Reduction Factors for Direct Radiation

Structure	DRF	Effectiveness (percent)
Wood frame house (first floor)	0.9	10
Wood frame house (basement)	0.6	40
Masonry house	0.6	40
Large office or industrial building	0.2 or less	80 or better

The second factor contributing to the degree of protection (primarily against exposure by inhalation) is the inside/outside air exchange rate. This is expressed as the number of air exchanges per hour, L (h^{-1}), or the volume of fresh air flowing into and out of the structure per hour divided by the volume of the structure. Virtually any structure that can be used for sheltering has some degree of outside/inside air exchange due to natural ventilation, forced ventilation, or uncontrollable outside forces, primarily wind.

Assuming constant atmospheric and source conditions and no effects from filtration, deposition, or radioactive decay, the following model can be used to estimate the buildup of indoor concentration of radioactivity from a given outdoor concentration as a function of time, after appearance of the plume, and of ventilation rate:

$$C_i = C_o(1 - e^{-Lt}),$$

where C_i = concentration inside,
C_o = concentration outside,
L = ventilation rate (h^{-1}), and
t = elapsed time (h).

Typical values for ventilation rates range from 0.2 to several air exchanges per hour. In the absence of measurements, an air exchange rate of 1.0/h may be assumed for structures with no special preparation except for closing the doors and windows. An air exchange rate of 0.3/h is appropriate for relatively air-tight structures, such as well-sealed residences, interior rooms with doors chinked and no windows, or large structures with ventilation shut off. Using the above model to calculate indoor concentrations relative to outdoor concentrations after one, two, and four complete air exchanges, the indoor concentrations would be about 64 percent, 87 percent, and 98 percent of the outside concentrations, respectively. It is apparent that staying in a shelter for more time than that required for one or two complete air exchanges is not very effective for reducing inhalation exposure.

The inhalation DRF is equal to the ratio of the average inside-to-outside air concentrations over the period of sheltering. Studies have been conducted of typical ventilation rates for dwellings (EP-78a) and for large commercial structures (GR-86). In each case the rate varies according to the air tightness of the structure, windspeed, and the indoor-to-outdoor temperature difference. It is not practical, however, to adjust the implementation of the PAGs for these variables, so average ventilation rates were chosen for the two types of structures that are of greatest interest for decisions on evacuation and sheltering. Table 5-7 shows calculated dose reduction factors for inhalation exposure as a function of plume duration, assuming average ventilation rates for these structures.

A potential problem with sheltering is that persons may not leave the shelter as soon as the plume passes and, as a result, will receive exposure from radioactive gases trapped inside. The values for DRFs tabulated in Table 5-7 ignore this potential contribution. This effect

Table 5-7 Dose Reduction Factors for Inhalation

Ventilation rate (air changes/h)	Duration of plume exposure	DRF
0.3[a]	0.5	0.07
	1	0.14
	2	0.25
	4	0.41
	6	0.54
1.0[b]	0.5	0.21
	1	0.36
	2	0.56
	4	0.75
	6	0.83

[a] Applicable to relatively "airtight" structures such as well-sealed residences, interior rooms with chinked doors and no windows, or large structures with outside ventilation shut off.

[b] Applicable to structures with no special preparation except for closing of doors and windows.

is minor for gamma dose (generally less than a 10 percent increase in the dose received during plume passage, (EP-78b)), but can be greater for inhalation dose.

Dose reduction factors for sheltering can be improved in several ways, including reducing air exchange rates by sealing cracks and openings with cloth or weather stripping, tape, etc. and filtering the inhaled air with common items like wet towels and handkerchiefs.

5.5.3 Dual Protective Actions

A combination of sheltering followed by evacuation may be effective for situations where the plume is projected to arrive too soon to permit effective evacuation or if there are longer than expected periods of exposure.

Another evacuation/shelter protective action combination that may be effective occurs when it is desirable to evacuate people in a high-dose area, but shelter those in areas farther downwind where sheltering could provide an adequate level of protection and thus reduce the possibility of overloading evacuation routes.

There may also be situations where sheltering in large structures will give adequate protection, but it is desirable to evacuate individuals from less effective shelters. This sort of "shelter-availability" split may be appropriate if timely evacuation is difficult in areas where large structures are more prevalent than small structures.

Situations may also occur in which sheltering is appropriate initially because of a prediction of a short duration plume, and, because the duration is more extended than anticipated, it becomes necessary to reduce the dose by evacuation.

5.5.4 General Guidance for Evacuation and Sheltering

The process of evaluating, recommending, and implementing evacuation or shelter for the public is far from an exact science, particularly in view of time constraints that prevent thorough analysis at the time of an incident. Its effectiveness, however, can be improved considerably by planning and testing. Early decisions should be based on information collected from the emergency planning zone during the planning phase and on information regarding conditions at the nuclear facility at the time of the incident. Generally, it is to be expected that evacuation will be appropriate initially near the point of release, with sheltering being preferred (at least temporarily until more information is available) at greater distances in the downwind direction.

The following should be helpful in making more detailed decisions:

1. Evacuation will provide total protection from any airborne release if it is completed before arrival of the plume.

2. Sheltering may be appropriate because:
   a. It is faster than evacuation,
   b. It may provide adequate protection,
   c. A majority of the public is already sheltered, or
   d. It is less expensive and disruptive.

3. Sheltering is usually not appropriate for significant exposure lasting longer than two complete air exchanges (2 to 6 hours for most structures).

4. Because sheltering may be implemented in less time than evacuation, it may be the protective action of choice if rapid evacuation is impeded, e.g.:
   a. Short time available--high wind velocity, location close to source;
   b. Severe environmental conditions--weather, flood;
   c. Health constraints--hospitals, nursing homes;

d. Public safety considerations--prisoners, emergency workers; and
e. Long mobilization times--certain industries, farms.

5. The longer the projected duration of exposure, the less attractive sheltering becomes, particularly in small structures. Effectiveness of shelters can be improved by turning off ventilation systems, closing cracks and other penetrations, and filtering inhaled air, Turning off ventilation systems could pose a severe hazard in some facilities, thus reducing their appropriateness as a shelter.

6. If the plume is expected to arrive during mobilization for evacuation, it may be appropriate to shelter first, then evaluate the desirability of subsequent evacuation.

7. The use of large structures, such as shopping centers, schools, churches, and commercial buildings, as collection points during evacuation mobilization will generally provide greater protection than use of small structures.

8. If a major release of radioiodine or particulate materials occurs, inhalation dose may be the controlling criterion. In this case:
   a. Ventilation control is essential for effective sheltering.
   b. Simple filtering of breath using common household items (i.e., folded wet handkerchiefs or towels) is of significant help.
   c. Following plume passage, people should exit shelters to avoid airborne activity trapped inside, and they should leave high exposure areas as soon as possible after cloud passage to avoid exposure to deposited radioactive material.
   d. Consideration should be given to the prophylactic administration of potassium iodide (KI) as a thyroid-blocking agent to emergency workers, prisoners, workers in critical industries, and others for whom State

and local plans may not include evacuation as a predetermined protective action.[6]

9. If whole body dose is the controlling criterion, shelter construction and size are the most important considerations; ventilation control and filtering are less important. The main factors which reduce whole body exposure are:
   a. Wall thickness and size of structure,
   b. Number of stories overhead, and
   c. Central location within the structure.

[6] Each State has the responsibility for formulating guidance to define when (and if) the public should be given potassium iodine and instructions on how to use it to reduce the thyroid uptake of radioiodine. Planning for its use should include the considerations in "Potassium Iodide as a Thyroid-blocking Agent in a Radiation Emergency: Final Recommendations on Use" (FD-82).

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CHAPTER 6

Implementing the PAGs for the Intermediate Phase (Food and Water)

(reserved)

CHAPTER 7

Implementation Guidance for Protective Actions During the Intermediate Phase (Exposure to Deposited Materials)

7.1 Introduction

This chapter provides guidance for implementing the PAGs set forth in Chapter 4. This guidance is for use by State and local officials in developing their radiological emergency response plans to protect the public from exposure to radiation from deposited radioactive materials. See Appendix A for definitions and Appendix F for the rationale on which these PAGs are based.

Contrary to the situation during the early phase of a nuclear incident, when decisions usually must be made and implemented quickly by State and local officials before Federal assistance is available, many decisions and actions during the intermediate phase can be delayed until Federal resources are present, as described in the Federal Radiological Monitoring and Assistance Plan (FE-84). Because of the reduced level of urgency for immediate implementation of these protective actions, somewhat less detail may be needed in State radiological emergency response plans than is required for the early phase.

At the time of decisions on relocation and early decontamination, some sheltering and evacuation may have already been completed to protect the public from exposure to the airborne plume. These protective actions may have been implemented prior to verification of the path of the plume and therefore some persons may have been unnecessarily evacuated from areas where actual dose is much lower than projected. Others who were in the path of the plume may have been sheltered or not protected at all. During the intermediate phase of the response persons must be relocated from areas where the projected dose exceeds the PAG for relocation, and other actions taken to reduce dose to persons who are not relocated.

7.1.1 Protective Actions

The main protective actions for protection of the public from exposure to deposited radioactivity are relocation, decontamination, shielding, time limits on exposure, and control of the spread of surface contamination. Relocation is the most effective, and, usually, the most costly and disruptive. It is therefore only applied when the dose is sufficiently high to warrant such. The others are generally applied to reduce exposure of persons who are not relocated, and apply to areas that receive lower levels of deposited radioactivity. This chapter provides guidance for translating radiological conditions in the environment to projected dose, to provide the basis for decisions on the appropriate protective actions.

7.1.2 Areas Involved

Figure 7-1 provides a generalized example of the different areas and population groups to be dealt with. The path of the plume is assumed to be represented by area 1. In reality, variations in meteorological conditions would almost certainly produce a more complicated shape, but the same principles would apply.

Because of plant conditions and other considerations prior to or after the release, persons will already have been evacuated from area 2 and sheltered in area 3. Persons who have been evacuated from or sheltered in areas 2 and 3, respectively, as precautionary actions for protection from the plume, but whose homes are outside the plume deposition area (area 1), may return to their homes or discontinue shelter as soon as environmental monitoring verifies the boundary of the area that received deposition (area 1).

Area 4 is designated a restricted zone and is defined as the area where projected doses are equal to or greater than the relocation PAG. Persons residing just outside the boundary of the restricted zone may receive a dose near the PAG for relocation if decontamination or other dose reduction efforts are not implemented.

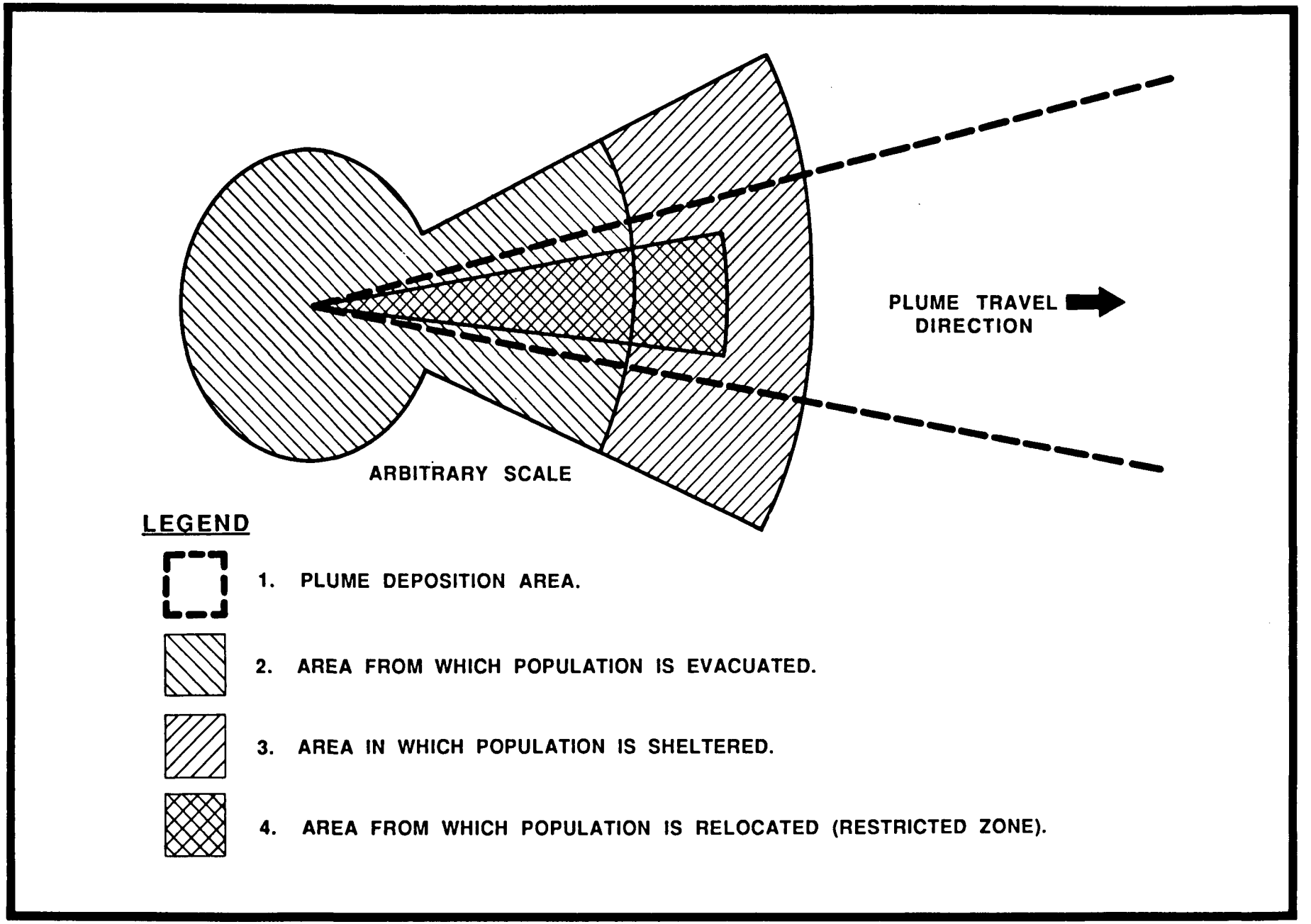

FIGURE 7-1. RESPONSE AREAS.

Area 1, with the exception of the restricted zone, represents the area of contamination that may continue to be occupied by the general public. Nevertheless, there will be contamination levels in this area that will require continued monitoring and dose reduction efforts other than relocation.

The relative positions of the boundaries shown in Figure 7-1 depend on areas evacuated and sheltered, and the radiological characteristics of the release. For example, area 4 (the restricted zone) could fall entirely inside area 2 (area evacuated), so that the only persons to be relocated would be those residing in area 4 who were missed in the evacuation process.

At the time the restricted zone is established, a temporary buffer zone (not shown in Figure 7-1) may be needed outside portions of the restricted zone in which occupants will not be allowed to return until monitoring confirms the stability of deposited contamination. Such zones would be near highly contaminated areas in the restricted zone where deposited radionuclides might be resuspended and then redeposited outside the restricted zone. This could be especially important at locations close to the accident site where the radioactivity levels are high and the restricted zone may be narrow. The extent of the buffer zone will depend on local conditions. Similarly, a buffer zone encompassing the most highly contaminated areas in which persons are allowed to reside may be needed. This area should be monitored routinely to assure acceptability for continued occupancy.

7.1.3 Sequence of Events

Following passage of the airborne plume, several tasks, as shown in Figure 7-2, must be accomplished simultaneously to provide for timely protection of the public. The decisions on the early task of relocating persons from high exposure rate areas must be based on exposure rate measurements and dose analyses. It is expected that monitoring and dose assessment will be an on-going process, with priority given to the areas

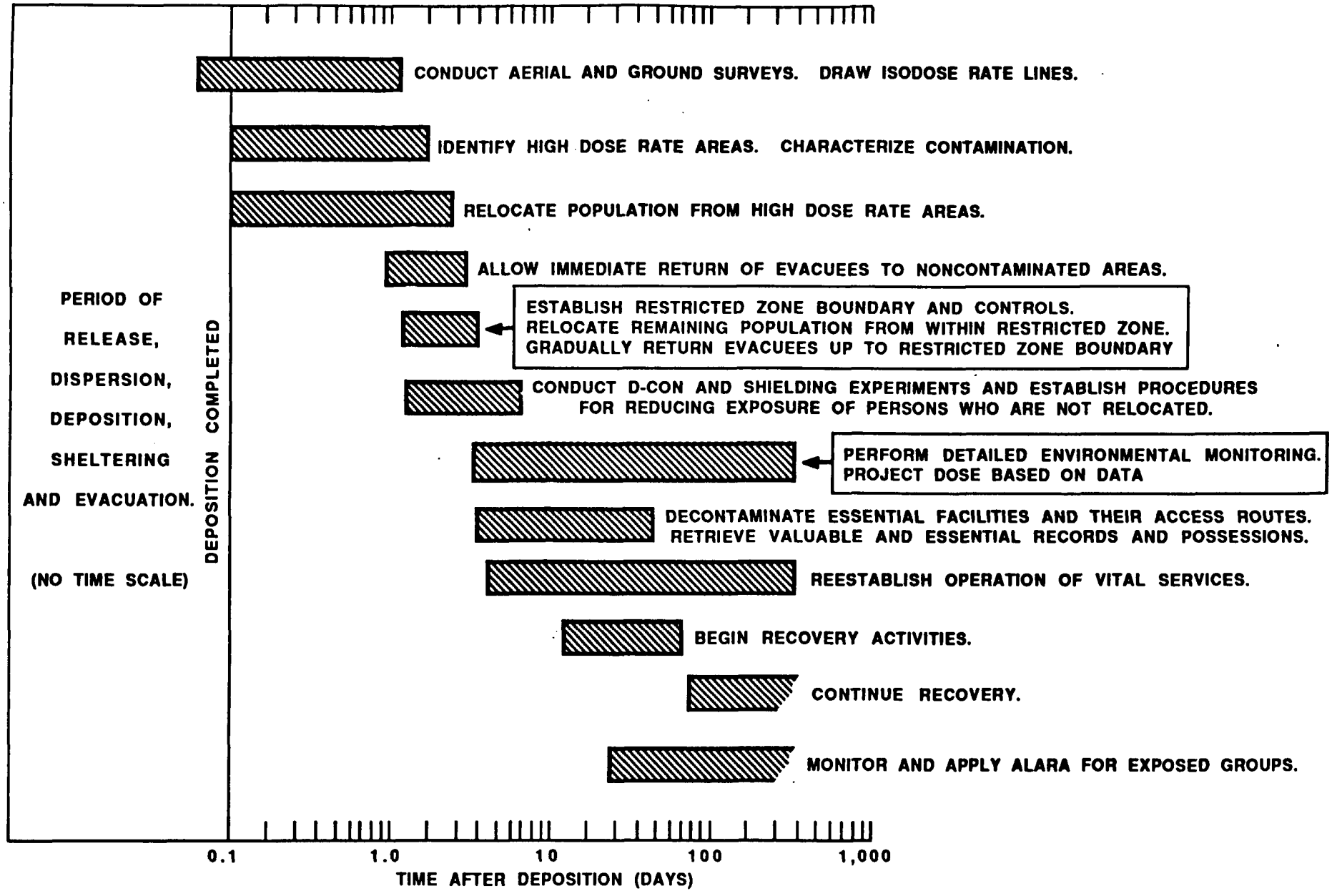

FIGURE 7-2. TIME FRAME OF RESPONSE TO A MAJOR NUCLEAR REACTOR ACCIDENT (ASSUMED).

with the highest exposure rate. The general sequence of events is itemized below, but the time frames will overlap, as demonstrated in Figure 7-2.

A. Based on environmental data, determine the areas where the projected one-year dose will exceed 2 rems and relocate persons from those areas, with priority given persons in the highest exposure rate areas.

B. Allow persons who were evacuated to return immediately to their residences if they are in areas where field gamma measurements indicate that exposure rates are near normal background levels (not in excess of twice the normal background in the area before the accident). If, however, areas of high deposition are found to be near areas with low deposition such that resuspended activity could drift into the occupied areas, a buffer zone should be established to restrict occupancy until the situation is analyzed and dose projections are confirmed.

C. Conduct experiments to determine the dose reduction effectiveness of simple decontamination techniques and of sheltering due to partial occupancy of residences and workplaces. Results of these experiments may influence recommendations for reducing exposure rates for persons who are not relocated from areas near, but outside, the restricted zone.

D. Determine the location of the isodose line corresponding to the relocation PAG, establish the boundary of the restricted zone, and relocate any persons who still reside within the zone. Also, convert any evacuees who reside within the restricted zone to relocation status. Evacuated persons whose residence is in the area between the boundary of the plume deposition and the boundary to the restricted zone may return gradually as confidence is gained regarding the projected dose in the area.

E. Establish a mechanism for controlling access to and egress from the restricted zone. Typically this would be accomplished through control points at roadway accesses to the restricted zone.

F. Establish monitoring and decontamination stations.

G. Implement simple decontamination techniques in occupied areas, with priorities for areas with higher exposure rates and for residences of pregnant women. This includes institutions such as hospitals.

H. Collect data needed to establish long-term radiation protection criteria for recovery and data to determine the effectiveness of various decontamination or other recovery techniques.

I. Begin operations to recover contaminated property in the restricted zone.

7.2 Establishment of Isodose Rate Lines

As soon as Federal or other assistance is available for aerial and ground monitoring, a concentrated effort should begin to establish isodose-rate lines on maps and the identification of boundaries to the restricted zone. Planning for this effort should include the development of standard gridded maps that can be used by all of the involved monitoring and dose assessment organizations to record monitoring data.

Aerial monitoring (e.g., the Department of Energy Aerial Monitoring Service) can be used to collect data for establishing general patterns of radiation exposure rates from deposited radioactive material. These data, after translation to readings at 1 meter above ground, may form the primary basis for the development of isodose lines out to a distance where aerial monitoring shows no radiation above twice natural background levels. Air sample measurements will also be needed to verify the contribution to dose from this pathway.

Gamma exposure rates measured at 1 meter will no doubt vary as a function of the location of the measurement within a very small area. This could be caused by different deposition rates for different types of surfaces (e.g., smooth surfaces versus heavy vegetation). Rinsing or precipitation could also reduce levels in some areas and raise levels in others where runoff settles. In general, where exposure rates vary within designated areas, the higher values should be used for dose projection for persons within these areas unless judgment can be used to estimate an appropriate average exposure rate.

Measurements made at 1 meter to project whole body dose from gamma radiation should be made with instruments of the "closed window" type so as to avoid the detection of beta radiation. Although beta exposure will contribute to skin dose, its contribution to the overall risk of health effects from the radionuclides expected to be associated with reactor accidents should be minor in comparison to the whole body gamma dose (AB-88). Special beta dose analyses should be made when time permits to determine its contribution to skin dose. Since beta dose rate measurements require sophisticated equipment that is generally not available for field use, beta dose to the skin should generally be calculated based on concentrations of radionuclides per unit area. These data will already be available for use in gamma dose projections.

7.3 Dose Projection

The primary dose of interest for reactor accidents is the sum of the effective gamma dose equivalent from external exposure and the committed effective dose equivalent from inhalation. Skin dose from exposure to beta radiation may also be significant in some cases and should be evaluated. The exposure periods of interest are first year, second year, and up to 50 years after the accident.

Calculation of the projected gamma dose from measurements will require knowledge of the principal radionuclides contributing to exposure and their relative abundances. Information on these radiological characteristics can

be compiled either through the use of portable gamma spectrometers or by radionuclide analysis of environmental samples. Several measurement locations may be required to determine whether any selective radionuclide deposition occurred as a function of weather, surface type, or distance from the point of release. As part of the Federal Radiological Monitoring and Assessment Plan (FE-84), the U. S. Department of Energy and the U. S. Environmental Protection Agency have equipment and procedures to assist State officials in performing environmental measurements, including determination of the radiological characteristics of deposited materials.

The gamma exposure rate may decrease rapidly if deposited material includes a significant fraction of short-lived radionuclides. Therefore, the relationship between instantaneous exposure rate and projected first- and second-year annual or the 50-year doses will change as a function of time, and these relationships must be established for the particular mix of deposited radioactive materials present at the time of the gamma exposure rate measurement.

For accidents involving releases from nuclear power plants, gamma radiation from deposited radioactive materials is expected to be the principal exposure pathway, as noted above. Other pathways should also be evaluated, and their contributions added, if significant. These may include inhalation of resuspended material and beta dose to the skin. Exposure from ingestion of food and water is normally limited independently of decisions for relocation and decontamination (see Chapters 3 and 6). In some instances, however, where withdrawal of food and/or water from use would, in itself, create a health risk, relocation may be an appropriate protective action for protection from exposure via ingestion. In this case, the committed effective dose equivalent from ingestion should be added to the projected dose from other exposure pathways for decisions on relocation.

The following sections provide methods for evaluating the projected dose from whole body external exposure and from inhalation of resuspended particulate material, based on environmental information.

7.3.1 Projected External Gamma Dose

Projected whole body external gamma doses at 1 meter in height at particular locations during the first year, second year, and over the 50-year period after the accident are the parameters of interest. The environmental information available for calculating these doses is expected to be the instantaneous gamma exposure rate at 1 meter in height and the relative abundance of each radionuclide contributing significantly to that exposure rate. Calculational models are available for predicting exposure rate as a function of time due to radioactive decay and weathering (NR-75), and information is available for relating surface concentrations to a gamma exposure rate at 1 meter (KO-81).

Following the accident, experiments should be conducted to determine the dose reduction factors associated with part-time occupancy of dwellings and workplaces, and with simple, rapid, decontamination techniques, so that these factors can also be applied to the calculation of dose to persons who are not relocated. However, these factors should not be included in the calculation of projected dose for decisions on relocation.

Relocation decisions can generally be made on the basis of the first year projected dose. However, projected doses during the second year and over 50 years are needed for decisions on the need for other protective actions for persons who are not relocated. Dose conversion factors are therefore needed for converting environmental measurements to projected dose during the first year, second year, and over 50 years following the accident. Of the two types of environmental measurements that can be made to project whole body external gamma dose, gamma exposure rate in air is the easiest to make and is the most directly linked to gamma dose rate. However, a few measurements of the second type (radionuclide concentrations on surfaces) will also be needed to properly project decreasing dose rates.

Tables 7-1 and 7-2 provide information to simplify the development of dose conversion factors through the use of data on the radionuclide mix, as determined from environmental measurements. These tables list the deposited radionuclides most likely to be the major contributors to dose from

Table 7-1 Initial Gamma Exposure Rate and the Effective Dose Equivalent (Corrected for Radioactive Decay and Weathering) Calculated from an Initial Radionuclide Concentration of 1 pCi/m^2 on Ground Surface

Radionuclide	Half-life hours	Initial exposure[a] rate at 1 m (mR/h per pCi/m^2)	Integrated dose (weathering factor included)[b] year 1 (mrem per pCi/m^2)	year 2 (mrem per pCi/m^2)	0-50 year (mrem per pCi/m^2)
Zr-95	1.54E+03	1.4E-08	3.3E-05	4.0E-07	3.4E-05
Nb-95	8.41E+02	1.5E-08	(b)	(b)	(b)
Ru-103	9.44E+02	9.8E-09	7.1E-06	0	7.1E-06
Ru-106	8.84E+03	4.1E-09	2.1E-05	6.7E-06	3.3E-05
Te-132	7.82E+01	5.3E-09	3.4E-06	0	3.4E-06
I-131	1.93E+02	7.9E-09	1.3E-06	0	1.3E-06
I-132	2.30E+00	4.4E-08	(b)	(b)	(b)
I-133	2.08E+01	1.2E-08	2.3E-07	0	2.3E-07
I-135	6.61E+00	2.7E-08	1.6E-07	0	1.6E-07
Cs-134	1.81E+04	3.0E-08	1.0E-04	4.8E-05	2.4E-04
Cs-137	2.65E+05	1.2E-08	4.7E-05	3.0E-05	6.4E-04
Ba-140	3.07E+02	4.1E-09	1.2E-05	0	1.2E-05
La-140	4.02E+01	4.0E-08	(b)	(b)	(b)

[a]Body surface exposure rate at 1 meter above contaminated ground surface. Based on data from Kocher (KO-81).

[b]Radionuclides that have short-lived daughters (Zr/Nb-95, Te/I-132, Ru/Rh-106, Cs-137/Ba-137m, Ba/La-140) are assumed to quickly reach equilibrium. The integrated dose factors listed are the effective whole body gamma dose due to the parent and the daughter. Based on data from Kocher (KO-83).

Table 7-2 Initial Exposure Rate and the Effective Dose Equivalent (Corrected for Radioactive Decay) Calculated from an Initial Radionuclide Concentration of 1 pCi/m^2 on Ground Surface

Radionuclide	Half-life hours	Initial exposure[a] rate at 1 m (mR/h per pCi/m^2)	Integrated dose (weathering factor not included)[b] year 1 (mrem per pCi/m^2)	year 2 (mrem per pCi/m^2)	0-50 year (mrem per pCi/m^2)
Zr-95	1.54E+03	1.4E-08	3.8E-05	7.0E-07	3.9E-05
Nb-95	8.41E+02	1.5E-08	(b)	(b)	(b)
Ru-103	9.44E+02	9.8E-09	7.9E-06	0	7.9E-06
Ru-106	8.84E+03	4.1E-09	2.7E-05	1.4E-05	5.4E-05
Te-132	7.82E+01	5.3E-09	3.4E-06	0	3.4E-06
I-131	1.93E+02	7.9E-09	1.3E-06	0	1.3E-06
I-132	2.30E+00	4.4E-08	(b)	(b)	(b)
I-133	2.08E+01	1.2E-08	2.3E-07	0	2.3E-07
I-135	6.61E+00	2.7E-08	1.6E-07	0	1.6E-07
Cs-134	1.81E+04	3.0E-08	1.4E-04	9.8E-05	4.8E-04
Cs-137	2.65E+05	1.2E-08	6.3E-05	6.2E-05	1.9E-03
Ba-140	3.07E+02	4.1E-09	1.2E-05	0	1.2E-05
La-140	4.02E+01	4.0E-08	(b)	(b)	(b)

[a]Body surface exposure rate at 1 meter above contaminated ground surface. Based on data from Kocher (KO-81).

[b]Radionuclides that have short-lived daughters (Zr/Nb-95, Ru/Rh-106, Te/I-132, Cs-137/Ba-137m, Ba/La-140) are assumed to quickly reach equilibrium. The integrated dose factors listed are the effective whole body gamma dose due to the parent and the daughter. Based on data from Kocher (KO-83).

accidents at nuclear power facilities. In addition to providing integrated, effective doses per unit of surface concentration, they provide, in column three, the exposure rate (mR/h) in air per unit of surface contamination. All exposure rate values are based on those given by Kocher (KO-81), and the integrated effective doses are based on dose conversion factors also given by Kocher (KO-83). Table 7-1 takes into account both radioactive decay and weathering, whereas the values in Table 7-2 include only radioactive decay. The effect of weathering is uncertain and will vary depending of the type of weather, type of surface, and the chemical form of the radionuclides. The user may choose either table depending on the confidence accorded the assumed weathering factors.

The following steps can be used to develop dose conversion factors to calculate projected external whole body gamma dose from gamma exposure rate measurements for specific mixes of radionuclides:

A. By gamma spectral analysis of environmental samples of deposited radioactivity, determine the relative abundance of the principal gamma emitting radionuclides. Analyses of samples from several different locations may be necessary to determine whether the relative concentrations of radionuclides are constant. The results should be expressed as the activity (pCi) for each radionuclide in the sample.

B. Multiply the concentrations from step A by the corresponding values in column 3 of Table 7-1 or Table 7-2 (depending on whether or not weathering is to be considered) to determine the (relative) contributions to the gamma exposure rate (mR/h) at the 1-meter height for each radionuclide. (The total activity represented by the sample cancels in step E, thus removing the effect of sample size.)

C. Similarly, multiply the activities from step A by the corresponding values in columns 4, 5, and 6 to determine the 1-year, 2-year, and 50-year relative integrated doses contributed by each radionuclide. Radionuclides listed in Tables 7-1 and 7-2 that have short-lived daughters (Zr/Nb-95, Te/I-132, Ru/Rh-106, Cs-137/Ba-137m, Ba/La-140)

are assumed to be in equilibrium with their daughters when calculating the integrated dose, so that the values for the parents include the total dose from the parent and the daughter. (In the cases of Cs-137/Ba-137m, and Ru-106/Rh-106, the parents are not gamma emitters so the listed exposure rates and doses are actually those from the daughters alone.)

D. Sum the results of step B to determine a total (relative) exposure rate "$\dot{X}$" (mR/h) at 1 meter for the sample being considered. Likewise, for the total first year, second year, and 50-year (relative) doses "$\dot{H}_i$" (mrem), sum the respective results of step C.

E. Using the results from step D, calculate the ratios

$$DCF_i = H_i(\text{mrem})/X\ (\text{mR/h})$$

for the first, second, and 50-year doses. (Since the absolute activities represented in the numerator and denominator are identical, the effect of the size of the sample cancels.) The result is dose conversion factors DCF_i (mrem per mR/h) for any gamma exposure rate measurement for which the relative concentrations of radionuclides are the same as in the sample that was analyzed.

The following example demonstrates the use of the above procedures. For purposes of the example it is assumed that environmental measurements revealed a mix of radionuclides as shown in column 3 of Table 7-3. The (relative) exposure rate conversion factors in column 4 of Table 7-3 are taken from column 3 of Table 7-1. The (relative) exposure rates in column 5 are the products of columns 3 and 4. The (relative) doses for individual radionuclides in columns 6, 7, and 8 were calculated by multiplying the concentrations in column 3 by the dose conversion factors in columns 4, 5, and 6 of Table 7-1, respectively. (Columns 4, 5, and 6 of Table 7-2, which do not include weathering, could have been used instead of those in Table 7-1.)

Table 7-3 Example[a] Calculation of Dose Conversion Factors for Gamma Exposure Rate Measurements Based on Measured Isotopic Concentrations[b]

Radionuclide	Half-life (hours)	Measured concentration (pCi/sample[d])	$\frac{mR/h^{c}}{pCi/m^{2}}$	Calculated Exposure rate at 1 m (mR/hr)	Calculated effective dose at 1 meter year 1 (mrem)	year 2 (mrem)	50 year (mrem)
Iodine-131	193	2.6E+2	7.9E-9	2.0E-6	3.3E-4	0	3.3E-4
Tellurium-132	78	3.6E+3	5.3E-9	1.9E-5	1.2E-2	0	1.2E-2
I-132	2.3	3.6E+3	4.4E-8	1.6E-4	(e)	(e)	(e)
Ruthenium-103	944	2.2E+2	9.8E-9	2.1E-6	1.6E-3	0	1.6E-3
Rhodium-106[f]	8,840	5.0E+1	4.1E-9	2.0E-7	1.0E-3	3.4E-4	1.6E-3
Cesium-134	18,100	6.8E+1	3.0E-8	2.0E-6	7.0E-3	3.3E-3	1.6E-2
Barium-137m[f]	265,000	4.2E+1	1.2E-8	4.9E-7	2.0E-3	1.2E-3	2.7E-2
Totals				2.2E-4	2.4E-2	4.5E-3	5.8E-2

[a]The data in this table are only examples to demonstrate a calculational process. The results should not be used in the prediction of relationships that would exist following a nuclear incident.

[b]Calculations are based on data in Table 7-1, which includes consideration of both radioactive decay and weathering.

[c]External exposure rate factors at 1 meter above ground for a person standing on contaminated ground, based on data in Table 7-1.

[d]The size of the sample is not important for this analysis because only the relative concentrations are needed to calculate the ratio of integrated dose to exposure rate.

[e]The integrated dose from I-132 is not calculated because it is a short-lived daughter of Te-132, and the values for integrated doses in Tables 7-1 and 7-2 include the equilibrium doses from short-lived daughters in the values for the parents.

[f]This is a short lived daughter of a parent that has no gamma emissions and the halflife given is that of the parent.

For this example, the conversion factor for dose in the first year was obtained for the assumed radionuclide mix from the totals of columns 5 and 6 of Table 7-3, which indicate that a calculated dose of 0.024 mrem in one year corresponds to an initial exposure rate of 2.2E-4 mR/h. Therefore, the first year dose conversion factor (DCF_1) for this example is 109 mrem per mR/h.

This DCF may be multiplied by any gamma exposure rate measurement to estimate the dose in the first year for locations where the exposure rate is produced by a radionuclide mix the same as assumed for calculating the DCF,and where weathering affects the exposure rate as assumed. For example, if a gamma exposure rate measurement were taken at the location where the contamination sample in Table 7-3 was taken, this exposure rate could be multiplied by the DCF calculated in the above example to obtain the projected first year dose at that point. Based on the example analysis and a relocation PAG of 2 rems, for this case the exposure rate at the boundary of the restricted zone should be no greater than

$$\frac{2 \text{ rem}}{109 \text{ mrem/mR/h}} = 18 \text{ mR/h},$$

if the contribution to effective dose from inhalation of resuspended radioactive materials is zero (See Section 7.3.2). The example DCF for the second year and 50 years are obtained by a similar process, yielding DCFs of 20 and 263 mrem per mR/h, respectively.

The ratio of the second year to first year dose is 20/109 = 0.18. If this is the case, persons not relocated on the basis of a 2 rem PAG should, for this example, receive no more than 0.18 x 2 = 0.36 rems in year 2. Similarly, the dose in fifty years should be no more than 4.8 rems. Actual doses should be less than these values to the extent that exposure rates are reduced by shielding from structures and by decontamination.

Prior to reaching conclusions regarding the gamma exposure rate that would correspond to the relocation PAG, one would need to verify by multiple sampling the consistency of the relative abundance of specific radionuclides as well as the relative importance of the inhalation pathway.

Dose conversion factors will change as a function of the radiological makeup of the deposited material. Therefore, dose conversion factors must be calculated based on the best current information following the accident. Since the relative concentrations will change as a function of time due to different decay rates, dose conversion factors must be calculated for specific measurement times of interest. By calculating the decay of the original sample(s), a plot of dose conversion factors (mrem per mR/h) as a function of time after the accident can be developed. As weathering changes the radionuclide mix, and as more is learned about other dose reduction mechanisms, such predictions of dose conversion factors may require adjustment.

7.3.2 Inhalation Dose Projection

It can be shown, for the mixture of radionuclides assumed to be deposited from postulated reactor accidents, and an assumed average resuspension factor of 10^{-6} m^{-1}, that the effective dose from inhalation is small compared to the corresponding effective dose from external exposure to gamma radiation. However, air sample analyses should be performed for specific situations (e.g., areas of average and high dynamic activity) to determine the magnitude of possible inhalation exposure. The committed effective dose equivalent (H_{50}) resulting from the inhalation of resuspended airborne radioactive materials is calculated as follows:

$$H_{50} = I\ (DCF) \qquad (1)$$

where,

I = The total intake (uCi), and

DCF = effective dose per unit intake (rem/uCi).

It is assumed that the intake rate will decrease with time due to radioactive decay and weathering. No model is available to calculate the effect of weathering on resuspension of deposited materials, so the model developed for calculating its effect on gamma exposure rate (NR-75) is assumed to be valid. This should provide conservative results. The total intake (I) from inhalation over time t may be calculated for each radionuclide, using the following equation:

$$I = BC_o \left[\frac{0.63}{\lambda_1+\lambda_2} (1-e^{-(\lambda_1+\lambda_2)t}) + \frac{0.37}{\lambda_1+\lambda_3} (1-e^{-(\lambda_1+\lambda_3)t}) \right] \quad (2)$$

where

B = average breathing rate for adults
= 8 E+3 m^3/a (IC-75),

C_o = initial measured concentration of the resuspended radionuclide in air (pCi/m^3),

t = time during which radionuclides are inhaled (a),

λ_1 = radioactive decay constant (a^{-1}),

λ_2 = assumed weathering decay constant for 63 percent of the deposited activity, and is taken as 1.13 a^{-1} (NR-75), and

λ_3 = assumed weathering decay constant for 37 percent of the deposited activity, and is taken as 7.48 E-3 a^{-1} (NR-75).

Table 7-4 tabulates results calculated using the above assumptions for weathering. The table contains factors relating the committed effective dose from exposure during the first and second years after the accident to an initial air concentration of 1 pCi/m^3 for each of the principal radionuclides expected to be of concern from reactor accidents. The dose conversion factors are taken from ICRP-30 (IC-78). Parent radionuclides and their short lived daughters are grouped together because these dose conversion factors are based on the assumption that both parents and daughters will occur in equal concentrations and will decay with the half life of the parent. Therefore, measured concentrations of the short lived daughters should be ignored and only the parent concentrations should be used in calculating long term projected doses.

Table 7-4 lists factors which include the effects of both weathering and radioactive decay, as well as those that include only the effects of

Table 7-4 Dose Conversion Factors for Inhalation

Radionuclide[a]	Committed effective dose equivalent from specified exposure periods based on an initial concentration of one pCi/m^3 in air (with and without weathering)			
	Committed dose considering radioactive decay and weathering (mrem per pCi/m^3)		Committed dose considering radioactive decay only (mrem per pCi/m^3)	
	year 1	year 2	year 1	year 2
Sr-90/Y-90	1.3E0	7.7E-1	1.9E 0	1.4E 0
Z-95/Nb-95	3.0E-2	0	3.5E-2	0
Ru-103	3.4E-3	0	3.8E-3	0
Ru-106/Rh-106	2.5E-1	9.0E-2	3.3E-1	1.7E-1
Te-132/I-132	7.1E-4	1.0E-5	7.2E-4	1.0E-5
I-131	8.1E-3	0	8.3E-3	0
Cs-134	2.4E-1	1.1E-1	3.1E-1	2.3E-1
Cs-137/Ba-137^m	1.8E-1	1.1E-1	2.2E-1	2.3E-1
Ba-140/La-140	2.8E-3	0	2.9E-3	0
Ce-144/Pr-144	8.3E-1	1.7E-1	1.1E0	4.0E-1

[a]Short lived daughters are not listed separately because the entries include the dose from both the daughter and the parent. These factors are based on the concentration of the parent only, at the beginning of the exposure period.

radioactive decay. Users of these data should decide which factors to use based on their confidence on the applicability of the weathering models used (NR-75) to their environment.

The committed effective dose equivalent is calculated by multiplying the measured initial air concentration (pCi/m^3) for each radionuclide of concern by the appropriate factor from the table and summing the results. This sum may then be added to the corresponding external whole body gamma dose to yield the total committed effective dose equivalent from these two pathways.

The PAGs include a guide for dose to skin 50 times the magnitude of the PAG for effective dose. Analyses indicate (EP-88) that this guide is not likely to be controlling for radionuclide mixes expected to be associated with nuclear power plant accidents. Dose conversion factors are provided in Table 7-5 for use in case of accidents where the source term consists primarily of pure beta emitters. The skin dose from each radionuclide may be calculated using the corresponding dose conversion factor.

Table 7-5 Skin Beta Dose Conversion Factors for Exposure to Deposited Radionuclides

Radionuclides	Dose conversion factors[a] (mrem per pCi/m^2)	
	Radioactive decay plus weathering	Radioactive decay only
Sr/Y-90	6.8E-4	1.0E-3
Zr/Nb-95	3.5E-7	4.0E-7
Ru-103	1.3E-7	1.4E-7
Ru/Rh-106	6.8E-4	8.8E-4
Te/I-132	3.8E-6	3.9E-6
I-131	1.3E-7	1.4E-7
Cs-134	5.4E-6	7.1E-6
Cs-137/Ba-137m	3.0E-5	3.7E-5
Ba/La-140	5.0E-5	5.1E-5
Ce/Pr-144	5.5E-4	7.2E-4

[a]Dose equivalent integrated for a one-year exposure

7.4 Priorities

In most cases protective actions during the intermediate phase will be carried out over a period of many days. It is therefore useful to consider what priorities are appropriate. Further, for situations where the affected area is so large that it is impractical to relocate all of the public, especially from areas exceeding the PAGs by only a small amount, priorities are needed for protective actions. The following priorities are appropriate:

1. As a first priority, assure that all persons are protected from doses that could cause acute health effects from all exposure pathways, including previous exposure to the plume.

2. Recommend the application of simple decontamination techniques and that persons remain indoors as much as possible to reduce exposure rates.

3. Establish priorities for relocation with emphasis on high exposure rate areas and pregnant women (especially those in the 8th to 15th week of pregnancy).

7.5 Reentry

After the restricted zone is established, persons will need to reenter for a variety of reasons, including recovery activities, retrieval of property, security patrol, operation of vital services, and, in some cases, care and feeding of farm animals. It may be possible to quickly decontaminate access ways to vital institutions and businesses in certain areas so that they can be occupied by adults either for living (e.g., institutions such as nursing homes, prisons, and hospitals) or for employment. Clearance of these areas for such occupancy will require dose reduction to comply with occupational exposure limits (EP-87). Dose projections for individuals should take into account the maximum expected duration of exposure.

Persons residing or working in areas inside the restricted zone should operate under the controlled conditions normally established for occupational exposure.

7.6 Surface Contamination Control

Areas under the plume can be expected to contain deposited radioactive materials if aerosols or particulate materials were released during the accident. In extreme cases, individuals and equipment may be highly contaminated, and screening stations will be required for emergency monitoring and decontamination of individuals and to evaluate the need for medical evaluation. Equipment should be checked at this point and decontaminated as necessary to avoid the spread of contamination to other locations. This screening service would be required for only a few days following plume passage until all such persons have been evacuated or relocated.

After the restricted zone is established, based on the PAGs for relocation, adults may reenter the restricted zone under controlled conditions in accordance with occupational exposure standards. Monitoring stations will be required along roadways to control surface contamination at exits from the restricted zone. Because of the possibly high background radiation levels at control points near exits, significant levels of surface contamination on persons and equipment may be undetectable at these locations. Therefore, additional monitoring and decontamination stations may be needed at nearby low background locations. Decontamination and other measurements should be implemented to maintain low exposure rates at monitoring stations.

7.6.1 Considerations and Constraints

Surface contamination limits recommended to control routine operations at nuclear facilities and to transport radioactive material are generally at set levels lower than are practical for accident situations involving high-level, widespread contamination of the environment.

The principal exposure pathways for loose surface contamination on persons, clothing, and equipment are (a) internal doses from ingestion by direct transfer, (b) internal doses from inhalation of resuspended materials, (c) skin dose from contaminated skin or clothing, and (d) whole body dose from external gamma radiation.

Because of the difficulties in predicting the destiny of uncontrolled surface contamination, a contaminated individual or item should not be released to an unrestricted area unless contamination levels are low enough that they produce only a small dose (e.g., less than 10 percent), compared to the whole body gamma dose in the area that is unrestricted. On the other hand, a level of contamination comparable to that existing on surfaces immediately outside the restricted zone may be acceptable on materials leaving the restricted zone. Otherwise, persons and equipment occupying areas immediately outside the restricted zone would not meet the surface contamination limits. These two constraints can be used to set permissible surface contamination values.

The contamination limit should be influenced by the potential for the contamination to be ingested, inhaled, or transferred to other locations. Therefore, it is reasonable to have lower limits for surfaces where contamination is loose than on surfaces where the contamination is fixed.

For routine (nonaccident) situations, measurement of gross beta-gamma surface contamination levels is commonly performed with a thin-window geiger counter or ionization chamber. In accident situations where gamma exposure rates are high enough to be measured with such equipment, the corresponding beta readings would not be predictable or interpretable in terms of dose, but they would yield much higher instrument readings than the gamma component. Therefore, it is recommended in these cases that surface contamination measurements be performed using gamma exposure rate measurements with the beta shield closed. In low background areas, thin window (approximately 30 mg/cm^2) measurements would be appropriate to improve detectability.

7.6.2 Numerical Relationships

As discussed in Section 7.3.1, a relationship can be established between projected first year doses and instantaneous gamma exposure rates from properly characterized surface contamination. Based on assumed radiological characteristics of releases from fuel melt accidents, gamma exposure rates in areas where the projected dose is equal to the relocation PAG of 2 rems in the first year will be in the range of 2 to 5 mR/h during the first few days following the deposition from an SST-2 accident. (This relationship must be determined for each specific release mixture.) Based on relationships in NUREG CR-1918 (KO-81) and a mixture of radionuclides expected to be typical of an SST-2 type accident, surface contamination levels of 8×10^7 pCi/m^2 would correspond approximately to a gamma exposure rate of 1 mR/h at 1 meter height.

7.6.3 Recommended Surface Contamination Limits

Surface contamination must be controlled both before and after relocation PAGs are implemented. Therefore, this section deals with the control of surface contamination on persons and equipment being protected during both the early and intermediate phases of a nuclear accident.

For emergency situations, the following general guidance regarding surface contamination is recommended:

A. Do not delay urgent medical care for decontamination efforts or for time-consuming protection of attendants.

B. Do not waste effort trying to contain contaminated wash water.

C. Do not allow monitoring and decontamination to delay evacuation from high or potentially high exposure rate areas.

D. Establish monitoring and personnel decontamination (bathing) facilities at evacuation centers. Encourage evacuated persons who did not go to an evacuation center but who were in specified

areas at specified times (based on the location of the airborne plume) to bathe, change clothes, wash clothes, and wash other exposed surfaces such as cars and trucks and their contents and then report to these evacuation centers for monitoring. Table 7-6 provides recommended surface contamination screening levels for use at these centers.

E. After plume passage, establish contamination screening stations in areas reading less than 5 mR/h gamma exposure rate. These screening stations should be used to monitor persons emerging from possible high exposure areas, provide simple (rapid) decontamination if needed, and make decisions on whether to send them for medical care or to a monitoring and decontamination station in a lower background area. Table 7-7 provides recommended surface contamination screening levels for use at these stations.

F. After the restricted zone is established, set up monitoring and decontamination stations at exits from the restricted zone. Because of the probably high background radiation levels at these locations, low levels of contamination may be undetectable. If contamination levels are undetectable, then they probably do not exceed those in some unrestricted areas occupied by the exposed population and no decontamination is required. Nevertheless, these individuals should be advised to bathe and change clothes at their first opportunity and certainly within the next 24 hours. If, after decontamination at the boundary of the restricted zone station, persons still exceed the limits for this station, they should be sent for further decontamination or for medical or other special attention. As an alternative to decontamination, contamination on other than persons or animals may be retained in the restricted zone for radioactive decay.

G. Establish auxiliary monitoring and decontamination stations in low background areas (background less than 0.1 mR/h). These stations should be used to achieve ALARA surface contamination levels. Table 7-6 provides surface contamination screening levels for use at those stations.

Table 7-6 Recommended Surface Contamination Screening Levels for Persons and Other Surfaces at Monitoring Stations in Low Background Radiation Areas (<0.1 mR/h Gamma Exposure Rate)

Condition	Geiger counter thin window[a] reading	Recommended action
Before decontamination	<2X bkgd	Unconditional release
	>2X bkgd	Decontaminate
After simple[b] decontamination effort	<2X bkgd	Unconditional release
	>2X bkgd	Full decontamination[c]
After full[c] decontamination effort	<2X bkgd	Unconditional release
	>2X bkgd	Continue to d-con persons
	<0.5 mR/h[d]	Release animals and equipment
After additional full decontamination effort	>2X bkgd	Send persons for medical or other special evaluation
	>0.5 mR/h[d]	Use informed judgment for control of animals and equipment

[a]Window thickness of approximately 30mg/cm^2 is considered acceptable.

[b]Vacuuming and flushing with water are examples of simple decontamination efforts.

[c]Washing with soap or solvent followed by flushing is an example of a full decontamination effort.

[d]Closed shield reading including background.

Table 7-7 Recommended Surface Contamination Screening Levels for Persons and Other Surfaces at Screening or Monitoring Stations in High Background Radiation Areas (0.1 mR/h to 5 mR/h Gamma Exposure)

Condition	Geiger counter-shielded window reading	Recommended action
Before decontamination	<2X bkgd and <0.5 mR/h above background	Unconditional release
	>2X bkgd or >0.5 mR/h above background	Decontaminate. Equipment may be stored or disposed of as appropriate.
After decontamination	<2X bkgd and <0.5 mR/h above background	Unconditional release
	>2X bkgd or >0.5 mR/h above background	Continue to decontaminate or refer to low background monitoring and d-con station. Equipment may also be stored for decay or disposed of as appropriate.

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CHAPTER 8

Radiation Protection Guidance for Recovery

(reserved)

APPENDIX A

Glossary

APPENDIX A

Glossary

The following definitions apply specifically to terms used in this manual.

Accident phase: This guidance distinguishes three phases of an incident (or accident): (a) early phase, (b) intermediate phase, and (c) late phase.

(a) Early phase: The period at the beginning of a nuclear accident when immediate decisions for protective actions are required, and must be based primarily on predictions of radiological conditions in the environment. This phase may last from hours to days. For the purpose of dose projection, it is assumed to last for four days.

(b) Intermediate phase: The period beginning after the accident source and releases have been brought under control and environmental measurements are available for use as a basis for decisions on protective actions and extending until these protective actions are terminated. This phase may overlap the early phase and may last from weeks to many months. For the purpose of dose projection, it is assumed to last for one year.

(c) Late phase: The period beginning when radiation levels have been reduced so that previously implemented protective actions can be withdrawn, and ending when all recovery actions have been completed. This period may extend from months to years (also referred to as the recovery phase).

Acute health effects: Prompt radiation effects for which a threshold exists above which the severity of the effect varies with the dose.

Buffer zone: An area selected for temporary radiation protection controls until the stability of radioactivity levels in the area is confirmed.

Committed dose: The total dose due to radionuclides in the body over a 50 year period following their inhalation or ingestion.

Delayed health effects: Radiation effects which are manifested long after the relevant exposure. The vast majority are stochastic, that is, the severity is independent of dose and the probability is assumed to be proportional to the dose, without threshold.

Derived response level (DRL): A level of radioactivity in an environmental medium that would be expected to produce a dose equal to its corresponding Protective Action Guide.

Dose equivalent: The product of the absorbed dose in rads, a quality factor related to the biological effectiveness of the radiation involved and any other modifying factors.

Effective dose equivalent: The sum of the products of the dose equivalent to each organ and a weighting factor, where the weighting factor is the ratio of the risk of mortality from delayed health effects arising from irradiation of a particular organ or tissue to the total risk of mortality from delayed health effects when the whole body is irradiated uniformly to the same dose.

Evacuation: The urgent removal of people from an area to avoid or reduce exposure, usually from the plume or from high levels of deposited activity.

Groundshine: Gamma radiation from radioactive materials deposited on the ground.

Nuclear incident (nuclear accident): An event or series of events leading to the release, or potential release, of radioactive materials into the environment of sufficient quantity to warrant consideration of protective actions.

Projected dose: Future dose calculated on the basis of estimated or measured initial concentrations of radionuclides or exposure rates.

Protective action: An activity conducted in response to an accident or potential accident to avoid or reduce radiation dose to members of the public (sometimes called a protective measure).

Protective Action Guide (PAG): The projected dose to standard man, or other defined individual, from an accidental release of radioactive material at which a specific protective action to reduce or avoid that dose is warranted.

Recovery: The process of reducing radiation exposure rates and concentrations in the environment to acceptable levels for unconditional occupancy or use.

Reentry: Temporary entry into a restricted zone under controlled conditions.

Relocation: The removal or continued exclusion of people from contaminated areas to avoid chronic radiation exposure.

Restricted zone: An area with controlled access from which the population has been relocated.

Return: The reoccupation of areas cleared for unrestricted residence or use.

Sheltering: The use of a structure for radiation protection from an airborne plume and/or deposited radioactive materials.

APPENDIX B

(reserved)

APPENDIX C

Protective Action Guides for the Early Phase:

Supporting Information

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APPENDIX C

Protective Action Guides for the Early Phase: Supporting Information

C.1 Introduction

This appendix describes the basis for the choice of Protective Action Guides (PAGs) for the early phase of the response to a nuclear incident, following an accidental release of airborne radioactive material, as well as the choice of exposure limits for emergency workers. These guides and limits are set forth in Chapter 2.

Response to a radiological emergency will normally be carried out in three phases, as discussed in Chapter 1. Decisions during the first (early) phase will be based primarily on predicted or potential radiological conditions in the environment, rather than on actual measurements. The principal protective action is evacuation, with sheltering serving as a suitable alternative under some conditions. This appendix therefore examines in some detail the potential magnitudes and consequences of predicted exposures of populations during the early phase, for selected accident scenarios, in relation to the benefits and other consequences of evacuation and sheltering. Supplementary protective actions, such as washing and change of clothing to reduce exposure of the skin and use of stable iodine to block uptake of radioiodine to the thyroid, are also considered, but in less detail.

C.1.1 Existing Federal Guidance

In the 1960's, the Federal Radiation Council (FRC) defined PAGs and established limiting guides for ingestion of strontium-89, strontium-90, cesium-137, and iodine-131 (FR-64; FR-65). That guidance applied to restricting the use of food products that had become contaminated as the result of release of radioactivity to the stratosphere from weapons

testing. During the period immediately following an incident at a domestic nuclear facility, when the critical source of exposure is expected to be a nearby airborne plume, the principal protective actions are evacuation or sheltering. The PAGs developed here thus do not supersede previous guidance, but provide additional guidance for prompt exposure pathways specific to a domestic nuclear incident.

C.1.2 Principal Exposure Pathways

The immediate exposure pathway from a sub-stratospheric airborne release of radioactive materials is direct exposure from the cloud of radioactive material carried by prevailing winds. Such a radioactive plume can contain noble gases, iodines, and/or particulate materials, depending on the source involved and conditions of the accident. These materials emit gamma rays, which are not significantly absorbed by air, and will expose the entire bodies of nearby individuals.

Another exposure pathway occurs when people are submerged in the radioactive cloud. In this case radioactivity is inhaled, and the skin and clothes are contaminated. Inhaled radioactive materials, depending on their solubility in body fluids, may either remain in the lungs or move via the blood to other organs. Many radionuclides which enter the bloodstream tend to be predominantly concentrated in a single organ. For example, if radioiodines are inhaled, they will tend to move rapidly from the lungs through the bloodstream to the thyroid gland, where most of the dose will be delivered. Although beta exposure from materials deposited on the skin and clothing could be significant, it will be less important than exposure from inhalation if early protective actions include washing of exposed skin and changes of clothing.

As the plume passes over an area, radioactive materials may settle onto the ground and other surfaces. People remaining in the area will then continue to be exposed through ingestion and direct radiation, and through inhalation of resuspended materials. Doses from such deposited materials may be more significant than those due to direct exposure to the plume, because the length of exposure can be much longer. However, since

the protective actions considered here (evacuation and/or sheltering) may not be appropriate or may not apply to the same individuals for this longer term exposure, doses from these exposures are not included in the dose considered in the PAGs for the early phase. It is assumed that, within four days after an incident, the population will be protected from these subsequent doses on the basis of the PAGs for relocation and for contaminated food and water. (See Chapters 3 and 4.)

Based on the foregoing considerations, the PAGs for the early phase are expressed in terms of estimated doses from exposure due to direct radiation, inhalation, and contamination of the skin during the first four days, only, following an incident.

C.1.3 Units of Dose

The objective of protective action is to reduce the risk to health from exposure to radiation. Ideally, one would like to assure the same level of protection for each member of the population. However, protective actions cannot take into account individual variations in radiosensitivity, since these are not known. Therefore, these PAGs are based on assumed average values of risk. We further assume that these risks are proportional to the dose, for any level of dose below the threshold for acute effects (see Section C.2.).

The dose from exposure to radioactive materials may be delivered during the period of environmental exposure only (e.g., external gamma radiation), or over a longer period (e.g., inhaled radionuclides which deposit in body organs). In the latter case, dose is delivered not only during intake from the environment, but continues until all of the radioactive material has decayed or is eliminated from the body. Because of the variable time over which such doses may be delivered, the PAGs are expressed in terms of a quantity called the "committed dose." Committed dose is conceptually the dose delivered over an individual's remaining lifetime following an intake of radioactive material. However, due to differences in physiology and remaining years of life, the committed dose

to a child from internal radioactivity may differ from that to an adult. For simplicity, adult physiology and a remaining lifetime of 50 years are assumed for the purpose of calculating committed dose, unless the differences are large.

Another important consideration is that different parts of the body are at different risk from the same dose. Since the objective of protective actions is the reduction of health risk, it is appropriate to use a quantity called "effective dose." Effective dose is the sum of the products of the dose to each organ or tissue of the body and a weighting factor for risk. These weighting factors are chosen as the ratio of mortality (from delayed health effects) from irradiation of particular organs or tissues to the total risk of mortality when the whole body is irradiated uniformly at the same dose.

Finally, doses from different types of radiation (e.g. alpha, beta, gamma, and neutron radiations) have different biological effectiveness. These differences are customarily accounted for, for purposes of radiation protection, by multiplicative modifying factors. A dose modified by these factors is designated the "dose equivalent." The PAGs are therefore expressed in terms of committed effective dose equivalent.

PAGs are intended to apply to all individuals in a population other than emergency workers. However, there may be identifiable groups that have different average sensitivity to radiation or, because of their living situation, will receive higher or lower doses. In addition, some groups may be at greater risk from taking a given protective action. These factors are separately considered below, when it is appropriate, in establishing values for the PAGs.

C.1.4 Principles for Establishing Protective Action Guides

The following four principles provide the basis for establishing values for Protective Action Guides:

1. Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which they are not likely to occur) should be avoided.

2. The risk of delayed effects on health (primarily cancer and genetic effects, for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health, under emergency conditions, and are reasonably achievable.

3. PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health avoidable at acceptable cost should be carried out.

4. Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.

With the exception of the second, these principles are similar to those set forth by the International Commission on Radiological Protection (IC-84) as the basis for establishing intervention levels for nuclear accidents.

C.2 Acute Effects

This section provides information relevant to the first principle: avoidance of acute effects on health from radiation.

Acute radiation health effects are those clinically observable effects on health which are manifested within two or three months after exposure. Their severity depends on the amount of radiation dose that is received. Acute effects do not occur unless the dose is relatively large, and there is generally a level of dose (i.e., threshold) below which an effect is not expected to occur. Acute effects may be classified as severe or nonsevere clinical pathophysiological effects. Severe

pathophysiological effects are those which have clinically observable symptoms and may lead to serious disease and death. Other pathophysiological effects, such as hematologic deficiencies, temporary infertility, and chromosome changes, are not considered to be severe, but may be detrimental in varying degrees. Some pathophysiological effects, such as erythema, nonmalignant skin damage, loss of appetite, nausea, fatigue, and diarrhea, when associated with whole body gamma or neutron exposure, are prodromal (forewarning of more serious pathophysiological effects, including death).

C.2.1 Review of Acute Effects

This section summarizes the results of a literature survey of reports of acute effects from short-term (a few days) radiation exposure in some detail. Many reports of observed effects at lower doses differ, and some are contradictory; however, most have been included for the sake of completeness. The results of the detailed review described in this Section are summarized in Section C.2.2.

The biological response to the rapid delivery of large radiation doses to man has been studied since the end of World War II. Dose-response relationships for prodromal (forewarning) symptoms (ED_x) and for death within 60 days ($LD_{x/60}$), where x is the probability (in percent) of response, have been developed from data on the Japanese A-bomb survivors, Marshall Island natives exposed to fallout, and patients undergoing radiotherapy. This work has been supplemented by a number of animal studies under controlled conditions.

The animal studies, usually using lethality as the end point, show that many factors can influence the degree of response. The rate at which the dose is delivered can affect the median lethal dose (LD_{50}) in many species, particularly at dose rates less than 5 R/min (PA-68a; BA-68). However, in primates there is less than a 50 percent increase in the LD_{50} as dose rates are decreased from 50 R/min to about 0.01R/min (PA-68a). There is good evidence of species specificity (PA-68a; BO-69). The LD_{50} ranges from about 100 rads for burros to over 1000 rads for lagomorphs (e.g., rabbits). Response is modulated by: age (CA-68), extent

of shielding (partial body irradiation) (BO-65), radiation quality (PA-68a; BO-69), diet, and state of health (CA-68).

While animal studies provide support and supplemental information, they cannot be used to infer the response for man. This lack of comparability of man and animals had already been noted by a review committee for the National Academy of Sciences as early as 1956, in considering the length of time over which acute effects might be expressed (NA-56): "Thus, an LD_{50}, 30-day consideration is inadequate to characterize the acute lethal dose response of man, and an LD_{50}, 60 days would be preferable."[1]

Several estimates of the levels at which acute effects of radiation occur in man have been published. For example, an early estimate of the dose-response curves for prodromal (forewarning) symptoms and for lethality was made in the first edition of "The Effects of Nuclear Weapons" (1957) (GL-57), and a more recent and well documented estimate is given in a NASA publication, "Radiobiological Factors in Manned Space Flight" (LA-67).

C.2.1.1 The Median Dose for Lethality

The radiation dose that would cause 50 percent mortality in 60 days was estimated as 450 Roentgens in early reports (NA-56; GL-57; RD-51).The NCRP calculated that this would correspond to a midline absorbed dose of 315 rads (NC-74). The ratio of 315 rads to 450 Roentgens is 0.70, which is about the estimated ratio of the active marrow dose, in rads, to the tissue kerma in air, in rads (KE-80). The BEAR Committee noted that the customary reference to LD_{50} in animal studies, as if it were a specific property, independent of age, was not justifiable (NA-56): "...it is evident, now, that the susceptibility of a whole population is not

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[1]The committee (known as the BEAR Committee) also noted "The reservation must be made here that the exposed Japanese population was heterogeneous with respect to age, sex, physical condition and degree of added trauma from burns or blast. The extent to which these factors affected the survival time has not been determined. In studies on laboratory animals the converse is true--homogeneous populations are studied" (NA-56, p.I-6).

describable by a single LD_{50}. The published values are usually obtained for young adults and are therefore maximal or nearly maximal for the strain. In attempts to estimate LD_{50} in man, this age dependence should be taken into consideration" (NA-56, pp.4-5). They observed that the LD_{50} approximately doubled as rats went from neonates to young adults and then decreased as the animals aged further. Finally, the BEAR Committee concluded: "The situation is complex, and it became evident that it is not possible to extrapolate with confidence from one condition of radiation exposure to another, or from animal data to man" (NA-56, p.I-8). Nevertheless, results from animal studies can aid in interpreting the human data that are available.

The NCRP suggested the $LD_{50/60}$ might be 10 to 20 percent lower for the old, very young, or sick, and somewhat greater for healthy adults of intermediate age (RD-51). Other estimates of adult $LD_{50/60}$ have ranged from about 300 rads to 243 $\pm$ 22 rads. These lower estimates are apparently based on a ratio of air to tissue dose similar to those calculated for midline organs in the body; 0.54 to 0.66 (KE-80; OB-76; KO-81).

A NASA panel examined all patient and accident studies, tried to remove confounding factors, and concluded, "On this basis, it may be assumed that the LD_{50} value of 286 rads obtained by a normal fit to the patient data is the preferred value for healthy man" (LA-67).

An $LD_{50/60}$ of 286 $\pm$ 25 rads (standard deviation) midline absorbed dose and an absorbed dose/air dose ratio of 0.66, suggested by NAS (LA-67), is probably a reasonable value for healthy males. In the absence of more complete information, we assume that a value of 300 rads $\pm$ 30 rads is a reasonable reflection of current uncertainties for average members of the population.

C.2.1.2 Variation of Response for Lethality

Uncertainty in the dose-response function for acute effects has been expressed in various ways. The slope of the estimated dose-response

function has most commonly been estimated on the basis of the percent difference in the LD_{50} and the $LD_{15.9}$ or $LD_{84.1}$ (one standard deviation from the LD_{50}), as was done by NASA (GL-57). These and other parameters derived in a similar manner describe the uncertainty in the central risk estimate for the dose-response function.

Another means is to use an estimate of upper and lower bounds for the central risk estimate, e.g., the 95 percent fiducial limits. At any given response point on the dose-response function, for example, the LD_{10}, the dose causing that response has a 95 percent probability of lying between the lower and upper bounds of the 95 percent fiducial limit for that point. To estimate this value, probit analyses were run for each species using data in published reports (KO-81; TA-71). This provided estimates for each species for comparability analyses. The 95 percent fiducial limits at the LD_{50} response for $LD_{50/30}$ studies averaged $\pm$9 percent (range -9 to +26 percent) and for $LD_{50/60}$ studies $\pm$17 percent (range -20 to +45 percent). At the LD_{15} response, values were $\pm$16 percent (range -12 to +50 percent) for $LD_{15/30}$ data and $\pm$26 percent (range -20 to +65 percent) for $LD_{15/60}$ data. For the LD_{85} response, values were $\pm$17 percent (range -36 to +36 percent) for the $LD_{85/30}$ data and $\pm$24 percent (range -46 to +31 percent) for $LD_{85/60}$ data.

The differences in the magnitude of the fiducial limits are a function of the differences in age, sex, radiation quality, degree of homogeneity of the experimental animals, husbandry, and other factors. The estimates show that the fiducial limits, expressed as a percent of the dose at any response, get greater the farther from the LD_{50} the estimate is made. For the purpose of estimating fiducial limits for humans, the 95 percent fiducial limits will be considered to be LD_{15} $\pm$15 percent, LD_{50} $\pm$10 percent, and LD_{85} $\pm$15 percent. Beyond these response levels, the fiducial limits are too uncertain and should not be used.

If the median lethal dose, $LD_{50/60}$, is taken as 300 $\pm$30 rads midline absorbed dose, the response to higher and lower doses depends on the degree of biological variation in the exposed population. The NASA panel decided the wide variation in the sensitivity of patients was a

reflection of the heterogeneity of the sample; and that the variation in sensitivity, the slope of the central estimate of the response function, would be stated in the form of one standard deviation calculated as 58 percent of the LD_{50}. They further decided the deviation in the patients (58 percent) was too great, and the standard deviation for "normal" man should be closer to that of dogs and monkeys (18 percent) (LA-67). (The rationale for selecting these species was not given.)

Jones attempted to evaluate the hematologic syndrome from mammalian lethality studies using the ratio of dose to LD_{50} dose as an indicator of the steepness of the slope of the dose-response function (JO-81). However, he evaluated LD_{50} studies only of species having a rather steep slope, i.e., dogs, monkeys, mice, and swine. He also looked at several different statistical models for dose-response functions and pointed out the problems caused by different models and assumptions, particularly in evaluating the tails of the dose-response function (less than LD_{10} and greater than LD_{90}). Jones recommended using a log-log model, which he felt provided a better fit at low doses (JO-81).

Scott and Hahn also evaluated acute effects from mammalian lethality, but suggested using a Weibull model (SC-80). One of the advantages of the Weibull model is that in addition to developing the dose-response function, it can also be used to develop hazard functions. These hazard functions, if developed using the same model, can be summed to find the joint hazard of several different types of exposure (SC-83). This would allow estimation of the total hazard from multiple organ exposures to different types of radiation.

As mentioned earlier, the human median lethal dose is commonly reported in terms of the $LD_{50/60}$. Most laboratory animal median lethal doses are reported in terms of the $LD_{50/30}$. In those cases where estimates of both $LD_{50/30}$ and $LD_{50/60}$ are available, i.e., the burro (ST-69), the variation (that is, the slope of the dose-response curve) is greater in the $LD_{50/60}$ study than in the $LD_{50/30}$ study. Both the dog and the monkey data are for $LD_{50/30}$, and so are not appropriate for direct comparison to man.

If an estimate of the deviation is made for data from other studies and species, those where most of the fatalities occur within 30 days (like dogs and monkeys) have standard deviations of from around 20 percent (swine (x-ray) (ST-69), dogs (NA-66), hamsters (AI-65), primates (Macaca) (DA-65)] to 30 percent [swine (60_{Co}) (HO-68)). Those in which most deaths occur in 60 days, like man, have deviations from around 20 percent (sheep (CH-64)) to 40 percent (goats (PA-68b), burros (TA-71)). Nachtwey, et al. (NA-66) suggested the steepness of the slope of the exposure response curve depends on the inherent variability of the subjects exposed and any variation induced by uncontrolled factors, e.g., temperature, diurnal rhythm, and state of stimulation or arousal. So, while the slope of the response curve for the patients studied by the NASA panel may be unrealistically shallow for normal human populations, there is no reason to think it should be as steep as those for dogs and monkeys.

The average deviation for those species (burros, sheep, and goats) for which the standard deviation of the $LD_{50/60}$ is available has been used as an estimator for man. The mean value is 34 $\pm$ 13 percent. This is only slightly greater than the average value for all physically large animals (swine, burros, sheep, and goats), 32 $\pm$ 12 percent.

C.2.1.3 Estimated Lethality vs Dose for Man

As noted in Section C.2.1.1, dose-response estimates vary for a number of reasons. Some factors affecting estimates for humans are:

1. Age:

   Casarett has published studies on rats which indicate the LD_{50} is minimal for perinatal exposure, rises to maximum around puberty, and then decreases again with increasing age (CA-68). The perinatal LD_{50} is about one-third of that for the healthy young adult rats; that for the geriatric rat is about one-half of that for the young adult rat.

2. Sex:

   Females are slightly more sensitive than males in most species (CA-68).

3. Health:

Animals in poor health are usually more sensitive than healthy animals (CA-68), unless elevated hematopoietic activity is occurring in healthy animals (SU-69).

While these and other factors will affect the $LD_{50/60}$ and the response curve for man, there are no numerical data available.

The variation in response at a given dose level increases as the population at risk becomes more heterogeneous and as the length of time over which mortality is expressed increases. In general, larger species show greater variance and longer periods of expression than do small mammals, e.g., rodents. It is likely that the human population would show at least the same amount of variation as do the larger animals, i.e., a coefficient of variation of about one-third.

The degree of variation exhibited in animal studies follows a Gaussian distribution as well as or better than a log normal distribution over that range of mortality where there are reasonable statistics. We have assumed here that the functional form of human response is Gaussian. Generally, sample sizes for extreme values (the upper and lower tails of the distribution) are too small to give meaningful results. Therefore, we have not projected risks for doses more than 2 standard deviations from the $LD_{50/60}$. We recognize that estimates of acute effects may not be reliable even beyond one standard deviation for a population containing persons of all ages and states of health. However, in spite of these uncertainties, previous estimates have been made of the acute effects caused by total body exposure to ionizing radiation as a function of the magnitude of the exposure (NC-71; LU-68; FA-73; NA-73).

Given the large uncertainties in the available data, a median lethal dose value of about 300 rads at the midline, with a standard deviation of 100 rads, may be assumed for planning purposes. Such risk estimates should be assumed to apply only in the interval from 5 percent to 95 percent fatality, as shown in Figure C-1. (See also the discussion at C.2.1.4.)

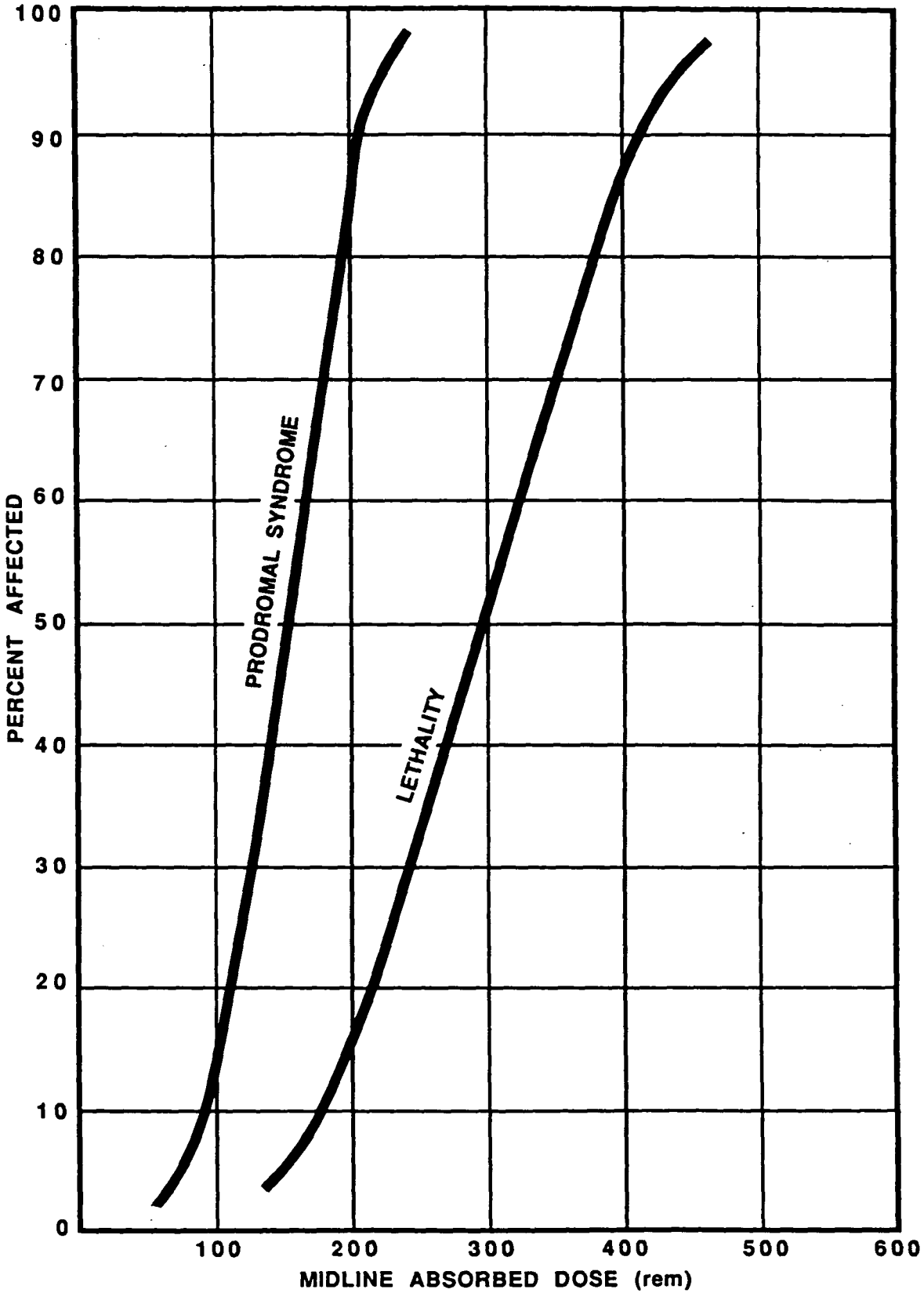

FIGURE C-1. ACUTE HEALTH EFFECTS AS A FUNCTION OF WHOLE BODY DOSE.

Figure C-1 is based on the following values:

Dose (rads)	Percent fatalities
<140	none[2]
140	5
200	15
300	50
400	85
460	95

For moderately severe prodromal (forewarning) effects, we believe the dose at which the same percentage of exposed would show effects would be approximately half of that causing fatality. This yields the following results (see also Figure C-1):

Dose (rads)	Percent affected
50	<2
100	15
150	50
200	85
250	98

Although some incidence of prodromal effects has been observed at doses in the range of 15 to 20 rads in patients (LU-68) and in the 0 to 10 rads range of dose in Japanese A-bomb survivors (SU-80a; GI-84), there is great uncertainty in interpreting the data. Patients may be abnormally sensitive, so that the dose-response function in patients may represent the lower bound of doses that would show a response in a healthy population (LU-67). The response of Japanese survivors in the low dose ranges is complicated by the blast and thermal exposure that occurred at the same time (SU-80b). For these reasons, care should be taken in applying estimates of prodromal effects. The prodomal dose-response function listed above is more likely to overestimate the proportion of persons affected than to underestimate it.

These estimated ranges and effects are in agreement with estimates made for manned space flights (LA-67; LU-67), which included consideration

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[2]The risk of fatality below 140 rads is not necessarily zero; rather, it is indeterminate and likely to remain so. This also applies to prodromal effects below 50 rads.

of the effect of abnormal physiology or sickness in the patients to which the data apply. Uncertainty in estimates of the biological effects of radiation exposure is great. It is probably due in part to variation in the health of individuals in exposed populations. These estimates assume a healthy young adult population and may not be a conservative estimate of risk for other population groups, such as children or the elderly. Lushbaugh, et al. (LU-68) found that prodromal effects probably occur in both healthy and ill persons in about the same dose range. However, Lushbaugh, et al. (LU-68) and NATO (NA-73) suggest that acute mortality in a population which is ill, injured, or in other ways debilitated will occur in 50 percent of that population at doses of 200-250 rads in about 60 days ($LD_{50/60}$), in contrast to an $LD_{50/60}$ from doses of 220-310 rads for a healthy young adult population. Thus, the ill or injured are assumed to have an increased risk of acute mortality at high doses.

The above estimates for $LD_{50/60}$ are also based on the assumption of minimal medical care following exposure. Although the threshold for some specific acute effects would undoubtedly be higher in the presence of more intense medical care, no data are available to quantify the effects of increased medical care and no such quantification is attempted here.

C.2.1.4 Threshold Dose Levels for Acute Effects

This section summarizes information available in the literature regarding thresholds for health effects. It also reviews actions that have been taken as a result of radiation exposure to provide insight on dose levels at which actions to avoid dose may be appropriate.

Some acute effects, such as cellular changes, may occur at low doses with no dose threshold. Most such effects have a minimum threshold of detectability; for example, five rems is about the lower limit of whole body dose which causes a cellular effect detectable by chromosome or other special analyses (NC-71; FA-73). This value is recommended by UNSCEAR as the starting point for biological dosimetry (UN-69). Purrott, et al. have reported a lower limit of detection of chromosome aberrations of 4 rads for x-rays and 10 rads for gamma rays (PU-75).

More recent advanced chromosome banding techniques permit detection of increased incidence of chromosome abnormalities from continuous exposure to systematically deposited radioisotopes or radioisotopes deposited in the lung at very low levels, e.g., body burdens of 100 to 1200 pCi of plutonium-239 (BR-77). While the exact dose associated with such burdens is not known, it is probably on the order of ten to one hundred millirems per year. Lymphocytes exposed to 5 rems in vitro show severe metabolic dysfunction and interphase cell death (ST-64). The extent to which similar effects occur after in vivo exposure is unknown. While chromosome abnormalities in circulating lymphocytes are reported to persist for long periods (UN-69), the significance of such abnormalities is not known (BR-77).

Hug has suggested 5 rems as the lower limit of exposure which might produce acute effects (WH-65). Five rems is also in the low dose, short-term exposure range defined by Cronkite and Haley, and is below the 10 rads which they thought would cause only a slight detectable physiological effect of unknown clinical significance (CR-71).

Although the ICRP has suggested that annual doses of 15 rems would not impair the fertility of normal fertile men (IC-69), an acute dose of 15 rads causes "moderate" oligospermia (approximately 70 percent reduction in sperm count) which lasts for some months (LA-67). Popescu and Lancranjan reported alterations of spermatogenesis and impaired fertility in men exposed to from 500 millirems to 3 rems per year for periods varying from 2 to 22 years (PO-75). The shortest exposure period in which abnormal spermatogenesis was reported was 31 to 41 months (PO-75); at the highest dose rate reported (3 rems/a), this is a cumulative dose of 8 to 10 rems. While more study is required, these results suggest the need to restrict acute doses to below 10 rems to avoid this effect, because a given acute dose is anticipated to be more effective than the same cumulative dose given over a longer period of time (NA-56; UN-58).

Many observations have indicated that doses of 10 rems or more to the pregnant woman are hazardous to the fetus. Mental retardation due to exposure of the fetus is discussed in Section C.3; this discussion is

restricted to acute effects. The World Health Organization (WHO) indicates that there is no evidence of teratogenic effects from short term exposure of the fetus to a dose less than ten rems during the early phase of gestation, the period when the fetus is most sensitive to these effects(WH-84).

Hammer-Jacobsen recommended that exposures of 10 Roentgens or higher be considered an indication for induced abortion (HA-59). Brent and Gorson also suggest that at doses of 10 rads or more, it is appropriate to investigate the merits of terminating the pregnancy (BR-72). The Swedish Government Committee on Urban Siting of Nuclear Power Stations stated the situation more succinctly: "What we have called unconditional indication of abortion involves the exposure of pregnant women where radiation dose to the fetus is higher than 10 rads. When such doses are received in connection with medical treatment, it has hitherto been assumed that the probability of damage to the fetus is so high that an abortion is recommended. The probability for such injury is still moderate compared with the normal frequency of similar fetal injuries, and the probability is particularly reduced when the dose is received late in the pregnancy" (NA-74).

Hammer-Jacobsen stated that although there may be a question of whether or not therapeutic abortion should be considered in the case of exposures of 1 to 10 R, there is no need for therapeutic abortion for exposures of 1 R or less (HA-59). Although Brent and Gorson suggest that 10 rads is a "practical" threshold for induction of fetal abnormalities, they do extend their discussion to counseling a pregnant women who have received 1 to 2 rads (BR-72). The general suggestion is that the possibility of acute effects in the fetus is avoided as long as the fetal dose does not exceed 1 rad.

Devick examined in detail the Scandinavian countries' basis for recommending induced abortion following radiation exposure (DE-70). Their basis seemed to be a risk of greater than 1 in 10 of radiation-induced fetal injury. Sweden, Denmark, and Finland recommended termination of the pregnancy in cases of prenatal radiation exposure if

the exposure exceeded 10 Roentgens. If the exposure was under 1 Roentgen (Sweden and Denmark) or under 2 Roentgens (Finland), the irradiation was not considered to cause significant damage. For exposures between these limits, termination of pregnancy was a subject of judgment (DE-70). In the German Democratic Republic, also, termination of pregnancy is recommended in cases of exposure to 10 Roentgens or more (NE-76).

Federal Radiation Protection Guidance, adopted in 1987, recommends that dose to occupationally exposed pregnant women be controlled to keep the fetal dose below 0.5 rem over the entire term of pregnancy, and that no dose be delivered at more than the uniform monthly rate that would satisfy this limit (i.e., approximately 50-60 mrems/month)(EP-87). The NCRP has, for many years, recommended a limit of 0.5 rem (NC-71). ICRP recommends controlling exposure of the fetus to less than 0.5 rem in the first 2 months to provide appropriate protection during the essential period of organogenesis (IC-77).

C.2.1.5 Acute Effects in the Thyroid

Acute effects are produced in the thyroid by doses from radioiodine on the order of 3000 to 100,000 rads. Ablation of the thyroid requires doses of 100,000 rads (BE-68). The thyroid can be rendered hypothyroid by doses of about 3000 to 10,000 rads (IC-71). A thyroid dose from radioiodines of 1000 rads in adults and 400 rads in children implies an associated whole body dose of about 1 rem due to radioiodines circulating in the blood. Following inhalation of ^{131}I, the committed thyroid dose is about one rad/μCi intake of ^{131}I in adults. In the developing fetus, the thyroid dose ranges from 1 to 6 rads per μCi of ^{131}I entering the mother's body (IL-74).

Although acute clinical effects are only observed at high doses, subclinical acute thyroid radiation effects may occur at lower doses (DO-72). Impaired thyroid capability may occur above a threshold of about 200 rads (DO-72).

Effects of radiation exposure of the thyroid have been shown in animal experiments. Walinder and Sjoden found that doses in excess of 3,000 rads from ^{131}I caused noticeable depression of fetal and juvenile mouse thyroid development (WA-69). Moore and Calvin, working with the Chinese hamster, showed that an exposure as low as 10 Roentgens (x-rays) would give rise to 3 percent aberrant cells when the thyroid was cultured (MO-68). While the direct relationship of these results to human effects is not certain, mammalian thyroid cells can be injured at exposures as low as 10 Roentgens.

C.2.1.6 Acute Effects in the Skin

The first stage of skin reaction to radiation exposure is erythema (reddening) with a threshold of from 300 to 800 rads. Acute exudative radiodermatitis results from doses of 1200 to 2000 rads (WH-84).

C.2.1.7 Clinical Pathophysiological Effects

A large amount of anecdotal information is available on the injury of organ tissues by high doses of radiation. Acute injury to tissue includes swelling and vacuolation of the cells which make up the blood vessels, increased permeability of vessels to fluids so that exudates form, formation of fibrin clots and thrombi, fibrinoid thickening in the walls of blood vessels, and swelling and vacuolization of parenchymal cells. In summary, there is an initial exudative reaction followed in time by fibrosis and sclerosis (WH-76, CA-76).

Estimates of radiation doses necessary to cause severe tissue response in various organs are given in Table C-1. These tissue dose estimates are based on response to radiotherapy treatment, which is normally given on a fractionated dose basis, but also may be given as a continuous exposure. Therefore, these estimates must be adjusted to the equivalent single radiation dose for use in the present analysis. The formalism of Kirk, et al.(KI-71) is used to estimate the equivalent dose for a single acute exposure in rad-equivalent therapy units (rets: the dose calculated from the fractionated exposure which is equivalent to a

Table C-1 Radiation Doses Causing Acute Injury to Organs (RU-72, RU-73)

Organ	Volume or area of exposure[a]	Risk of injury in five years		Type of injury
		5 percent (rad)	50 percent (rad)	
Bone marrow	whole	250	450	aplasia and pancytopenia
Liver	segment	3000	4000	acute and chronic hepatitis
	whole	2500	4000	
Stomach	100 cm^2	4500	5500	ulcer, perforation, hemorrhage
Intestine	400 cm^2	4500	5500	ulcer, perforation, hemorrhage
	100 cm^2	5000	6500	
Lung	whole	1500	2500	acute and chronic pneumonitis
	100 cm^2	3000	3500	
Kidney	whole	2000	2500	acute and chronic nephrosclerosis
Brain	whole	6000	7000	infarction, necrosis
Spinal cord	10 cm	4500	5500	infarction, necrosis
Heart	60 percent	4500	5500	pericarditis and pancarditis
Skin	---	5500	7000	ulcers, fibrosis
Fetus	whole	200	400	death
Lens of eye	whole	500	1200	cataracts
Ovary	whole	200-300	625-1200	permanent sterilization
Testes	whole	500-1500	2000	permanent sterilization

[a]Dose delivered in 200-rad fractions, 5 fractions/week.
--- Unspecified.

single acute exposure for a specific biological endpoint.) Table C-2 lists acute exposure equivalents in rets for various organs.

With the exception of bone marrow, the exposures required to cause 5 percent injury within 5 years (TD 5/5) in internal organs are in the range of 1000 to 5000 rads. Since, with this type of injury, the dose response is nonlinear and has a threshold (i.e., is nonstochastic), there is an exposure below which injury is not expected. If the shape of the injury dose-response curve is the same for all internal organs as it is for the lung, plotting the two acute exposure equivalents (TD 50/5 and 5/5) for each organ on log probability paper allows a crude estimation of the number of clinical pathophysiological effects per 1000 persons exposed as a function of dose level. If one acute effect per 1000 persons within 5 years (TD 0.1/5) is taken as the threshold for the initiation of clinical pathophysiological effects in organs other than thyroid, the equivalent dose level for most organs is 550 rets or more; testes 440 $\pm$ 150 rets, ovary 170 $\pm$ 70 rets, and bone marrow 165 rets.

The radiation exposure to organs in rad units that will cause clinical pathophysiological effects within 5 years to 0.1 percent of the exposed population as a function of the duration of a continuous level of exposure can then be estimated by using Goitein's modification of the Kirk methodology (GO-76). This relationship is shown in Table C-3.

Bone marrow is an organ of particular concern because radionuclides known to concentrate in this organ system occur in nuclear accidents. The acute lethality due to the hematologic syndrome (LA-67) is estimated to occur in the range of 200 to 1,000 rads, so that the difference is small between exposure levels that might cause acute lethality and exposure levels that might cause only "severe clinical pathophysiology," as derived from radiotherapy data.

In summary, organ systems are not expected to show symptoms of severe clinical pathophysiology for projected short-term exposure doses less than a few hundred rads. Projected doses to bone marrow at this high

Table C-2 Acute Radiation Exposure as a Function of Rad Equivalent Therapy Units (Rets)

Organ	Volume or area of exposure	Risk of injury in five years	
		5 percent (rets)	50 percent (rets)
Bone marrow	whole	230	340
	segment	1135	1360
Liver	whole	1000	1360
Stomach	100 cm^2	1465	1665
Intestine	400 cm^2	1465	1665
	100 cm^2	1570	1855
Lung	whole	720	1000
	100 cm^2	1135	1245
	75 percent	770[b]	---
Kidney	whole	875	1000
Brain	whole	1770	1950
Spinal cord	10 cm	1465	1665
Heart	60 percent	1465	1665
Skin	---	1665	1950
Fetus	whole	200	315
Lens of eye	whole	355	620
Ovary	whole	200-430[a]	410-875[a]
Testes	whole (sterilization)	340-720[a]	410-875[a]

[a]For a 200-rad/treatment, 5 treatments/week schedule (LU-76).

[b]Reference WA-73.

--- Unspecified.

Table C-3 Radiation Exposure to Organs Estimated to Cause Clinical Pathophysiological Effects within 5 Years to 0.1 percent of the Exposed Population (GO-76)

Duration of exposure (days)	Ovary (rad)	Bone marrow (rad)	Testes (rad)	Other organs (rad)
(acute)	(170 rets)[a]	(165 rets)	(440 rets)	(550 rets)
1	315	300	810	1020
2	390	380	1010	1260
4	470	450	1210	1510
7	550	540	1430	1790
30	840	820	2190	2740
365[b]	1740	1690	4510	5640

[a]The dose in rets is numerically equal to the dose in rads.

[b]Assuming tissue recovery can continue at the same rate as observed during 30- to 60-day therapeutic exposure courses.

level are relatively more serious and more likely to result in injury than doses to other organ systems.

Even if severe clinical pathophysiological effects can be avoided, there is still a possibility of clinical pathophysiological effects of a less severe or transitory nature. The 1982 UNSCEAR report (UN-82) reviewed much of the data on animals and man. In the animal studies, there were reports of: changes in stomach acid secretion and stomach emptying at 50 to 130 rads; stunting in growing animals at the rate of 3 to 5 percent per 100 rads; degeneration of some cells or functions in the brain at 100 rads, particularly in growing animals; temporary changes in weight of hematopoietic tissues at 40 rads; and more damage in ovaries and testes caused by fractionated doses rather than acute doses. Some of the effects are transitory, others are long-lasting, but with only minor reductions in functional capacity.

Human data are limited and are reported primarily in the radiotherapy literature. The data suggest most tissues in man are more radiation resistant than those in animals. However, the human hematopoietic system shows a transient response, reflected by decreased circulating white cells

and platelets, at about 50 rads. Temporary sterility has been observed after doses of 150 rads to the ovaries and 10 rads to the testes, when given as fractionated doses.

There is not sufficient data to determine dose-response functions, nor to describe the duration and severity of dysfunction expected.

C.2.2 Summary and Conclusions Regarding Acute Effects

Based on the foregoing review of acute health effects and other biological effects, the following whole body doses from acute exposures provide useful reference levels for decisionmaking:

50 rems - Less than 2 percent of the exposed population would be expected to exhibit prodromal (forewarning) symptoms.

25 rems - Below the dose where prodromal symptoms have been observed.

10 rems - The bottom of a range of doses above which most members of the medical profession have recommended abortion. This is also the dose level below which a fetus would not be expected to suffer teratogenesis (but see Section C.3, Mental Retardation.).

5 rems - The approximate minimum level of detectability for acute cellular effects using the most sensitive methods. Although these are not severe pathophysiological effects, they may be detrimental.

1 rem - The dose below which abortion has not been considered necessary by the medical profession.

Based on the first principle to be satisfied by PAGs (paragraph C.1.6), which calls for avoiding acute health effects, values of 50 rems for adults and 10 rems for fetuses appear to represent upper bounds. The effects of the other three principles are considered in the sections that follow.

C.3 Mental Retardation

Brain damage to the unborn is a class of injury reported in atomic bomb survivors which does not fall into either an acute or delayed effect category, but exhibits elements of both. What has been observed is a significant, dose-related increase in the incidence and severity of mental retardation, microencephaly (small head size), and microcephaly (small brain size) in Japanese exposed to radiation *in utero* during the 8th to 15th week after conception (BL-73; MI-76). While the actual injury may be acute, it is not identified until some time after birth.

In an early study Mole (MO-82) suggested that, although radiation may not be the sole cause of these conditions, it is prudent to treat the phenomenon as radiation related. More recently, Otake and Schull (OT-83) have concluded: (1) there is no risk to live-born due to doses delivered up to 8 weeks after conception, (2) most damage occurs at the time when rapid proliferation of neuronal elements occurs, i.e., 8 to 15 weeks of gestational age, (3) the dose-response function for incidence during this period appears to fit a linear model, (4) the risk of occurrence is about five times greater during the period 8-15 weeks of gestation than in subsequent weeks, and (5) in later stages of gestation, e.g., after the 15th week, a threshold for damage may exist.

In their published reports, Otake and Schull (OT-83) evaluated the incidence of severe mental retardation using the T-65 dosimetry and the dosimetry estimates developed in the ongoing dose reassessment program for the atomic bomb survivors, and using two tissue dose models. Their estimated ranges of risk were:

8 to 15 weeks after gestation: $3\text{-}4\times10^{-3}$ cases/rad;

16 or more weeks after gestation: $5\text{-}7\times10^{-4}$ cases/rad.

The higher values are based on the T-65 dosimetry and the Oak Ridge National Laboratory estimate of tissue dose. The lower values are based on Oak Ridge National Laboratory dosimetry and the Japanese National

Institute of Radiological Sciences estimates of tissue dose. Later estimates based on the dose reasessment completed in 1986 are consistent with these published results (SC-87).

In view of the foregoing, the risk of mental retardation from exposure of a fetus in the 8th to 15th week of pregnancy is taken to be about 4×10^{-3} per rem. Because of this relatively high risk, special consideration should be given to protection of the fetus during this period. The risk to a fetus exposed after the 15th week is taken as 6×10^{-4} per rem. For the cases studied (OT-84), no increased incidence of mental retardation was observed for exposure during the 1st to the 7th week of pregnancy. In order to prevent the risk of mental retardation from exceeding the risk of fatal cancer for the general population (see section C.4) it would appear necessary that the dose to fetuses of gestational age 8 to 15 weeks not exceed about one tenth the dose to members of the general population.

C.4 Delayed Health Effects

This section addresses information relevant to the second principle (paragraph C.1.5) for establishing PAGs, the risk of delayed health effects in exposed individuals. The following subsections summarize the estimated risks of cancer and genetic effects, the two types of delayed effects caused by exposure to radiation.

C.4.1 Cancer

Because the effects of radiation on human health have been more extensively studied than the effects of many other environmental pollutants, it is possible to make numerical estimates of the risk as a result of a particular dose of radiation. Such estimates, may, however, give an unwarranted aura of certainty to estimated radiation risks. Compared to the baseline incidence of cancer and genetic defects, radiogenic cancer and genetic defects do not occur very frequently. Even in heavily irradiated populations, the number of cancers and genetic defects resulting from radiation is known with only limited accuracy. In

addition, all members of existing exposed populations have not been followed for their full lifetimes, so data on the ultimate numbers of effects is not yet available. Moreover, when considered in light of information gained from experiments with animals and from various theories of carcinogenesis and mutagenesis, the observed data on the effects of human exposure are subject to a number of interpretations. This, in turn, leads to differing estimates of radiation risks by individual scientists and expert groups. In summary, the estimation of radiation risks is not a fully mature science and the evaluation of radiation hazards will continue to change as additional information becomes available.

Most of the observations of radiation-induced carcinogenesis in humans are on groups exposed to low-LET radiations. These groups include the Japanese A-bomb survivors and medical patients treated with X-rays for ankylosing spondylitis in England from 1935 to 1954 (SM-78). The National Academy of Science Committee on the Biological Effects of Ionizing Radiations (BEIR) (NA-80) and UNSCEAR (UN-77) have provided knowledgeable and exhaustive reviews of these and other data on the carcinogenic effects of human exposures. The most recent of the BEIR studies was published in 1980 and is here designated BEIR-3 to distinguish it from previous reports of the BEIR committee.

The most important epidemiological data on radiogenic cancer is that from the A-bomb survivors. The Japanese A-bomb survivors have been studied for more than 40 years, and most of them have been followed in a major, carefully planned and monitored epidemiological survey, the Life Span Study Sample, since 1950 (KA-82, WA-83). They were exposed to a wide range of doses and are the largest group that has been studied. They are virtually the only group providing extensive information on the response pattern at various levels of exposure to low-LET radiation.

The estimated cancer risk from low-LET, whole body, lifetime exposure presented here is based on a life table analysis using a linear response model. We use the arithmetic average of relative and absolute risk projections (the BEIR-3 L-L model) for solid cancers, and an absolute risk projection for leukemia and bone cancer (the BEIR-3 L-L model). For whole

body dose, this yields an estimated 280 (with a possible range of 120 to 1200) fatalities per million person-rem for a population cohort representative of the U.S. population. (The rounded value, 3×10^{-4} fatalities[3] per person-rem, has been selected for this analysis.)

Whole body dose means a uniform dose to every organ in the body. In practice, such exposure situations seldom occur, particularly for ingested or inhaled radioactivity. Inhaled radioactive particulate materials may be either soluble or insoluble. Soluble particulate materials deposited in the lung will be rapidly absorbed, and the radionuclides associated with them distributed throughout the body by the bloodstream. As these radionuclides are transported in the blood, they irradiate the entire body. Usually, they then redeposit in one or more organs, causing increased irradiation of that organ. Insoluble particulate materials, on the other hand, are only partially absorbed into body fluids. (This fraction is typically assumed to be about 8 percent.) This absorption occurs over a period of years, with a portion entering the bloodstream and another retained in the pulmonary lymph nodes. The balance (92 percent) of inhaled insoluble particulate materials are removed from the lung within a few days by passing up the air passages to the pharynx where they are swallowed. Inhaled insoluble particulate materials thus irradiate both the lung and the gastrointestinal tract, with a small fraction being eventually absorbed into the bloodstream (TG-66). These nonuniform distributions of dose (and therefore risk) are taken into account through use of the weighting factors for calculating effective dose.

There is a latent period associated with the onset of radiation-induced cancers, so the increased risk is not immediately apparent. The increased risk is assumed to commence 2 to 10 years after the time of exposure and continue the remainder of the exposed individual's lifespan (NA-80; EL-84).

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[3]Preliminary reviews of new results from studies of populations exposed at Hiroshima and Nagasaki indicate that these risk estimates may be revised upwards significantly in the near future, particularly for acute exposure situations. EPA will publish revised risk estimates to reflect new results following appropriate review.

For uniform exposure of the whole body, about 50 percent of radiation-induced cancers in women and about 65 percent in men are fatal (NA-80). Therefore, 1 rem of low-LET radiation would be expected to cause a total of about 500 cancer cases if delivered to a population of one million. (In the case of thyroid and skin, the ratio of nonfatal to fatal cancers are much higher. These are addressed separately below.) This corresponds to an average annual individual probability of developing cancer of about 7×10^{-6} per year. For perspective, the average annual risk of dying of cancer from all causes in the United States, in 1982, was 1.9×10^{-3}.

C.4.1.1 Cancer Risk Due to Radiation Exposure of the Thyroid

Exposure of the thyroid to extremely high levels of radiation may cause it to degenerate. At moderate levels of exposure some loss of thyroid function will occur. At lower levels of exposure, there are delayed health effects, which take the form of both thyroid nodules and thyroid malignancies (NA-72; NA-80). Doses as low as 14 rads to the thyroid have been associated with thyroid malignancy in the Marshall Islanders (CO-70). The increased risk of radiation-induced cancer is assumed to commence about 10 years after initial exposure and to continue for the remaining lifespan of an exposed individual.

The true nature of thyroid nodules cannot be established until they are surgically removed and examined histologically, and those that are malignant can lead to death if not surgically removed (SA-68; DE-73; PA-74). Although thyroid malignancies are not necessarily fatal, effects requiring surgical removal of the thyroid cannot be considered benign. In this analysis, all thyroid cancers, both fatal and nonfatal, are counted for the purpose of estimating the severity of thyroid exposures.

Based on findings in BEIR-3, we estimate that 1 rem of thyroid exposure carries a risk of producing a thyroid cancer of 3.6×10^{-4}, of which a small fraction (on the order of 1 in 10) will be fatal (NA-80). Since the calculation of effective dose equivalent does not include consideration of nonfatal thyroid cancers and the severity of the medical

procedures for their cure, it is appropriate to limit the dose to the thyroid by an additional factor beyond that provided by the PAG expressed in terms of effective dose equivalent. Protective action to limit dose to thyroid is therefore recommended at a thyroid dose 5 times the numerical value of the PAG for effective dose.

C.4.1.2 Cancer Risk Due to Exposure of the Skin

The risk of fatal skin cancer is estimated to be on the order of one percent of the total risk of fatal cancer for uniform irradiation of the entire body (IC-78). However, since the weighting scheme for calculating effective dose equivalent does not include skin, the PAG expressed in terms of effective dose does not provide protection against radionuclides which primarily expose skin. As in the case of the thyroid, the ratio of nonfatal to fatal cancers from irradiation of the skin is high (on the order of 100 to 1). It would not be appropriate to ignore this high incidence of nonfatal skin cancers by allowing 100 times as much dose to the skin as to the whole body. For this reason, evacuation is recommended at a skin dose 50 times the numerical value of the PAG for effective dose to the entire body. (Bathing and change of clothing are also effective protective actions for radionuclides deposited on skin and clothing. Since these are low-cost, low-risk actions, no dose level is specified below which they are not recommended.)

C.4.1.3 Cancer Risk Due to Radiation Exposure of the Fetus

The fetus is estimated to be 5 to 10 times as sensitive to radiogenic cancer as an adult (FA-73; WH-65). Stewart reports increased relative incidence of childhood cancers following prenatal x-ray doses as low as 0.20 to 0.25 rem and doubling of childhood cancers between 1-4 rems (ST-73). She concluded that the fetus is about equally sensitive to cancer induction in each trimester. Her findings are supported by similar results reported by MacMahon and Hutchinson (MA-64), Kaplan (KA-58), Polhemus and Kock (PO-59), MacMahon (MA-63), Ford, et al. (FO-59), Stewart and Kneale (ST-70b), and an AEC report (AE-61). MacMahon reported that although there were both positive and negative findings, the combination

of weighted data indicates a 40 percent increase in childhood cancer mortality after *in vivo* exposure to diagnostic X rays (1.0 to 5.0 rads): about 1 cancer per 2,000 exposed children in the first 10 years after birth (MA-63). He concluded that although the range of dose within which these effects are observed is wide, effects will be fewer at 1 rem than at 5 rems.

Graham, *et al.*, investigating diagnostic x-ray exposure, found a significantly increased relative risk of leukemia in children: by a factor of 1.6 following preconception irradiation of mothers or *in utero* exposure of the fetus; by a factor of 2 following postnatal irradiation of the children; and by a factor of 2 following preconception irradiation of the mother and *in utero* exposure of the child (GR-66).

C.4.1.4 Age Dependence of Doses

Almost all dose models are based on ICRP "Reference Man," which adopts the characteristics of male and female adults of working age. ICRP-30 dosimetric models, which use "Reference Man" as a basis, are therefore appropriate for only adult workers and do not take into account differences in dose resulting from the differences in physiological parameters between children and adults, e.g., intake rates, metabolism, and organ size. Although it is difficult to generalize for all radionuclides, in some cases these differences tend to counterbalance each other. For example, the ratio of volume of air breathed per unit time to lung mass is relatively constant with age, so that the ICRP adult model for inhaled materials provides a reasonably good estimate of the dose from a given air concentration of radioactive material throughout life.

The thyroid is an exception because the very young have a relatively high uptake of radioiodine into a gland that is much smaller than the adult thyroid (see Section C.4.2.2.). This results in a larger childhood dose and an increased risk which persists throughout life. Since this is a worst case situation, we have examined it with some care, using the age-specific risk coefficients for thyroid cancer in Table V-14 of the

BEIR-3 report (NA-80) and an age-dependent dose model (OR-84). The analysis indicates that, for iodine-131 ingestion, the estimated lifetime risk is increased by a factor of 1.6, due to a 30 percent increase in lifetime dose over that obtained for an adult by the same model. Results are the same for inhalation of iodine-131, that is, the estimated lifetime risk of fatal thyroid cancer is increased by a factor of 1.6.

C.4.2 Genetic Risk

An average parental dose of 1 rem before conception has been estimated to produce 5 to 75 significant genetically-related disorders per million liveborn offspring (NA-80). For this analysis we use the geometric mean of this range, i.e. 1.9×10^{-5}. This estimate applies to effects in the first generation only, as a result of dose to parents of liveborn offspring. The sum of effects over all generations is estimated to be approximately twelve times greater; that is, 2.3×10^{-4}. In addition, since any radiation dose delivered after a parent's last conception has no genetic effect, and not all members of the population become parents, less than half of the entire dose in an average population is of genetic significance. Taking the above factors into account, we estimate that the risk of genetically-related disorders in all generations is 1×10^{-4} per person-rem to a typical population.

Although the overall severity of the genetic effects included as "significant" in the above estimates is not well known, rough judgements can be made. The 1980 BEIR report referred to "....disorders and traits that cause a serious handicap at some time during lifetime" (NA-80). From the types of defects reported by Stevenson (ST-59), it can be estimated that, of all radiation-induced genetic effects, 50 percent lead to minor to moderate medical problems (i.e., hair or ear anomalies, polydactyly, strabismus, etc.), 25 percent lead to severe medical problems (i.e., congenital cataracts, diabetes insipidus, deaf mutism, etc.), 23 percent would require extended hospitalization (i.e., mongolism, pernicious anemia, manic-depressive psychoses, etc.), and 2 percent would die before age 20 (i.e., anencephalus, hydrocephalus, pancreatic fibrocytic disease, etc.).

C.4.3 Summary of Risks of Delayed Effects

Table C-4 summarizes average lifetime risks of delayed health effects based on results from the above discussion. Because of the nature of the dose-effect relationships assumed for delayed health effects from radiation (linear, nonthreshold), there is no dose value below which no risk can be assumed to exist.

Table C-4 Average Risk of Delayed Health Effects in a Population[a]

	Effects per person-rem		
	Whole Body	Thyroid[c]	Skin
Fatal cancers	2.8E-4[b]	3.6E-5	3.0E-6
Nonfatal cancers	2.4E-4[b]	3.2E-4	3.0E-4
Genetic disorders (all generations)	1.0E-4		

[a] We assume a population with the same age distribution as that of the U.S. population in 1970.

[b] Risk to the fetus is estimated to be 5 to 10 times higher.

[c] Risk to young children is estimated to be about 1.6 times higher

C.4.4 Risks Associated with Other Radiation Standards

A review of radiation standards for protection of members of the general population from radiation shows a range of values spanning several orders of magnitude. This occurs because of the variety of bases (risk, cost, practicability of implementation, and the situations to which they apply) that influenced the choice of these standards. Some source-specific standards are relatively protective, e.g., the standard limiting exposure of the public from nuclear power operations (25 mrem/y) corresponds to a risk (for cancer death) of 5×10^{-4} for lifetime exposure. Others permit much higher risks. For example, the level at

which the Environmental Protection Agency recommends action to reduce exposure to indoor radon (0.02 working levels) corresponds to a risk of about $2x10^{-2}$ (for fatal lung cancer) for lifetime exposure. All of these standards apply to non-emergency situations and were based on considerations beyond a simple judgement of acceptable risk. The more protective standards provide some guidance on lower bounds for the use of sheltering. However, none of these source-specific standards for non-emergency situations provide a useful basis for decisions on PAGs for evacuation during the early phase of an accident.

Federal Radiation Protection Guidance for non-emergency situations recommends that the dose from all sources combined (except from exposure to medical and natural background radiation) to individuals in the population not exceed 0.5 rem in a single year (FR-60) and that the dose to the fetus of occupationally-exposed mothers not exceed 0.5 rem during the 9-month gestation period (EP-87). These doses correspond to a lifetime risk of fatal cancer to members of the general population of about $1.4x10^{-4}$ and, for exposure of fetuses, a 5 to 10 times greater risk. If exposure of the fetus is limited to one ninth of 0.5 rems per month over the entire gestation period, as recommended, the risk of severe mental retardation in liveborn is limited to about $7x10^{-4}$.

The International Commission on Radiation Protection recommends that the dose to members of the public not exceed 0.5 rems per year due to non-recurring exposure to radiation from other than natural sources or beneficial medical uses of radiation (IC-77). They also recommend a limiting dose to members of the public of 0.1 rems per year from all such sources combined for chronic (i.e., planned) exposure (IC-84). Environmental Protection Agency regulations limit the dose due to the combined emissions of radionuclides to air from routine operation of all facilities combined to the same values; that is, to 0.5 rem per year for non-recurring releases, and to 0.1 rem per year for chronic releases. (These values are upper bounds for the combined exposure from multiple sources under variance provisions; lower values normally apply to most single sources.)

These upper bounds may be taken as representative of acceptable values for the situations to which they apply. That is, these are levels of individual risk that are acceptable for the sum of all sources and exposure pathways, for circumstances that are justified on the basis of public benefit, and when actual doses from individual sources are "as low as reasonably achievable" (ALARA) within these upper bounds. Although these levels were not developed for the emergency situations governed by these PAGs, they do provide useful precedents for acceptable levels of involuntary risk in nonemergency situations. As such, the values for nonrecurring exposure may reasonably be assumed to provide guidance on the acceptability of risks in emergency situations (subject to the usual caveats regarding use of lower levels if justified by cost-risk (optimization) considerations.) The values for chronic exposure may also be useful guidance for decisions involving exposures originating from an accident that are avoidable in a nonemergency context, such as local exposure over the long term and the export (or import) of foodstuffs to locations remote from a nuclear accident.

C.5 Practicality of Implementation

Whereas Sections C.3 and C.4 dealt with the risk associated with the projected dose that could be avoided by protective actions, this section addresses the costs and risks associated with the protective actions themselves. These analyses of practicality relate to principles 3 and 4, as set forth in Section C.1.6.

The principal relevant protective actions during the early phase are, as noted earlier, evacuation and sheltering. In some cases, washing and changing of clothing, or thyroid blocking may also be appropriate actions. The costs, risks, and degrees of protection associated with evacuation are generally higher than those for sheltering. Although there may be some costs and risks associated with the other protective actions they are small and not readily quantifiable. Therefore, only the costs and risks associated with evacuation will be evaluated here. These factors are evaluated to determine whether the costs are low enough to justify lower PAGs than would be required to satisfy upper bounds of acceptable risk under principle 2.

C.5.1 Cost of Evacuation

Costs incurred to reduce the radiation risk from nuclear accidents can be considered to fall into several major categories. A first category includes the design, construction, and operation of nuclear facilities in such a manner as to minimize the probability and consequences of radiological accidents. It is recognized that the probability and consequences of such accidents cannot be reduced to zero. Therefore, a second category is necessary: the development of emergency response plans to invoke actions which would reduce exposure of potentially exposed populations, and consequently their risks, if a major nuclear accident should occur.

Both of the above categories of cost are properly attributed to the cost of design and operation of a nuclear facility. A third category of costs involves actual protective actions which are implemented only as a result of an accident. The choice of levels for PAGs affects only this category of costs. Conversely, all costs in the first two categories are unaffected by decisions on the levels of PAGs (unless the PAGs were to be set so high as to never require protective action, in which case response plans would be unnecessary). Therefore, the costs associated with implementing the PAGs are evaluated only in terms of the actual cost of response. In a similar manner, the risk incurred by protective actions is compared only to the risk associated with the radiation dose that would be avoided by the action, and is unaffected by any other measures taken to reduce risk that fall in the first two categories of cost identified above.

C.5.1.1 Cost Assumptions

The cost analyses in this section are based on an evaluation of the costs of evacuation and the population doses that would be received in the absence of protective actions for nuclear power plant accidents. These were calculated as a function of offsite location, meteorological condition, and accident type (TA-87). Cost and dose data are based on the following assumptions:

a. Airborne releases are those associated with fuel melt accidents followed by containment failure.

b. Meteorological conditions range from stable to unstable, and windspeeds are those typical of the stability class.

c. Plume dispersion follows a Gaussian distribution, with a 0.01 m/s dry deposition velocity for iodine and particulate materials.

d. Doses are those incurred during the first four days due to whole body gamma radiation from the plume, inhalation of radioactive material in the plume, and direct and inhalation exposure to deposited radioactive material.

e. Population distributions are the average values observed around 111 nuclear reactor plants, based on 1970 data.

f. The cost of evacuation is $185 per person for a 4-day evacuation and a 100-mile round trip, with an average of 3 persons per household. These evacuation costs include wages and salaries of personnel directing the evacuation, transportation costs of evacuees to and from the staging location, food and lodging for the evacuees during the evacuation period, loss of personal and corporate income during the evacuation period, and the costs of any special supplies.

The estimated costs and doses avoided are based on the following evacuation area model (see Figure C.2.):

a. All people within a 2-mile radius of the accident are evacuated for all scenarios.

b. People are also evacuated from a downwind area bounded by a ray on either side of the center line of the plume defining the angular spread of the area evacuated and by an arc at the distance beyond which the evacuation dose would not be exceeded on the plume centerline.

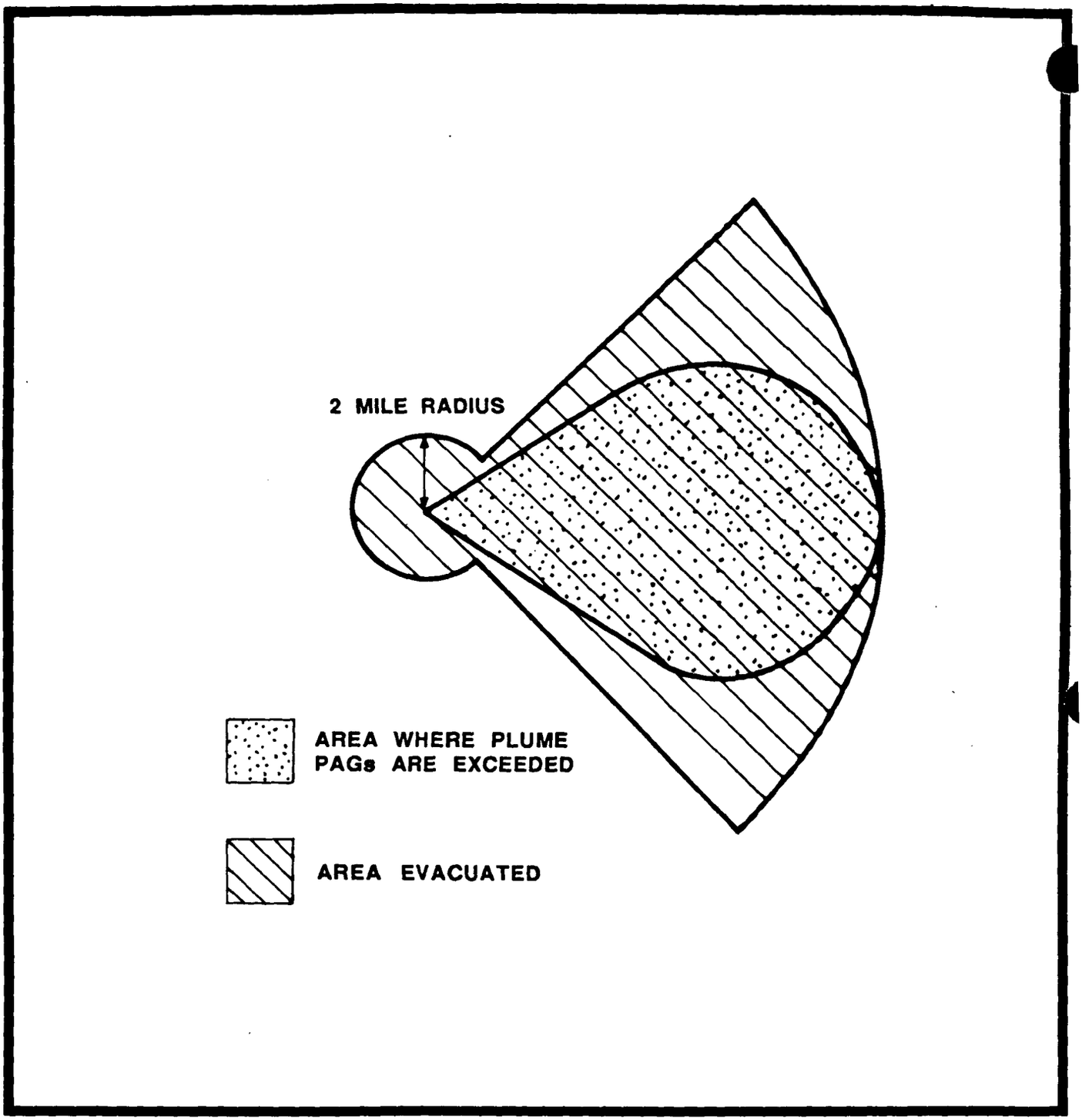

FIGURE C-2. EVACUATION MODEL.

Figure C-2 shows the relationship between the area in which the evacuation dose would be exceeded and the larger area that might be evacuated. As shown in the Figure, although the calculation assumes that the plume will be centered in the evacuation arc, in real cases this will generally not occur.

C.5.1.2 Analysis

Evaluation of costs for evacuation and doses to populations as a function of the area evacuated depends on a variety of assumptions. Three fuel-melt accident categories, six meteorological stability classes, and three evacuation area models were examined. Detailed assumptions and data are reported elsewhere (TA-87). Selected data, including the cost per unit of collective dose to the population (person-rem) avoided, are presented in Tables C-5, C-6, and C-7, for three stability classes, for the median nuclear accident category examined (SST-2).

The data are presented for both the total area and the incremental area evacuated for each change in dose level examined. When evaluating the cost per person-rem avoided for a specific set of circumstances, it is appropriate to assess the ratio of the total cost to the total dose avoided to calculate the average cost per person-rem avoided. However, when one is comparing the cost versus dose avoided to make a judgment between a variety of different limiting dose values, it is appropriate to compare the dose savings and costs at the margin, since the cost of evacuating the additional area is incurred to avoid the incremental collective dose. Therefore, the appropriate quantities are the cost and risk for the additional area evacuated. Results of analyses on both a total and incremental basis are presented in Tables C-5, C-6, and C-7 for accident category SST-2. This is the smallest category of fuel melt accident yielding effective dose equivalents during the first 4 days of exposure that are greater than 0.5 rems outside the assumed 2-mile evacuation circle for all stability classes. Data on costs verus dose saved for all three accident categories are summarized in Table C-8 in the next section.

Table C-5 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class A)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	ΔCost (dollars)	ΔDose avoided (person-rem)	ΔDollars/ Δperson-rem avoided
70	0.5	2.83E+7	8.97E+4	315			
	1	6.68E+6	4.06E+4	164	2.16E+7	4.91E+4	440
	2	1.49E+6	1.73E+4	88	5.19E+6	2.33E+4	223
	5	2.99E+5	5.22E+3	57	1.19E+6	1.21E+4	98
	10	(a)	(a)	(a)	9.70E+4	2.44E+3	40
90	0.5	3.63E+7	9.29E+4	391			
	1	8.54E+6	4.24E+4	201	2.78E+7	5.05E+4	550
	2	1.86E+6	1.82E+4	102	6.68E+6	2.42E+4	276
	5	3.26E+5	5.41E+3	60	1.54E+6	1.28E+4	120
	10	(a)	(a)	(a)	1.25E+5	2.63E+3	47
180	0.5	7.16E+7	9.33E+4	767			
	1	1.67E+7	4.27E+4	391	5.49E+7	5.06E+4	1080
	2	3.48E+6	1.84E+4	190	1.32E+7	2.43E+4	543
	5	4.48E+5	5.46E+3	82	3.04E+6	1.29E+4	235
	10	(a)	(a)	(a)	2.47E+5	2.68E+3	92

[a] The 4-day dose does not exceed the PAG outside the 2-mile radius of the accident site. The total cost of evacuation within this radius is 2.02E+5 dollars; the total dose avoided is 2.78E+3 person-rems; and the total cost per person-rem avoided is $73.

Table C-6 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class C)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	ΔCost (dollars)	ΔDose avoided (person-rem)	ΔDollars/ Δperson-rem avoided
70	0.5	4.95E+7	1.13E+5	439			
	1	1.23E+7	6.31E+4	195	3.71E+7	4.95E+4	750
	2	2.46E+6	3.73E+4	66	9.87E+6	2.58E+4	382
	5	7.82E+5	2.71E+4	29	1.68E+6	1.02E+4	165
	10	3.93E+5	2.10E+4	19	3.89E+5	6.15E+3	63
	20	2.60E+5	1.62E+4	16	1.32E+5	4.75E+3	28
	50	(a)	(a)	(a)	3.40E+4	2.50E+3	10
90	0.5	6.35E+7	1.13E+5	564			
	1	1.58E+7	6.32E+4	250	4.77E+7	4.95E+4	964
	2	3.11E+6	3.74E+4	83	1.27E+7	2.58E+4	491
	5	9.48E+5	2.72E+4	35	2.16E+6	1.02E+4	212
	10	4.47E+5	2.10E+4	21	5.00E+5	6.16E+3	81
	20	2.77E+5	1.63E+4	17	1.70E+5	4.76E+3	36
	50	(a)	(a)	(a)	3.40E+4	2.50E+3	14
180	0.5	1.25E+8	1.13E+5	1110			
	1	3.10E+7	6.32E+4	491	9.44E+7	4.95E+4	1910
	2	5.95E+6	3.74E+4	159	2.51E+7	2.58E+4	971
	5	1.68E+6	2.72E+4	62	4.28E+6	1.02E+4	419
	10	6.87E+5	2.10E+4	33	9.90E+5	6.16E+3	161
	20	3.51E+5	1.63E+4	22	3.36E+5	4.77E+3	70
	50	(a)	(a)	(a)	6.70E+4	2.50E+3	27

[a] The 4-day dose does not exceed the PAG outside the 2-mile radius of the accident site. The total cost of evacuation within this radius is 2.02E+5 dollars; the total dose avoided is 2.78E+3 person-rems; and the total cost per person-rem avoided is $73.

Table C-7 Costs for Implementing Various PAGs for an SST-2 Type Accident (Stability Class F)

Evacuation angle (degrees)	PAG value (rem)	Total Area			Marginal Area		
		Cost (dollars)	Dose avoided (person-rem)	Dollars/ person-rem avoided	ΔCost (dollars)	ΔDose avoided (person-rem)	ΔDollars/ Δperson-rem avoided
70	0.5	8.95E+7	4.61E+5	194			
	1	4.95E+7	4.41E+5	112	4.01E+7	1.98E+4	2020
	2	2.83E+7	4.19E+5	67	2.12E+7	2.17E+4	977
	5	1.23E+7	3.83E+5	32	1.59E+7	3.66E+4	436
	10	6.68E+6	3.53E+5	19	5.65E+6	2.93E+4	193
	20	3.65E+6	3.22E+5	11	3.03E+6	3.18E+4	95
	50	1.49E+6	2.68E+5	5.6	9.70E+5	3.10E+4	32
90	0.5	1.15E+8	4.61E+5	250			
	1	6.35E+7	4.41E+5	144	5.15E+7	1.98E+4	2600
	2	3.63E+7	4.19E+5	87	2.72E+7	2.17E+4	1260
	5	1.58E+7	3.83E+5	41	2.05E+7	3.66E+4	560
	10	8.54E+6	3.53E+5	24	7.26E+6	2.93E+4	248
	20	4.64E+6	3.22E+5	14	3.90E+6	3.18E+4	123
	50	1.86E+6	2.68E+5	6.9	1.30E+6	3.10E+4	41
180	05	2.27E+8	4.61E+5	493			
	1	1.25E+8	4.41E+5	285	1.02E+8	1.99E+4	5120
	2	7.16E+7	4.19E+5	171	5.39E+7	2.17E+4	2480
	5	3.10E+7	3.83E+5	81	4.05E+7	3.66E+4	1110
	10	1.67E+7	3.53E+5	47	1.44E+7	2.92E+4	492
	20	8.98E+6	3.22E+5	28	7.71E+6	3.18E+4	242
	50	3.51E+6	2.68E+5	13	2.40E+6	3.10E+4	80

Changes in population density would not affect the above results, since both cost and collective dose are proportional to the size of the population affected. Factors that could affect these results are different assumptions for cost of evacuation, accident scenarios, and evacuation models. The results will be directly proportional to different assumptions for the cost of evacuation. Some data on the variation with accident scenario are presented in the next section. In situations where different widths of evacuation are assumed, the change in cost per unit dose avoided will be approximately proportional to the change in width in degrees. This approximation is more accurate for the higher stability classes (E and F). Evacuation within a 2 mile radius circle and a 90 degree sector in the downwind direction is generally considered to be adequate for release durations not exceeding a few hours and where reliable wind direction forecasts are available.

C.5.1.3 Results of the Cost Analysis

As shown in Tables C-5, C-6, and C-7 for an SST-2 accident, the cost per unit dose avoided is greatest for wide angle evacuation and for the lowest stability class (F). Although some emergency plans call for evacuation over wider angles (up to 360 degrees), the model shown in Figure C-2 with a 90 degree angle is most common.

To estimate an upper bound on dose for evacuation based on cost, we first consider common values placed on avoiding risk. As one input into its risk management decisions, EPA has used a range of $400,000 to $7,000,000 as an acceptable range of costs for avoiding a statistical death from pollutants other than radiation. For a risk of 3×10^{-4} cancer deaths per person-rem, these dollar values are equivalent to a range of from about $120 to $2,000 per person-rem avoided. These values can be compared to the marginal cost-effectiveness (dollars per person-rem) of evacuation over an angle of 90 degrees. The resulting ranges of upper bounds on dose are shown in Table C-8 for SST-1, SST-2, and SST-3 accident scenarios. The maximum upper bounds (based on minimum costs for avoiding risk) range from 1 to 10 rems, with most values being approximately 5 rems. The minimum upper bounds (based on maximum costs for avoiding risk)

Table C-8 Upper Bounds on Dose for Evacuation, Based on the Cost of Avoiding Statistical Fatalities[a]

Accident Category	Atmospheric Stability Class[b]	Dose Upper Bounds[c] Maximum (rem)	Minimum (rem)
SST-1	A	5	0.4
	C	5	0.4
	F	10	0.8
SST-2	A	1	0.15
	C	3.5	0.25
	F	10	0.7
SST-3	A	(d)	(d)
	C	(d)	(d)
	F	5	0.45

[a] Based on data from TA-87.

[b] Windspeeds typical of each stability class were chosen.

[c] Based on an assumed range of $400,000 to $7,000,000 per statistical life saved.

[d] For stability classes A and C, the dose from an SST-3 accident is not predicted to exceed 0.5 rem outside a 2-mile radius. It is assumed that evacuation inside this radius would be carried out based on the emergency condition on the site. No differential evacuation costs were calculated within this area.

range from 0.15 to 0.8 rem, with 0.5 rem being representative of most situations. From these data we conclude that, based on the cost of evacuation, a PAG larger than the range of values 0.5 to 5 rems would be incompatible with principle three, Section C.1.4., for average members of the population.

C.5.2 Risk of Evacuation

Principle four requires that the risk of the protective action not exceed the risk associated with the dose that will be avoided. Risk from evacuation can come from several sources, including (1) transportation

accidents for both pedestrians and vehicle passengers, (2) exposure to severe weather conditions or a competing disaster, and (3), in the case of the infirm, anxiety, unusual activity, and separation from medical care or services. The first source, transportation accidents, is the only category for which the risk has been quantified. An EPA report (HA-75) evaluated the risk of transportation fatalities associated with emergency evacuations that have actually occurred and concluded that the risk of death per mile traveled is about the same as that for routine automobile travel. Using this as a basis, the risk of death from travel is about 9×10^{-8} deaths per person-mile, or 9×10^{-6} deaths per person for the 100-mile round trip assumed for evacuation. Assuming a risk of fatal cancer from radiation of approximately 3×10^{-4} per person-rem, such an evacuation risk is equivalent to a dose of about 0.03 rems.

In comparing this risk (or, more exactly, its equivalent in dose) to the risk avoided by evacuation, it is important to note that protective action must be implemented over a larger population than will actually be exposed at the level of the PAG. Because of uncertainty or unpredictable changes in wind direction, the exact location of the plume will not be precisely known. Dose projections are made for the maximum exposed individuals - those at the assumed location of the plume centerline. To assure that these individuals will be protected it is necessary that others on either side take protective action at exposures that are less than at the plume centerline, and, in some cases, are zero. Thus, the entire evacuated population might incur, on the average, a risk from the protective action which exceeds the risk of the radiation dose avoided.

We examined the average dose avoided for various choices of evacuation levels. Table C-9 presents the results, which are derived from the data in Tables C-5, C-6, and C-7. For the levels analyzed, the average dose avoided is always significantly greater than 0.03 rems. We conclude, therefore, that the choice of PAGs will not be influenced by the fourth principle, for persons in the general population whose risk from evacuation is primarily the normal risk of transportation, if the centerline dose avoided is at or above 0.5 rems.

Table C-9 Average Dose Avoided per Evacuated Individual for Incremental Evacuation Levels

Centerline dose (rem)	Average dose avoided (rem per individual) by stability class		
	A	C	F
0.5 to 1	0.34	0.19	0.07
1 to 2	0.67	0.38	0.15
2 to 5		0.87	0.33
5 to 10			0.75

As previously discussed, hazardous environmental conditions (e.g., severe weather or a competing disaster) could create transportation risks from evacuation that would be higher than normal. It is therefore appropriate to make an exception to allow higher projected doses for evacuation decisions under these conditions. In the absence of any definitive information on these higher risks from evacuation itself, we have arbitrarily assumed that it would be appropriate to increase the projected dose for decisions to evacuate the general population under hazardous environmental conditions up to a factor of 5 higher than under normal environmental conditions.

It is also recognized that infirm persons are at higher risk from evacuation than are average members of the population. It would be appropriate to adopt higher PAGs for evacuation of individuals who would be at greater risk from evacuation itself than for the typically healthy members of the population who are at low risk from evacuation. In the absence of definitive information on the higher risk associated with the evacuation of this group, we have arbitrarily assumed that it is appropriate to adopt PAGs a factor of five higher for evacuation of high risk groups under normal environmental conditions. If both conditions exist, (high risk groups and hazardous environmental conditions) projected doses up to 10 times higher than the PAGs for evacuation of the general population under normal conditions may be justified.

Evacuation the general population at a projected dose of five rems under hazardous environmental conditions, and 10 rems for special high risk groups, is expected to result in actual doses avoided by evacuation of one half (or more) of these values, depending on the effectiveness of sheltering as discussed in Section C.7. These doses are expected to satisfy Principle 4 without violating the other three principles.

C.5.3 Thyroid Blocking

The ingestion of stable potassium iodide (KI) to block the uptake of radioiodine by the thyroid has been identified as an effective protective action. The Food and Drug Administration (FDA) analyzed available information on dose-response for radioiodine-induced thyroid cancers and the incidence and severity of side effects from potassium iodide (FD 82). They concluded "...risks from the short-term use of relatively low doses of potassium iodide for thyroid blocking in a radiation emergency are outweighed by the risks of radioiodine-induced thyroid nodules or cancer at a projected dose to the thyroid gland of 25 rem. FDA recommends that potassium iodide in doses of 130 milligrams (mg) per day for adults and children above 1 year and 65 mg per day for children below 1 year of age be considered for thyroid blocking in radiation emergencies in those persons who are likely to receive a projected radiation dose of 25 rem or greater to the thyroid gland from radioiodines released into the environment. To have the greatest effect in decreasing the accumulation of radioiodine in the thyroid gland, these doses of potassium iodide should be administered immediately before or after exposure. If a person is exposed to radioiodine when circumstances do not permit the immediate administration of potassium iodide, the initial administration will still have substantial benefit even if it is taken 3 or 4 hours after acute exposure". Evacuation and sheltering are, however, preferred alternatives for most situations because they provide protection for the whole body and avoid the risk of misapplication of potassium iodide.

The Federal Emergency Management Agency has published a Federal policy developed by the Federal Radiological Preparedness Coordinating Committee regarding the use of KI as a protective action (FE-85). In

summary, the policy recommends the stockpiling of KI and distribution during emergencies to emergency workers and institutionalized persons, but does not recommend requiring stockpiling or distribution to the general public. The policy recognizes, however, that options on the distribution and use of KI rests with the States and, hence, the policy statement permits State and local governments, within the limits of their authority, to take measures beyond those recommended or required nationally.

C.6. Recommended PAGs for Exposure to a Plume

Previous sections have reviewed data, standards, and other information relevant to the principles set forth in section C.1.4. for establishing PAGs. The results of these reviews are summarized in Table C-10.

Based on principles 1 (avoidance of acute risk) and 3 (cost/risk considerations) 5 rems is an upper bound on the dose at which evacuation of the general population is justified. Principle 4 (risk of the protective action itself) supplies a lower bound of 0.03 rems for evacuation of most members of the public. However, under Principle 3 (cost/risk considerations) only values equal to or greater than 0.5 rems are justified. This will be limiting unless lower values are required for purely health-based reasons (Principle 2). This is not the case. The single lower purely health-based value, 0.1 rems, is only valid as a health-based criterion for chronic exposure. We have selected the value 0.5 rems as the dose which justifies evacuation, because 1) it satisfies the criterion for acceptable risk from nonrecurring doses to the general public, 2) it satisfies the criterion for acceptable risk to the fetus of occupationally exposed mothers (as well as falling well below dose values at which abortion is recommended), and 3) it falls within the range of acceptable costs for the risks avoided.

As noted in Section C.7, we assume that the dose avoidable by evacuation is one half of the projected dose. The value of the PAG for evacuation of the general public is therefore chosen as one rem projected committed effective dose equivalent.

Table C-10. Summary of Considerations for Selecting the Evacuation PAGs.

Dose[a] (rem)	Consideration	Principle	Section
50	Assumed threshold for acute health effects in adults.	1	C.2.1.1
10	Assumed threshold for acute health effects in the fetus.	1	C.2.1.4
5	Maximum acceptable dose for normal occupational exposure of adults.	2	C.4.4
5	Maximum dose justified to average members of the population, based on the cost of evacuation.	3	C.5.1.3
1	Dose above which abortion may be recommended.	1,2	C.2.1.4
0.5	Maximum acceptable dose to the general population from all sources from nonrecurring, non-accidental exposure.	2	C.4.4
0.5	Minimum dose justified to average members of the population, based on the cost of evacuation.	3	C.5.1.3
0.5	Maximum acceptable dose[b] to the fetus from occupational exposure of the mother.	2	C.4.4
0.1	Maximum acceptable dose to the general population from all sources from routine (chronic), nonaccidental exposure.	2	C.4.4
0.03	Dose that carries a risk assumed to be equal to or less than that from evacuation.	4	C.5.2

[a] These values are expressed in terms of avoided dose, whereas PAGs are expressed in terms of projected total dose. See Section C.6.1.

[b] This is also the dose to the 8- to 15-week-old fetus at which the risk of mental retardation is assumed to be equal to the risk of fatal cancer to adults from a dose of 5 rems.

These considerations apply to evacuation of typical members of the population and are based on effective dose equivalent. As discussed in previous sections, it may be appropriate to further limit dose to the thyroid and skin and to adjust the value for special groups of the population at unusually high risk from from evacuation. Different values may also apply for protective actions other than evacuation.

In the case of exposure of the thyroid to radioiodine, action based solely on effective dose would not occur until a thyroid dose about 33 times higher than the corresponding whole body dose. As noted in Section C.4.1.1, because the weighting factor for thyroid used to calculate effective dose does not reflect the high ratio of curable to fatal thyroid cancers, protective action to limit dose to the thyroid is recommended at a thyroid dose 5 times the numerical value of the PAG for effective dose.

Similarly, since effective dose does not include dose to the skin, and for other reasons discussed in Section C.4.1.1, protective action to limit dose to skin is recommended at a skin dose 50 times the numerical value of the PAG for effective dose. As in the case of the thyroid, this includes consideration of the risk of both curable and noncurable cancers.

Special risk groups include fetuses, and infirm persons. As noted in Sections C.3 and C.4.1.3, we assume that the risk of radiation-induced cancer is about 5 to 10 times higher for fetuses than for adults and that the risk of mental retardation in fetuses exposed during the 8th to 15th weeks of gestation is about 10 times higher than the risk of fatal cancer in equivalently exposed adults. However, due to the difficulty of rapidly evacuating only pregnant women in a population, and the assumed higher-than-average risk associated with their evacuation, it is not considered appropriate to establish separate PAGs for pregnant women. In part for this reason, the PAG is chosen sufficiently low to satisfy Federal guidance for limiting exposure of the fetus in pregnant workers.

Higher PAGs for situations involving higher risks from evacuation were discussed in section C.5.2. Under normal, low-risk, environmental conditions, PAGs for evacuation of groups who present higher than average

risks from evacuation (e.g., infirm persons) are recommended at projected doses up to 5 rems. Evacuation of the general population under high-risk environmental conditions is also recommended at projected doses up to 5 rems. If evacuation of high risk groups under hazardous environmental conditions is being considered, projected doses up to 10 rems may be justified.

Short-term sheltering is recognized as a low-cost, low-risk, protective action primarily suited for protection from exposure to an airborne plume. Sheltering is clearly justified to avoid any doses above 0.5 rems on the basis of avoidance of health risks alone. However, data are not available to establish the dose below 0.5 rems at which sheltering is no longer justified because of its cost or its risk from implementation. If such data were available, they would be likely to justify dose levels much lower than 0.5 rems. Because of this, and because sheltering has other benefits related to emergency communication with members of the public, no dose level is established below which sheltering is not recommended. It should always be carried out in situations where 0.5 rem or greater would be avoided, and sheltering will almost invariably still be appropriate if any appreciable dose is projected. However, for some specific situations (e.g. poor ventilation or high temperatures) when risks from sheltering can be identified, it may be appropriate to establish a dose value below which sheltering should not be implemented.

Bathing and changing of clothing are effective for reducing beta dose to the skin of persons exposed to an airborne plume of radioactive materials. Since these are also low-cost, low-risk actions, no PAG is recommended for initiating their implementation. It is expected that any persons sheltered in or evacuated from contaminated areas, or persons otherwise believed to have been exposed to an airborne plume, will be routinely advised by emergency response officials to take these actions within 12 hours after exposure.

The use of stable iodine to protect against uptake of inhaled radioiodine by the thyroid is recognized as an effective alternative to

evacuation for situations involving radioiodine releases where evacuation cannot be implemented. Use of stable iodine should be considered for any such situation in which evacuation or sheltering will not be effective in preventing thyroid doses of 25 rems.

C.7 Avoided Dose vs. Projected Dose

A further consideration in the selection of PAGs is whether to express them in terms of projected dose or avoided dose. The analysis for selecting the PAG for evacuation is carried out in terms of avoided dose. However, PAGs have commonly been expressed in terms of projected dose, which is more easily used during an emergency. Therefore, it is necessary to consider the relation between avoided and projected dose.

One factor that affects the dose avoided is whether evacuation can be completed before plume arrival. It is not possible to predict this. Emergency plans are, however, expected to include procedures for early notification and evacuation of populations in potentially high exposure areas. For these reasons, no difference in avoided and projected dose is assumed on the basis of delayed evacuation.

Another factor affecting the dose avoided by evacuation is the dose reduction by sheltering (where sheltering is assumed to mean staying inside a structure with doors and windows closed and exterior ventilation systems shut off). Since sheltering is a low-cost, low-impact protective action, it is assumed that sheltering will be implemented at any location where evacuation is considered. In this case, the dose avoidable by evacuation is the difference between the projected dose and the dose avoided by sheltering.

The effectiveness of sheltering as a protective action is discussed in Chapter 5, Section 5.5.2. Tables 5-6 and 5-7 summarize dose reduction factors as a function of type of structure, plume duration, and structure tightness. Dose reduction factors for gamma radiation range from 0.2 for large buildings to 0.9 for frame construction with no basement. For inhalation exposure in structures with no special measures except closing

doors and windows, the dose reduction factor is estimated as 0.6 or less for plume durations of up to 2 hours. For tight structures, the corresponding dose reduction factor is 0.3 or less.

Based on these data, dose reduction factors for sheltering are assumed to be about 0.5 for normal housing and about 0.25 for specially prepared or large structures with exterior ventilation ducts closed. Therefore the PAG for evacuating the general population is specified as 1 rem projected dose. For situations involving population groups at high risk from evacuation (for which the PAG is 5 rems) who are sheltered in specially prepared or large structures that would provide better than average radiation protection, the PAG is twice the projected dose for normal structures, or 10 rems. Other projected doses may be justified for shelters with confirmed dose reduction factors that are different from those assumed here.

C.8 Dose Limits for Emergency Workers

The dose limits for emergency workers are based on avoiding acute health effects and limiting the risk of delayed health effects in the context of the need to assure protection of the population and of valuable properties. It is assumed that most emergency workers are accustomed to accepting an element of risk as a condition of their employment. Examples of emergency worker occupations include law enforcement, firefighting, civil defense, traffic control, health services, environmental monitoring, animal care, and transportation services. Similarly, utility, industrial, and institutional facilities normally designate employees who are responsible for controlling releases and/or protecting property, as well as for protecting employees and others in the facility during an emergency. Persons involved in the emergency shutdown of facilities, including farms, may also be considered as emergency workers.

Radiation exposure of emergency workers should normally be governed by the Federal Radiation Protection Guidance for Occupational Exposure (EP-87). This guidance specifies an upper bound of five rems committed effective dose equivalent per year for most workers. (Pregnant women,

who, under this guidance should not normally engage in work situations that involve more than approximately 50 mrem/month, would normally be evacuated as part of the general population.) The guidance also specifies that doses should be maintained as low as reasonably achievable; that doses should be monitored; and that workers should be informed of the risks involved and of basic principles for radiation protection.

There are some emergency situations, however, for which higher doses may be justified. These include lifesaving operations and the protection of valuable property. International guidance (IC-77) recognizes two additional dose levels for workers under specially justified circumstances: two times the annual limit for any single event, and five times the annual limit in a lifetime. The dose limits recommended here adopt the former value (10 rems) for operations limited to the protection of property. The latter value (25 rems) may be permitted for situations involving lifesaving operations or activities that are essential to preventing substantial risks to populations. In this context "substantial risks" means collective doses that are significantly larger than those incurred through the protective activities engaged in by emergency workers. Emergency workers should not operate under dose limits higher than five rems unless the following conditions are satisfied:

1. Lower doses through the rotation of workers or other commonly-used dose reduction methods are not possible, and

2. Instrumentation is available to measure the dose.

Thyroid and skin doses to workers are normally limited to 50 rems. This level is sufficient to avoid acute effects, and it is expected that emergency plans will provide for special protection of emergency workers exposed to airborne radioiodine and beta radiation so that these limits for thyroid and skin can be satisfied.

Situations may occur in which a dose in excess of 25 rems would be required for lifesaving operations. It is not possible to prejudge the risk that one person should be allowed to take to save the life of

another. However, persons undertaking an emergency mission in which the dose would exceed 25 rems to the whole body should do so only on a voluntary basis and with full awareness of the risks involved, including the numerical levels of dose at which acute effects of radiation will be incurred and numerical estimates of the risk of delayed effects.

The risk of acute health effects is discussed in section C.2. Table C-11 presents estimated cancer mortality rates for a dose of 25 rems, as a function of age at the time of exposure. The risk of cancer from moderately higher doses will increase proportionately. These values were calculated using risk estimates from BEIR-3 (NA-80) as discussed in Section C.4.1, and life table analyses that assume the period of cancer risk lasts for the worker's lifetime (BU-81). The risk was calculated for the midpoint of each age range. Roughly equivalent risks of nonfatal cancers and serious genetic effects (if gonadal tissue is exposed) will also be incurred.

Table C-11 Cancer Risk to Emergency Workers Receiving 25 Rems Whole Body Dose

Age of the emergency worker at time of exposure (Years)	Approximate risk[a] of premature death (deaths per 1,000 persons exposed)	Average years of life lost if premature death occurs (Years)
20 to 30	9.1	24
30 to 40	7.2	19
40 to 50	5.3	15
50 to 60	3.5	11

[a]Life Plateau: Period following the latent cancer period and extending to death.

The dose limits of 75 rems previously recommended by EPA and 100 rems that has been recommended by NCRP (GL-57) for lifesaving action represents a very high level of risk of acute and delayed health effects. A dose of 100 rems is expected to result in an approximately 15 percent risk of temporary incapacity from nonlethal acute effects and an indeterminate, but less than 5 percent, chance of death within 60 days. This is in addition to a risk of about 1 in 30 of incurring fatal cancer. Such high risk levels can only be accepted by a recipient who has been made aware of the risks involved; therefore, no absolute dose limit for lifesaving activities is offered.

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APPENDIX D

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APPENDIX E

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APPENDIX F

Protective Action Guides for the Intermediate Phase (Deposited Radioactive Materials): Supporting Information

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Protective Action Guides for the Intermediate Phase (Deposited Radioactive Materials): Supporting Information

F.1 Introduction

The purpose of this Appendix is to provide background information and a rationale for the choice of Protective Action Guides (PAGs) for relocation and other protective actions during the intermediate phase of the response to a nuclear accident. The resulting PAGs and associated implementing guidance are provided in Chapters 4 and 7, respectively.

This rationale is based on the assumption that an airborne plume of radioactive material has already passed over an area and left a deposit of radioactive material behind, and that the public has been either sheltered or evacuated, as necessary, on the basis of PAGs for the early phase of a nuclear accident, as discussed in Chapters 2 and 5. PAGs for subsequent relocation of the public and other protective actions, as well as dose limits for persons reentering the area from which the public is relocated, are addressed in this Appendix.

We first set forth the assumptions used to derive information pertinent to choosing the dose level at which relocation of the public is appropriate. This is followed by an examination of information relevant to this decision, and selection of the PAG for relocation. The Appendix concludes with a brief discussion of the basis for dose limits for persons temporarily re-entering areas from which the public has been relocated.

F.1.1 Response Duration

In order to decide whether to initiate relocation of the public from specific areas it is necessary to predict the dose that would be avoided. One factor in this prediction is the duration of the exposure to be avoided. Relocation can begin as soon as patterns of exposure from deposited radioactivity permit restricted areas to be identified. For the purpose of this analysis, relocation of persons who have not already

been evacuated from the restricted zone is assumed to take place on the fourth day after the accident. Return of evacuated persons to their residences outside the restricted zone and transition to relocation status of persons already evacuated is assumed to occur over a period of a week or more.

The period of exposure avoided by relocation ends when the relocated person either returns to his property or is permanently resettled in a new location. At the time of relocation decisions, it will usually not be possible to predict when either of these actions will occur. Therefore, for convenience of dose projection, it is assumed that the period of exposure avoided is one year and that any extension beyond this period will be determined on the basis of recovery criteria. This assumption corresponds to emergency response planning guidance by ICRP (IC-84) and IAEA (IA-85).

F.1.2 Source Term

The "source term" for this analysis is comprised of the quantities and types of particulate radioactive material found in the environment following an accidental release. Nuclear accidents can be postulated with a wide range of release characteristics. The characteristics of the source terms assumed for the development of these PAGs are those postulated for releases from various types of fuel-melt accidents at nuclear power plants (SN-82). Table F-1 provides brief descriptions of these accident types. Radionuclide releases have been estimated for the three most severe accident types (SST-1, SST-2, SST-3) based on postulated core inventories and release fractions (Table F-2). The other types (SST-4 and SST-5) would generally not produce offsite doses from exposure to deposited material sufficient to warrant consideration of relocation.

If the release from an accident includes a large proportion of long-lived radionuclides, doses will continue to be delivered over a long period of time and, if no remedial actions are taken, the dose delivered in the first year may represent only a small portion of the total dose

Table F-1 Brief Descriptions Characterizing Various Nuclear Power Plant Accident Types (SN-82)

Type	Description
SST-1	Severe core damage. Essentially involves loss of all installed safety features. Severe direct breach of containment.
SST-2	Severe core damage. Containment fails to isolate. Fission product release mitigating systems (e.g., sprays, suppression pool, fan coolers) operate to reduce release.
SST-3	Severe core damage. Containment fails by base-mat melt-through. All other release mitigation systems function as designed.
SST-4	Modest core damage. Containment systems operate in a degraded mode.
SST-5	Limited core damage. No failures of engineered safety features beyond those postulated by the various design basis accidents. The most severe accident in this group assumes that the containment functions as designed following a substantial core melt.

Table F-2 Release Quantities for Postulated Nuclear Reactor Accidents

Principal radionuclides contributing to dose from deposited materials	Half-life (days)	Estimated quantity released[a] (Curies)		
		SST-1	SST-2	SST-3
Zr-95	6.52E+1	1.4E+6	4.5E+4	1.5E+2
Nb-95	3.50E+1	1.3E+6	4.2E+4	1.4E+2
Ru-103	3.95E+1	6.0E+6	2.4E+5	2.4E+2
Ru-106	3.66E+2	1.5E+6	5.8E+4	5.8E+1
Te-132	3.25	8.3E+7	3.9E+6	2.6E+3
I-131	8.05	3.9E+7	2.6E+5	1.7E+4
CS-134	7.50E+2	8.7E+6	1.2E+5	1.3E+2
CS-137	1.10E+4	4.4E+6	5.9E+4	6.5E+1
Ba-140	1.28E+1	1.2E+7	1.7E+5	1.7E+2
La-140	1.67	1.5E+6	5.1E+4	1.7E+2

[a] Based on the product of reactor inventories of radionuclides and estimated fractions released for three accident categories (SN-82).

delivered over a lifetime. On the other hand, if the release consists primarily of short-lived radionuclides, almost the entire dose may be delivered within the first year.

From the data in Table F-2, it is apparent that, for the groups of accidents listed, both long and short lived radionuclides would be released. Consequently, doses due to deposited materials from such accidents would be relatively high during the first year followed by long term exposures at lower rates.

F.1.3 Exposure Pathways

The principal exposure pathway to members of the public occupying land contaminated by deposits of radioactive materials from reactor accidents is expected to be exposure of the whole body to external gamma radiation. Although it is normally expected to be of only minor importance, the inhalation pathway would contribute additional doses to internal organs. The health risks from other pathways, such as beta dose to the skin and direct ingestion of dirt, are also expected to be minor in comparison to the risks due to external gamma radiation (EP-88). Skin and inhalation dose would, however, be important exposure pathways for source terms with significant fractions of pure beta emitters, and inhalation dose would be important for source terms with significant fractions of alpha emitters.

Since relocation, in most cases, would not be an appropriate action to prevent radiation exposure from ingestion of food and water, these exposure pathways have not been included in this analysis. They are addressed in Chapters 3 and 6. In some instances, however, where withdrawal of food and/or water from use would, in itself, create a health risk, relocation may be an appropriate alternative protective action. In this case, the committed effective dose equivalent from ingestion should be added to the projected dose from deposited radionuclides via other pathways, for decisions on relocation.

F.1.4 Response Scenario

This section defines the response zones, population groups, and the activities assumed for implementation of protective actions during the intermediate phase.

After passage of the radioactive plume, the results of environmental monitoring will become available for use in making decisions to protect the public. Sheltering, evacuation, and other actions taken to protect the public from the plume will have already been implemented. The tasks immediately ahead will be to (1) define the extent and characteristics of deposited radioactive material and identify a restricted zone in accordance with the PAG for relocation, (2) relocate persons from and control access to the restricted zone, (3) allow persons to return to areas outside the restricted zone, (4) control the spread of and exposure to surface contamination, and (5) apply simple decontamination and other low-cost, low-risk techniques to reduce the dose to persons who are not relocated.

Because of the various source term characteristics and the different protective actions involved (evacuation, sheltering, relocation, decontamination, and other actions to reduce doses to "as low as reasonably achievable" levels), the response areas for different protective actions may be complex and may vary in size with respect to each other. Figure F-1 shows a generic example of some of the principle areas involved. The area covered by the plume is assumed to be represented by area 1. In reality, variations in meteorological conditions would almost certainly produce a more complicated shape.

Based on plant conditions and other considerations prior to or after the release, members of the public are assumed to have already been evacuated from area 2 and sheltered in area 3. Persons who were evacuated or sheltered as a precautionary action for protection from the plume but whose homes are outside the plume deposition area (area 1) are

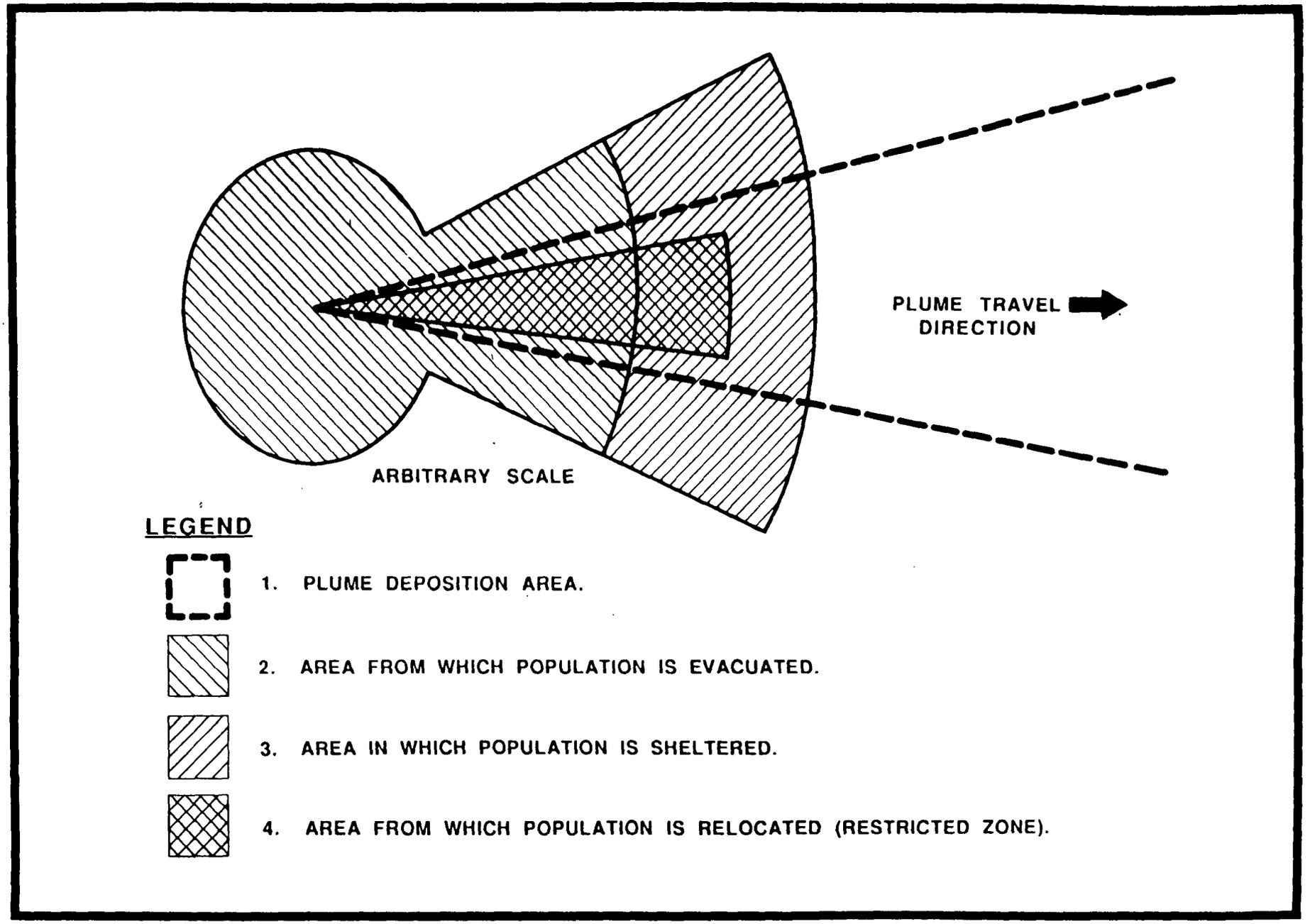

FIGURE F-1. RESPONSE AREAS.

assumed to return to their homes or discontinue sheltering when environmental monitoring verifies the outer boundary of area 1.

Area 4 is the restricted zone and is defined as the area where projected doses are equal to or greater than the relocation PAG. The portion of area 1 outside of area 4 is designated as a study zone and is assumed to be occupied by the public. However, contamination levels may exist here that would be of concern for continued monitoring and decontamination to maintain radiation doses "as low as reasonably achievable" (ALARA).

The relative positions of the boundaries shown in Figure F-1 are dependent on areas evacuated and sheltered. For example, area 4 could fall entirely inside area 2 (the area evacuated) so that relocation of persons from additional areas would not be required. In this case relocation PAG would be used only to determine areas to which evacuees could return.

Figure F-2 provides, for perspective, a schematic representation of the response activities expected to be in progress in association with implementation of the PAGs during the intermediate phase of the response to a nuclear accident.

F.2 Considerations for Establishing PAGs for the Intermediate Phase

The major considerations in selecting values for these PAGs for relocation and other actions during the intermediate phase are the four principles that form the basis for selecting all PAGs. Those are discussed in Section F.2.1. Other considerations (Federal radiation protection guidance and risks commonly confronting the public) are discussed in Sections F.2.2 and F.4.

In addition, a planning group consisting of State, Federal, and industry officials provided recommendations in 1982 which EPA considered in the development of the format, nature, and applicability of PAGs for relocation. Abbreviated versions of these recommendations are as follows:

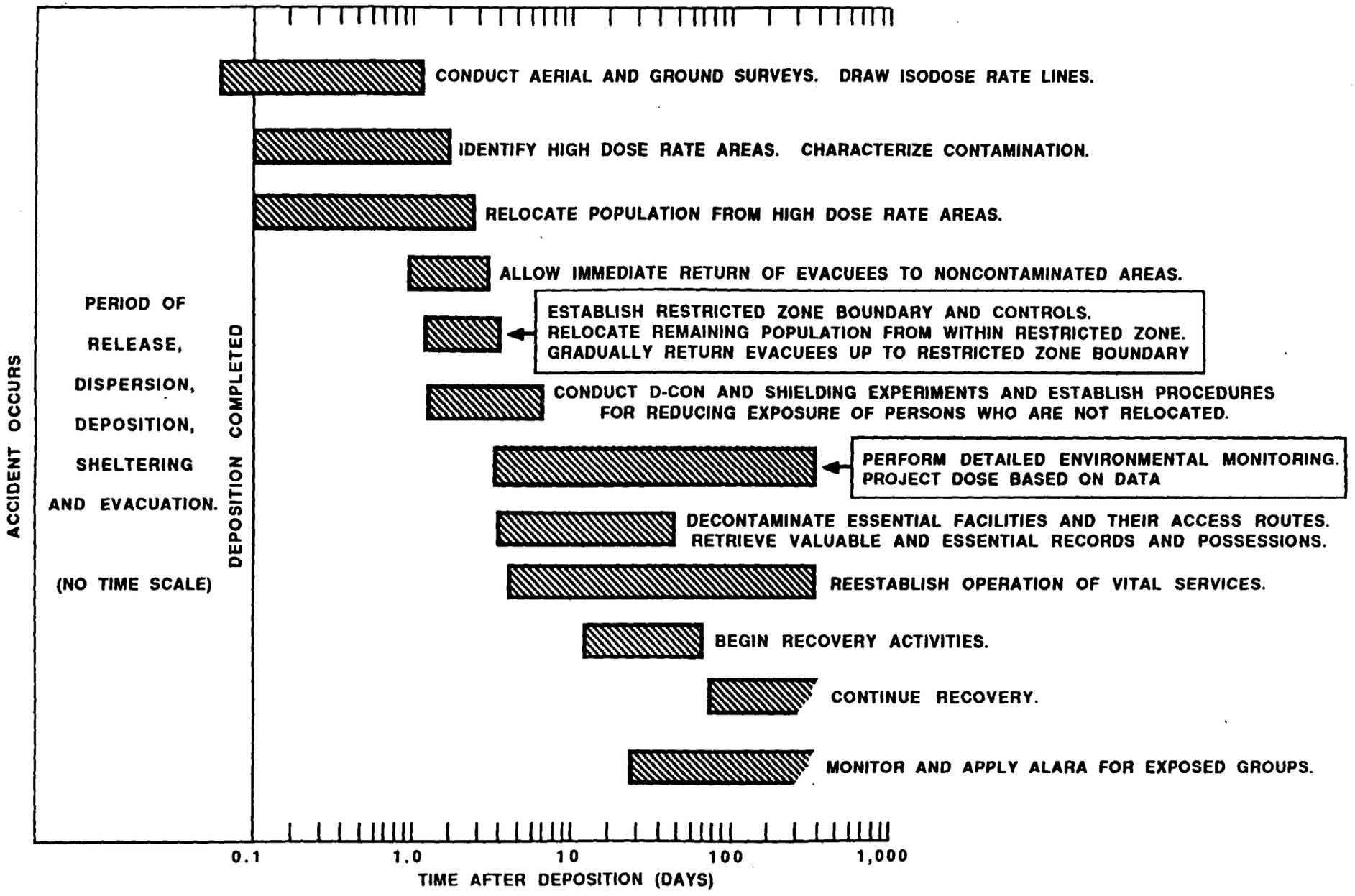

FIGURE F-2. TIME FRAME OF RESPONSE TO A MAJOR NUCLEAR REACTOR ACCIDENT (ASSUME

a. The PAGs should apply to commercial, light-water power reactors.

b. The PAGs should be based primarily on health effects.

c. Consideration should be given to establishing a range of PAG values.

d. The PAGs should be established as high as justifiable because at the time of the response, it would be possible to lower them, if justified, but it probably would not be possible to increase them.

e. Only two zones (restricted and unrestricted) should be established to simplify implementation of the PAGs.

f. The PAGs should not include past exposures.

g. Separate PAGs should be used for ingestion pathways.

h. PAGs should apply only to exposure during the first year after an accident.

Although these PAGS may be applied to any nuclear accident, they were derived primarily for the case of commercial U.S. reactors. In general, we have found it possible to accommodate most of the above recommendations.

F.2.1 Principles

In selecting values for these PAGs, EPA has been guided by the same principles that were applied in the selection of PAGs for the early phase of a nuclear accident (Appendix C). They are repeated here for convenience:

1. Acute effects on health (those that would be observable within a short period of time and which have a dose threshold below which they are not likely to occur) should be avoided.

2. The risk of delayed effects on health (primarily cancer and genetic effects, for which linear nonthreshold relationships to dose are assumed) should not exceed upper bounds that are judged to be adequately protective of public health, under emergency conditions, and are reasonably achievable.

3. PAGs should not be higher than justified on the basis of optimization of cost and the collective risk of effects on health. That is, any reduction of risk to public health avoidable at acceptable cost should be carried out.

4. Regardless of the above principles, the risk to health from a protective action should not itself exceed the risk to health from the dose that would be avoided.

These four principles were discussed in detail in Appendix C as they relate to the PAGs derived there. The portions of Appendix C that analyzed the risks of health effects as a function of dose (Principles 1 and 2) also apply to doses associated with these PAGs. Considerations for selection of PAGs for the intermediate phase of a nuclear accident differ from those for selection of PAGs for the early phase primarily with regard to implementation factors (i.e., Principles 3 and 4). Specifically, they differ with regard to cost of avoiding dose, the practicability of leaving infirm persons and prisoners in the restricted zone, and avoiding dose to fetuses. Although sheltering is not generally a suitable alternative to relocation, other alternatives (e.g., decontamination and shielding) are suitable. These considerations are reviewed in the sections that follow.

F.2.1.1 Cost/Risk Considerations

The Environmental Protection Agency has issued guidelines for internal use in for performing regulatory impact analyses (EP-83). These include consideration of the appropriate range of costs for avoiding a statistical death. The values are inferred from the additional compensation associated with employment carrying a higher than normal

risk of mortality, and is expressed as a range of $0.4 to $7 million per statistical death avoided. The following discussion compares these values to the cost of avoiding radiation-induced fatal cancers through relocation.

A report by Bunger (BU-88) is used as a basis for estimating the costs for relocation. The estimated incremental costs per day per person relocated are shown below to be approximately $27.00. Moving and loss of inventory costs are averaged over one year.

Moving	$1.60
Loss of use of residence	2.80
Maintain and secure vacated property	0.90
Extra living costs	1.20
Lost business and inventories	14.00
Extra travel costs	4.10
Idle government facilities	2.30
Total	$26.90

The quantity of interest is the dose at which the value of the risk avoided is equal to the cost of relocation. Since the above costs are expressed in dollars/person-day, it is convenient to calculate the dose that must be avoided per-person day. The equation for this is:

$$D = \frac{C}{VR}$$

where:

D = dose (rem/day)

C = cost of relocation (dollars/day).

V = value of avoiding a statistical death (dollars/death)

R = statistical risk of death from radiation dose (deaths/rem)

Using the values cited above, and a value for R of 3×10^{-4} deaths/rem (See Appendix C), one obtains a range of doses of about 0.01 to 0.2 rems/day. Thus, over a period of one year the total dose that should be avoided to justify the cost of relocation would be about 4 to 70 rems.

These doses are based on exposure accumulated over a period of one year. However, exposure rates decrease with time due to radioactive decay and weathering. Thus, for any given cumulative dose in the first year, the daily exposure rate continually decreases, so that a relocated person will avoid dose more rapidly in the first part of the year than later. Figure F-3 shows the effect of changing exposure rate on the relationship between the cost of avoiding a statistical death and the time after an SST-2 accident (See Table F-1) for several assumed cumulative annual doses. The points on the curves represent the cost per day divided by the dose avoided per day, at time t, for the annual dose under consideration, where t is the number of days after the accident. The right ordinate shows the gamma exposure rate (mR/h) as a function of time for the postulated radionuclide mix at one meter height.

The convex downward curvature results from the rapid decay of short-lived radionuclides during the first few weeks following the accident. Since the cost per day for relocation is assumed to be constant and the dose avoided per day decreases, the cost effectiveness of relocation decreases with time. For this reason it is cost effective to quickly recover areas where the population has been relocated at projected doses only marginally greater than the PAG.

Only trends and general relationships can be inferred from Figure F-3 because it applies to a specific mix of radionuclides. However, for this radionuclide mix, cost analysis supports relocation at doses as low as one rem for the first week and two rems for up to 25 days after an accident.

F.2.1.2 Protection of Special Groups

Contrary to the situation for evacuation during the early phase of an accident, it is generally not practical to leave a few persons behind when most members of the general population have been relocated from a specified area for extended periods of time. Further, no data are available on differing risks of relocation for different population groups. In the absence of such data, we have assumed that these risks will be similar to those from evacuation. Those risks were taken as equivalent to the health

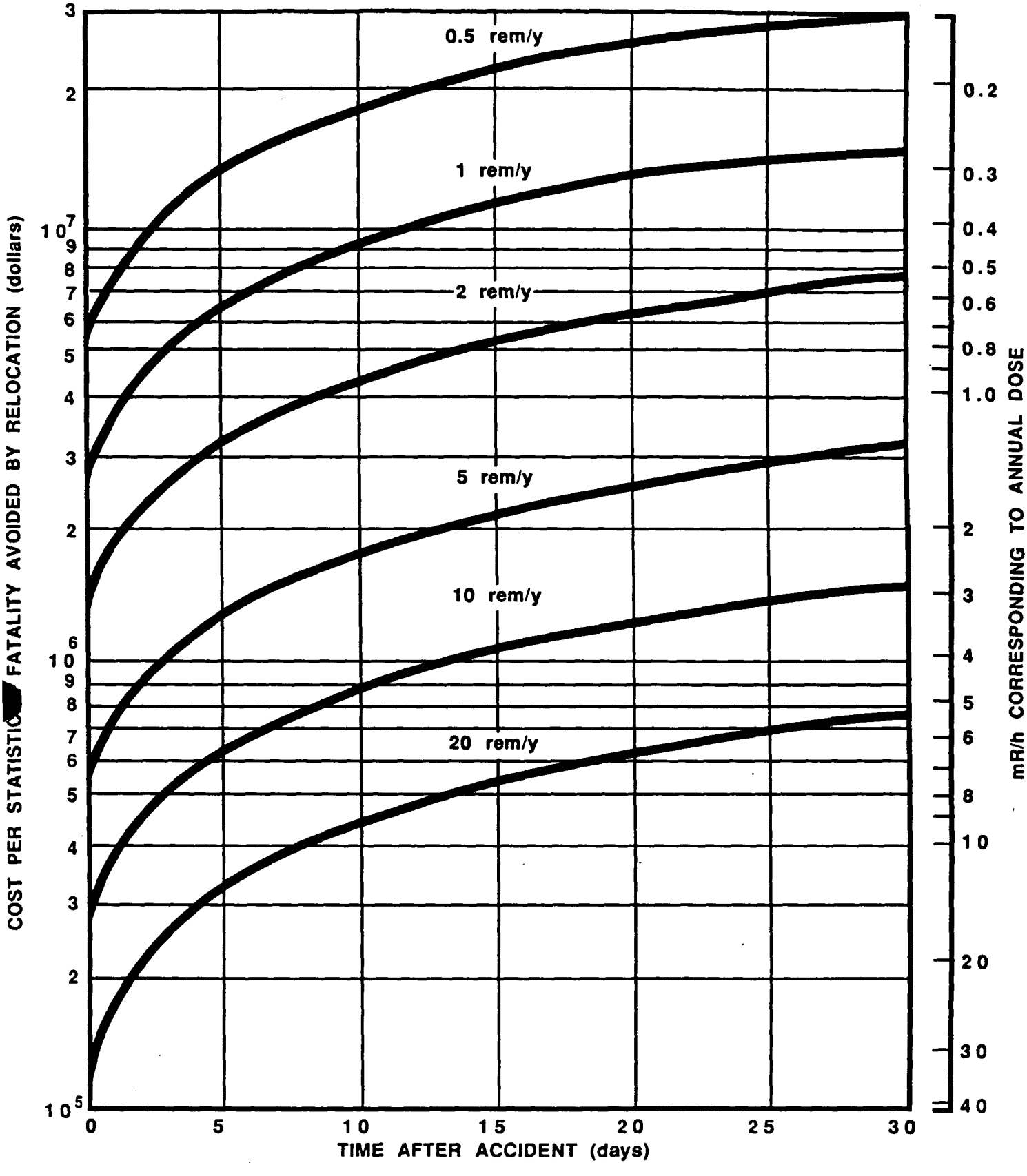

FIGURE F-3. COST OF AVOIDING STATISTICAL FATALITIES AND EXPOSURE RATES CORRESPONDING TO VARIOUS TOTAL FIRST YEAR DOSES (ASSUMES AN SST-2 ACCIDENT AND A $27 PER PERSON-DAY COST OF RELOCATION).

risk from doses of 30 mrems for members of the general population and of 150 mrems for persons at high risk from evacuation (see Appendix C). Therefore, to satisfy Principle 4 for population groups at high risk, the PAG for relocation should not be lower than 150 millirems. Given the arbitrary nature of this derivation, it is fortunate that this value is much lower than the PAG selected, and is therefore not an important factor in its choice.

Fetuses are a special group at greater risk of health effects from radiation dose than is the general population, but not at significantly greater risk from relocation itself. The risk of mental retardation from fetal exposure (see Appendix C) is significant. It is affected by the stage of pregnancy relative to the assumed one-year exposure, because the 8 - week critical period during which the risk is greatest, must be considered in relation to the rapidly changing dose rate. Taking these factors into account, it can be postulated that the risk of mental retardation due to exposure of the fetus during the intermediate phase will range from one to five times the cancer risk of an average member of the public, depending upon when conception occurs relative to the time of the accident. The elevated risk of radiation-induced cancer from exposure of fetuses is less significant, as discussed in Appendix C.

It will usually be practicable to reduce these risks by establishing a high priority for efforts other than relocation to reduce the dose in cases where they reside near the boundary of the restricted zone. However, women who are less than seven months pregnant should relocate for the balance of their pregnancy if the projected dose during pregnancy cannot be reduced below 0.5 rem.

F.2.2 Federal Radiation Protection Guides

The choice of a PAG at which relocation should be implemented does not mean that persons outside the boundary of the restricted zone should not be the subject of other protective actions to reduce dose. Such actions are justified on the basis of existing Federal radiation protection guidance (FR-65) for protecting the public, including implementation of the principle of maintaining doses "as low as reasonably achievable" (ALARA).

The intended actions to protect the public from radiation doses on the basis of RPGs are those related to source control. Although it is reasonable for members of the public to receive higher exposure rates prior to the accident source term being brought under control, the establishment of acceptable values for relocation PAGs must include consideration of the total dose over the average remaining lifetime of exposed individuals (usually taken as 50 years).

The nationally and internationally recommended upper bound for dose in a single year from man-made sources excluding medical radiation, is 500 mrem per year to the whole body of individuals in the general population (IC-77, FR-65). These recommendations were not developed for accidents. They are also not appropriate for chronic exposure. The ICRP recommends an upper bound of 100 mrem per year, from all sources combined, for chronic exposure (IC-77). The corresponding 50-year dose at 100 mrem/yr is 5 rems. We have chosen to limit the projected first year dose to individuals from an accident to the Relocation PAG, the projected second year dose to 500 mrem, and the dose projected over a fifty year period to 5 rems. Due to the extended duration of exposures and the short halflife of important radioiodines, no special limits for thyroid dose are needed.

F.3. Dose from Reactor Accidents

Doses from an environmental source will be reduced through the natural processes of weathering and radioactive decay, and from the shielding associated with part time occupancy in homes and other structures. Results of dose calculations based on the radiological characteristics of releases from three categories of postulated, fuel-melt, reactor accidents (SST-1, SST-2, and SST-3) (SN-82) and a weathering model from WASH-1400 (NR-75) are shown in Table F-3. This table shows the relationship between annual doses for the case where the sum, over fifty years, of the effective dose equivalent from gamma radiation and the committed effective dose equivalent from inhalation of resuspended materials, is 5 rems. Radioactive decay and weathering reduces the second year dose from reactor accidents to 20 to 40 percent of the first year dose, depending on the radionuclide mix in the release.

Table F-3 Annual Doses Corresponding to 5 Rems in 50 Years[a]

Year[c]	Dose According to Accident Category[b]		
	SST-1(rem)	SST-2(rem)	SST-3(rem)
1	1.25	1.60	1.91
2	0.52	0.44	0.38
3	0.33	0.28	0.24
4	0.24	0.20	0.17
5	0.18	0.16	0.13
6	0.14	0.12	0.11
7	0.12	0.11	0.090
8	0.10	0.085	0.070
9	0.085	0.075	0.065
10	0.080	0.070	0.060
11	0.070	0.060	0.050
12	0.060	0.055	0.050
13	0.060	0.055	0.045
14	0.055	0.050	0.040
15	0.055	0.045	0.040
16	0.050	0.045	0.040

[a]Whole body dose equivalent from gamma radiation plus committed effective dose equivalent from inhalation assuming a resuspension factor of 10^{-6} m^{-1}. Weathering according to the WASH-1400 model (NR-75) and radioactive decay are assumed.

[b]Radionuclide abundance ratios are based on reactor inventories from WASH-1400 (NR-75) and release fractions for accident categories SST-1, SST-2 and SST-3 are as described in reference SN-82. Initial concentrations are assumed to have decayed for 4 days after reactor shutdown.

[c]Annual doses after 16 years would be less than 0.05 rems.

Based on studies reported in WASH-1400 (NR-75), the most conservative dose reduction factor for structures (frame structures) is about 0.4 (dose inside divided by dose outside) and the average fraction of time spent in a home is about 0.7. Combining these factors yields a net dose reduction factor of about 0.6. In most cases, therefore, structural shielding would be expected to reduce the dose to persons who are not relocated to 60 percent (or less) of the values shown in Table F-3 before the application of decontamination.

F.4 Alternatives to Relocation

Persons who are not relocated, in addition to dose reduction provided by partial occupancy in homes and other structures, can reduce their dose by the application of various techniques. Dose reduction efforts can range from the simple processes of scrubbing and/or flushing surfaces, soaking or plowing of soil, removal and disposal of small spots of soil found to be highly contaminated (e.g., from settlement of water), and spending more time than usual in lower exposure rate areas (e.g., indoors), to the difficult and time consuming processes of removal, disposal, and replacement of contaminated surfaces. It is anticipated that simple processes would be most appropriate to reduce exposure rates for persons living in contaminated areas outside the restricted zone. Many of these can be carried out by the residents with support from officials for monitoring, guidance on appropriate actions, and disposal. The more difficult processes will usually be appropriate for recovery of areas from which the population is relocated.

Decontamination experiments involving radioactive fallout from nuclear weapons tests have shown reduction factors for simple decontamination methods in the vicinity of 0.1 (i.e., exposure rate reduced to 10 percent of original values). However, recent experiments at the Riso National Laboratory in Denmark (WA-82, WA-84), using firehoses to flush asphalt and concrete surfaces contaminated with radioactive material of the type that might be deposited from reactor accidents, show decontamination factors for radionuclides chemically similar to cesium that are in the range of 0.5 to 0.95, depending on the delay time after deposition before flushing is applied. The factor for ruthenium on asphalt was about 0.7 and was independent of the delay of flushing. The results of these experiments indicate that decontamination of the important reactor fission products from asphalt or concrete surfaces may be much more difficult than decontamination of nuclear weapons fallout. Other simple dose reduction methods listed above would be effective to varying degrees. The average dose reduction factor for gamma radiation from combinations of simple decontamination methods is estimated to be at least 0.7. Combining this with the 40 percent reduction estimated above for structural shielding indicates that the doses listed in Table F-3 may be more than twice as high as those which would actually be received by persons who are not relocated.

F.5 Risk Comparisons

Many hazardous conditions and their associated risks are routinely faced by the public. A lingering radiation dose will add to those risks, as opposed to substituting one risk for another, and, therefore, radiation protection criteria cannot be justified on the basis of the existence of other risks. It is, however, useful to review those risks to provide perspective. This section compares the risks associated with radiation doses to those associated with several other risks to which the public is commonly exposed.

Figure F-4 compares recent statistics for the average lifetime risk of accidental death in various occupations to the estimated lifetime risk of fatal cancer for members of the general population exposed to radiation doses ranging up to 25 rems. Non-radiation risk values are derived from information in reference (EP-81) and radiation risk values are from Appendix C. These comparisons show, for example, that the lifetime cancer risk associated with a dose of 5 rems is comparable to the lifetime risk of accidental death in some of the safest occupations, and is well below the average lifetime risk of accidental death for all industry.

Risks of health effects associated with radiation dose can also be compared to other risks facing individuals in the general population. The risks listed in Table F-4 are expressed as the number of premature deaths and the average reduction of life-span due to these deaths within a group of 100,000 persons. For purposes of comparison, a dose of 5 rems to each member of a population group of 100,000 persons representative of the average U.S. population carries an estimated lifetime risk of about 150 fatal cancers (see Appendix C). The number of deaths resulting from the various causes listed in Table F-4 is based on data from mortality records.

In Summary, the risk of premature death normally confronting the public from specific types of accidents ranges from about 2 to 1000 per 100,000 population. The estimated radiation doses required to produce a similar risk of death from radiation-induced cancer range from about 0.07 to 33 rems.

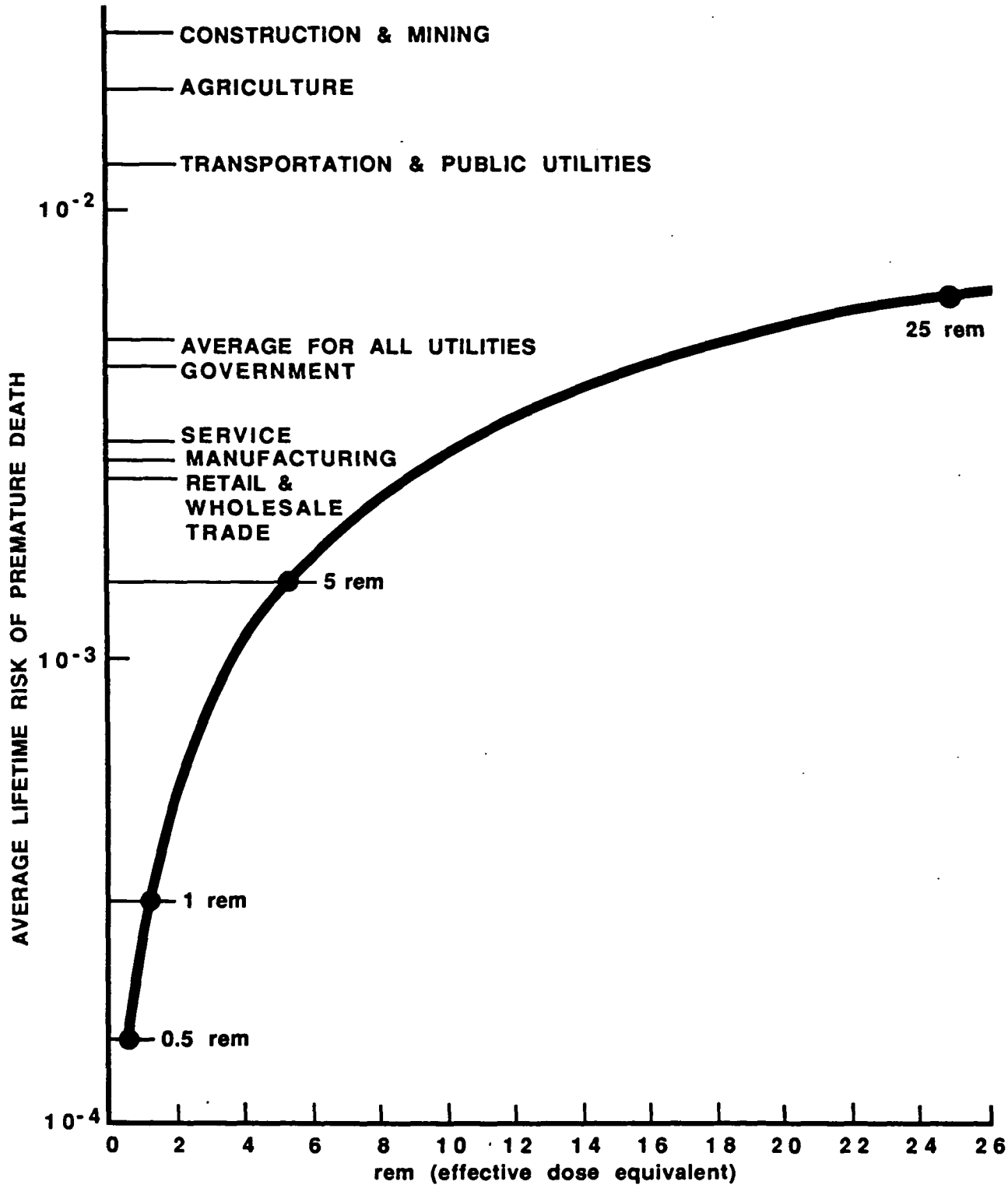

FIGURE F-4. AVERAGE LIFETIME RISK OF DEATH FROM WHOLE BODY RADIATION DOSE COMPARED TO THE AVERAGE RISK OF ACCIDENTAL DEATH FROM LIFETIME (47 YEARS) OCCUPATION IN VARIOUS INDUSTRIES.

Table F-4 Measure of Lifetime Risk of Mortality from a Variety of Causes[a] (Cohort Size = 100,000)

Nature of accident	Premature deaths	Aggregate years of life lost to cohort	Reduction of life expectancy at birth (years)	Average years of life lost to premature deaths
Falls	1,000	12,000	0.12	11
Fires	300	7,600	0.076	25
Drowning	190	8,700	0.087	45
Poisoning by drugs and medicaments	69	2,500	0.025	37
Cataclysm[b]	17	490	0.005	30
Bites and stings[c]	8	220	0.002	27
Electric current in homes[d]	8	290	0.003	37

[a]All mortality effects shown are calculated as changes from the U.S. Life Tables for 1970 to life tables with the cause of death under investigation removed. These effects also can be interpreted as changes in the opposite direction, from life tables with the cause of death removed to the 1970 Life Table. Therefore, the premature deaths and years of life lost are those that would be experienced in changing from an environment where the indicated cause of death is not present to one where it is present. All values are rounded to no more than two significant figures.

[b]Cataclysm is defined to include cloudburst, cyclone, earthquake, flood, hurricane, tidal waves, tornado, torrential rain, and volcanic eruption.

[c]Accidents by bite and sting of venomous animals and insects include bites by centipedes, venomous sea animals, snakes, and spiders; stings of bees, insects, scorpions, and wasps; and other venomous bites and stings. Other accidents caused by animals include bites by any animal and nonvenomous insect; fallen on by horse or other animal; gored; kicked or stepped on by animal; ant bites; and run over by horse or other animal. It excludes transport accidents involving ridden animals; and tripping, falling over an animal. Rabies is also excluded.

[d]Accidents caused by electric current from home wiring and appliances include burn by electric current, electric shock or electrocution from exposed wires, faulty appliances, high voltage cable, live rail, and open socket. It excludes burn by heat from electrical appliances and lighting.

F.6 Relocation PAG Recommendations

Previous sections have reviewed data, standards, and other information relevant to establishing PAGs for relocation. The results are summarized in Table F-5, in relation to the principles set forth in Section F.2.1.

Based on the avoidance of acute effects alone (Principle 1) 50 rems and 10 rems are upper bounds on the dose at which relocation of the general population and fetuses, respectively, is justified. However, on the basis of control of chronic risks (Principle 2) a lower upper bound is appropriate. Five rems is taken as an upper bound on acceptable risk for controllable lifetime exposure to radiation, including avoidable exposure to accidentally deposited radioactive materials. This corresponds to an average of 100 mrem per year for fifty years, a value commonly accepted as an upper bound for chronic annual exposure of members of the public from all sources of exposure combined, other than natural background and medical radiation (IC-77). In the case of projected doses from nuclear reactor accidents, a five rem lifetime dose corresponds to about 1.25 to 2 rems from exposure during the first year and 0.4 to 0.5 rems from exposure during the second year.

Analyses based on Principle 3 (cost/risk) indicate that considering cost alone would not drive the PAG to values less than 5 rems. Analyses in support of Principle 4 (risk of the protective action itself) provide a lower bound for relocation PAGs of 0.15 rems.

Based on the above, 2 rems projected committed effective dose equivalent from exposure in the first year is selected as the PAG for relocation. Implementation of relocation at this value will provide reasonable assurance that, for a reactor accident, a person relocated from the outer margin of the relocation zone will, by such action, avoid an exposure rate which, if continued over a period of one year, would result in a dose of about 1.2 rems. This assumes that 0.8 rems would be avoided without relocation through normal partial occupancy of homes and other structures. This PAG will provide reasonable assurance that persons outside the relocation zone, following a reactor accident, will not exceed 1.2 rems in the first year, 0.5 rems in the second year, and 5 rems in 50 years. The implementation of simple dose

Table F.5 Summary of Considerations for Selecting PAGs for Relocation

Dose (rem)	Consideration	Principle
50	Assumed threshold for acute health effects in adults.	1
10	Assumed threshold for acute health effects in the fetus.	1
6	Maximum projected dose in first year to meet 0.5 rems in the second year[a].	2
5	Maximum acceptable annual dose for normal occupational exposure of adults.	2
5	Minimum dose that must be avoided by one year relocation based on cost.	3
3	Minimum projected first-year dose corresponding to 5 rems in 50 years[a].	2
3	Minimum projected first-year dose corresponding to 0.5 rems in the second year[a].	2
2	Maximum dose in first year corresponding to 5 rems in 50 years from a reactor accident, based on radioactive decay and weathering only.	2
1.25	Minimum dose in first year corresponding to 5 rems in 50 years from a reactor accident based on radioactive decay and weathering only.	2
0.5	Maximum acceptable single-year dose to the general population from all sources from non-recurring, non-accident exposure.	2
0.5	Maximum acceptable dose to the fetus from occupational exposure of the mother.	2
0.1	Maximum acceptable annual dose to the general population from all sources due to routine (chronic), non-accident, exposure.	2
0.03	Dose that carries a risk assumed to be equal to or less than that from relocation.	4

[a]Assumes the source term is from a reactor accident and that simple dose reduction methods are applied during the first month after the accident to reduce the dose to persons not relocated from contaminated areas.

reduction techniques, as discussed in section F-4, will further reduce dose to persons who are not relocated from contaminated areas. Table F-6 summarizes the estimated maximum dose that would be received by these persons for various reactor accident categories with and without the application of simple dose reduction techniques.

Since effective dose does not include dose to the skin (and for other reasons discussed in Appendix C) protective action to limit dose to skin is recommended at a skin dose 50 times the numerical value of the PAG for effective dose. This includes consideration of the risk of both curable and fatal cancers.

Table F-6 Estimated Maximum Doses to Nonrelocated Persons[a]

	Dose (rem)					
Accident	No additional dose reduction			Early simple dose reduction[b]		
Category	Year 1	Year 2	50 years	Year 1	Year 2	50 years
SST-1	1.2	0.5	5.0	0.9	0.35	3.5
SST-2	1.2	0.34	3.9	0.9	0.24	2.7
SST-3	1.2	0.20	3.3	0.9	0.14	2.3

[a]Based on relocation at a projected dose of 2 rems in the first year and 40 percent dose reduction from normal, partial occupancy in structures. No dose reduction from applied decontamination, shielding, or time controls are assumed.

[b]The projected dose is assumed to be reduced 30 percent by the application of simple dose reduction techniques during the first month.

F.7 Criteria for Reentry into the Restricted Zone

Persons may need to reenter the restricted zone for a variety of reasons, including radiation monitoring, recovery work, animal care, property maintenance, and factory or utility operation. Some persons outside the restricted zone, by nature of their employment or habits, may also receive higher than average radiation doses. Tasks that could cause such exposures include, 1) changing of filters on air handling equipment (including vehicles), 2) handling and disposal of contaminated vegetation (e.g., grass and leaves) and, 3) operation of control points for the restricted zone.

Individuals who reenter the restricted zone or who perform tasks involving exposure rates that would cause their radiation dose to exceed that permitted by the PAGs should do so in accordance with existing Federal radiation protection guidance for occupationally exposed workers (EP-87). The basis for that guidance has been provided elsewhere (EP-87)

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