

EPA-520/1-75-001

AD A119287

Manual
of
Protective Action Guides
and
Protective Actions
for
Nuclear Incidents

September 1975
(Revised June 1980)

Environmental Protection Agency
Office of Radiation Programs
Environmental Analysis Division
Washington, D.C. 20460

DTIC
ELECTE
SEP 15 1982
S D E

This document has been approved
for public release and sale; its
distribution is unlimited.

82 08 16 271

DTIC FILE COPY

Contents

	<u>Page</u>
Chapter 1 - Perspectives for Protective Action	1.1
1.0 Introduction	1.1
1.1 The Need for Planning	1.2
1.2 Nature of Protective Action Guides, Protective Action, and Restorative Action	1.3
1.3 Protective Action Decision Making	1.7
1.3.1 Action Factors	1.8
1.3.2 Incident Determinations	1.8
1.3.3 Exposure Pathways	1.11
1.3.4 Populations at Risk	1.13
1.3.5 Radiation Effects	1.14
1.4 Response Plan Action Times	1.17
1.4.1 Preparation of Plans	1.17
1.4.2 Implementation of Plans	1.19
1.5 Types of Action	1.22
1.6 Goals of Protective Action	1.24
1.6.1 Balancing Factors to Achieve Protective Goals	1.25
1.6.2 Constraints on Goal Attainment	1.26
1.6.3 Evaluation of Constraints	1.28
1.6.3.1 Constraints on Evacuation	1.28
1.6.3.2 Seeking Shelter	1.38
1.6.3.3 Access Control	1.40
1.6.3.4 Respiratory Protection	1.40
1.6.3.5 Prophylaxis (Thyroid Protection)	1.41
1.6.3.6 Milk Control	1.42
1.6.3.7 Food Control	1.46
1.6.3.8 Water Control	1.47
1.6.3.9 Restorative Actions	1.48
Chapter 2 - Protective Action Guides for Exposure to Airborne Radioactive Materials	2.1
2.0 Introduction	2.1
2.1 Whole Body External Exposure	2.2
2.2 Inhalation Dose	2.4
2.2.1 Exposure to Radioiodines in a Plume	2.4
2.2.2 Exposure to Particulate Material in a Plume	2.6
2.3 Interpretation of PAGs	2.6

Contents (Continued)

	<u>Page</u>
Chapter 3 - Protective Action Guides for Exposure from Foodstuffs or Water	3.1
Chapter 4 - Protective Action Guides for Exposure from Material Deposited on Property or Equipment	4.1
Chapter 5 - Application of Protective Action Guides for Exposure to Airborne Radioactive Materials from an Accident at a Nuclear Power Facility	5.1
5.0 Introduction	5.1
5.1 Release Assumptions	5.2
5.1.1 Radioactive Noble Gas and Radioiodine Releases	5.4
5.1.2 Radioactive Particulate Material Releases	5.5
5.2 Sequence of Events	5.5
5.2.1 Accident Notification	5.7
5.2.2 Immediate Actions	5.8
5.3 Establishment of Exposure Rate Patterns	5.9
5.4 Dose Projection	5.12
5.4.1 Duration of Exposure	5.14
5.4.2 Whole Body Dose Projection	5.15
5.4.3 Thyroid Dose Projection	5.18
5.4.3.1 Concentrations Based on Release Rates	5.21
5.4.3.2 Concentrations Based on Gamma Exposure Rate Measurements	5.24
5.5 Protective Action Decisions	5.30
Chapter 6 - Application of PAGs for Foodstuffs and Water Contamination	6.1
Chapter 7 - Application of PAGs for Contaminated Property or Equipment	7.1
Chapter 8 - Application of PAGs for Transportation Incidents	8.1
References	B-1

Contents (Continued)

	<u>Page</u>
Appendix A - Summary of Interim Guidance on Offsite Emergency Radiation Measurement Systems	A-1
Appendix B - Planner's Evaluation Guide for Protective Actions	B-1
Appendix C - Summary of Technical Bases for Protective Action Guides	C-1
Appendix D - Technical Bases for Dose Projection Methods	D-1

Accession For	
NTIS GRA&I	<input checked="" type="checkbox"/>
DTIC TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	<i>As on file</i>
By _____	
Distribution/	
Availability Codes	
Dist	Avail and/or Special
	

DTIC
COPY
INSPECTED
?

Tables

	<u>Page</u>
Table 1.1 Exposure Pathways and Appropriate Responses	1.5
Table 1.2 Action and Health Effects Versus Exposure Pathways	1.16
Table 1.3 Protective and Restorative Actions for Nuclear Incidents Resulting in Airborne Releases	1.29
Table 1.4 Initiation Times for Protective Actions	1.30
Table 1.5 Approximate Range of Time Segments Making Up the Evacuation Time	1.36
Table 1.6 Parameters Affecting the Cost of Evacuation	1.39
Table 2.1 Protective Action Guides for Whole Body Exposure to Airborne Radioactive Materials	2.3
Table 2.2 Protective Action Guides for Thyroid Dose Due to Inhalation from a Passing Plume	2.5
Table 5.1 Recommended Protective Actions to Reduce Whole Body and Thyroid Dose from Exposure to a Gaseous Plume	5.31

Figures

Figure 1.1 Sequence of Events for Response Planning and Responding to Nuclear Incidents	1.18
Figure 5.1 Projected Whole Body Gamma Dose as a Function of Gamma Exposure Rate and Projected Duration of Exposure	5.17
Figure 5.2 Projected Thyroid Dose as a Function of Either Gamma Exposure Rate, or Radioiodine Concentration in Air and the Projected Exposure Time	5.19
Figure 5.3 Typical Values for $\chi U/Q$ as a Function of Atmospheric Stability Class and Downwind Distance	5.22
Figure 5.4 Radioiodine Release Correction Factor	5.27
Figure 5.5 Gamma Exposure Rate Finite Cloud Correction Factor	5.28

Preface

This manual has been prepared to provide practical guidance to State, local, and other officials on criteria to use in planning protective actions for radiological emergencies that could present a hazard to the public. The guidance presented here is not intended as a substitute for, or an addendum to, a State radiological emergency response plan. It is intended only to provide information for use in the development of such a plan.

In conformance with a Federal Register Notice of interagency responsibilities for nuclear incident response planning dated January 17, 1973, EPA is responsible for (1) establishment of protective action guidelines, (2) recommendations as to appropriate protective actions, (3) assistance to State agencies in the development of emergency response plans, and (4) establishment of radiation detection and measurement systems. This document is intended to be responsive to these assigned responsibilities.

The manual is organized to provide first, a general discussion of Protective Action Guides and their use in planning for the implementation of protective actions to protect the public. This is followed by chapters dealing with Protective Action Guides for specific exposure pathways and time periods. The application of Protective Action Guides and protective actions is discussed separately for various categories of source terms. Support information that has not been previously published is provided as appendices.

The loose leaf format was chosen for flexibility. Copies of additional or revised sections will be forwarded routinely to manual recipients designated as having responsibilities for developing or updating State radiological emergency response plans.

Users of this manual are encouraged to provide comments and suggestions for improving the content. Comments should be sent to the EPA Office of Radiation Programs, Environmental Analysis Division, Washington, D. C. 20460.

CHAPTER 1

Perspectives for Protective Action

1.0 Introduction

In emergency preparedness planning for a nuclear incident with potential for exposing the general public to harmful radiation, public health officials require criteria to determine the need for protective actions and for choosing appropriate protective actions. EPA is responsible for providing these criteria and for assisting the States in preparing emergency response plans to implement these criteria.

After a nuclear incident occurs, an estimate is made of the radiation dose which affected population groups may potentially receive. This dose estimate is called the projected dose. A protective action is an action taken to avoid or reduce this projected dose when the benefits derived from such action are sufficient to offset any undesirable features of the protective action. The Protective Action Guide (PAG) is the projected dose to individuals in the population which warrants taking protective action.

A Protective Action Guide under no circumstances implies an acceptable dose. Since the PAG is based on a projected dose, it is used only in an ex post facto effort to minimize the risk from an event which is occurring or has already occurred.

Exposures to populations from an incident may well be above acceptable levels, in an absolute sense. However, since the event has occurred, PAGs should be implemented to ameliorate the impact on already exposed or yet-to-be exposed populations.

On this basis there is no direct relationship between acceptable levels of societal risk and Protective Action Guides. PAGs balance risks and costs against the benefits obtained from protective action, assuming that the projected threat will transpire. The responses made in a given situation should be based on PAGs and the spectrum of possible protective actions available at that time.

1.1 The Need for Planning

Within the general framework of providing maximum health protection for an endangered public, the public official charged with response to a hazardous situation may be faced with a number of decisions which must be made in a short time. A number of possible alternatives for action may be available, but the information needed to select the optimum alternative may not be available. In those situations where a public official must rapidly select the best of several alternatives, it is helpful if the number of decision points can be reduced during the accident response planning phase.

The efforts of planning activities can usually be based on the need for immediate response. Therefore, the objective is to minimize the number of possible responses so that resources are expended only on viable alternatives in emergency situations. During planning it is possible to assess value judgments and determine which steps in

response are not required, which steps can be answered on the basis of prior judgments, and which remain to be decided in an actual emergency. From this exercise, it is then possible to devise a set or several sets of operational plans which can be called out to answer the spectrum of hazardous situations which may develop.

In the case of an accident at a nuclear reactor, a hazardous situation could develop which may have public health implications over a large area with diverse populations and population densities. Probably little time will be available to make decisions. The availability of "action guides" based on advance planning will facilitate rational decisions in emergency situations. During the planning stage, the responsible public official must consider the total range of possible release scenarios and consider in each what goals are achievable keeping in mind both fiscal and societal costs. Because of this knowledge of local conditions, he will be aware of any constraints which may restrict his scope of response, such as specific industries, institutions, traffic patterns, etc. He will then be able to select the optimum response for each situation.

1.2 Nature of Protective Action Guides, Protective Action, and Restorative Action

Protective Action Guides are the numerical projected doses which act as trigger points to initiate protective action.

PAGs must be provided for three broad pathways of radiation exposure:

- (1) Exposure from airborne radioactive releases. This type of exposure could occur within a short period following an

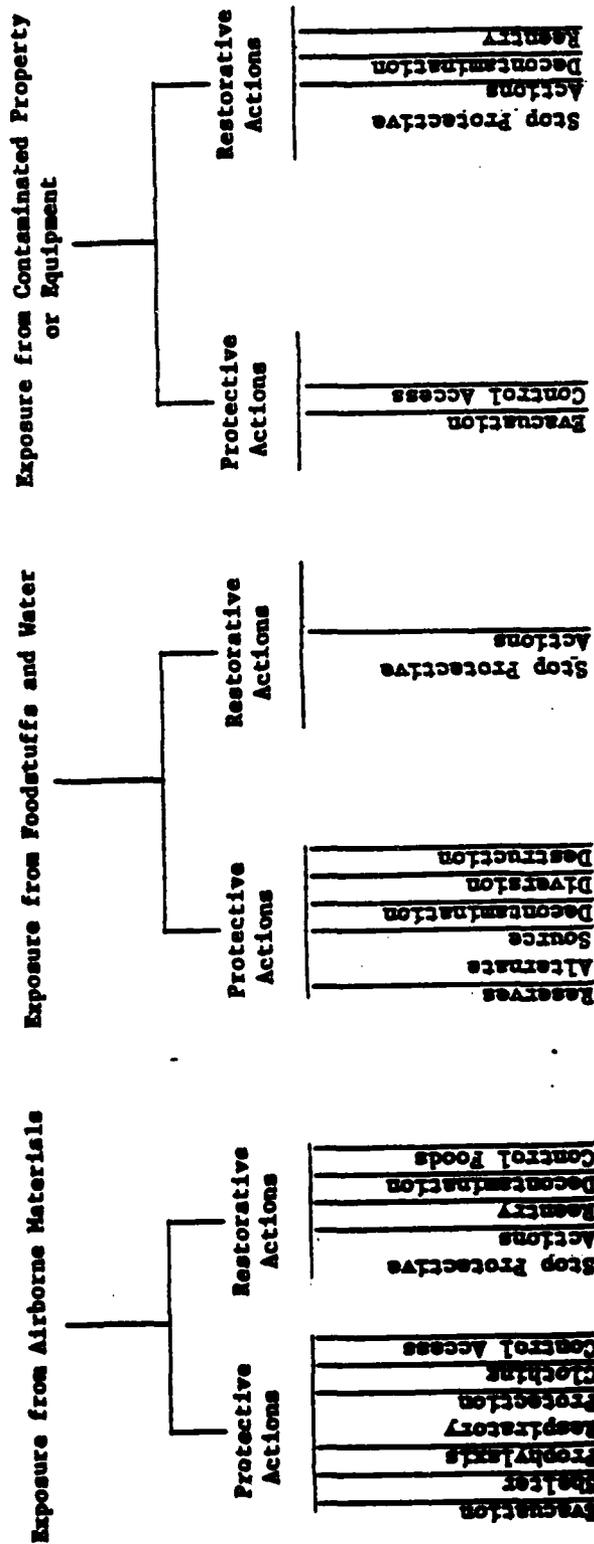
incident as a result of inhalation of radioactive materials or from external whole body exposure.

- (2) Exposure through the food chain. This exposure will be from ingestion of contaminated foodstuff and water. It may commence shortly after the passage of airborne radioactive materials and may continue for a long or short time depending on the radionuclides involved.
- (3) Exposure from radioactive materials deposited on the ground. Here we are dealing with a change in background radiation levels, and exposure pathways may include inhalation, ingestion, and external whole body exposures.

Different PACs must be developed for each pathway of exposure since different criteria of risk, cost, and benefit are involved. Each exposure pathway would involve different sets of protective or restorative actions as indicated in table 1.1. Each action listed applies to the general population except for prophylaxis, respiratory protection, and protective clothing. These actions would primarily apply to emergency workers.

Exposure to the airborne plume is related to the duration of a release into the atmosphere. While release durations as long as 30 days or more are theoretically possible, for emergency purposes, release durations of a few hours up to a few days are more realistic. Protective action to be taken for this pathway may include any or all of the following:

Table 1.1 Exposure Pathways and Appropriate Responses



- (1) evacuation,
- (2) respiratory protection,
- (3) shelter,
- (4) prophylaxis (thyroid protection), and
- (5) controlled access.

Restorative actions would then include:

- (1) reentry first by survey and decontamination teams,
- (2) removal of respiratory protection,
- (3) exit from shelters,
- (4) stopping prophylactic measures, and
- (5) allowing free access by the population.

Exposure through the food chain may be either short term or chronic depending on the characteristics and half-lives of the radionuclides involved. Control of this pathway of exposure would be by:

- (1) control of access to contaminated animal feeds,
- (2) decontamination of certain foodstuffs,
- (3) diversion and storage to allow decay of short half-life radionuclides, and
- (4) destruction of contaminated foods.

Exposure from materials deposited on the ground might also be either short term or chronic depending on the radionuclides involved. Protective actions would include:

- (1) evacuation, and
- (2) controlled access.

Since the problem for ground contamination involves an increase in background levels, denial of access might continue for extended periods of time. Decontamination may then be the only action which will allow free access to and utilization of contaminated areas within a short time. Restorative actions would be reentry, decontamination, and lifting of controls.

The PAGs are to provide standardized criteria for selecting predetermined actions at the sacrifice of some flexibility in balancing the risk of health effects versus the effects of protective actions during an emergency. The loss of flexibility in response is expected to be within the limits of accuracy of determining the factors involved. The loss of flexibility is also offset by the advantage of being able to respond to the immediacy of the risks in the case of an emergency.

The range of PAG values allows consideration for local constraints during planning for implementation. PAGs should be assigned for each site to assure that local constraints are properly introduced.

1.3 Protective Action Decision Making

A nuclear incident as defined herein refers to a series of events leading to the release of radioactive materials into the environment of sufficient magnitude to warrant consideration of protective actions. Protective actions are those actions taken following a nuclear incident

that are intended to minimize the radiation exposure of the general public resulting from incidents.

The decision to initiate a protective action may be a complex process with the benefits of taking the action being weighed against the risks and constraints involved in taking the action. In addition, the decision will likely be made under difficult emergency conditions, probably with little detailed information available. Therefore, considerable planning is necessary to reduce to manageable levels the ~~types of decisions leading to effective~~ responses to protect the public in the event of a nuclear incident.

1.3.1 Action Factors

Within the context of nuclear incidents, a wide variety of possible situations may develop. Some perspective of the needs of the responsible planning officer can be shown in a brief description of the factors involved. Basically, the officer must balance problems involving identification of the magnitude of the release, possible pathways to the population at risk, how much time is available to take action, what action to take, and what the effects might be.

1.3.2 Incident Determinations

The first problem to arise will be that of identifying the type of incident and the magnitude of the release. Nuclear incidents may be extremely variable and may range from very small releases having no measurable consequences offsite to large scale releases possibly involving large populations and areas. Responses must be appropriate to the incident reported.

One of the variables will be the source term, which refers to the characteristics and release rate of the radioactive material. The amounts and types of radionuclides available for release should be immediately calculable by site personnel. What is actually being released to the environment can be estimated but may not be confirmed for some time after the incident.

The magnitude and duration of the release may be estimated by site personnel from plant conditions or from knowledge of the type of incident that has occurred. However, the estimate may be highly uncertain and must be updated on the basis of onsite and offsite monitoring observations and operational status of engineered safeguards.

If source term information is not available immediately, default values should be available from planning efforts. These values could be based on accident scenarios from WASH-1400 (1), design basis accidents evaluated in the NRC safety evaluation report for individual facilities, or other scenarios appropriate for a specific facility.

The second major variable will be where the released material is expected to go. Meteorology and geography will affect this variable. Current meteorological conditions can be observed directly at the site and relevant locations. However, complete meteorological data will never be available, and extension of observed data must be made to predict the course of released material.

Current weather conditions may restrict the options for response, e.g., evacuation in a blizzard may be reduced or impossible. Weather

forecasts have all of the inherent uncertainty of the current condition estimates since they are derived from these.

Geography is important both in its influence on meteorology and on demography and in its influence on value judgments to be made. The planning for a coastal site or a river valley site may be different due to road patterns and methods for communicating or applying protective actions.

Demography is a variable to be considered during the planning stage. Demography is of most importance in helping to assess the possible impact of an incident. Population numbers, age distribution, distribution within an area, etc., will have some influence on responses available in any situation.

Providing for the ability to detect and measure a release are important factors for planning. Although it may be possible to detect releases and measure release rates at the site, information from environmental measurements will be needed to confirm any estimates made on the basis of onsite measurements. Detection and measurement at locations offsite are necessary to update and/or confirm predictions about the movement of the release in the environment. Locations for installed equipment must be planned, probably on the basis of average area meteorology. Instrumentation needs are discussed in more detail in Appendix A.

The source term, meteorology, and geography parameters are utilized in making a prediction of the path and time profile for the

release. This prediction, in combination with demography data, will be used to select the best responses for the situation. The most reasonable approach is to plan path and time profiles (isopleths) for unit release situations and then to modify them as real data are obtained.

1.3.3 Exposure Pathways

The next decision after the determination of an accident situation will probably concern identification of important pathways of radionuclides to the population. Exposure pathways of immediate importance and the time available to interrupt them can be decided to a large extent on the basis of planning judgments.

The single most important pathway during the emergency phase is probably by air. The air pathway will be via inhalation of either gases or particulates and whole body exposure to the plume. Released gases will be either radioactive noble gases, organic iodides, inorganic iodides, or volatile inorganic materials. Particles will probably form by the condensation of vaporized material.

Water is a pathway for exposure by ingestion or immersion. Released material may enter the water directly or in the form of fallout or rainout followed by surface runoff. The immersion pathway of exposure is unlikely to have significance except in very specialized circumstances. Ingestion of water is probably only a minor pathway

of exposure in the short run. However, the gastrointestinal system must be considered for longer term ingestion of contaminated drinking water.

Ingestion of food is an important exposure pathway. However, with the possible exception of drinking water, milk, and contaminated leafy vegetables, entry of released materials into food and passage along this pathway is delayed. Identification of sensitive points for control should be made during planning.

Characterization of release materials involved in air, water, and food pathways will not be done for some time after an accident. The initial decisions will have to be made on the basis of estimates developed in planning and modified as real information becomes available.

Direct external whole body radiation exposure may be a hazard. Released material deposited in soil or water or suspended in air and material still at the site serve as sources of direct radiation, mostly by gamma and beta radiations. Although exposure rate may be measured directly at specific locations, the distribution must be estimated and the estimates updated on the basis of monitoring data. Fairly complete monitoring will be needed during implementation of restorative actions.

Soil contamination, in addition to providing part of the direct whole body exposure, also provides a contribution to the air pathway. Released material deposited on soil can be resuspended, thus possibly

entering the air, water, and food pathways. Evaluation of these hazards will be particularly important in deciding appropriate actions during the restoration phase, e.g., level of decontamination needed.

1.3.4 Populations at Risk

The next consideration of importance to the responsible official is what population is to be protected. Prior judgment and planning based on the geography and demography of the area around the site and on critical pathways are essential to identifying populations at greatest risk.

The average population is made up of persons with varying sensitivities to radiation exposure, and responses may be keyed to the most sensitive, or responses may be restricted, depending on characteristics of the local population.

- (1) For purposes of response planning, the general population will be evaluated on the basis of risk to individuals within the population, usually on the basis of avoiding clinical effects. However, the population as a whole will also be considered in planning some responses on the basis of statistical risk of somatic and/or genetic effects.
- (2) Sensitive populations may be considered on a special basis. Children, including the fetus and unborn children, are generally more sensitive than healthy adults. For this reason, such members of the population may be selected

either as the most sensitive receptors or as a special group for protection.

- (3) Selected populations will also be present. These populations may be selected on voluntary or involuntary bases. Workers at a nuclear facility are classified as radiation workers and fall under different criteria for protection than the general population. Those persons who are engaged in public service activities during or after the accident are voluntarily placing themselves under different criteria for protection than the general population. Finally, some persons are involuntarily included under different criteria because the risk of taking action is different than for the general population. This involuntarily selected population may include bedridden and critically ill patients, patients in intensive care units, prisoners, etc.

1.3.5 Radiation Effects

A final parameter which must be considered is radiation effects. These may fall into two categories, early or delayed, but are not mutually exclusive.

- (1) Early (acute) effects, occurring within 90 days, may include fatalities, symptoms of radiation sickness, or clinically detectable changes. Efforts to protect selected populations will extend to prevention of fatalities, minimization of

symptoms of radiation sickness in radiation workers and public service personnel, and prevention of clinically detectable changes of uncertain significance in the rest of the population. The basis for decisions regarding early effects is not hard to justify because of the imminence of such effects. However, they must be made rapidly under conditions of competing needs to protect the public.

- (2) Delayed statistical effects (i.e., biological effects which can only be observed on a statistical basis) will occur at random in a population after exposure to released materials. These effects may be fatalities or disabilities of somatic or genetic origin. The incidence of these effects is estimated on the basis of statistical evaluation of epidemiological studies in groups of people who had been exposed to radiation. Decisions concerning statistical effects on populations will be more difficult because of the lack of immediacy of the effects. But in the long run, these effects might cause the greatest impact on the general population.

The response times, actions to consider, and possible health effects for each pathway are shown in table 1.2 for a typical population.

Effects on animals, vegetation, or real estate are also possible but may be controlled or alleviated to the extent that decontamination is employed or that destruction of the affected items is employed.

**Table 1.2 Action and Health Effects
Versus Exposure Pathways**

Exposure Pathway	Response Time	Action Available	Public Health Effects
Air - Particulate	Min - Hr	P	D
Gas	Min - Hr	P	F,E,D
Water - Particulate			
Rainout	Hr - Da	P	D
Fallout	Min - Hr	P	D
Immersion	Day	P&R	D,F,E
Food - Milk	Da - Mo	P&R	D
Drinking Water	Hr - Mo	P&R	D
Beverages	Da - Mo	P&R	D
Foodstuffs	Da - Mo	P&R	D
Soil - Resuspension	Da	R	D
Direct	Min - Da	P&R	E,D,F
Direct - Facility	Min	P&R	F,E,D
Air	Min - Hr	P	F,E,D
Water	Hr	P&R	D,F,E

Actions: P - Protective R - Restorative
Effects: F - Rapid Fatality E - Early D - Delayed

1.4 Response Plan Action Times

A typical sequence of events for developing emergency plans and responding to nuclear incidents is shown in figure 1.1. This figure illustrates the general order of events but not relative lengths of time for each event. These will vary according to individual circumstances.

1.4.1 Preparation of Plans

Considerable preparation will be required to ensure the adequacy of emergency response plans. This preparatory time includes the following elements:

- (1) The decision must be made to prepare emergency response plans according to the legislative mandates or needs within a given State.
- (2) Then basic plans should be developed using appropriate guidance from this manual and the AEC "Guide and Checklist" (2). These plans should include emergency response actions for coping with nuclear incidents and directions on the use of EPA Protective Action Guides for these situations.
- (3) These plans should be approved by responsible persons or agencies.
- (4) Scenarios must be developed from the basic plans to cover major contingencies which can be identified.

Methods of implementation must be prepared and tested so that nonviable responses and contingency plans may be identified and discarded. This discarding of nonviable responses may be based in part

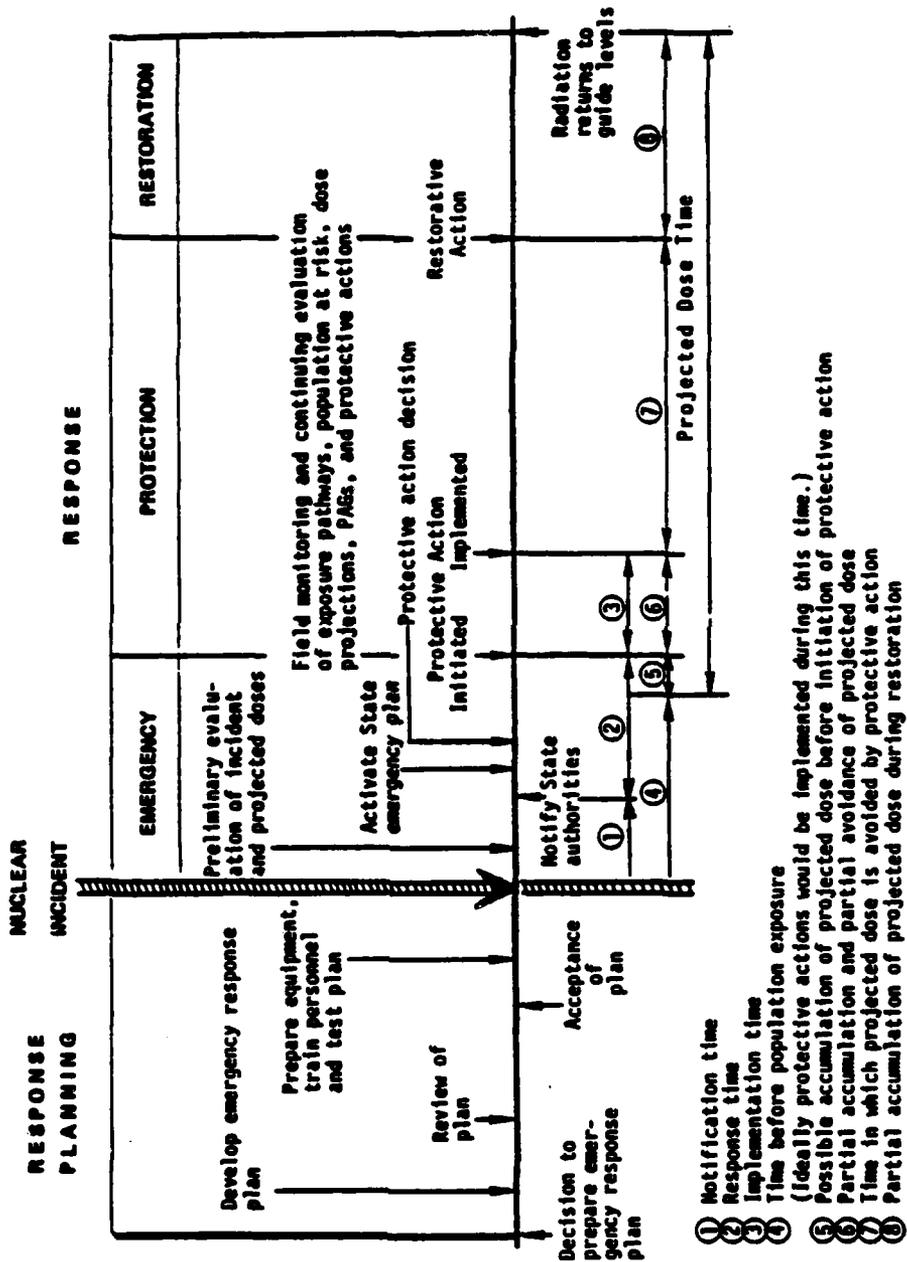


FIGURE 1.1 SEQUENCE OF EVENTS FOR RESPONSE PLANNING AND RESPONDING TO NUCLEAR INCIDENTS

on evaluation of local constraints. For example, evacuation of prisoners or critically ill persons might not be considered viable while alternative protective actions may be at least partially effective.

Development of the basic emergency response plan may run a course of several months or longer. However, planning should be a continuing activity after the basic plans are developed. Advances in meteorology, development of new protective actions, changing demography, etc., should be used in reevaluation of the original scenarios. And of course, recurrent testing of implementation methods should be carried out.

1.4.2 Implementation of Plans

A sequence of steps to implement a response plan following a nuclear incident is also shown in figure 1.1. The time after an incident may be divided into three phases which are called emergency, protection, and restoration. These phases are not necessarily distinct consecutive time periods, but they do serve to indicate the general nature of activities in a typical response sequence.

The emergency phase includes all those activities leading to initiation of protective actions. This phase involves assessment of the situations and is characterized by urgency in determining the need for protective action and getting the action initiated. In general, this may be considered to be the first few hours following notification of an incident and deals primarily with protection of the population

from exposure to the airborne plume.

The most important step in emergency response is the prompt notification that an incident has occurred that could result in an offsite exposure such that there is a need for initiating protective action. It is the facility operator's responsibility to notify State or local authorities that such an incident has occurred. It is important that agreements be reached during the planning phase on who is to be notified, data to be provided, offsite measurements that will be made, and actions to be initiated at the site so that there will be a minimum time loss in starting implementation of protective action in the offsite area. Proper planning must include incentives to prevent delays in notification. Nuclear facility operators have the initial responsibility for accident assessment. This includes prompt action necessary to evaluate public health and safety both onsite and offsite (2). Ideally, this notification should occur as soon as conditions in the facility are such that an impending accidental release potential exists. While such notification could lead to false alarms on rare occasions, they could also permit more timely protective actions than postponing the notification until a release has occurred.¹

The sequence of events during the emergency phase includes the notification of responsible authorities, evaluation and recommendations for action, and warning of the public. In this early phase of response, the time available for effective action will probably be quite limited.

¹As part of their plans, the State should establish with the facility operator a strict protocol for notification of the State such that early responding of possible impending releases would not involve disincentives to the facility operator.

Immediately upon becoming aware that an incident has occurred that may result in exposure of the offsite population, a preliminary evaluation should be made by the facility operator to determine the nature and potential magnitude of the incident. This evaluation, if possible, should determine potential exposure pathways, population at risk, and projected doses. At this time, projected doses may be estimated from monitoring data at the point of radionuclide release or from releases anticipated for particular types of nuclear incidents. The incident evaluation information should then be presented to the proper authorities. If authorities were notified earlier and have mobilized resources, protective actions can be started immediately in predesignated areas or in the areas indicated by projected dose based on facility operator information. In the absence of detailed information from the facility operator as indicated above, the emergency plans should provide for action in the immediate downwind area of the facility based on notification that a substantial release has occurred or that plant conditions are such that a substantial release potential exists.

The next step is to gather additional information on radiation levels in the environment, meteorology, and environmental conditions. Further actions or modifications to actions already taken should be based on these data and Protective Action Guides considering constraints discussed in section 1.6 of this chapter.

The State should continue to seek information on radionuclide releases and environmental monitoring data. In fact, an evaluation of

such information, as well as exposure pathways, population at risk, dose projections, and PAGs should be a continuing activity in both the emergency and protection phases in order to modify protective actions as needed.

The protection phase begins with the initiation of protective action and continues until that action is terminated. Figure 1.1 indicates that ideally the protective action such as evacuation would be implemented before any population exposure. However, the action may not be initiated in time to avoid all of the projected dose, and some dose may be received during implementation of the action.

The restoration phase includes those actions taken to restore conditions to "normal". Restorative actions include the halting of protective actions, the lifting of restrictions, and possible decontamination procedures.

1.5 Types of Action

The action taken may be, as previously indicated, either protective or restorative. It may also be voluntary or involuntary, or no action at all may be taken.

- (1) No action would usually be taken by State authorities if the risk of undesirable radiation effects is anticipated to be much less than the risk of taking action.
- (2) Voluntary action may be suggested for the population at risk, or it may be taken by them anyway on the basis of public information provided during an accident situation. Voluntary action may be valid in the gray area where the

risk of exposure to released material and the risk of taking action are not too different. It may also be taken at lower levels of exposure by individuals to alleviate their fears. The negative aspects of possible confusion and possible panic where incomplete knowledge exists must be considered during decisions to implement protective actions.

- (3) Involuntary (mandatory) action by State authorities should be implemented when the risk of undesirable effects exceeds the risk of taking action to such an extent that public well-being can be adversely affected. This is when action must be taken in the public interest.

The types of action which can be taken include:

- (1) Protective actions, such as evacuation, taking shelter in homes or civil defense shelters, controlling food and water distribution, prophylaxis (e.g., thyroid protection), or individual protective actions (e.g., gas masks, protective clothing, etc.); and
- (2) Restorative action where everything is returned to "normal". This action includes lifting restrictions or halting activities initiated as protective actions. It also includes decontamination where necessary.

The actions to be taken should be evaluated and set in priority or sequence with identification of ranges for appropriate action and of decision points during planning. Based on prior judgment of which

actions may be effective in any given situation, scenarios can be prepared which will indicate which actions or mix of actions are appropriate for various situations.

1.6 Goals of Protective Action

The ideal goal of protective action in an emergency is complete protection of the endangered population. However, various constraints may prevent attaining this ideal, so a more realistic goal is minimization of harmful effects.

In the case of an emergency involving a radiological hazard, efforts are directed towards minimizing:

- (1) early somatic effects such as death within days or development of extensive symptoms of radiation sickness;
- (2) delayed somatic effects, such as increased probability of death due to radiation related cancer; and
- (3) genetic effects such as increased prenatal mortality or increased probability of hereditary defects in future generations.

The minimization of effects implies that the radiation exposure under consideration is an avoidable exposure. However, for purposes of determining whether to take a protective action on the basis of projected dose from an airborne plume, the projected dose should not include unavoidable dose that has been received prior to the time the dose projection is done. If a situation should occur where the unavoidable dose would be very large as compared to the avoidable dose, different protective actions might be warranted.

.6.1 Balancing Factors to Achieve Protection Goals

The ideal goal is maximum protection of the public with the least cost and disruption. Within the need to protect the public several constraints, including physical, social, and fiscal, will be operating.

The planner should balance the cost of not taking action (risk of radiation exposure) against the cost of taking action from both fiscal and societal aspects. In particular, the fiscal costs of preparing for action, as well as the costs of all actions to be taken, should be balanced against the need for response to protect the public. Also, the societal costs such as panic and disruption of life style should be balanced against the risk to society of not taking action.

This balancing of costs and risks will place constraints on the options available for action. This balancing also implies that in planning, certain cut-off points can be identified, e.g., a marginal increase in protection probably may not justify the required expenditures or extensive disruption of families or daily activities. These costs and constraints should be evaluated in planning by the responsible public officials in determining the responses to be made in a given situation.

Even if the balance of costs indicates that a response or set of actions is reasonable, other constraints may preclude their use. These additional constraints on action are primarily physical in nature (e.g., in the case of a puff release, exposure time may be too short to allow effective protective action).

1.6.2 Constraints on Goal Attainment

The constraints which operate to prevent attaining the ideal goal include those of environmental, demographic, temporal, resource availability, and exposure duration.

Environmental constraints will include meteorologic and geographic considerations. Protective action options may be restricted by severe weather conditions, windstorms, blizzards, tornadoes, large accumulations of snow, etc. Options are also restricted by numbers, types and directions of roads, and obstruction of easy egress from a site by rivers, mountains, or other geologic formations.

Options are further constrained by the density and distribution of population, the total size of the population involved, the age and health status of segments of the population, and other demographic considerations.

Temporal constraints will be present during all phases of protective action and some situations during restorative action. Time available for action may be a real constraint for evacuation of close-in populations, particularly in the case of short term (puff) releases. After an incident, exposures of the population close to the site may occur before control of the situation is established. Even after a decision for action has been made, notification of the population and implementation of the action may require enough time such that substantial exposures occur. The constraint of time in restorative action will probably be more related to reduction of costs rather than to direct protection of the population. Rapid decontamination to allow

access to utilities, food stores, crops, etc., will reduce the total cost due to the accident.

Resources will be one of the largest constraints on viable options for action. The best planning will fail if the resources to implement actions are not available. Resources needed are fiscal, manpower, and property, although fiscal will probably be the limiting factor. Given sufficient fiscal investment, then manpower, equipment, and training, all will be available in adequate quantities. However, since only limited amounts of fiscal support may be available, the lack of equipment and manpower with sufficient training and practice in implementation of protective actions will limit the number of viable options for protecting the public.

In general, as the population to be protected increases, less protection is available for the same total cost (equal levels of protection require greater fiscal investment in large populations than in small populations). Likewise, as the level of preparedness increases, the cost of obtaining and maintaining this preparedness increases. The cost of protective action, however, will probably be a step function. Each decision to take an action or extend an action will cause an incremental step increase in the cost. All of these constraints must be considered in planning operations so that the optimum protection of the public can be obtained with the least expenditure, both social and fiscal, commensurate with the goal of protective action.

1.6.3 Evaluation of Constraints

Local officials involved in developing emergency response plans must be thoroughly informed on what protective actions are available for limiting the radiation exposure of the general public during a nuclear incident. These actions are a vital part of the emergency response plan and should be specified during the planning phase rather than at the time of the incident. There are, however, local constraints associated with each protective action which will influence the decision to implement a given protective action. The local planner must also be familiar with and apply these constraints to any emergency situation. Ideally, it should be possible to balance these constraints in some analytical fashion which would place each constraint in its proper perspective on a common scale. Since many of the constraints cannot be quantified, local planners must use rational, subjective judgment in evaluating them.

Tables 1.3 and 1.4 list protective actions that are available for various types of reactor incidents as a function of approximate time periods following the incident, and the following discussion attempts to evaluate constraints such as costs, time, societal considerations, etc., that relate to each protective action. This information should be valuable to the local planner in making the value judgments that are necessary to plan actions during an emergency.

1.6.3.1 Constraints on Evacuation

While evacuation may seem to be the protective action of choice following a nuclear incident at a fixed nuclear facility, constraints

Table 1.3 Protective and Restorative Actions for Nuclear Incidents Resulting in Airborne Releases

Nuclear Incident	Protection Phase			Restoration Phase (c)
	Approximate Time of Initiation			
	0-4 hr.	4-8 hr.	> 8 hr.	
Puff Release (a) - Gaseous or Gaseous and Particulate	1,2,3,4,5	3,4,5	3,4,5,6,7,8	9,10,11
Continuous Release (b) - Gaseous or Gaseous and Particulate	1,2,3,4,5	1,2,3,4,5	1,2,3,4,5,6,7,8	9,10,11

- 1 Evacuation
- 2 Shelter
- 3 Access control
- 4 Respiratory protection for emergency workers
- 5 Thyroid protection for emergency workers
- 6 Pasture control
- 7 Milk control
- 8 Food and water control
- 9 Lift protection controls
- 10 Reentry
- 11 Decontamination

(a) Puff release - less than 2 hours

(b) Continuous release - 2 hours or more

(c) Restoration phase may begin at any time as appropriate

Table 1.4 Initiation Times for Protective Actions

Approximate Initiation Time	Exposure Pathway	Action to be Initiated
0-4 hours	inhalation of gases or particulates	evacuation, shelter, access control, respiratory protection, prophylaxis (thyroid protection)
	direct radiation	evacuation, shelter, access control
4-48 hours	milk	take cows off pasture, prevent cows from drinking surface water, quarantine contaminated milk
	harvested fruits and vegetable	wash all produce, or impound produce
	drinking water	cut off contaminated supplies, substitute from other sources
	unharvested produce	delay harvest until approved
	harvested produce	substitute uncontaminated produce
2-14 days	milk	discard or divert to stored products, such as cheese
	drinking water	filter, demineralize

associated with a specific site could render the evacuation ineffective or undesirable. Other optional protective actions such as taking shelter should be considered. The planner must take into consideration all local constraints to determine whether or not evacuation is a viable protective action for the given situation. Examples of the effects of constraints could be provided on a general basis. However, it remains the responsibility of the planner to determine the most reasonable protective actions for each site.

A. Effectiveness of Evacuation

The effectiveness of evacuation in limiting radiation dose is a function of the time required to evacuate. If a radioactive cloud is present, the dose will increase with the time of exposure; if the evacuation is completed before the cloud arrives, then evacuation is obviously 100 percent effective. Anything that delays an evacuation is therefore a constraint, and such constraints are likely to be very much a function of local site conditions and planning. The planner should be aware of these constraints in order to minimize their impact, thus maximizing the effectiveness of the evacuation.

The evacuation time, $T(EV)$, at a particular site is defined as the time from the start of the nuclear incident to the time when evacuees have cleared the affected areas. It may be expressed as:

$$T(EV) = T_D + T_N + T_M + T_T$$

where:

T_D = time delay after occurrence of the incident associated with

notification of responsible officials, interpretation of data, and the decision to evacuate as a protective action.

T_N = time required by officials to notify people to evacuate.

T_M = time required for people to mobilize and get underway.

T_T = travel time required to leave the affected areas.

T_D includes several separate time elements as defined above, and all of them can be reduced by effective planning. Nominal values for T_D may range from 0.5 hours up to 1.5 hours and possibly longer depending on the adequacy of planning and whether the decision is to be based on onsite information or offsite environmental measurements.

The least well defined time constraint is T_N , which is strongly influenced by local population, geographic conditions, and planning. T_N has been postulated to be inversely proportional to population density; the closer people are together, the quicker it is to notify them to evacuate. For fast developing incidents, news media warnings must be augmented by telephone, public address, and door knocking, the effectiveness of which is a function of local planning and resources. There are new innovations such as computer telephoning, planes with loud speakers, etc., which the local planner may find worthwhile to explore. The value of T_N under the best conditions of local planning is estimated to range from 15 minutes to 1 hour or more.

T_M , the time required for people to prepare to leave, depends on such parameters as:

- (1) Is the family together?
- (2) Rural or urban community? Some farms or industries require more shutdown time than others.
- (3) Special evacuations - special planning effort is required to evacuate schools, hospitals, nursing homes, penal institutions, and the like.
- (4) There will be some people who will refuse to evacuate.

The best time for T_M for an urban family together might be 0.2 to 0.5 hours, while to shut down a farm or factory might take hours.

The evacuation travel time, T_T , is related to:

- (1) Total number of people to be evacuated.
- (2) The capacity of a lane of traffic.
- (3) The number of lanes of highway available.
- (4) Distance of travel.
- (5) Roadway obstructions such as uncontrolled merging of traffic or accidents.

The total number of people to be evacuated depends on the population density and affected area. It is an advantage if good planning can keep the area and thus the number of people to as small a value as possible, or possibly to evacuate one area at a time so that the number of people on the move at one time is within the capacity of the roads.

The capacity of a lane of traffic depends on the number of vehicles per hour and the capacity of each. Surveys during evacuations found

4 persons/car on the average indicating that at 2,500 cars/hr at 35 mph, the capacity of a lane is 10,000 persons/hr. Commuter traffic, however, contains about 1.2 persons/car, lowering the capacity to about 3,000 persons/hr-lane. Use of buses exclusively, if this is practical, increases the lane capacity by a factor of about 10 such that 100,000 persons/hr-lane could be moved. However, if buses are used, the increase in time caused by getting the buses to the evacuation area and by return trips must be considered. If the average speed of traffic is less than 35 mph, capacity/lane-hr is lowered in proportion.

The number of lanes of traffic is ordinarily sufficient for evacuation from the low population zone around fixed nuclear facilities. Lanes may be increased by using lanes that ordinarily carry traffic into the area. All these lanes cannot be used, however, since some, at the option of the planner, must be held open for emergency vehicles coming into the area.

Traffic control will be effective in reducing the evacuation travel time. If lanes ordinarily inbound are used for outbound traffic, traffic officers will be required to direct vehicles to them; otherwise they will not be used. Traffic barriers, signs, traffic light overrides, disabled vehicle removals, etc., will be required to keep traffic speeds high. Traffic control at bottlenecks will be of particular importance. Allowing single lanes to run alternately rather than having cars dovetail through an intersection will significantly

increase traffic flow. Access controls to keep unauthorized vehicles and persons out of the evacuated areas will be needed also.

Examination of specific sectors around four different light-water power reactors indicates that T_T may range from 0.2 to as much as 1.5 hours under exceptional conditions where the road system is inadequate compared to the population to be evacuated. An average traffic speed of 35 mph was assumed if road capacity was great enough to preclude traffic jams.

Table 1.5 summarizes the various time segments that act as constraints on evacuation. These values are rough estimates that should be improved upon by the local planner for each site. An example of a one-hour evacuation might be the evacuation late in the evening of a rural area including a small town (250 persons). In such a case the population is small, concentrated, and at that time the families would be united. An example of an evacuation in the longer time range might be evacuation during the daytime of a rural, low population zone containing farms. Warning would be time consuming, and the preparation for farm shutdown might be lengthy. The road system is adequate, but families may be separated during the day, requiring longer evacuation travel distances. Emergency plans for areas located near State boundaries would require interstate cooperation and planning. High population, high density areas such as those around Indian Point present a different situation, and evacuation times are more complex, probably longer, and must be analyzed on a case by case basis. In these areas, notification time may be short but access

Table 1.5 Approximate Range of Time Segments Making Up the Evacuation Time^(a)

Time Segment	Approximate Range Hours
T_D	0.5 - 1.5 ^(b)
T_N	0.2 - 1.0 ^(c)
T_M	0.2 - 2.0 ^(d)
T_T	$\frac{0.2 - 1.5}{1.1 - 6.0}$ ^(e)

- (a) High population, high density areas such as those around Indian Point, present a different situation, and evacuation times are more complex, probably longer, and must be analyzed on a case by case basis.
- (b) Maximum time may occur when offsite radiation measurements and dose projections are required before protective action is taken.
- (c) Maximum time may occur when population density is low and evacuation area is large.
- (d) Maximum time may occur when families are separated, a large number of farms or industries must be shut down, and special evacuations are required.
- (e) Maximum time may occur when road system is inadequate for the large population to be evacuated and there are bottlenecks.

limited. Appendix B provides techniques for evaluating the various time periods involved in evacuation.

B. Risk of Death or Injury

If evacuation were likely to greatly increase an individual's risk of death or injury, this would act as a significant constraint on the use of evacuation as a protective action for a nuclear incident. Fortunately, examination of numerous evacuations indicate that risk of death or injury is not likely to be increased when evacuation is made by motor vehicle (3). Premature childbirth is routinely encountered in emergencies and subsequent evacuations, and in at least one State emergency plan, prior arrangements are made for this problem.

C. Evacuation Costs

For evacuations caused by storms or floods, cost is not usually a constraint because hazard to life and limb is obvious and because the evacuation cost is judged to be small compared to the damage caused by the disaster. However, in the event of a nuclear incident where there may be the strong inclination to evacuate even though the radiation dose to be saved is vanishingly small, the economic cost of the evacuation may act as a constraint. Therefore, the planner may wish to estimate this cost for various kinds of evacuation.

Evacuation costs may be broken into four categories:

- (1) costs involving evacuees,
- (2) costs involving evacuators,
- (3) financial losses of farm areas, and
- (4) financial losses of urban and industrial areas.

Limited information on estimated costs is given in reference (3). For a specific site, the various costs probably can be ascertained with more accuracy. Parameters that would affect the costs of an evacuation around a specific site are listed in table 1.6. Consideration of these parameters and how they affect cost should allow the planner to calculate the approximate monetary cost of an evacuation and thus estimate and evaluate this constraint.

1.6.3.2 Seeking Shelter

The local constraints on seeking shelter as a protective action, such as time to take action, cost of taking the action, and societal considerations, intuitively tend to support taking such action since the cost in each case is relatively small. However, if one compares the effect of seeking shelter with some other action such as evacuation on the basis of dose savings, it may be concluded that evacuation will save a far greater dose than seeking shelter. Generally, shelter provided by dwellings with windows and doors closed and ventilation turned off would provide good protection from inhalation of gases and vapors for a short period (i.e., one hour or less) but would be generally ineffective after about two hours due to natural ventilation of the shelter.

Not every constraint can be evaluated using established techniques; therefore, a certain amount of subjective judgment must be made on the part of the local planner. The important thing is that the local planner be aware of the constraints associated with each action and that these constraints be balanced on whatever basis possible in order

Table 1.6 Parameters Affecting the Cost of Evacuation

Area

Size of area affected
Location

Population

Number
Distribution
Makeup

Institutions

Type
Population in
Care required

Farms

Size
Type
Product values

Business and Industry

Type
Size
Work force
Product value

Mode of Travel

Number of Evacuators Required

Shelters Needed

Duration of the Evacuation

Anti-looting Efforts

to arrive at a decision.

1.6.3.3 Access Control

Access control can be a very effective protective action to avoid exposure of personnel who might otherwise enter high exposure areas unnecessarily. Whether or not it can be applied effectively at all sites will depend upon several considerations which are site specific. For example, the time required to establish the necessary roadblocks may be longer than the exposure time. The cost of maintaining the capability for roadblocks and control of access points may be prohibitive. Furthermore, personnel that would be used in maintaining roadblocks might be more effectively used for other emergency functions. All of these factors must be considered in deciding whether to plan for full or partial access control during the early phases of an incident.

1.6.3.4 Respiratory Protection

Radiation exposure from inhalation of gaseous or particulate radionuclides may be reduced by the use of respirators. These devices protect the wearer by removing radioiodines (the primary gaseous nuclide of concern) on activated charcoal and by removing particulate material by filtration. Several types of respirators are commercially available for use by adult male workers in contaminated atmospheres. However, respirators designed for women and children, i.e., the most radiation sensitive part of the population, may not be readily available. The first constraint on the use of respirators, therefore, is whether suitable devices are available. Secondly, for respirators to be

effective for the general population, they should be kept on hand by each person for immediate use upon notification and they must have been individually fitted. This means they should be distributed to the population at risk prior to a nuclear incident, and training should be provided for their use. The logistics of distributing such devices after an incident would greatly reduce their effectiveness by limiting their time of use. The cost of providing respirators for the entire population at risk is also a constraint, especially for large populations. Additional constraints include upsetting the population by acknowledging the danger with visible means and the failure of individuals to have their respirators personally available over long periods (years). Even if funding is available to provide the necessary respirators, it should be noted that use of such devices can only be a short term action of 2 to 3 hours. Therefore, they might best be used in conjunction with other protective actions such as seeking shelter or evacuation. It should also be kept in mind that respirators would not be of value where the exposure of concern was from direct radiation and not from inhalation of iodines or particulate material. Respirators may be most effective for emergency workers or other persons required to remain in evacuation zones.

1.6.3.5 Prophylaxis (Thyroid Protection)

The uptake of inhaled or ingested radioiodine by the thyroid gland may be reduced by the ingestion of stable iodine. The oral administration of about 100 milligrams of potassium iodide will result

in sufficient accumulation of stable iodine in the thyroid to prevent significant uptake of radioiodine. The main constraint in the use of this means of thyroid protection is that potassium iodide is normally administered only by prescription and would have to be distributed in accordance with State health laws. Potassium iodide as a prophylaxis is only effective if the exposure of concern is from radioiodine and only if the stable iodine is administered before or shortly after the start of intake of radioiodine. All emergency workers for areas possibly involving radioiodine contamination should receive this kind of thyroid protection, especially if appropriate respirators are not available. The cost constraint would not be significant for potassium iodide itself, but the cost for administering this material should be considered, including the cost of testing emergency workers for sensitivity to iodine prior to issue or use.

The use of stable iodine as a protective action for emergency workers has been recommended by EPA, but only in accordance with State health laws and under the direction of State medical officials as indicated above. However, the efficacy of administering stable iodine as a protective action for the general population is still under consideration by government agencies and should not be construed to be the policy of EPA at this time.

1.6.3.6 Milk Control

In order to protect the population from exposure to ingestion of contaminated milk, the planner has two basic alternative actions, which are:

- (1) Cow-feed or pasture control to prevent the ingestion of radioactive materials by dairy cattle, or
- (2) Milk control either by diverting the milk to other uses that allow the radioactivity to decay before ingestion or by destroying the milk and substituting uncontaminated milk from other areas.

The optimum action would be to prevent, through pasture and feed control, contamination of the milk. This would be followed up by milk control only in contaminated areas where pasture and feed control were not carried out or were not adequate. Local constraints may reduce the acceptability or effectiveness of these two protective actions.

The alternatives to taking these actions include:

- (1) Permitting the population to receive higher dosage.
(Thyroid cancer is generally not fatal.)
- (2) Suggest voluntary avoidance of the use of contaminated milk by children and pregnant women. (Children are more sensitive than adults because of greater intake of milk and greater concentration within the thyroid.)
- (3) Administer stable iodine as discussed earlier under thyroid protection (section 1.6.3.5).

The local constraints on the control of dairy cow feed or pasture may include the following:

- (1) A shortage of uncontaminated feed.

- (2) A shortage of personnel to carry out feed and pasture controls in evacuated areas.
- (3) The short time available to implement feed and pasture controls over a large area (possibly hundreds of square miles) may create communication problems and uncertainties as to the areas where pasture and feed control should be implemented.
- (4) The cost of the stored feed and the cost of transporting it to needed areas might be prohibitive.

Local constraints on the control of milk may include:

- (1) The shortage of nearby processing plants.
- (2) Inadequate storage capacity to wait for radioactive decay.
- (3) Objections to shipment of contaminated milk to other jurisdictions for processing.
- (4) Pollution from disposal of large volumes of milk.
- (5) Shortage of monitoring personnel and equipment for all milk producers.
- (6) Shortage of milk for critical users.
- (7) Costs associated with transporting, storage, or disposal of milk.

The dose to the thyroid of a child from drinking milk contaminated with radioiodine through the atmosphere-pasture-cow-milk exposure pathway may be hundreds of times the thyroid dose that would be received by the same child from breathing the air that caused the contamination of the pasture. Therefore, the size of the area over which milk might

have to be controlled could be much larger than the size of the area that would be evacuated to prevent inhalation of the iodine.

To avoid the problems and constraints associated with milk storage, transport, or disposal, the planner should prepare for pasture or feed control in all directions from the plant out to five times the distance planned for evacuation and in predominantly downwind directions out to about 50 to 100 miles. Controls over greater distances could be needed if the wind persisted in a single direction for an extended period. If pasture and feed control actions have been implemented (even if only partially implemented), noncontaminated milk supplies may be available at least for critical users.

All milk producers in the affected area should be restricted from using or distributing milk until monitored. If monitoring of all milk supplies is a constraint, monitoring efforts could be concentrated on milk supplies where pasture and feed control had been implemented and on the fringes of the contaminated area.

The planner can reduce the effect of constraints related to uncontaminated feed supplies and processing plants by identifying their locations and procedure for access.

Resistance by milk producers to protective actions for milk may be reduced by the planner having answers to questions regarding reimbursements of costs incurred by the producer.

1.6.3.7 Food Control

Food exposed to airborne radioactive materials may become contaminated by deposition of radiiodine and particulate material. To avoid population exposure from ingestion of these materials, the response planner should consider the following protective actions for short term protection.

- (1) Prohibition on use of potentially contaminated food such as field and orchard crops and substitution from uncontaminated supplies.
- (2) Decontamination.

The primary constraint on the use of these controls will be the availability of adequate substitute supplies at a reasonable cost. If other supplies are not available or the cost is high, then it may be necessary to implement decontamination procedures. For protection beyond a few days where availability and cost constraints would be more critical, then decontamination may be even more cost effective. The primary means of decontamination would be through washing and peeling (where appropriate) of fresh fruits and vegetables. The constraints on such procedures would be the ability to monitor the decontaminated items to assure adequate decontamination. Monitoring of food will likely be a much demanded service both by the individual farmer-consumer and by the distributor.

Other alternative controls would be to impound food stocks and store them to allow decay of radiation levels or destroy them to prevent consumption. The main constraint on these alternatives would be spoilage

and the value of the food stocks in relation to the costs of storage or destruction.

1.6.3.8 Water Control

Water may be contaminated either by direct release of radionuclides to surface waters or by deposition from an atmospheric release. Water reservoirs supplied by land surface run-off or cisterns supplied by roof run-off would be most severely affected by atmospheric deposition, whereas reservoirs supplied from streams and lakes would be most affected by contaminated liquid effluents. Spring and well water should not be affected by an accidental release of radioactive material to the atmosphere or to waterways. However, springs or wells that appear muddy after a rain might be suspect and should be monitored after a rain if they are in the area receiving heavy deposition. Some accident scenarios involve fuel melting its way into the soil, and such a condition could contaminate underground water supplies.

The protective actions for water can be either to prevent contamination or decontamination of the water supply or to condemn the use of the water for consumption.

In the case of reservoirs supplied from surface or roof run-off, prevention of reservoir contamination would not be possible unless methods existed for diverting the run-off. Reservoirs receiving their supply from a stream or lake normally are filled through pumping and filtration stations which are controlled by operators. These stations could be shut off if the source of the water supply became contaminated.

This may also be true for food processors using a stream or lake directly for their water supply. Many reservoirs supply water to municipal systems through a filtration plant. Such a plant would tend to decontaminate the water supply, and monitoring of water after filtration would provide data that should be taken into consideration in the process of deciding whether or not to condemn the supply.

The constraints associated with restrictions on supplies to reservoirs or condemnation of water systems are related to the difficulties, hardships, and costs associated with the resulting shortage of water supplies. If the planner determines that these protective actions may be appropriate for particular water systems, he should also identify the hardships that may result and plan methods for alternative supplies. These may include rationing of uncontaminated supplies, substitution of other beverages, importing water from other uncontaminated areas, and the designation of certain critical users that could be allowed to use contaminated supplies. These might be fire-water systems and process cooling systems.

1.6.3.9 Restorative Actions

A. Lifting Protection Controls

The lifting of controls for protective actions may be justified on the basis of cost savings when the corresponding health risks have been adequately reduced. For example, the costs to the public and the State in maintaining access control, pasture control, milk control, or food and water control will exceed the risk reduction value of

these controls after some period, and then the controls should be lifted. The costs for maintaining these controls will be relatively constant with respect to time while their significance in reducing risk will decrease as the source of radionuclides is halted and the released nuclides disperse or decay away. Therefore, it may be desirable to lift controls even though some additional dose may be accrued.

B. Reentry

After evacuation, persons will be allowed to reenter the zone when the potential radiation risk has been averted or reduced to guide levels for members of the general population. However, it may be necessary for certain essential personnel to return even before the dose is reduced to these guide levels. In addition, reentry may be allowed earlier for less radiosensitive persons such as adult males who may need to return to their homes or jobs. The criteria for reentry will require a balancing of remaining radiation risk such as from ground contamination and the cost of disrupted services, ~~loss of income, etc., resulting from~~ the evacuation. Time is not a constraint on reentry except as a factor in the cost of remaining out of the evacuated area.

C. Decontamination

The movement of radionuclides along several pathways involving milk, food, and water may result in prolonged contamination. Each of these elements may require processing to remove radioactive contaminants

prior to consumption. In each case, the radionuclide concentrations would be reduced to levels "as low as practicable" commensurate with treatment costs.

CHAPTER 2

Protective Action Guides for Exposure to Airborne Radioactive Materials

2.0 Introduction

Following an incident involving a release of radioactive material to the atmosphere, there may be a need for rapid action to protect the public from radiation exposure from inhalation and/or from whole body external radiation. This chapter provides Protective Action Guides (PAGs) for whole body external gamma radiation and for inhalation of radioactive material in an airborne plume. A person who is exposed to the plume of airborne radioactive materials may also be exposed at a later date from contaminated food, water, or other pathways. However, the PAGs in this chapter refer only to the exposure received directly from the airborne plume. The emergency response situation addressed in this chapter is the period from initiation of an atmospheric release until perhaps two to four days after the event occurs. During this period, the principal effort would be directed toward protection of the public from direct exposure to the plume or from inhalation of radioactive material in the plume.

It is important to recognize that the PAGs are defined in terms of projected dose. Projected dose is the dose that would be received by the population if no protective action were taken. For

these PAGs, the projected dose does not include dose that may have been received prior to the time of estimating the projected dose. For protective actions to be most effective, they must be instituted before exposure to the plume begins. PAGs should be considered mandatory values for purposes of planning, but under accident conditions, the values are guidance subject to unanticipated conditions and constraints such that considerable judgment may be required for their application.

2.1 Whole Body External Exposure

A radioactive plume will consist of gaseous and/or particulate material. Either of these can result in whole body external exposure. Measurements or calculations of environmental levels of radioactivity are usually in terms of exposure. To translate from whole body gamma exposure to whole body dose requires a correction factor of approximately 0.67. However, due to the many uncertainties in projecting dose from exposure to a plume, it is generally conservatively assumed that gamma exposure and whole body gamma dose are equivalent.

Recommended PAGs for emergency response in the case of whole body external exposure to radionuclides in the atmosphere are summarized in table 2.1. These guidelines represent numerical values as to when, under the conditions most likely to occur, intervention is indicated to avoid radiation exposure that would otherwise result from the incident. When ranges are shown, the

**Table 2.1 Protective Action Guides for Whole Body
Exposure to Airborne Radioactive Materials**

Population at Risk	Projected Whole Body Gamma Dose (Rem)
General population	1 to 5^(a)
Emergency workers	25
Lifesaving activities	75

(a) When ranges are shown, the lowest value should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations. Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action.

lowest value should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations. Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action. The rationale and technical bases for the numerical guides and their ranges are described in greater detail in Reference (4) and are summarized in Appendix C. It is recommended that anyone responsible for applying these guides in a nuclear emergency become familiar with the rationale on which the guidance was based.

2.2 Inhalation Doses

The gaseous portion of a radioactive plume may consist of noble gases and/or vapors such as radioiodines. The noble gases will not cause as much dose from inhalation as from whole body external exposure and therefore need not be considered as a separate contributor to inhalation exposure. The principal inhalation dose will be from the iodines and particulate material in the plume.

2.2.1 Exposure to Radioiodines in a Plume

Due to the ability of the thyroid to concentrate iodines, the thyroid dose due to inhaling radioiodines may be hundreds of times greater than the corresponding whole body external gamma dose that would be received. The PAGs for thyroid dose due to inhalation from a passing plume are shown in table 2.2. The technical support for their development is provided in reference (4) and is summarized in Appendix C.

Table 2.2 Protective Action Guides for Thyroid Dose
Due to Inhalation from a Passing Plume

Population at Risk	Projected Thyroid Dose rem
General population	5-25 ^(a)
Emergency workers	125
Lifesaving activities	(b)

(a) When ranges are shown, the lowest value should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations. Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action.

(b) No specific upper limit is given for thyroid exposure since in the extreme case complete thyroid loss might be an acceptable penalty for a life saved. However, this should not be necessary if respirators and/or thyroid protection for rescue personnel are available as the result of adequate planning.

2.2.2 Exposure to Particulate Material in a Plume

This section is being developed.

2.3 Interpretation of PAGs

The guides for the general population listed in tables 2.1 and 2.2 were arrived at in consideration of protection of the public from early effects of radiation and maintaining the delayed biological effects at a low probability. Consideration has been made of the higher sensitivity of children and pregnant women and the need to protect all members of the public. Consideration has also been made that personnel may continue to be exposed via some pathways after the plume passes, and that additional PAGs may have to be applied to these exposure pathways.

Where a range of values is presented, the lower guide is a suggested level at which the responsible officials should consider initiating protective action particularly for the more sensitive populations indicated above. The higher guide is a mandatory level at which the respective governmental agency should plan to take effective action to protect the general public unless the action would have greater risk than the projected dose.

At projected doses below the lower guide, responsible officials may suggest voluntary action available to the public at risk. This should be done with the philosophy that population doses be kept as low as possible as long as the effects of

action are not more hazardous than the projected dose. The concept of voluntary action and the types of action that may be considered were discussed in Chapter 1.

The need for selected populations, such as emergency response team members and persons involved in lifesaving activities, to be allowed higher exposures than the general public is in line with policies wherein these categories of individuals normally accept greater risk. Public safety and nuclear plant personnel will be essential to provide services for the public even though they may receive a greater radiation exposure.

In the event greater exposures to selected populations are required to save lives, these should be taken. However, if the radiation injury in these lifesaving activities is excessive, the harm may exceed the good, so some restrictions must be made.

Because of the variations in sensitivity of the population to radiation effects and in local conditions (weather, etc.), a range of values is recommended for the general population. Where selective protective actions (i.e. evacuation) for the general population is possible, children and women of childbearing age should be protected at the lower levels of the range. A further interpretation of the range is that plans should be made to consider organized protective action at the lower end of the range whereas it is mandatory that plans be made to implement protective action at the upper end. However, if no constraints existed, the lower range should

always be used. Since constraints exist on a local basis under different conditions, the range allows adjustment by local officials during the planning stage for special local problems as discussed in Chapter 1.

The values given for emergency workers recognize the need for some civil functions to continue in the event of an evacuation of the general population. The risks are considered to be warranted when necessary on the basis of the individual exposure and the benefits derived. In such cases, precautions should be taken to minimize exposures to emergency workers.

PAGs for lifesaving missions are given for those persons whose normal duties might involve such missions, i.e., police, firemen, radiation workers, etc. These guides would normally be limited to healthy males. No specific upper limits are given for thyroid exposure since in the extreme case, complete thyroid loss might be an acceptable penalty for a life saved. However, this should not be necessary if appropriate protective measures for rescue personnel are available as the result of adequate planning. For example, respiratory protection and/or stable iodine for blocking thyroid uptake of radiiodine should be available to the extent possible for personnel involved in lifesaving missions and other emergency actions. The issuance of stable iodine must be in accordance with state medical procedures.

CHAPTER 3

Protective Action Guides for Exposure from Foodstuffs or Water

3.1 Whole Body External Exposure

3.2 Ingestion

3.2.1 Milk

3.2.2 Food

3.2.3 Water

(Guidance to be Developed)

CHAPTER 4

Protective Action Guides
for Exposure from Material Deposited on Property or Equipment

4.1 Reentry and Release

4.2 Decontamination

4.3 Land Use

(Guidance to be Developed)

CHAPTER 5

Application of Protective Action Guides for Exposure to Airborne Radioactive Materials from an Accident at a Nuclear Power Facility

5.0 Introduction

This chapter deals with methods for estimating population dose from plume exposure based on release rates and meteorological conditions or based on offsite radiological measurements. It also provides guidance for comparison of projected dose with PAGs for decisions on protective actions. These dose projection methods are recommended for use by State and local officials for development of operational plans for responding to incidents at nuclear power facilities.

Following a radiological incident involving an atmospheric release that may require protection of the public, State authorities will need information to make decisions on what protective actions to implement and where they should be implemented. The information needed includes (1) Protective Action Guides adjusted for local situations and (2) projected doses in specific areas for comparison to the Guides. Protective Action Guides were provided in Chapter 2. Projected doses must be determined on the basis of data available following the incident. These data may come from (1) plant conditions, (2) release rates and meteorological conditions, or (3) offsite radiological measurements, or combinations thereof.

Revised 6/79

The methods presented in this Chapter for relating data at the time of the incident to projected dose are recommended for use in development of operational response plans for atmospheric releases at nuclear power facilities.

Planners are encouraged to improve on the methods where possible and to alter them as necessary to respond to special circumstances. State planners should specifically consider the use of any improved dose projection methods developed by the nuclear facility operator.

5.1 Release Assumptions

The guidance in this Chapter is directly related to releases to the atmosphere that have been postulated for nuclear power facilities. WASH-1400 (1) indicates that should there be an accident at a nuclear power station, there is an extremely wide spectrum of different kinds of possible releases to the atmosphere and different time frames for releases depending on the severity and the exact sequence of the failure modes.

A nuclear power reactor may suffer a loss of coolant but without a meltdown of the reactor core. For this class of accident, the release to the atmosphere should be mostly radioactive noble gases and iodines. Accidents of increasingly larger environmental impact would occur in association with a meltdown of the reactor core and eventual loss of containment integrity. This class of

Revised 6/79

accident could release quantities of radioactive particulate material as well as the radioactive noble gases and iodines. However, for planning purposes, it is recommended that radiiodines be assumed to represent the principal contributor to inhalation dose, and for situations where whole body dose from the plume would be the controlling exposure pathway, it should be assumed that noble gases would be the principal contributors.

Guidance on time frames for releases cannot be very specific because of the wide range of time frames that could be associated with the potential spectrum of accidents that could occur. Therefore, it will be necessary for planners to consider the possible different time periods between the initiating event and arrival of the plume and possible time periods of releases in relationship to time needed to implement protective actions. The Reactor Safety Study indicates, for example, that major releases may begin in the range of one-half hour to as much as 30 hours after an initiating event and that the duration of the releases may range from one-half hour to several days with the major portion of the release occurring within the first day. In addition, significant plume travel times are associated with the most adverse meteorological conditions that might result in large potential exposures far from the site. For example, under poor dispersion conditions associated with low windspeeds, two hours or more might

Revised 6/79

be required for the plume to travel a distance of five miles. Higher windspeeds would result in shorter travel times but would provide more dispersion, making high exposures at long distances much less likely. Additional information on time frames for releases may be found in Reference (7).

5.1.1 Radioactive Noble Gas and Radioiodine Releases

For an atmospheric release at a nuclear power facility that involved only noble gases and radioiodines, it would usually be conservative to assume that 100 percent of the equilibrium noble gas inventory and 25 percent of the equilibrium radioiodine inventory¹ would be available for release from containment. In the absence of more accurate information from the facility operator regarding the release composition, it should be assumed that this composition is released to the environment. The relative abundance of radioiodines and noble gases in an actual release from containment would be a function of the effectiveness of engineered safeguards (e.g., filters, spray systems, and scrubbing systems) in removing each component.

¹This assumption is in agreement with NRC guidance (2,5,6) on assumptions that may be used in evaluating the radiological consequences of a loss of coolant accident at a light water cooled nuclear power facility.

Revised 6/79

Table 3.1 of Appendix D summarizes the total quantities of radiologically significant gaseous radionuclides that would be in inventory under equilibrium conditions for a 1000 MWe plant. Calculations of the projected population dose based on a release mixture consisting of 100% of the noble gases and 25% of the radioiodines indicate that the thyroid dose from inhalation of radioiodine ranges up to 400 times greater than the whole body gamma dose from noble gases and radioiodines. However, if the engineered safeguards function as designed, they should reduce the iodine concentration such that the whole body gamma radiation exposure from noble gases would be the controlling pathway.

5.1.2 Radioactive Particulate Material Releases

Except for the most severe and improbable accidents postulated by WASH-1400, protective actions (prophylaxis iodine excepted) chosen on the basis of assuming the iodine exposure pathway is critical (figure 5.2) should be sufficient to provide protection from radioactive particulate material. This particulate material will deliver an additional dose to the lung and to the whole body from material located in the lung. However, it is not anticipated that lung exposure would represent the controlling exposure pathway for accidents at nuclear power facilities.

5.2 Sequence of Events

Following an incident at a nuclear power facility involving a release to the atmosphere, the most urgent protective actions in terms of response time will be those needed to protect the

Revised 6/79

population from inhalation of radioactive materials in the plume and from direct whole body exposure to gamma radiation from the plume. The time of exposure to the plume can be divided into two periods; (1) the period immediately following the incident when little or no environmental data are available to confirm the seriousness of population exposures, and (2) a period when environmental levels and/or concentrations are known. During the first period, speed for completing such actions as evacuation, seeking shelter, and access control may be critical to minimize exposure in areas where PAGs are postulated to be exceeded. Furthermore, environmental measurements made during this period may have little meaning because of uncertainty concerning plume location when measurements were made or uncertainty concerning changes in release rate due to changes in pressure and radionuclide concentrations within containment. Therefore, it would generally be advisable to initiate early predetermined protective actions on the basis of dose projections provided by the facility operator. During the second period when environmental levels are known, these actions can be adjusted as appropriate.

For accidents involving a release to the atmosphere at a nuclear power facility, the following sequence of events is suggested to minimize population exposure.

Revised 6/79

- (1) Notification by the facility operators that an incident has occurred with potential to cause offsite projected doses that exceed the PAGs. This notification should be provided as soon as possible following the incident and prior to the release if possible.
- (2) Immediate evacuation or shelter of populations in predesignated areas without waiting for confirming release rate measurements or environmental radiation measurements.
- (3) Monitor gamma exposure rates (and iodine concentrations if possible) in the environment. The facility operator should monitor release rates and plant conditions.
- (4) Calculate plume centerline exposure rate at various distances downwind from the release point, or use prepared isopleths to estimate exposure rates in downwind areas.
- (5) Use exposure rates, airborne concentrations, and estimated exposure duration to convert to projected dose.
- (6) Compare projected dose to PAGs and adjust areas for protective actions as indicated.
- (7) Continue to make adjustments as more data become available.

5.2.1 Accident Notification

The first indication that a nuclear accident has occurred should come to State authorities from the facility operator. The notification from a nuclear power facility to the State and local

Revised 6/79

response organizations should include an estimate of the projected dose to the population at the site boundary and at more distant locations along with estimated time frames. The State emergency response planners should make arrangements with the facility operator to assure this information will be made available on a timely basis (within 1/2 hour or less following the incident and prior to the start of the release) and that it will be provided in units that can be compared to PAGs (i.e., projected dose in rem to the whole body or thyroid).

5.2.2 Immediate Actions

The Planning Basis (7) recommends that States designate an Emergency Planning Zone (EPZ) for protective actions for plume exposure out to about 10 miles from a nuclear power facility. Within this distance it may also be practical to plan an area for immediate response prior to the availability of information for making dose projections. This could be a circular area described by a designated radial distance from the facility. Actions would be taken within approximately a 90 degree sector downwind out to the designated distance based on notification from the facility operator that plant conditions exist which present a potential for offsite doses in excess of the PAGs. The remaining area out to the EPZ would be placed on alert pending more information. When additional information or forecasts on wind direction and meteorology became available, decisions could be made on additional areas for

Revised 6/79

protective actions. With good meteorological and wind direction information, it might be possible to reduce the width of the sector for protective actions. However, if wind direction is variable or if the start of the release is delayed, or if the release duration is long, the width of the sector may increase or possibly extend to a complete circle. The importance of good information and forecasts on wind direction cannot be overemphasized.

The designated distance for immediate actions would be used only in situations where the facility operator could not estimate offsite projected doses. If the facility operator provides projections of population dose, then these should be used by the State to determine the downwind distance for immediate action in lieu of the predesignated distances. The outer edge of the low population zone is a suggested radial distance for immediate actions in the absence of reasons for other distances.

5.3 Establishment of Exposure Rate Patterns

During or following initial actions to protect the close-in population, environmental exposure rate measurements should be made to provide a data base for projecting dose and for reevaluating the need for additional protective actions or termination of those actions already taken. Planning guidance for the collection of these data is provided in Appendix A. (Note: Appendix A is still under development. Reference (8) will form the basis for Appendix A and is recommended as an alternate source of information.)

Revised 6/79

After obtaining exposure rates or concentrations at selected locations in the environment, these must be translated to additional locations to identify the pattern of the exposed area. Exposure rate patterns based on a few downwind measurements can be estimated in a variety of ways. One simple way is to measure plume centerline exposure rate² at ground level at some known distance from the release point and use these data to calculate exposure rates at other designated distances downwind by assuming that the cloud centerline exposure rate is inversely proportional to the distance from the release point.

The following relationship can be used for this calculation:

$$D_2 = D_1 \left(\frac{R_1}{R_2} \right)^x$$

Where: D_1 = exposure rate measured at distance R_1

D_2 = exposure rate at distance R_2

x = rate of diffusion as a function of distance.

This relationship can be used to develop a crude pattern of estimated exposure rates by assuming that $x = 1.5$ and that the

²The centerline exposure rate can be determined by traversing the plume at a point sufficiently far downwind (usually greater than one mile from the site) while taking continuous exposure rate measurements. The highest reading should be at the center-line of the plume.

Revised 6/79

exposure rate calculated for the plume centerline would also exist at 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.

A second and easier method for estimating exposure rate patterns is to use a series of prepared exposure rate isopleths (maps with lines connecting points of equal exposure rates) plotted on transparencies. These isopleth plots are frequently available from the licensee, thus eliminating the need for the State to develop them. Since both the meteorological stability class and the windspeed existing at the time of the release affect the shape of the exposure rate isopleth curves, several sets of curves would be needed to represent the variety of stability conditions and windspeeds likely to exist at that site. The appropriate transparency can be selected on the basis of windspeed and meteorological conditions at the time of the incident. The transparency can then be placed over a map of the area that has the same scale as the isopleth curves such that the curves are properly oriented with regard to wind direction. The isopleth curves are

³The value of 1.5 for x is for average meteorological conditions. If the meteorological stability condition is known, it would be more accurate to use x = 2 for stability classes A and B; x = 1.5 for classes C and D; and x = 1 for classes E and F.

Revised 6/79

used to estimate exposure rate by plotting the exposure rates known at specific locations on the curves. Exposure rates at other locations are simple multiples of the known exposure rates as indicated by the multipliers associated with each curve.

A third alternative for determining exposure rate patterns is to obtain gamma exposure rate measurements at a large number of locations and plot these data on a map of the area. This method would provide the most accurate data but would require a large number of radiation instruments and trained persons to make the measurements as well as a method for communicating the data to the control center on a continuing basis. This method is primarily recommended for developing information for determining the need to revise previous protective action recommendations. Protective actions for plume exposure should be taken prior to plume arrival, if possible.

5.4 Dose Projection

The projected dose (or dose commitment in the case of inhaled radionuclides) should be calculated only for the early phase of an emergency. Early phase includes the duration of the plume exposure for inhalation PAGs and up to 2 to 4 days following the accident for whole body exposure. Exposures that may have occurred before the dose projection is made are not normally to be used for evaluating the need for protective actions. Radiation doses that might be

Revised 6/79

received at later times following an accident also should not be included within the projected dose for this guidance. These latter doses, which may be from reentry operations, food pathways, or long term groundshine are committed over a longer time period and will require different kinds of protective actions. Therefore, they will require separate guidance recommendations to be addressed in subsequent chapters.

The best method for early determination of the need for protective actions immediately following an incident and prior to the start of the release is for the facility operator to estimate potential offsite dose based on information in the control room using relationships developed during the planning stage that relate abnormal plant conditions and meteorological conditions to potential offsite doses. After the release starts and the release rate is measurable and when plant conditions or instrumentation can be used to estimate the characteristics of the release and release rate as a function of time, ~~then these factors, along with meteorological~~ conditions and windspeed and direction, can be used with techniques presented here to estimate projected dose. Projected dose can also be determined on the basis of environmental measurements when these are available. Procedures are provided herein to use either release rates or environmental measurements to project dose. Supporting documentation for the procedures is provided in Appendix D.

Revised 6/79

5.4.1 Duration of Exposure

Dose projection is a function of the time integrated exposure rate or of the time integrated concentration. Although exposure rate would most likely vary with time, this relationship cannot be predicted. For purposes of these calculations, exposure rate is assumed to be constant over the exposure period. Therefore, projected dose becomes a product of exposure rate, duration of exposure, and a dose conversion factor.

The time period of exposure may be difficult to predict. Exposure would start at a particular site when the plume arrived and would be ended by a change in wind direction or by an end to the release. 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 the incidents in addition to information received from the facility operator. If neither wind change nor the time until the end of the release can be predicted, the period of exposure could be conservatively assumed to be equal to the 99% probable maximum duration of wind direction persistence for that site and for existing meteorological stability conditions. Historical data on wind direction persistence as a function of atmospheric stability class for a particular site are available in the Final Safety Analysis Report prepared by the facility operator.

Revised 6/79

5.4.2 Whole Body Dose Projection

Having established exposure rate patterns in the environment and having determined (or estimated) the time period of exposure, the next task is to estimate the projected whole body and thyroid dose to members of the population so that the projected dose can be compared with appropriate PAGs.

An airborne release from a light water reactor would be expected to consist primarily of radioactive noble gases and iodines. If engineered safeguards operate as designed, they may reduce iodine concentrations to levels such that the whole body gamma radiation dose from noble gases will be the controlling pathway. Otherwise, the controlling pathway will be inhalation of radiiodines resulting in committed thyroid dose ranging up to hundreds of times the whole body gamma dose depending on the effectiveness of the engineered safeguards.

To avoid the necessity for calculating projected dose at the time of the incident, it is recommended that dose projection nomograms be developed. Figures 5.1 and 5.2 (pages 5.17 and 5.19) are examples of such nomograms. Appendix D provides details regarding their development. Other shortcut dose projection methods may have been developed by the facility operators that are fully as accurate as these methods and should be used if appropriate.

Revised 6/79

The projected whole body gamma dose can be estimated by simply multiplying the gamma exposure rate at a particular location by the time period of exposure. (The dose conversion factor is assumed to be 1). Figure 5.1 provides this multiplication. This figure also provides a relationship between exposure rate in mR/hr and the noble gas concentration based on the mixture of radioactive noble gases that would be expected to exist at about 4.5 hours after shutdown. If the noble gases have decayed for a longer time, these curves would significantly overestimate the projected dose as determined from concentrations and exposure time. If the gamma exposure rate from a semi-infinite cloud of airborne noble gases is to be determined from known mixtures other than those assumed, the following relationship may be used:

$$R = 9 \times 10^5 \sum_1^n C_n E_n$$

where: R = exposure rate (mR/hr)

C_n = concentration in air (Ci/m³) for radionuclide "n"

E_n = average gamma energy per disintegration (MeV) for radionuclide "n". See table 3.1 of Appendix D for values of E for specific radionuclides.

9×10^5 = a dimensionless constant.

Revised 6/79

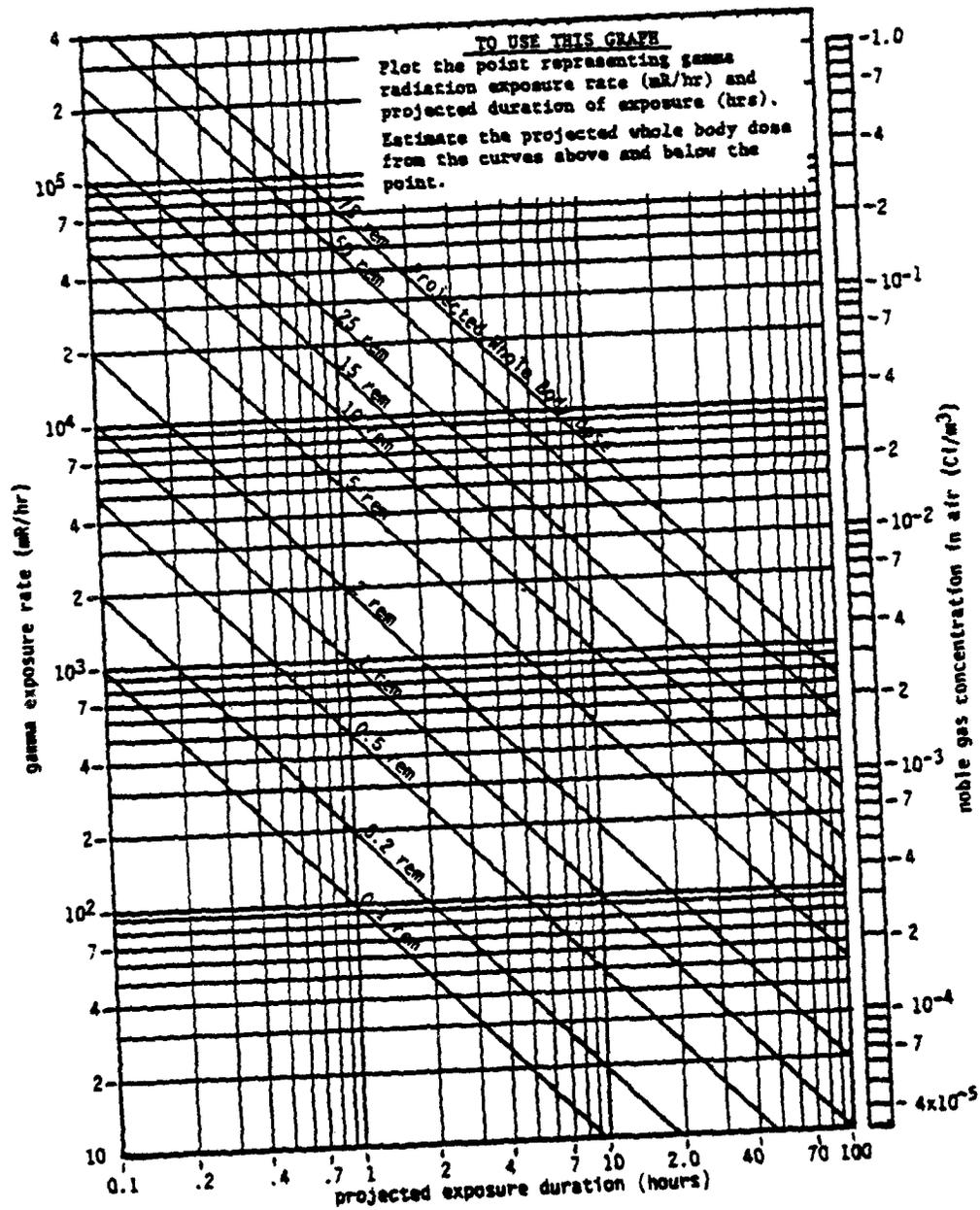


Figure 5.1 Projected whole body gamma dose as a function of gamma exposure rate and projected duration of exposure.

Copy available to DTIC does not
permit fully legible reproduction

This equation is the familiar expression for gamma exposure rate from a semi-infinite cloud, $R = .25E$, with the units for R changed from R/sec to mR/hr.

5.4.3 Thyroid Dose Projection

Thyroid dose commitment from inhalation is primarily a function of the concentrations of radioactive iodines in the air integrated over the duration of exposure. This section provides techniques for projecting the thyroid dose using a variety of types of data that may be available. The bases for these techniques are provided in Appendix D.

The basic data, concentration of iodines in the air and duration of exposure, may be obtained from a variety of sources. The concentration may be measured either as gross iodines or as specific isotopes. The concentration may also be calculated based on release rates and characteristics and meteorological conditions or based on measured gamma exposure rates. The duration of exposure may be predicted as discussed in section 5.4.1.

Figure 5.2 provides a family of curves for projected thyroid dose as a function of airborne concentration (right ordinate) and duration of exposure (abscissa).

To estimate projected thyroid dose for a particular site, plot the point on figure 5.2 corresponding to the radioiodine concentrations in Ci/m^3 and the expected time period of exposure for persons at that location. Using a logarithmic interpolation,

Revised 6/79

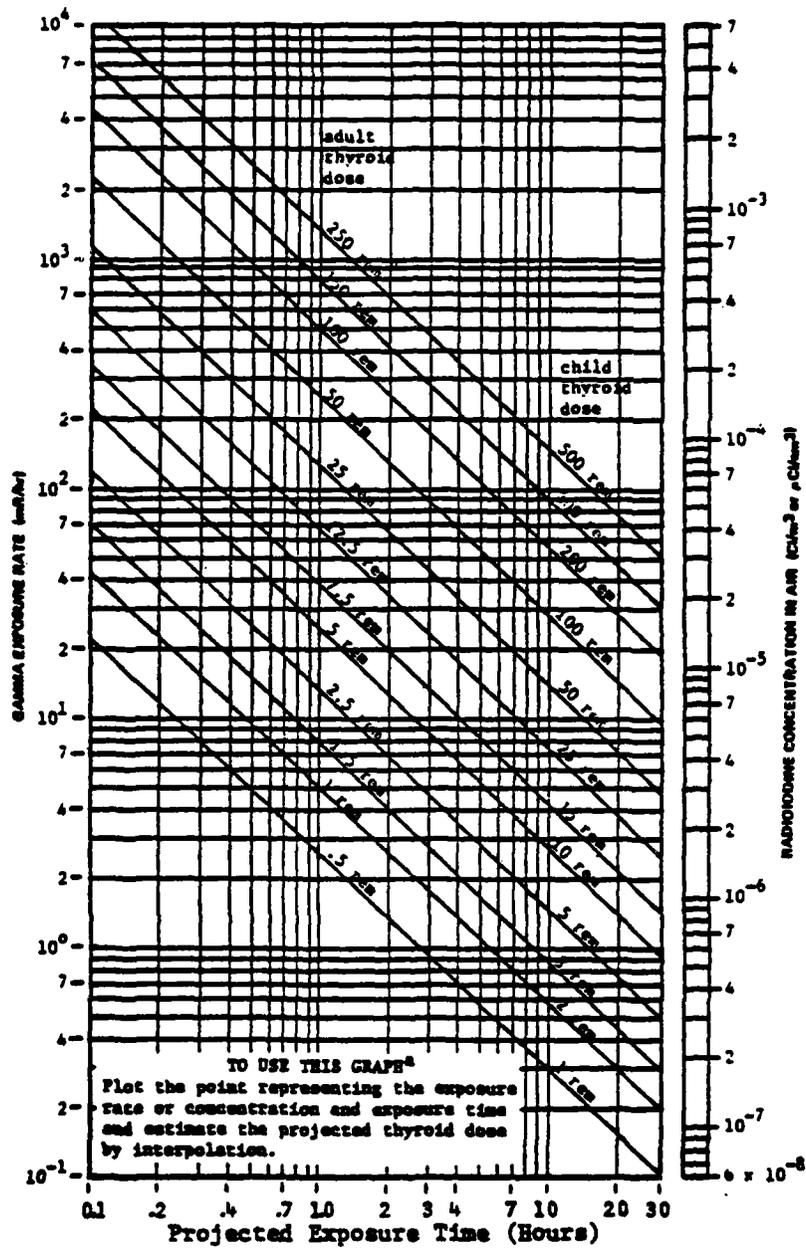


Figure 5.2 Projected thyroid dose as a function of either gamma exposure rate, or radioiodine concentration in air and the projected exposure time.

estimate the projected thyroid dose from the dose values on the curves below and above the point. For example, if the iodine concentration is 10^{-5} Ci/m³ and is expected to last two hours, then the projected adult thyroid dose would be approximately 6 rem, and the child thyroid dose would be approximately 12 rem. Note that the child thyroid dose is two times the adult thyroid dose. The child dose would apply to general populations while the adult dose would apply to emergency teams or to other adults.

Dose conversion factors to convert from time integrated airborne concentrations to projected dose would vary as a function of the time after reactor shutdown that concentrations were determined. The dose conversion factors for iodine concentrations used in figure 5.2 are based on a mix of radioiodines that would be expected to exist at about 4 hours after reactor shutdown. If the concentration were determined at some other time, the dose conversion factor (and thus the projected dose) would be in error. This error would be less than 30% for measurements made in the range of 1 to 12 hours as shown in figure 4.4 of Appendix D. This error is considered too small to justify the use of a correction factor, but figure 4.4 from Appendix D could be used for this purpose, if desired.

Air samples would provide the best source of concentration data for use in figure 5.2. However, with present day equipment, field measurements of environmental radioiodine concentrations may be

Revised 6/79 .

difficult and too time consuming for quick decisions on implementation of protective actions. In the absence of measured iodine concentrations in air, one may calculate the concentrations based on release rates and meteorological conditions or based on gamma exposure rate measurements in the environment.

5.4.3.1 Concentrations Based on Release Rates

If information is available on the total curies released or on the release rate and duration of release, one can use these data with meteorological information to calculate concentrations at specific locations downwind. Similarly, this information can be used to determine the downwind distance at which a particular concentration would occur. These methods are discussed below.

Figure 5.3 provides the atmospheric dilution factor, $\chi\bar{U}/Q$, as a function of downwind distance and for different atmospheric stability classes. This factor is the concentration (χ) in Ci/m³ that would exist for an average windspeed (\bar{U}) of 1 m/sec and for a release rate (Q) of 1 curie/sec. To find the downwind concentration (χ) for a specific windspeed and release rate, divide the value of $\chi\bar{U}/Q$ by the windspeed in m/sec and multiply by the release rate in Ci/sec.

To find the projected thyroid dose associated with a particular concentration, find the point corresponding to the concentration and the estimated duration of exposure on the nomogram in figure 5.2. Interpolate logarithmically between the dose lines as necessary.

Revised 6/79

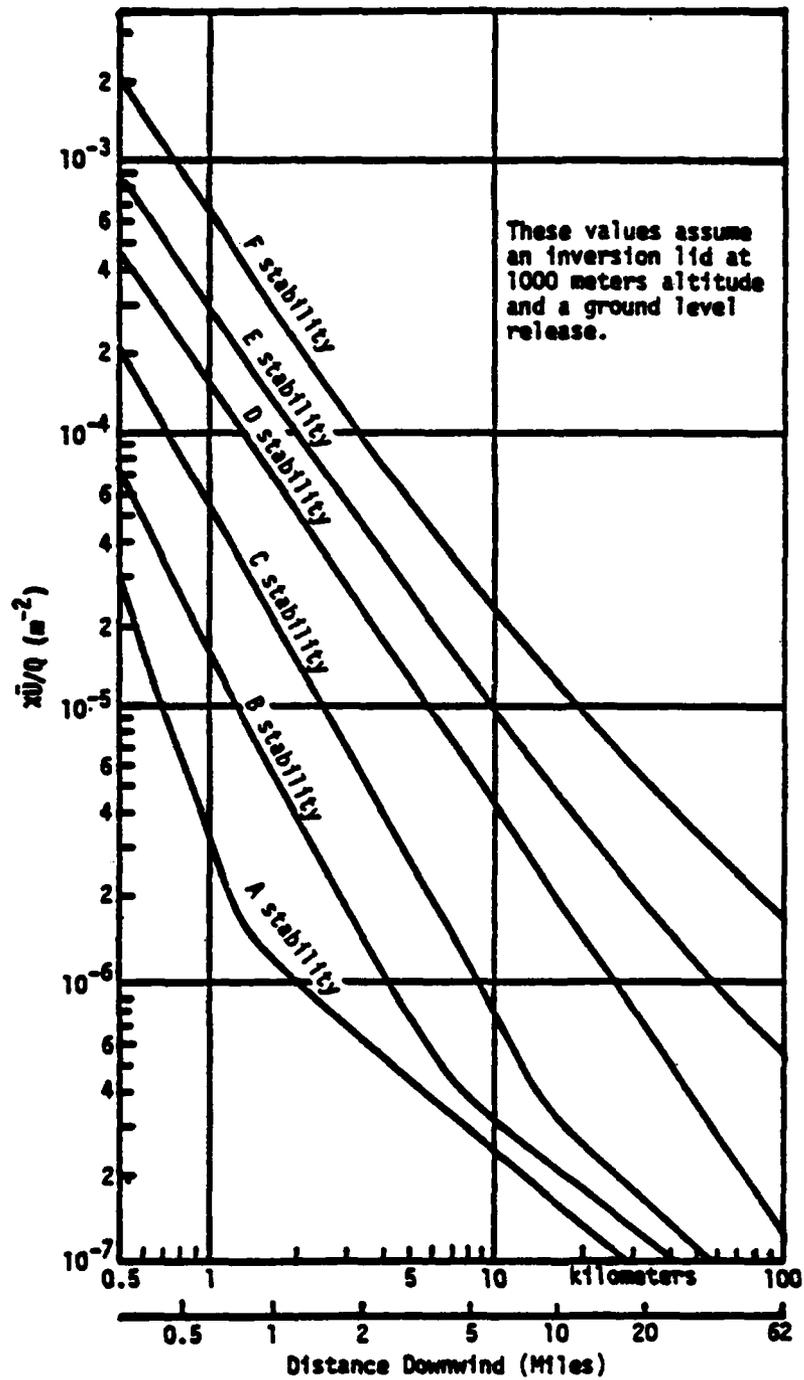


Figure 5.3 Typical values for $\bar{x}\bar{U}/Q$ as a function of atmospheric stability class and downwind distance

If the release is expressed in total curies as opposed to Ci/sec, any release period can be assumed for purposes of using figure 5.2 to estimate the projected dose. Assuming a release period of one hour, the total release in curies can be converted to release rate in Ci/sec by dividing by 3600 sec/hr.

A more common problem may be to determine the downwind distance at which a particular dose would occur. The following steps would be appropriate for solving this problem.

1. From figure 5.2 (page 5.19) determine the iodine concentration in Ci/m^3 that would cause the thyroid dose of concern for the estimated duration of the exposure.

2. Multiply this concentration " χ " by the windspeed " \bar{U} " in m/sec and divide by the release rate " Q " in Ci/sec. This provides a dilution factor, $\chi\bar{U}/Q$ (m^{-2}), which can be applied in figure 5.3 (page 5.22).

3. Using figure 5.3, follow the value for $\chi\bar{U}/Q$ across to the existing stability class and follow this point down to find the corresponding distance. This is the downwind distance where the dose of concern should occur at the plume centerline.

Example Problem

Assume an accident involves a puff release of 20,000 curies of iodines. The release occurs at two hours after reactor shutdown, the windspeed is 8 mph = 4 m/sec, and the atmospheric stability class is D. Determine the downwind distance at which the projected dose would be 5 rem to the child thyroid.

Revised 6/79

Solution

Since no duration of exposure was given, one can assume one hour = 3600 seconds for purposes of calculations.

From figure 5.2 (page 5.19) note that the concentration, X , corresponding to a 5 rem dose to the child thyroid from a one hour exposure would be about 8×10^{-6} Ci/m³.

The release rate, Q , can be assumed to be

$$\frac{20,000 \text{ curies}}{3,600 \text{ seconds}} = 5.5 \text{ Ci/sec}$$

Therefore:

$$\frac{XU}{Q} = \frac{8 \times 10^{-6} \text{ Ci/m}^3 \times 4 \text{ m/sec}}{5.5 \text{ Ci/sec}} = 5.8 \times 10^{-6} \text{ m}^{-2}$$

From figure 5.3 (page 5.22) the distance corresponding to a dilution factor of $5.8 \times 10^{-6} \text{ m}^{-2}$ under stability class D is about 8 Km or 5 miles.

5.4.3.2 Concentrations Based on Gamma Exposure Rate Measurements

If environmental concentrations of radioiodines are determined from air samples at selected locations, it would be useful to obtain simultaneous average gamma exposure rate measurements at the same locations in accordance with recommendations of the Task Force on Instrumentation (8). The ratio of gamma exposure rate to iodine

Revised 6/79

concentration should be approximately constant for different locations if the measurements are not spread out over more than about 2 hours. The process of collecting and analyzing a few air samples and estimating concentrations based on gamma exposure rate measurements at other locations could save considerable monitoring time.

If no air sample measurements are available, it is possible to obtain a crude estimate of radioiodine air concentrations from gamma exposure rate measurements. Because of the large potential for errors, this would be the last choice of methods for estimating airborne iodine concentrations.

The left ordinate in figure 5.2 (page 5.19) provides a relationship between the gamma exposure rate from airborne radioactive noble gases plus iodines and the radioiodine concentration (right ordinate) that would contribute to this dose. This relationship changes with the ratio of iodines to noble gases in the release, the atmospheric stability class, time after shutdown, the gamma exposure coming from material already deposited on surfaces, and the gamma exposure from airborne particulate material.

Because of the assumptions that were made in the development of figure 5.2, its use to estimate thyroid inhalation dose solely on the basis of gamma exposure rates without confirmatory concentration

Revised 6/79

measurements or without correction factors would generally result in projected thyroid doses higher than those that would actually occur. The relationships in figure 5.2 between gamma exposure rate and iodine concentration are based on the following assumptions:

1. The ratio of concentrations of iodines to noble gases would be about 0.3 which is the ratio that corresponds to a mixture consisting of 25% of the iodines and 100% of the noble gases in a nuclear power reactor at full power equilibrium conditions. Figure 5.4 provides correction factors that can be multiplied times the gamma exposure rate before its use in figure 5.2 in situations where actual values are provided for iodine to noble gas activity ratio.

2. The atmospheric stability class would be "A". Figure 5.5 provides correction factors as a function of downwind distance and atmospheric stability class for use in situations where these data are known.

3. Measurements would be made within the range of 1 to 12 hours after reactor shutdown. Concentrations based on measurements made during the first 4 hours after shutdown would be slightly lower than estimated, thus causing a conservative dose estimate. Concentrations based on measurements made 6 or more hours after the reactor shutdown would produce low dose estimates. However, this nonconservative error would be somewhat compensated by the conservative error introduced by the assumption that there would be

Revised 6/79

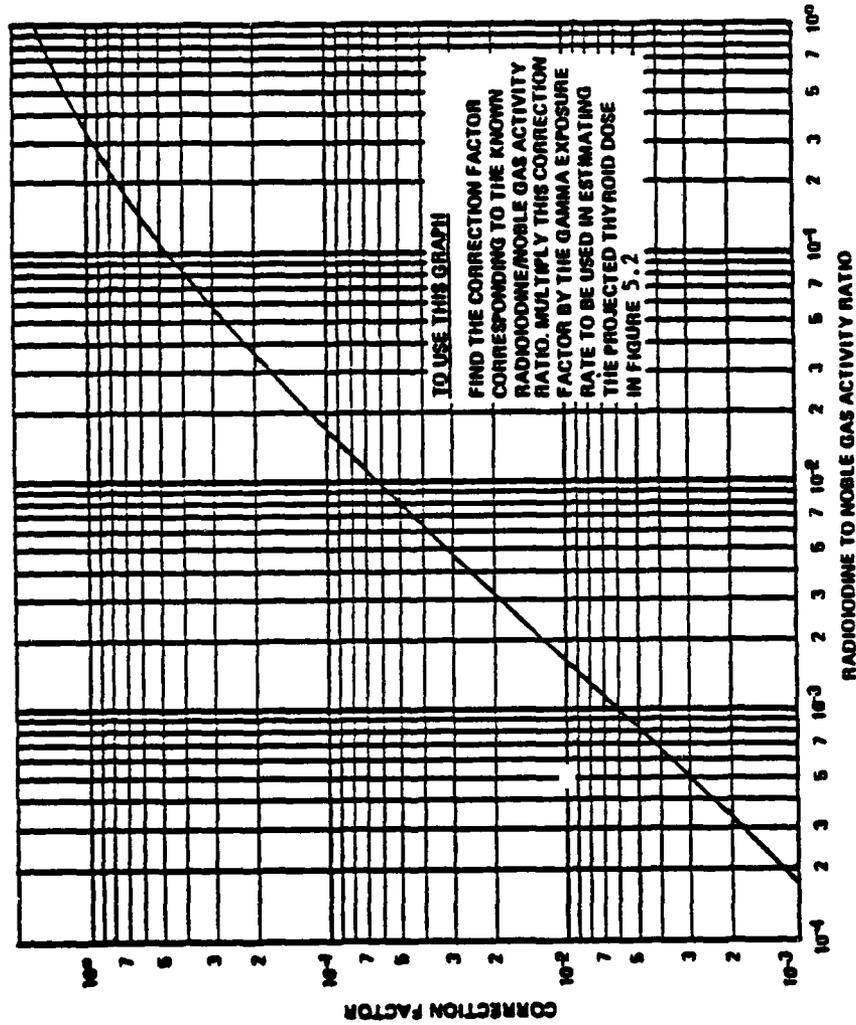


Figure 5.4 Radioiodine release correction factor

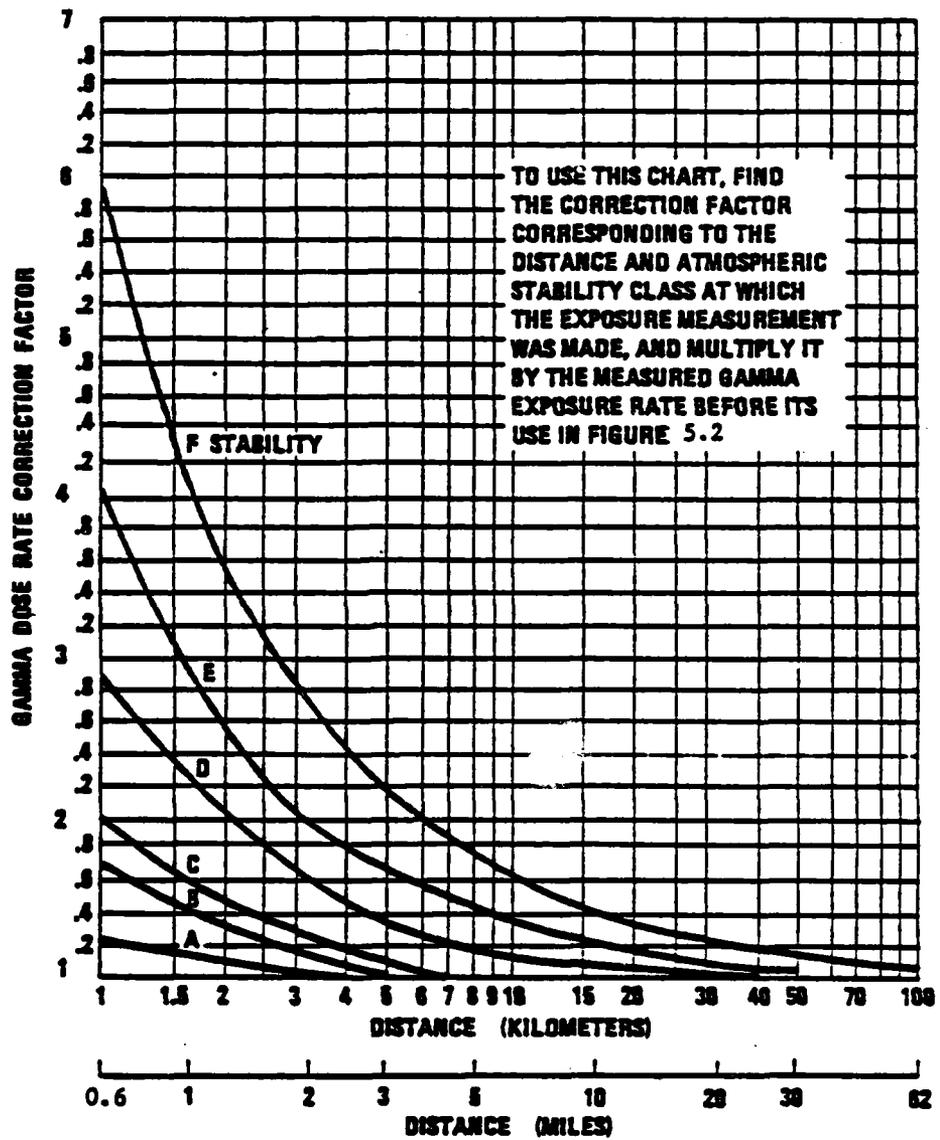


Figure 5.5 Gamma exposure rate finite cloud correction factor.

no contribution to gamma exposure rate from radiiodines deposited on the ground. Both of these errors would increase in intensity with time after the start of the release.

Caution should be exercised in this method of estimating thyroid dose to avoid projecting thyroid inhalation doses on the basis of gamma exposure coming entirely from deposited material after the plume has passed. For this situation the gamma exposure rate would increase as the detector approached the ground.

Example Problem

No iodine concentration measurements have been made, but gamma exposure rate measurements indicate maximum levels of 10 mR/hour at 2 miles downwind. The stability class is D, and the nuclear utility reports the iodine to noble gas ratio in the release is 0.1. What is the projected child thyroid dose for a 2 hour exposure?

Solution

Referring to figure 5.2 (page 5.19) the projected dose without correction factors for 10 mR/hr and 2 hours is about 8 rem to the child thyroid. From figure 5.5 (page 5.28) the correction factor for D stability and 2 miles = 1.6. From Figure 5.4 (page 5.27) the correction factor for iodine to noble gas ratio of 0.1 = 0.45.

$10 \text{ mR/hr} \times 1.6 \times .45 = 7.2 \text{ mR/hr}$. Referring to figure 5.2, the corrected thyroid dose is projected to be slightly more than 5 rem for a 2 hour exposure.

Revised 6/79

5.5 Protective Action Decisions

The most effective protective actions for the plume exposure pathway are evacuation and shelter. Access control is also effective and appropriate but generally would be taken in conjunction with one of the other two actions. When contamination of the skin is suspected, protective actions such as washing and changes of clothing are justified without the need for planned procedures because these actions are easy to take and involve little or no risk. Chapter 1 provides a general discussion of protective actions, and Appendix B will provide planning guidance with regard to evacuation and shelter. (Appendix B has not been published as of this revision).

After dose projections are made and constraints are identified, responsible officials must decide what protective actions should be implemented and in what areas. They must also decide which of the emergency actions that were taken prior to having release information from the facility or environmental measurements should be expanded, maintained, or canceled.

Table 5.1 provides broad guidance for these decisions on the basis of comparing projected doses to PAGs. This guidance is primarily for planning purposes. Acceptable values for emergency doses to the public under actual conditions of a nuclear accident cannot be predetermined. Protective action recommendations in any individual case must be based on the actual conditions that exist and are projected at the time of the accident.

Revised 6/79

Table 5.1 Recommended protective actions to reduce whole body and thyroid dose from exposure to a gaseous plume

Projected Dose (Rem) to the Population	Recommended Actions (a)	Comments
Whole body <1 Thyroid <5	No planned protective actions. (b) State may issue an advisory to seek shelter and await further instructions. Monitor environmental radiation levels.	Previously recommended protective actions may be reconsidered or terminated.
Whole body 1 to <5 Thyroid 5 to <25	Seek shelter as a minimum. Consider evacuation. Evacuate unless constraints make it impractical. Monitor environmental radiation levels. Control access.	If constraints exist, special consideration should be given for evacuation of children and pregnant women.
Whole body 5 and above Thyroid 25 and above	Conduct mandatory evacuation. Monitor environmental radiation levels and adjust area for mandatory evacuation based on these levels. Control access.	Seeking shelter would be an alternative if evacuation were not immediately possible.
Projected Dose (Rem) to Emergency Team Workers		
Whole body 25 Thyroid 125	Control exposure of emergency team members to these levels except for lifesaving missions. (Appropriate controls for emergency workers, include time limitations, respirators, and stable iodine.)	Although respirators and stable iodine should be used where effective to control dose to emergency team workers, thyroid dose may not be a limiting factor for lifesaving missions.
Whole body 75	Control exposure of emergency team members performing lifesaving missions to this level. (Control of time of exposure will be most effective.)	

(a) These actions are recommended for planning purposes. Protective action decisions at the time of the incident must take existing conditions into consideration.

(b) At the time of the incident, officials may implement low-impact protective actions in keeping with the principle of maintaining radiation exposure as low as reasonably achievable.

PAGs cannot be used to assure that a given level of exposure to individuals in the population is prevented. In any particular response situation, a range of doses may be experienced, depending mostly on the distance from the point of release. Some of these doses may be in excess of the PAG levels and clearly warrant the initiation of any feasible protective actions. This does not mean, however, that all doses above PAG levels can be prevented. Furthermore, PAGs represent only trigger levels and are not intended to represent acceptable dose levels. PAGs are tools to be used in planning and as decision aids in the actual response situation for purposes of dose savings.

Under emergency conditions all reasonable measures should be taken to minimize radiation exposures to the general public and to emergency workers. In the absence of significant constraints and in consideration of the generally accepted public health practice of limiting radiation exposures to as low as reasonably achievable levels, responsible authorities may want to implement low impact protective actions at projected doses below the PAGs.

The recommendations provide a range of PAG values because implementation of the guidance will always require the use of good judgment and a consideration of local constraints. The lowest value should be used if there are no major local constraints in providing protection at that level, especially to sensitive populations.

Revised 6/79

Local constraints may make lower values impractical to use, but in no case should the higher value be exceeded in determining the need for protective action. The question inevitably arises, then, at what projected dose below the minimum PAG values should protective actions no longer be considered. This is a value judgment on the part of the emergency coordinator but should be based on the following considerations:

a. Are the risks associated with taking protective action at low projected doses greater than the risks associated with the low projected radiation doses?

b. Is there a reasonable probability that the protective action being considered can be successfully implemented without unreasonable cost or hardship on the participants?

c. At very low projected doses, efforts to protect the population may do more harm than good.

The intent is to allow for flexibility in the implementation of the guidance because local conditions will vary and because special information may be available. But above the upper PAG range, there is significant risk to the exposed populations, and responsible agencies should consider it mandatory to plan to implement effective protective actions, recognizing that when an accident actually occurs, unforeseen conditions or constraints may prevail such that professional judgment will be required with regard to priorities for protecting the public.

Revised 6/79

Guidance for emergency workers is given as dose limits because it is recognized that critical civil functions must continue while protective actions are taken for the general population, and this may require emergency workers to receive radiation exposures during emergencies that otherwise would not be permitted. Exposure of emergency workers to any dose level is not justified unless it is determined that benefits to society are being achieved and efforts are being made to limit their doses to levels as low as reasonably achievable. Emergency workers should consist of healthy adults and should not include women that could potentially be pregnant.

Emergency response planning should provide for specialized protection for emergency workers during emergency activities. This would include respiratory protection, if needed, to reduce internal organ and thyroid doses from inhalation and perhaps prophylactic drugs that prevent thyroid exposures from inhaled radioiodine. There should be appropriate instrumentation to verify exposures and communication techniques to prevent overexposures by warning emergency workers when to withdraw from radiation fields.

The health risk associated with dose limits recommended for lifesaving missions are extremely high, and such high doses should be received only on a voluntary basis by individuals aware of the risks involved. Lifesaving actions should be performed by persons in good health whose normal duties have trained them for such missions.

Revised 6/79

REFERENCES

- (1) U.S. NUCLEAR REGULATORY COMMISSION. An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. (WASH-1400), U.S. Nuclear Regulatory Commission, Washington, D.C., October 1975.
- (2) U.S. NUCLEAR REGULATORY COMMISSION. Guide and Checklist for the Development and Evaluation of State and Local Government Radiological Emergency Response Plans in Support of Fixed Nuclear Facilities (WASH-1293). U.S. Nuclear Regulatory Commission, Washington, D.C. December 1974.
- (3) HANS, JOSEPH M., JR., AND THOMAS C. SELL. Evacuation Risks - an Evaluation (EPA-520/6-74-002). U.S. Environmental Protection Agency, Washington, D.C. June 1974.
- (4) NELSON, W. S. Approaches to Population Protection in Case of Nuclear Accidents. U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C. (Draft, December 1974).
- (5) U.S. ATOMIC ENERGY COMMISSION. Regulatory Guide 1.3. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors. Directorate of Regulatory Standards, Nuclear Regulatory Commission, Washington, D.C. June 1973.
- (6) U.S. ATOMIC ENERGY COMMISSION. Regulatory Guide 1.4. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors. Directorate of Regulatory Standards, Nuclear Regulatory Commission, Washington, D.C. June 1973.
- (7) U.S. NUCLEAR REGULATORY COMMISSION AND U.S. ENVIRONMENTAL PROTECTION AGENCY. Task Force Report. Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants, NUREG-0396 or EPA-520/1-78-016, Washington, D.C. 20460, November 1978.
- (8) U.S. NUCLEAR REGULATORY COMMISSION. Interim Guidance on Offsite Radiation Measurement Systems, A Report to Developers of State Radiological Emergency Response Plans by the Federal Interagency Task Force on (offsite) Emergency Instrumentation for Nuclear Incidents at Fixed Facilities, U.S. Nuclear Regulatory Commission, Washington, D.C., August 1977

Revised 6/79

CHAPTER 6

Application of PACs for Foodstuffs and Water Contamination

6.1 Relocation

6.1.1 Whole Body

6.1.2 Organ Exposure

6.2 Shelter

6.2.1 Whole Body

6.3 Access Control

6.4 Milk Control

6.5 Food Control

6.6 Water Control

(Guidance to be Developed)

CHAPTER 7

Application of PAGs for Contaminated Property or Equipment

7.1 Release and Reentry

7.2 Decontamination

7.3 Land Use

(Guidance to be Developed)

7.1

CHAPTER 8

Application of PACs for Transportation Incidents

(Guidance to be Developed)

APPENDIX A

**Summary of Interim Guidance on
Offsite Emergency Radiation Measurement Systems**

(to be developed)

APPENDIX B

Planner's Evaluation Guide for Protective Actions

(to be developed)

APPENDIX C

**Summary of Technical Bases for
Protective Action Guides**

(to be developed)

APPENDIX D

to the

**Manual of Protective Action Guides
and Protective Actions
for Nuclear Incidents**

TECHNICAL BASES FOR DOSE PROJECTION METHODS

January 1979

**Environmental Protection Agency
Office of Radiation Programs
Environmental Analysis Division
Washington, D.C. 20460**

Contents

	<u>Page</u>
Technical Bases for Methods that Estimate the Projected Thyroid Dose and Projected Whole Body Gamma Dose from Exposure to Airborne Radioiodines and Radioactive Noble Gases	D-1
1.0 Introduction	D-1
1.1 Approach	D-3
2.0 Units	D-6
2.1 Radionuclide Concentration in Air	D-7
2.2 Dose Calculations	D-11
2.2.1 Whole Body Cloud Gamma Doses	D-11
2.2.2 Thyroid Inhalation Doses	D-15
2.2.3 Finite Cloud Correction	D-22
3.0 Input Parameters	D-24
3.1 Radionuclide Source Terms	D-24
3.2 Thyroid Dose Conversion Factors for Radioiodine Inhalation	D-27
3.2.1 Dependence of Thyroid Mass and Breathing Rate on Age	D-28
3.2.2 Uptake of Inhaled Radioiodine into the Thyroid	D-30
3.2.3 Effective Decay Energies of I-131, I-132, I-133, I-134, and I-135 in Human Thyroid	D-31
3.2.4 Effective Decay Constants of Iodine Isotopes I-131 through I-135 in the Human Thyroid as a Function of Subject Age	D-35
3.2.5 Dependence of Thyroid Dose Conversion Factor on Age	D-39
4.0 Results	D-39
4.1 Whole Body Dose	D-43
4.2 Thyroid Dose	D-45

Contents (continued)

	<u>Page</u>
5.0 Accuracy of Dose Projection Methods	D-61
5.1 Calculational Errors Associated with Release Rate Assumptions	D-61
5.2 Calculational Errors Associated with Assumptions on Release Characteristics	D-62
5.2.1 Errors in Whole Body Dose	D-62
5.2.2 Errors in Thyroid Dose	D-63
5.3 Errors Associated with Input Data	D-64
5.3.1 Duration of Exposure	D-65
5.3.2 Errors in Release Rate Data	D-65
5.3.3 Errors in Data on Release Characteristics	D-66
5.3.4 Errors in Environmental Measurements and Information	D-66
5.4 Summary	D-67
References	D-69

Tables

	<u>Page</u>
<u>Section 3</u>	
3.1 Radionuclide source data	D-25
3.2 Body mass, thyroid mass, and breathing rate as a function of age	D-29
3.3 Absorbed fractions (ϕ) in the thyroid as a function of age and iodine isotope	D-36
3.4 Effective decay energies for I-131 through I-135 present in the thyroid as a function of age	D-37
3.5 Effective decay constants of I-131 through I-135 in the human thyroid as a function of age	D-38
3.6 Thyroid dose conversion factor as a function of age and iodine isotope	D-40
 <u>Section 4</u>	
4.1 Noble gas and iodine inventory in the reactor core and containment as a function of time	D-41
4.2 Iodine to noble gas activity ratio as a function of iodine release fraction and time after shutdown	D-42
4.3 Ratio of noble gas gamma dose rate to noble gas concentration, RGC_n^g , as a function of time after shutdown	D-44
4.4 Ratio of a child thyroid inhalation dose to radioiodine concentration, RIC, as a function of time after reactor shutdown at which exposure begins and the inhalation exposure duration $\left(\frac{REM}{Ci/m^3}\right)$	D-47
4.5 Radioiodine concentration in air which would result in a 5 rem thyroid inhalation dose to a child as a function of time after reactor shutdown, t_a , at which exposure begins and the inhalation time (Ci/m^3)	D-49
4.6 Ratio of iodine concentration to total iodine and noble gas gamma dose rate as a function of iodine release fraction and time after shutdown $\left(\frac{Ci/m^3}{REM/hr}\right)$	D-53
 <u>Section 5</u>	
5.1 Estimated errors associated with dose calculation methods	D-68

Figures

	<u>Page</u>
<u>Section 3</u>	
3.1 Radioiodine and noble gas decay chains	D-26
<u>Section 4</u>	
4.1 Projected whole body gamma dose as a function of gamma radiation dose rate and projected time period of exposure	D-46
4.2 Five rem isodose line for child thyroid as a function of radioiodine concentration at the start of exposure, exposure duration time and time after shutdown at which exposure begins, t_a	D-50
4.3 Projected thyroid dose as a function of either gamma exposure rate or radioiodine concentration in air and the projected exposure time . .	D-54
4.4 Correction factors for thyroid inhalation dose as a function of time after reactor shutdown that radioiodine concentration is measured . .	D-56
4.5 Gamma exposure rate finite cloud correction factor	D-58
4.6 Radioiodine release correction factor	D-60

Appendix D

Technical Bases for Methods that Estimate the Projected Thyroid Dose and Projected Whole Body Gamma Dose from Exposure to Airborne Radioiodines and Radioactive Noble Gases

1.0 Introduction

If an incident were to occur at a reactor resulting in mobilization of the fission product inventory, the radioactive isotopes of iodine and the noble gases plus a smaller quantity of particulates might be released to the environment in quantities exceeding normal operating limits. Under these conditions, it would be necessary for responsible public officials to quickly determine whether protective actions should be taken to protect the public. The decision to implement protective actions would be based, in part, on the projected radiation dose¹ that might be received by individuals in the population. Dose projections may be determined from one of three information bases or combinations thereof: (1) reactor system status, (2) release rate of radioactive materials, and (3) environmental measurements. Dose projection based on reactor system status will be primarily the responsibility of nuclear facility officials and will not be discussed here. The

¹Projected radiation dose is defined as the dose the exposed persons would receive in the absence of protective actions and includes committed dose that may be received as a result of ingested or inhaled radioactive material.

estimation of projected dose based on release rates and environmental measurements will to some extent be the responsibility of State and local government officials. Procedures for making these estimates were given in Chapter 5, and this Appendix provides the technical bases for those procedures.

Two exposure pathways are considered: (1) whole body gamma exposure from radioactive noble gases and iodines in the plume, and (2) inhalation of radioiodines in the plume. Additional whole body external exposure would occur from deposited radioactive particulates and iodines. Over an extended period of days to weeks or months this source could be significant or even dominant. However, during the period of plume passage, exposure from deposited materials is not expected to be significant compared to exposure from the plume. Therefore, separate procedures for estimating the whole body dose from deposited materials are not provided in this Appendix.

The environmental measurement techniques considered are gamma exposure rate measurements and gross radioiodine concentration measurements. Methods are developed for estimating the projected thyroid dose commitment from either of these measurements. Although the estimation of thyroid dose commitment from gamma exposure rate measurements is recognized as a crude approximation, it is a currently implementable and rapid method. Field instrumentation

capable of measuring gross radioiodine concentration in the presence of noble gases is under development. This method should replace or supplement the gamma exposure rate method for estimating projected thyroid dose commitment as soon as possible. Projected whole body gamma dose from external exposure to the plume is simply the integral of dose rate over the duration of exposure.

1.1 Approach

Calculated values for projected thyroid dose commitment and projected whole body dose are a function of the isotopic composition of the radionuclide bearing cloud. This cloud composition is, in turn, determined by the respective release rates of specific radionuclides from the reactor containment and the age of the fission products. In addition, the projected dose from inhalation among human receptors will vary as a function of the pertinent physiological and metabolic characteristics ascribed to the individual incurring the dose.

Given sufficient time, one could project the thyroid dose commitment by measuring or calculating the airborne concentration of each isotope of radioiodine, integrate these concentrations over the period of exposure, multiply by the appropriate dose conversion factor for each isotope, and then sum these values. However, during the emergency period following an incident, such analyses would be too time-consuming, and more simple methods must be used.

The recommended simplified approach for dose projection is to make use of charts or nomograms to translate calculated or measured environmental parameters into estimated projected dose. Estimating the whole body external dose is only a matter of integrating the gamma exposure rate over the estimated duration of exposure. The corresponding method for projecting thyroid dose is similar with the addition of factors to convert from time integrated concentration to dose and correction factors to adjust for variables that may be known.

This Appendix is a presentation of the processes and assumptions used to develop nomograms for projecting both thyroid inhalation dose commitment and whole body gamma dose. The nomograms are based on releases defined for a design basis accident without the benefits of engineered safeguards to reduce concentrations in containment. Correction factor charts are provided for adjusting the dose projections for (1) different release characteristics, (2) time for radioactive decay, and (3) actual meteorological conditions at the time of the accident. Other methods involving different types of charts and nomograms for projecting dose have been developed by nuclear facility operators and others. Such methods may be fully as accurate and acceptable as those developed in this Appendix.

The charts and nomograms developed in this Appendix allow one to quickly estimate projected whole body dose or projected thyroid dose commitment from any of the following data when these data are used with the estimated duration of exposure:

Whole Body Projected Dose

1. Calculated gross concentrations of iodine and/or noble gases.
2. Measured gamma exposure rates.

Thyroid Dose Commitment

1. Calculated gross concentration of iodines.
2. Measured gross concentration of iodines.
3. Measured gamma exposure rate.

Because the dose projection nomograms (1) are based on gross concentrations, (2) consider only a specific time for radioactive decay, and (3) do not consider differing dimensional characteristics of the plume, the resulting dose projections are subject to gross errors. However, the methods are based on generally conservative assumptions, and therefore, the dose projection errors are likely to be conservative. Correction factor curves are provided for use in situations where actual data are available to substitute for these assumptions so that dose projection estimates can be more accurate.

2.0 Units

All radiation units used are those defined by the ICRU (1). However, the ICRU has yet to define the concept of dose commitment and propose a symbol for it even though the ICRP utilizes the concept.

Richardson (2) has traced the history of the dose commitment concept; the following definition is taken from his work. "Dose Commitment is a future dose implied by a specific event in the past."

Mathematically, this concept is defined by the following integral equation:

$$\bar{D} = \int_{t_0}^{t_1} D_0(t) dt \quad (1.1)$$

where \bar{D} is the dose commitment in rad and D_0 is an initial or reference dose rate.

As shown here, dose commitment and dose rate are averages. These average value(s) result from application of the assumption that radioactive material is deposited uniformly throughout the target organ.

\bar{D} will be determined by the values selected for the limits of integration. The lower value, t_0 , is taken as zero which defines a reference time or starting point at which time a value for D_0 is known. The ICRP has suggested upper limits of 50 years as the value

to be used for occupational considerations and 70 years for members of the general public. EPA uses 100 years (3) when computing environmental dose commitments. In selecting an upper limit for use in calculating the dose commitments correlated with iodine concentration, it is recognized that due to the short half lives for the radioiodines of concern, most of the dose commitment to the thyroid will be delivered in less than one month. Therefore, the difference in dose delivered in 50 or 100 years or infinity is effectively 0, and infinity is used for convenience. The calculational formula becomes:

$$\bar{D} = \int_0^{\infty} D_0 e^{-\lambda_e t} dt = \frac{D_0}{\lambda_e} \quad (1.2)$$

λ_e is the effective removal coefficient in reciprocal time units.

2.1 Radionuclide Concentration in Air

The air concentration of fission products downwind from the point of release is determined by their rate of release from the reactor containment, their manner of dispersal in the atmosphere, and the elapsed time since reactor shutdown. For a given inventory of radionuclides in the reactor core at the time of shutdown, the containment release rate of a particular radionuclide depends on three factors: (1) the fraction of the core inventory of the

nuclide which is released to the containment; (2) the rate of its removal from the containment atmosphere by the engineered safety systems and by such mechanisms as precipitation, surface deposition, and radioactive decay; and (3) the containment leakage rate. These three factors can vary widely depending on the magnitude of the accident and the functional status of the engineered safety systems. However, if one assumes that a given fraction of the core inventory of a specific radionuclide is available for release to the containment immediately after reactor shutdown (4,5) and that the engineered safety systems act to reduce the containment inventory of the radionuclide by some fixed factor within a short time after the radionuclide release into containment, then the analysis of the radionuclide release from the containment can be simplified. Under these assumptions, the removal of a radionuclide from the containment atmosphere by the engineered safety systems can be regarded as an additional barrier, or filter, affecting the fraction of the core inventory of the radionuclide which is released to the containment. If F_{1k} is the fraction of the core inventory of the k th radionuclide which is released to the containment, F_{2k} is the fraction of the released radionuclide which is not removed by the engineered safety systems, and A_k is the activity of the k th radionuclide in curies, then the containment inventory of the k th radionuclide at time t , $C_k(t)$, is given by

$$C_k(t) = F_{1k} \cdot F_{2k} \cdot A_k(t) \quad \text{curies.} \quad (2.1)$$

Combining the product of F_{1k} and F_{2k} into a total release fraction F_k ,

$$C_k(t) = F_k A_k(t) \quad \text{curies.} \quad (2.2)$$

Assuming that 100 percent of the containment inventory is available for release to the environment via containment leakage, the radionuclide release rate from the containment is determined by the product of the radionuclide core inventory, its total release fraction, and the containment leakage rate. In these terms, the release rate from the containment of the k th radionuclide may be written as:

$$\dot{Q}_k(t') = A_k(t') \cdot F_k \cdot L(t') \quad , \quad (2.3)$$

where:

$\dot{Q}_k(t')$ = containment release rate of the k th radionuclide
(Ci/s)

t' = time of release after reactor shutdown (s)

$A_k(t')$ = core inventory of k th radionuclide at time t' (Ci)

F_k = total release fraction of the k th radionuclide

$L(t')$ = containment fractional leakage rate at time t' (s^{-1}).

After the fission products have been released to the environment, their concentration, as a function of downwind distance, is dependent on the atmospheric conditions at the time of release and on their respective deposition velocities. However, if the deposition velocity of the radionuclides is neglected and the containment leakage rate is assumed to be constant, the air concentration of the kth radionuclide is given by the following equation:

$$\begin{aligned}
 X_k(r,t) &= \dot{Q}_k(t) X/\dot{Q}(r) \\
 &= A_k(t) \cdot F_k \cdot L \cdot X/\dot{Q}(r) \quad , \quad (2.4)
 \end{aligned}$$

where:

$X_k(r,t)$ = concentration of kth radionuclide at point r relative to the point of release and time t after reactor shutdown (Ci/m³).

$X/\dot{Q}(r)$ = time invariant atmospheric diffusion function relative to the point of release (s/m³), and A_k is evaluated at the same time as X_k to allow for fission product decay and ingrowth during time of flight.

The total radionuclide concentration of a cloud consisting of M radionuclides is given by the sum of concentrations of its individual components. Thus,

$$\begin{aligned} X(r,t) &= \sum_{k=1}^M A_k(t) F_k L X/\dot{Q}(r) \\ &= L X/\dot{Q}(r) \sum_{k=1}^M A_k(t) F_k \end{aligned} \quad (2.5)$$

2.2 Dose Calculations

The dose projection methods developed in this Appendix are limited to consideration of thyroid doses due to inhalation of radioiodines and whole body cloud gamma doses due to radioiodines and noble gases which might be released in a potential nuclear reactor accident. Doses to other organs are not considered.

2.2.1 Whole Body Cloud Gamma Doses

The cloud gamma dose is a dose which is received as a consequence of external exposure to gamma radiation emitted by the airborne radioactive fission products. In some cases, the whole body dose would be projected based on measurements of exposure rate in the environment and an estimated duration of exposure. In other cases, projected whole body dose may be based on calculated concentrations in the environment and estimated duration of exposure. Since gamma rays can travel great distances in air,

calculations of whole body gamma doses from airborne concentrations must consider the radionuclide composition and concentration spatial distributions within the cloud. Rigorous calculations of cloud gamma doses require three dimensional integration of appropriate dose attenuation kernels with respect to space, as well as with respect to time. However, if the cloud can be considered to be semi-infinite in extent (reference (6), section 7.4.1.1), then, for a point located on the ground, the gamma dose rate in air from the kth radionuclide is given by

$$\dot{D}_k^{\gamma}(r,t) = 0.25 \bar{E}_k^{\gamma} \chi_k(r,t) \quad , \quad (2.6)$$

where:

$\dot{D}_k^{\gamma}(r,t)$ = gamma dose rate from the kth radionuclide distributed in a semi-infinite cloud (rad/s)

\bar{E}_k^{γ} = average gamma energy per disintegration of the kth radionuclide (MeV/disintegration), and $\chi_k(r,t)$, which has been defined previously, has the units of Ci/m^3 .

Using Eq. (2.6), and assuming that the whole body gamma dose rate is equal to the gamma exposure rate in air, one could calculate the whole body gamma dose that would be received by an individual

exposed to an infinite cloud of gaseous fission products by integrating the dose rate with respect to time over the duration of exposure. However, since it is expected that the cloud gamma exposure rate would be measured at a given location within a short time after plume arrival, the dose at that location can be conservatively estimated by simply multiplying the measured gamma exposure rate by the expected duration of exposure. This dose projection method would tend to be conservative because the radiological decay of the fission products after the measurement would be neglected. Other factors such as changes in plume direction, changes in meteorological conditions, or changes in release rate could cause either high or low dose projections.

A method can also be developed for projecting whole body gamma doses based on known or calculated fission product concentrations. Since the gamma dose rate from a semi-infinite cloud consisting of M gaseous fission products is equal to the sum of the doses from the various radionuclides, the total whole body dose rate is defined by:

$$\begin{aligned}
 \dot{D}^{\gamma}(r,t) &= \sum_{k=1}^M \dot{D}_k^{\gamma}(r,t) \\
 &= \sum_{k=1}^M 0.25 E_k^{\gamma} \chi_k(r,t) \quad \text{rad/s.} \quad (2.7)
 \end{aligned}$$

Since $X_k(r,t)$ is given by Eq. (2.4), substitution of that expression into Eq. (2.7) yields the following:

$$\begin{aligned} \dot{D}^{\gamma}(\tau,t) &= 0.25 \sum_{k=1}^M \bar{F}_k A_k(t) F_k L X/\dot{Q}(\tau) \\ &= 0.25 L X/\dot{Q}(\tau) \sum_{k=1}^M \bar{F}_k^{\gamma} A_k(t) F_k \quad \text{rad/s.} \end{aligned} \quad (2.8)$$

Furthermore, since the total radionuclide concentration at (r,t) is given by Eq. (2.5), the ratio of the semi-infinite cloud gamma dose rate to the total radionuclide concentration, (RGC^{γ}) , is given by

$$\begin{aligned} RGC^{\gamma}(t) &= \frac{0.25 L X/\dot{Q}(\tau) \sum_{k=1}^M \bar{F}_k^{\gamma} A_k(t) F_k}{L X/\dot{Q}(\tau) \sum_{k=1}^M A_k(t) F_k} \\ &= \frac{0.25 \sum_{k=1}^M \bar{F}_k^{\gamma} A_k(t) F_k}{\sum_{k=1}^M A_k(t) F_k} \quad \frac{\text{rad/sec}}{\text{Ci/m}^3} \end{aligned} \quad (2.9)$$

Thus, given a knowledge of gaseous fission product concentration at a given location soon after plume arrival, the whole body cloud gamma dose to an individual at that location may be projected by multiplying the concentration by the factor $RGC^{\gamma}(t)$ and

by the expected duration of exposure. This method may also be used to project whole body cloud gamma doses from noble gases which might be released in a reactor accident.

2.2.2 Thyroid Inhalation Doses

The thyroid inhalation dose is an internal dose commitment which is received as a consequence of inhaling radioiodines present in the air at the point of exposure. (The term inhalation dose or thyroid dose as used in this report means thyroid dose commitment.)

The inhalation dose due to the exposure to air containing the kth iodine isotope is given by the integral of the concentration over the period of exposure,

$$D_k^{th}(r, t_a, t_e) = \int_{t_a}^{t_a + t_e} DCF_k^{th} X_k(r, t) dt \quad , \quad (2.10)$$

where:

$D_k^{th}(r, t_a, t_e)$ = thyroid inhalation dose resulting from exposure to the kth iodine isotope (rad)

t_a = time after reactor shutdown at which exposure commences (s)

t_e = duration of exposure, or the inhalation time (s)

DCF_k^{th} = thyroid inhalation dose conversion factor for the kth iodine isotope, $\frac{\text{rad/sec}}{\text{Ci/m}^3}$, and $X(r, t)$ has been defined previously.

If the radioiodine concentration in air is composed of N iodine isotopes, then the inhalation dose is equal to the sum of the doses received from inhaling the individual iodine isotopes. Thus, the combined dose is

$$\begin{aligned}
 D^{\text{th}}(r, t_a, t_e) &= \sum_{k=1}^N D_k^{\text{th}}(r, t_a, t_e) \\
 &= \sum_{k=1}^N \int_{t_a}^{t_a + t_e} \text{DCF}_k^{\text{th}} X(r, t) dt \quad \text{rad.} \quad (2.11)
 \end{aligned}$$

Substituting the expression for $X_k(r, t)$ from Eq. (2.4) into Eq. (2.11), one obtains

$$\begin{aligned}
 D^{\text{th}}(r, t_a, t_e) &= \sum_{k=1}^N \int_{t_a}^{t_a + t_e} \text{DCF}_k^{\text{th}} \cdot A_k(t) F_k L X/\dot{Q}(r) dt \\
 &= L X/\dot{Q}(r) \sum_{k=1}^N \int_{t_a}^{t_a + t_e} \text{DCF}_k^{\text{th}} A_k(t) F_k dt \quad \text{rad.} \quad (2.12)
 \end{aligned}$$

The ratio, $RIC(t_a, t_e, t_c)$, of the combined thyroid inhalation dose, $D(r, t_a, t_e)$, to the total radioiodine concentration, $X(r, t_c)$, at point r , and time t_c , where $t_a < t_c < t_a + t_e$, can be obtained by dividing Eq. (2.12) by Eq. (2.5). It can be written as

$$\begin{aligned}
 RIC(t_a, t_e, t_c) &= \frac{L X/\dot{Q}(r) \sum_{k=1}^N \int_{t_a}^{t_a + t_e} DCF_k A_k(t) F_k dt}{L X/\dot{Q}(r) \sum_{k=1}^N F_k A_k(t_c)} \\
 &= \frac{\sum_{k=1}^N \int_{t_a}^{t_a + t_e} DCF_k^{th} F_k A_k(t) dt}{\sum_{k=1}^N F_k A_k(t_c)} \quad \frac{\text{rad}}{\text{Ci/m}^3} \quad (2.13)
 \end{aligned}$$

Since $RIC(t_a, t_e, t_c)$ is the ratio of thyroid inhalation dose to radioiodine concentration, given a knowledge of the total radioiodine concentration at a given location, at time t_c after reactor shutdown, one can project the thyroid inhalation dose resulting from an exposure beginning at t_a seconds after reactor shutdown, and lasting for a period of t_e seconds, by simply multiplying $RIC(t_a, t_e, t_c)$ by the known radioiodine concentration.

Expressed mathematically,

$$D(r, t_a, t_e) = RIC(t_a, t_e, t_c) \cdot X(r, t_c) \quad \text{rad.} \quad (2.14)$$

Since $RIC(t_a, t_e, t_c)$ is independent of position, this procedure may be used anywhere within the radioactive plume, provided that the total radioiodine concentration in air is determined at the location for which the thyroid inhalation dose is projected, and that the temporal parameters t_a , t_e , and t_c are known.

Using a similar method, it is also possible to estimate projected thyroid inhalation doses on the basis of environmental measurements of cloud gamma dose rates. To do this it is necessary to develop a relationship between gamma dose rates and iodine concentrations in the plume and then to use this to determine the projected thyroid dose.

If the gaseous fission product concentration at a given position is composed of N radioiodines and M noble gases, then the ratio of total iodine concentration to the semi-infinite cloud gamma dose rate, $RIG^m(t)$, is given by

$$RIG^m(t) = \frac{X(r, t)}{D^m(r, t)} = \frac{\sum_{i=1}^N A_i(t) F_i}{0.25 \sum_{k=1}^{N+M} A_k(t) F_k} \quad \frac{\text{Ci/m}^3}{\text{rad/sec}} \quad (2.15)$$

Since the ratio of thyroid inhalation dose to radioiodine concentration is given by the factor $RIC(t_a, t_e, t_c)$, the thyroid inhalation dose

$$D^{th}(r, t_a, t_e) = [RIC(t_a, t_e, t_c) \cdot RIG^m(t_c)] \cdot \dot{D}^m(r, t_c) \quad \text{rad.} \quad (2.16)$$

Thus, if the time that has elapsed since reactor shutdown is known, the radioiodine thyroid inhalation dose can be projected at a given location for an expected inhalation period by measuring the cloud gamma dose rate at that location and by multiplying it by the expression in parentheses in the above equation.

While the factors RIC and RIG were expressed as functions of radionuclide core inventories and release fractions, in view of Eq. (2.4), it should be recalled that they are actually functions of fission product release rates from the containment. Since the release rate of the k th radionuclide from the containment is given by $\dot{Q}_k(t')$, the factor RIG , in particular, can be expressed in terms of release rates as

$$RIG^m(t) = \frac{\sum_{i=1}^N \dot{Q}_i(t)}{0.25 \sum_{k=1}^{N+M} Y_k \dot{Q}_k(t)} \quad (2.17)$$

or, in terms of containment radioiodine and noble gas inventories, as

$$\text{RIG}^{\text{m}}(t) = \frac{\sum_{i=1}^N C_i(t)}{0.25 \sum_{k=1}^{N+M} \bar{E}_k^Y C_k(t)} \quad (2.18)$$

where \dot{Q}_k and C_k are evaluated at time t to allow for radiological decay during time of flight.

Defining the average gamma energy released per disintegration of a radioiodine atom to be

$$\bar{E}_I^Y(t) = \frac{\sum_{i=1}^N \bar{E}_i^Y \dot{Q}_i(t)}{\sum_{i=1}^N \dot{Q}_i(t)}$$

and the average gamma energy released per disintegration of a noble gas atom to be

$$\bar{E}_{\text{NG}}^Y(t) = \frac{\sum_{j=1}^M \bar{E}_j^Y \dot{Q}_j(t)}{\sum_{j=1}^M \dot{Q}_j(t)}$$

Eq. (2.18) may be written as

$$\begin{aligned}
 \text{RIG}^{\text{m}}(\tau) &= \frac{\sum_{i=1}^N \dot{Q}_i(\tau) \cdot 4}{\sum_{i=1}^N \dot{Q}_i(\tau) + \sum_{j=1}^M \dot{Q}_j(\tau)} \\
 &= \frac{4}{\sum_{i=1}^N \dot{Q}_i(\tau) + \sum_{j=1}^M \dot{Q}_j(\tau)} \quad (2.19)
 \end{aligned}$$

Eq. (2.19) illustrates the obvious fact that the ratio of iodine concentration to gamma dose rate depends on the relative release rates of the iodines and noble gases from the reactor containment or, assuming a radionuclide independent containment leakage rate, on their relative inventories in the containment. Thus, in order to be able to project thyroid inhalation doses on the basis of cloud gamma dose rates, it is only necessary to know the relative containment release rates of radioiodines and noble gases and not their absolute magnitudes. Furthermore, since release from the containment would reduce the radioiodine and noble gas inventories by the same fractional amounts, their depletion by leakage into the environment need not be considered in assessing their relative release rates.

2.2.3 Finite Cloud Correction

The above method for projecting thyroid inhalation doses by measuring cloud gamma dose rates was based on the assumption that the cloud is semi-infinite in extent. However, for a particular concentration, the actual gamma dose rate from a finite plume would tend to be smaller than that from an infinite cloud. Thus, projections of whole body gamma doses based on calculated radionuclide concentrations in the plume would tend to overestimate the doses. Conversely, projections of thyroid inhalation doses based on measurements of gamma dose rates would tend to underestimate the inhalation doses because of reduced gamma dose rates.

The ratio of gamma dose rate in a finite cloud to the gamma dose rate in an infinite cloud having the same concentration as the centerline of the finite cloud for 0.7 MeV gamma photons is shown in figure 7.14 of reference (6). It depends only slightly on gamma photon energy and may be assumed to be valid for the gamma energy spectrum of radiiodines and noble gases. This ratio is plotted as a function of σ , the standard deviation of the cloud concentration for the cloud centerline and for locations off the centerline. For a ground level release, the value of σ can be replaced by σ average which is $(\sigma_y \cdot \sigma_z)^{1/2}$. Figures 3.10 and 3.11 of reference (6) provide values for σ_y and σ_z as a function of downwind distance

for the Pasquill stability classes A through F. The resulting values for σ can be used in figure 7.14 of reference (6) to determine the ratio of the gamma dose rate in a finite cloud to the gamma dose rate in a semi-infinite cloud for the different stability classes and at different downwind distances.

This functional dependence can be expressed mathematically as

$$\frac{\dot{D}^Y}{\dot{D}^{Y\infty}} (\sigma, x, KK) \quad , \quad (2.20)$$

where:

$\frac{\dot{D}^Y}{\dot{D}^{Y\infty}}$ = ratio of gamma dose rate from a finite cloud to that from an infinite cloud

x = downwind distance of exposed location from point of release

KK = atmospheric stability class (A, B, C, D, E, or F)

σ = average radionuclide concentration standard deviation.

By dividing the measured cloud gamma dose rate by the ratio $\frac{\dot{D}^Y}{\dot{D}^{Y\infty}}$, or by multiplying it by its inverse, $\frac{\dot{D}^{Y\infty}}{\dot{D}^Y}$, one can compensate for the reduced gamma dose rate from a finite cloud in projecting radioiodine thyroid inhalation doses based on environmental measurements of gamma dose rates in air.

3.0 Input Parameters

3.1 Radionuclide Source Terms

Table 3.1 gives the fission product source inventory and associated data which was used in this Appendix to develop whole body and thyroid inhalation dose projection methods.

The radionuclide source terms are essentially the same as those given in WASH-1400, Appendix VI (7), except for the inventories of metastable Xe-133m and Xe-135m, which are based on RSAC code calculations (8). They are also in good agreement with source terms calculated by Anno, et al. (9), and represent the equilibrium core inventory of radioiodines and noble gases in a typical 1,000 MWe (3,200 MWt) power reactor. These initial core inventories were used to calculate radionuclide activities as a function of time according to decay relationships presented in figure 3.1. Since Cs-135 can be regarded as stable (half-life = 2.3×10^6 years), eleven decay chains² are of sufficient length to describe the temporal behavior of radionuclides listed in table 3.1.

²Eleven chains were used to account for multiple decay modes. The fraction of a nuclide in a decay chain is determined by the branching fraction for decay within that chain.

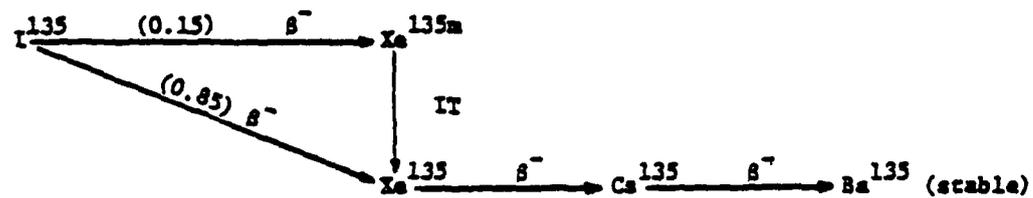
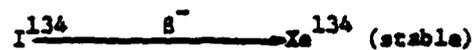
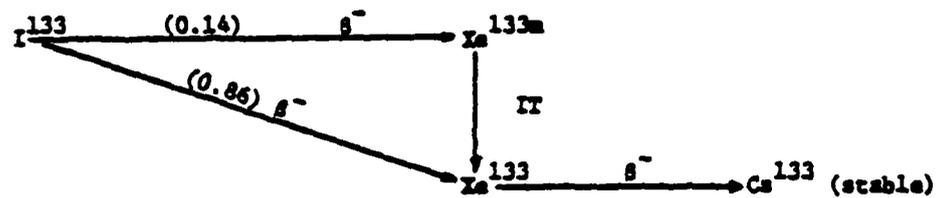
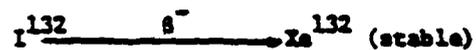
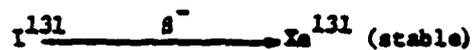
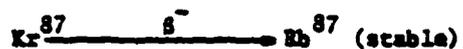
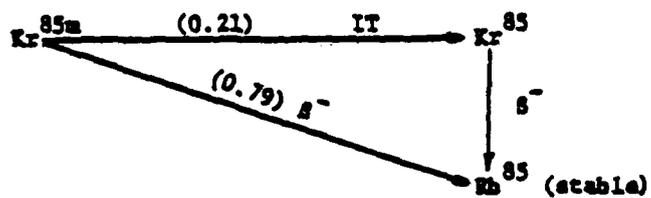
Table 3.1. Radionuclide source data.

Nuclide	Half-life ^a (hr)	Initial Inventory ^b (10 ⁶ Ci)	Average Beta Energy ^a per Disintegration \bar{E}_β (MeV)	Average Gamma Energy ^a per Disintegration \bar{E}_γ (MeV)
Kr-85	9.4×10^4	0.0056	0.251	0.0022
Kr-85m	4.48	0.24	0.226	0.18
Kr-87	1.27	0.47	1.33	0.79
Kr-88	2.8	0.68	0.249	2.2
Xe-133	127	1.7	0.102	0.030 ^c
Xe-133m	53.5	0.04	0.0	0.020 ^c
Xe-135	9.17	0.34	0.310	0.26
Xe-135m	0.27	0.19	0.0	0.53
I-131	193	0.85	0.185	0.39
I-132	2.29	1.2	0.525	2.2
I-133	20.8	1.7	0.417	0.60
I-134	0.877	1.9	0.691	2.6
I-135	6.59	1.5	0.394	1.5

^aFrom table VII, reference (10).

^bBased on references (7) and (8).

^cCorrected for internal conversion (table VI, reference (10)).



Based on data in reference (10).
 IT = isomeric transition.
 Branching ratios in parentheses.

Figure 3.1. Radioiodine and noble gas decay chains.

3.2 Thyroid Dose Conversion Factors for Radioiodine Inhalation

To use the thyroid inhalation dose projection methods discussed in section 2.2.2 of this Appendix, it is necessary to determine the appropriate dose conversion factors for the individual radioiodine isotopes which might be present in air at the point of exposure.

The thyroid inhalation dose conversion factor, DCF_k^{th} , has been defined to be equal to the inhalation dose to the thyroid resulting from the exposure to a unit integrated activity in air of the kth radioiodine isotope. It may be written as

$$\begin{aligned} DCF_k^{th} &= 5.92 \times 10^2 \frac{BR f_{ak} \bar{E}_k \int_0^{\infty} \exp(-\lambda_{EK} t) dt}{m} \\ &= 5.92 \times 10^2 \frac{BR f_{ak} \bar{E}_k}{m \lambda_{EK}} \end{aligned} \quad (3.1)$$

where:

DCF_k^{th} = thyroid inhalation dose conversion factor for the kth iodine isotope (rad-m³/Ci-s)

BR = breathing rate (m³/s)

f_{ak} = fraction of inhaled activity of the kth radioiodine isotope which deposits in the thyroid

m = mass of the thyroid (g)

\bar{E}_k = effective energy absorbed in the thyroid per disintegration of the kth radioiodine atom (MeV/dis)

$$5.92 \times 10^2 = 1.6 \times 10^{-8} \text{ rad-g/MeV} \times 3.7 \times 10^{10} \text{ dis/s-Ci}$$

(rad-g-dis/MeV-s-Ci)

λ_{Ek} = effective decay constant of the kth radioiodine in the thyroid (s^{-1})

$$\lambda_{Ek} = \frac{0.693}{t_{1/2Nk}} + \frac{0.693}{t_{1/2Bk}}$$

where:

$t_{1/2Nk}$ = nuclear half-life of the kth radioiodine (s)

$t_{1/2Bk}$ = biological half-life in the thyroid of the kth radioiodine (s).

3.2.1 Dependence of Thyroid Mass and Breathing Rate on Age

Since the thyroid mass, as well as metabolic activity, depends on a person's age, the dose conversion factor can be expected to be a function of age, and, to properly evaluate it, the age dependence of the parameters BR, f_a , \bar{E} , m , and λ_T must be determined.

Table 3.2 presents values of total body mass, thyroid mass, and breathing rate as a function of age. All values are based on data in reference (11). The values of breathing rate are characteristic of the "light activity" phase, which is greater than the daily average breathing rate, especially in the case of a newborn. The breathing rates of the 5 year old and 15 year old were determined by graphical interpolation on the basis of body mass.

Table 3.2. Body mass, thyroid mass, and breathing rate as a function of age

Age Years	Body Mass kg	Thyroid Mass g	Breathing Rate m^3/s
Newborn	3.5	1	2.5 E-05
1	10	1.8	6.9 E-05
5	19	3.6	1.3 E-04 ^(a)
10	33	7.4	2.2 E-04
15	60	12.1	3.2 E-04 ^(a)
Adult	70	16	3.3 E-04

^(a) Interpolated on the basis of body mass.

3.2.2 Uptake of Inhaled Radioiodine into the Thyroid

Thyroidal iodine uptake is dependent to a large extent on the total iodine in the diet. The Federation of American Societies for Experimental Biology prepared a report on "Iodine in Foods" for the Food and Drug Administration (12). In this report, iodine was noted as coming from diet with a range of 382 to 454 μg I/day; and from the atmosphere, 5 to 100 μg I/day. The total estimated intake is more than twice the recommended daily allowance of 35 to 150 μg I/day.

The reflection of variation in dietary intake of iodine in the fractional uptake of iodine is well known (13,14,15). The effects of the changing dietary iodine values have been reflected in the 24-hour thyroid uptake values recently reported for iodine-131 (12,16-22). The new values reported include $21.5\% \pm 6\%$ (18), $12.1\% \pm 6.1\%$ (19), $19\% \pm 8\%$ (20), $15.6\% \pm 4.5\%$ (21), $15.4\% \pm 6.8\%$ (22), $20.0\% \pm 6.5\%$ (23), and $17.4\% \pm (\sim) 7.2\%$ (24). The average of these values is 17.3% uptake.

Karhausen, et al. (23), reviewed the reports in the literature and compared the 24-hour I-131 uptake values reported in children from birth to 20 years of age with their own data. The results support the thesis that from birth to about 1 year of age there is a reduction in the thyroid uptake value. At birth, thyroid uptake is

from 1.5 to 2 times higher than the adult value, but by 1 year of age it has dropped down to about the adult value (in Karhausen, et al. (23), from 40 to 70% uptake at birth down to ~ 30% uptake at 1 year of age and older). The particularly high values (60-70%) have been observed in the first few days after birth (24). Il'in, et al. (25), found in their review of the literature that after 2 years of age the thyroid uptake value was relatively constant. Wellman, et al. (26), reported similar findings.

On the basis of this literature survey, the fraction of ingested radioiodine activity which deposits in the thyroid, f_w , is assumed to be 30 percent for individuals less than 1 year old and 17 percent for individuals above the age of 1 year. Since this value is based on data for I-131, it should be conservative for the shorter lived iodine isotopes. If the fraction of inhaled radioiodine which reaches the thyroid, f_g , is assumed to be 75 percent of f_w (27), then f_g is equal to 23 percent for individuals under 1 year of age and 13 percent for individuals 1 year old and older.

3.2.3 Effective Decay Energies of I-131, I-132, I-133, I-134, and I-135 in Human Thyroid

Nuclei of iodine isotopes I-131 through I-135 all decay by the emission of beta (β) particles. In general, when a nucleus emits a beta particle, it is left in an excited state and sheds its excess energy by either emitting a gamma (γ) ray or by internally converting an orbital electron (28).

Conservatively assuming that the total beta and electron energy is locally absorbed in the thyroid, the effective decay energy of each radionuclide is the sum of the average beta energy, the energy of the converted and Auger electrons, and the fraction of emitted x-ray and gamma-ray energy which is absorbed locally in the thyroid.

Thus, the effective decay energy

$$\bar{E} = \bar{E}_\beta + E_e + \sum_i \phi_i E_{\gamma_i} \quad (3.2)$$

where:

\bar{E}_β = the average beta energy

E_e = the energy of the converted and Auger electrons

E_{γ_i} = the energy of the i th x or gamma-ray, and

ϕ_i = the fraction E_{γ_i} which is locally absorbed in the thyroid..

For radionuclides which have complicated decay schemes, rigorous calculation of \bar{E} can become quite tedious. Hence, an approximate method of calculating the effective decay energies of I-131 through I-135 was developed which, at a substantial savings in effort, yields values of \bar{E} which are believed to be sufficiently accurate for accident dose calculations.

Table 3.1, in section 3.1, presents the radioactive half-lives and average beta and gamma energies emitted per disintegration by nuclei of I-131 through I-135. The value of E_{γ} in table 3.1 is the total transition energy³ and includes any internal conversion energy as well as the average gamma energy emitted per disintegration.

In radionuclides under consideration, the process of internal conversion is relatively unimportant. England, et al. (10) (tables VI and VII), indicate that in I-131 and I-135 the internal conversion energy (energy of ejected electrons and associated x-rays) accounts for only 0.0104 and 0.0236 of the total transition energy of the two radionuclides, respectively. Conservatively assuming that all of the internal conversion energy is imparted to ejected electrons, the energy of these electrons would account for only about 2 percent of the average I-131 beta energy and approximately 9 percent of the average I-135 beta energy. Dillman, et al. (28), indicate that the sum of the energies of the converted and Auger electrons accounts for as much as .5 percent of the average I-131 beta energy and for about 1 percent of the average I-133 beta energy. Considering the relative contributions of the five iodine isotopes in a reactor grade isotopic mixture to the thyroid

³Energy liberated in transition from an excited state to the ground state.

inhalation dose (figure VI 13-4, reference (7)) and the degree of accuracy required for projecting doses in accident situations, internal conversion can clearly be neglected in calculating the effective decay energies of I-131 through I-135 in the human thyroid.

As indicated in Eq. (3.2), the absorbed fraction, ϕ , is a function of gamma photon energy. However, as a first approximation, ϕ may be taken to be a constant, equal to its value at the average photon energy, \bar{E}_{γ_1} . Then, the effective decay energy is

$$\bar{E} = \bar{E}_\beta + \bar{\phi} \bar{E}_\gamma \quad (3.3)$$

where $\bar{\phi} = \phi(\bar{E}_{\gamma_1})$, and $\bar{E}_\gamma = \sum_i E_{\gamma_i}$.

Values of \bar{E}_{γ_1} for I-131 through I-135 are presented below and, except for I-134, were all taken from table I, reference (8). The value of \bar{E}_{γ_1} for I-134 was estimated from decay data in table 1, reference (29).

Iodine Isotope	I-131	I-132	I-133	I-134	I-135
\bar{E}_{γ_1} (MeV/photon)	0.4	0.79	0.56	0.9	1.5

Values of ϕ as a function of individual age and iodine isotope, which were determined by this method, are presented in table 3.3. Table 3.4 presents the calculated effective disintegration energies of the five iodine isotopes in the thyroid as a function of age.

The accuracy of this method of calculating effective decay energies was tested by comparing the values of \bar{E} for I-131 and I-133, for a five year old, to values of \bar{E} calculated rigorously according to Eq. (3.2). The conversion process was fully considered, decay data in reference (28) was used, and values of ϕ as a function of thyroid mass and photon energy were obtained by graphical interpolation of data in table 22.1, reference (30).

To within two significant figures, the values of \bar{E} were found to be 0.20 MeV and 0.42 for I-131 and I-133, respectively. The differences are mainly due to slight discrepancies in decay energies in references (10) and (28), and to round off errors.

3.2.4 Effective Decay Constants of Iodine Isotopes I-131 through I-135 in the Human Thyroid as a Function of Subject Age

Table 3.5 shows the age dependence of the effective decay constants (λ_E 's) of the five iodine isotopes under consideration in the human thyroid. These values were calculated using the nuclear decay half-lives in table 3.1 and estimates of biological half-lives in reference (31).

Table 3.3. Absorbed fractions (ϕ) in the thyroid as a function of age and iodine isotope

Age Years	Thyroid Mass g	Absorbed Fraction (ϕ) ^(a) for				
		I-131	I-132	I-133	I-134	I-135
Newborn	1	0.0048	0.0048	0.0050	0.0047	0.0043
1	1.8	.0060	.0060	.0062	.0059	.0054
5	3.6	.018	.017	.018	.017	.015
10	7.4	.025	.023	.025	.023	.021
15	12.1	.028	.027	.028	.026	.023
Adult	16	.031	.029	.031	.029	.026

(a) This information was derived from information in table 22.1, reference (30). The absorbed fraction for a 1 gram thyroid was obtained by multiplying the value of ϕ for a 2 gram thyroid by the ratio of cube roots of the masses. Values of ϕ for specific photon energies and thyroid masses were obtained by either choosing the closest values presented in the reference or by interpolation.

Table 3.4. Effective decay energies for I-131 through I-135 present in the thyroid as a function of age

Age Years	Effective Decay Energy \bar{E} (MeV) for				
	I-131	I-132	I-133	I-134	I-135
Newborn	0.19	0.54	0.42	0.70	0.40
1	.19	.54	.42	.70	.40
5	.19	.56	.43	.74	.42
10	.19	.58	.43	.75	.42
15	.20	.59	.43	.76	.43
Adult	.20	.59	.44	.77	.43

Table 3.5 Effective decay constants of I-131 through I-135 in the human thyroid as a function of age

Age Years	Effective Decay Constant (s^{-1})				
	I-131	I-132	I-133	I-134	I-135
Newborn	1.4E-06	8.5E-05	9.7E-06	2.2E-04	3.0E-05
1	1.3E-06	8.5E-05	9.5E-06	2.2E-04	3.0E-05
5	1.3E-06	8.5E-05	9.5E-06	2.2E-04	3.0E-05
10	1.1E-06	8.4E-05	9.4E-06	2.2E-04	2.9E-05
15	1.1E-06	8.4E-05	9.4E-06	2.2E-04	2.9E-05
Adult	1.1E-06	8.4E-05	9.3E-06	2.2E-04	2.9E-05

3.2.5 Dependence of Thyroid Dose Conversion Factor on Age

The age dependent thyroid dose conversion factors for iodine isotopes I-131 through I-135 have been calculated according to Eq. (3.1) and are presented in table 3.6. The age group which would receive the greatest thyroid inhalation dose from an exposure to a given radioiodine activity concentration in air appears to be comprised of newborn babies whose dose conversion factor is from 1.6 to 2 times greater than the dose conversion factor for adults. Table 3.6 also indicates that the variation of the dose conversion factor with age is rather small, especially below to the age of 10 years.

As in the case of whole body gamma dose calculations, it is assumed that the thyroid dose equivalent in rems is equal to the absorbed dose in rads.

4.0 Results

Table 4.1 presents the combined core and containment inventory, $A_k(t)$, of noble gases and halogens as a function of time after shutdown. The containment leakage rate is assumed to be zero, and thus, the decrease of the radioiodine and noble gas inventories with time is due only to radioactive decay.

Based on data in table 4.1, table 4.2 presents the ratio of iodine to noble gas inventory in the containment as a function of time after shutdown and the iodine release fraction. Assuming a

Table 3.6. Thyroid dose conversion factor
as a function of age and iodine isotope

Age Years	Inhalation Dose Per Unit Activity Exposure, rads				
	Ci-sec/m ³				
	I-131	I-132	I-133	I-134	I-135
Newborn	450	22	150	11	45
1	430	19	130	9.7	39
5	400	18	130	9.4	39
10	400	16	110	7.7	33
15	380	14	93	7.0	30
Adult	290	11	76	5.6	23
Maximum Age Group Newborn	450	22	150	11	45
Ratio of Maximum Age Group to Adult	1.6	2.0	2.0	2.0	2.0

Table 4.1. Noble gas and iodine inventory in the reactor core and containment as a function of time^a

<u>Time After Shutdown (hr)</u>	<u>Total Iodine Inventory (10⁸ Ci)</u>	<u>Total Noble Gas Inventory (10⁸ Ci)</u>
0.0	7.2	3.7
1.0	5.6	3.4
2.0	4.7	3.2
3.0	4.1	3.0
4.0	3.8	2.9
6.0	3.2	2.8
12.0	2.4	2.5

^aBased on the shutdown equilibrium core inventory of a typical 1,000 MWe (3,200 MWe) power reactor and zero containment leakage rate.

Table 4.2. Iodine to noble gas activity ratio as a function of iodine release fraction and time after shutdown

Iodine Release Fraction	Time after Shutdown (hr)									
	0.0	1.0	2.0	3.0	4.0	6.0	12.0			
1.0	2.0	1.6	1.5	1.4	1.3	1.1	.96			
0.5	0.98	8.2	.73	.68	.66	.57	.48			
0.25	.49	.41	.37	.34	.33	.29	.24			
0.1	.20	.16	.15	.14	.13	.11	.096			
0.05	.098	.082	.073	.068	.066	.057	.048			
0.025	.049	.041	.037	.034	.033	.029	.024			
0.01	.020	.016	.015	.014	.013	.011	.0096			
0.005	.0098	.0082	.0073	.0068	.0066	.0057	.0048			
0.0025	.0049	.0041	.0037	.0034	.0033	.0029	.0024			
0.001	.0020	.0016	.0015	.0014	.0013	.0011	.00096			
0.0005	.00098	.00082	.00073	.00068	.00066	.00057	.00048			
0.00025	.00049	.00041	.00037	.00034	.00033	.00029	.00024			
0.0001	.00020	.00016	.00015	.00014	.00013	.00011	.000096			

radionuclide independent containment leakage rate and X/\dot{Q} , this would also be the ratio of iodine to noble gas release rates and concentrations in air.⁴ The release fraction of noble gases is taken to be equal to one. Because of their similar chemical properties, all iodine isotopes are assumed to have equal release fractions.

The values in table 4.2 indicate that the ratio of total iodines to noble gases varies from approximately 2 at shutdown to 1 at 12 hours. At an iodine release fraction equal to 0.25, corresponding to a design basis accident (4,5), this ratio varies from approximately 0.5 to 0.25 over the 12-hour period after shutdown.

4.1 Whole Body Dose

Table 4.3 presents the ratio of the semi-infinite cloud gamma dose rate to the noble gas concentration ($RG\dot{C}_n^m$) as a function of time after shutdown calculated in accordance with the methods presented in section 2.2.1 of this Appendix. Since they are highly volatile, noble gases resulting from decay of the core equilibrium

⁴Although a particular iodine fraction may be released to containment, deposition of the iodines on surfaces and the operation of any engineered safeguards to reduce the airborne concentrations in containment would reduce the fraction of radiiodines released to the environment. These factors will influence the correction factors regarding the iodine to noble gas activity ratio as discussed later.

Table 4.3. Ratio of noble gas gamma dose rate to noble gas concentration, RGC_n^m , as a function of time after shutdown

Time after Shutdown (hr)	RGC_n^m $\frac{\text{rem/hr}}{\text{Ci/m}^3}$
0	5.3E+02
1.5	5.0E+02
2.5	4.3E+02
3.5	3.7E+02
4.5	3.1E+02
6.5	2.3E+02
12.5	1.2E+02

inventory of radiiodines are assumed to contribute to the noble gas source term, and the gamma dose rate also includes a component from Rb-86, which is a daughter product of Kr-86. Also, the time units in $RGC_{\text{N}}^{\text{m}}$ have been converted from seconds to hours.

Figure 4.1 (figure 5.1 of Chapter 5) presents a graph of the projected whole body gamma dose as a function of gamma dose rate in air and the projected duration of exposure. The projected whole body dose is simply the result of multiplying the gamma dose rate in air by the projected exposure duration. The projected exposure duration is in hours, and the gamma dose rate is in mrem/hr (10^{-3} rem/hr). The ordinate on the right, noble gas concentration in air, was added by assuming a gamma dose rate to noble gas concentration ratio of $3.1 \times 10^2 \frac{\text{rem/hr}}{\text{Ci/m}^3}$. This particular value was calculated to correspond to radionuclide mixtures that would exist at 4.5 hours after reactor shutdown, as indicated in table 4.3. For shutdown times greater than 4.5 hours, this choice of $RGC_{\text{N}}^{\text{m}}$ for noble gases will tend to overestimate the gamma dose rate relative to noble gas concentration. In instances of long decay periods where only the long lived noble gases remain, equation 2.7 and the gamma decay energies listed in table 3.1 may be used to calculate dose rate more accurately than those in figure 4.1.

4.2 Thyroid Dose

The ratio of the thyroid inhalation dose to the total radiiodine concentration in air, (RIC), calculated by methods presented in section 2.2.2 of this Appendix, is given in table 4.4 as a function of time after shutdown at which exposure begins, t_a ,

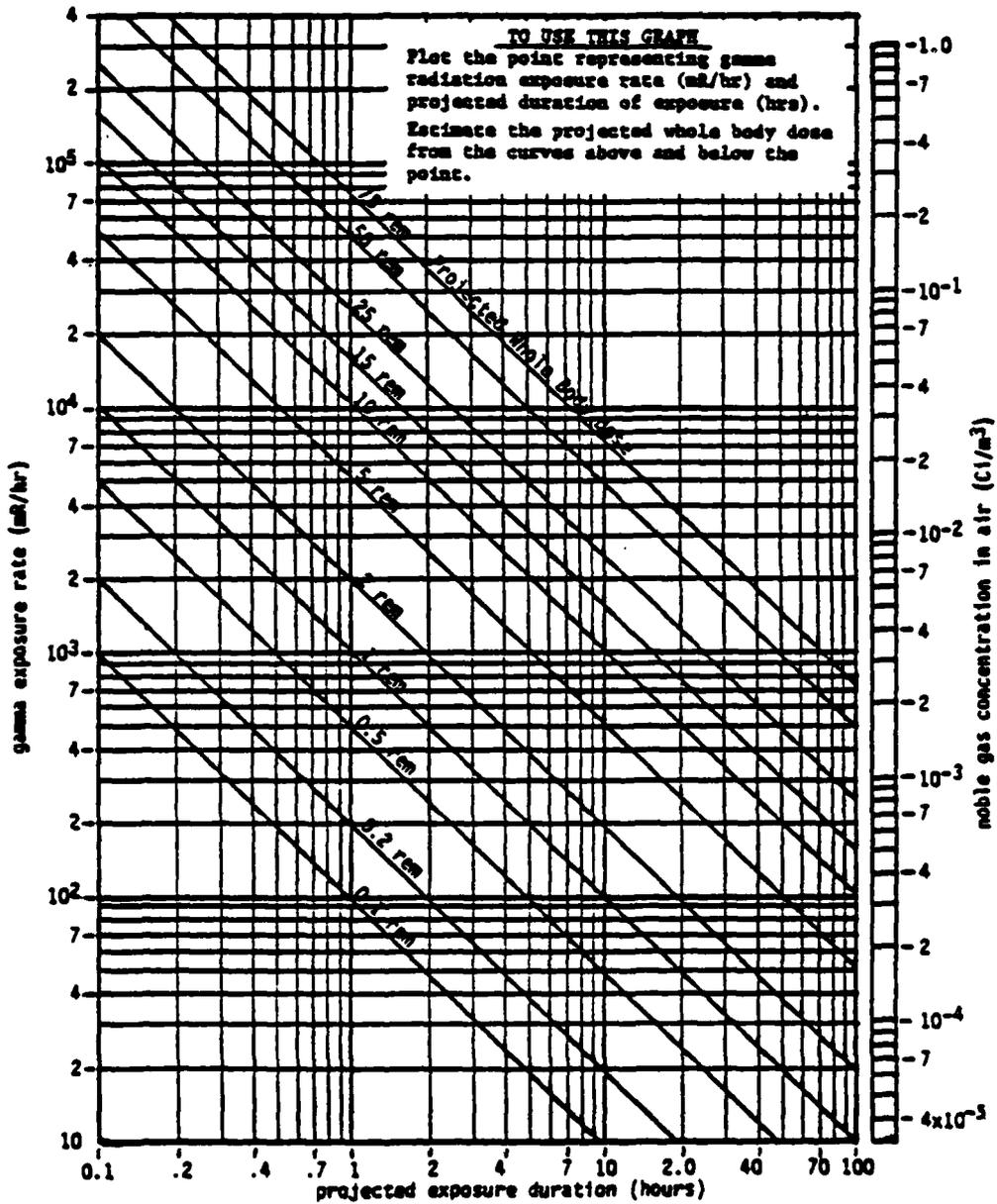


Figure 4.1 Projected whole body gamma dose as a function of gamma exposure rate and projected duration of exposure

Table 4.4. Ratio of a child thyroid inhalation dose to radioiodine concentration, RIC, as a function of time after reactor shutdown at which exposure begins and the inhalation exposure duration $\left(\frac{I_{em}}{C_i/m^3}\right)$

Time after shutdown at which exposure starts (hr)	RIC, $\left(\frac{I_{em}}{C_i/m^3}\right)$ for inhalation periods ranging from 1 to 12 hours						
	1.0/hr	2.0/hr	3.0/hr	4.0/hr	6.0/hr	12.0/hr	
1.0	5.0E+05	9.8E+05	1.4E+06	1.9E+06	2.8E+06	5.2E+06	
2.0	5.6E+05	1.1E+06	1.6E+06	2.1E+06	3.2E+06	5.9E+06	
3.0	6.1E+05	1.2E+06	1.8E+06	2.3E+06	3.4E+06	6.5E+06	
4.0	6.5E+05	1.3E+06	1.9E+06	2.5E+06	3.7E+06	7.0E+06	
6.0	7.1E+05	1.4E+06	2.1E+06	2.8E+06	4.1E+06	7.7E+06	
12.0	8.4E+05	1.7E+06	2.5E+06	3.3E+06	4.9E+06	9.3E+06	

and the inhalation exposure duration, t_a . The time t_a is the sum of the time after shutdown at which release occurs and the plume travel time. The projected exposure duration would be determined by the functional status of the engineered safety systems or the wind direction persistence at the time of the accident. It is assumed that monitoring personnel would be able to reach the projected exposure point such that environmental measurements could be taken within approximately 0.5 hours after plume arrival. A change in the time of measurement, t_m , of 0.5 hours was found to change RIC by at most 10 percent at t_a equal to 1 hour and by 2 percent at t_a equal to 12 hours.

Table 4.5 presents the values of radioiodine concentration in air which would deliver a 5 rem thyroid inhalation dose to a newborn baby (critical age group) as a function of inhalation time and six different times after shutdown when the exposure is assumed to be started. These values were obtained by dividing 5 rem by the ratio of projected thyroid dose to radioiodine concentration, RIC, and are plotted in figure 4.2.

As would be expected, the concentration of radioiodines required to deliver a 5 rem thyroid dose decreases with increase in time after shutdown since the short-lived isotopes decay, and only the long-lived isotopes I-131 and I-133 (with large dose conversion factors) remain in the radioiodine mixture.

Table 4.5. Radioiodine concentration in air which would result in a 5 rem thyroid inhalation dose to a child as a function of time after reactor shutdown, t_a , at which exposure begins and the inhalation time (Ci/m³)

Time after Shutdown, t_a (hr)	Inhalation Time					
	1.0/hr	2.0/hr	3.0/hr	4.0/hr	6.0/hr	12.0/hr
	Radioiodine concentration yielding 5 rem thyroid dose to child (Ci/m ³)					
1.0	1.0E-05	5.1E-06	3.5E-06	2.6E-06	1.8E-06	9.5E-07
2.0	8.9E-06	4.5E-06	3.1E-06	2.3E-06	1.6E-06	8.4E-07
3.0	8.2E-06	4.2E-06	2.8E-06	2.1E-06	1.5E-06	7.7E-07
4.0	7.7E-06	3.9E-06	2.6E-06	2.0E-06	1.4E-06	7.2E-07
6.0	7.1E-06	3.6E-06	2.4E-06	1.8E-06	1.2E-06	6.5E-07
12.0	5.9E-06	3.0E-06	2.0E-06	1.5E-06	1.0E-06	5.4E-07

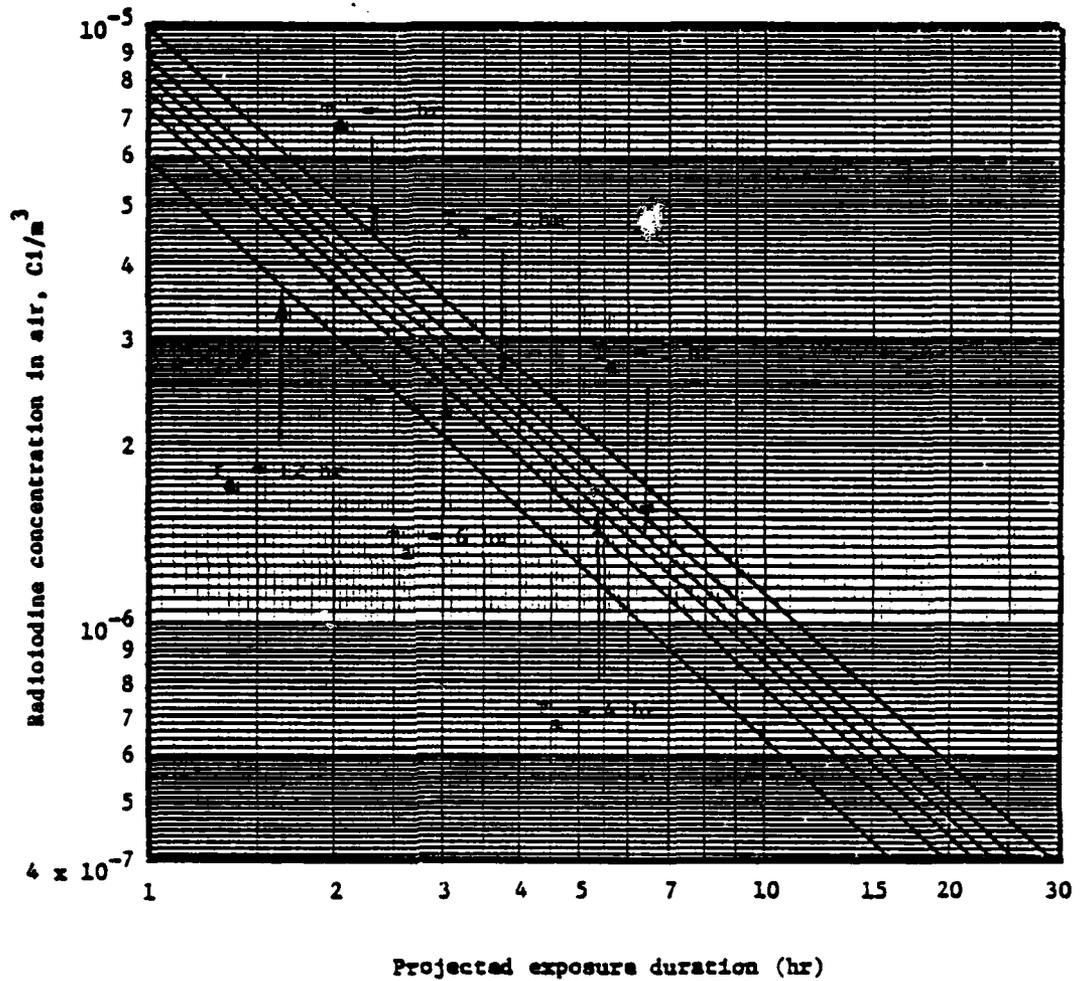


Figure 4.2. Five rem isodose line for child thyroid as a function of radioiodine concentration at the start of exposure, exposure duration and time after shutdown at which exposure begins, t_a .

Given a knowledge of the time after reactor shutdown at which exposure begins and the projected inhalation period, figure 4.2 may be used to determine the radioiodine concentration which would deliver a 5 rem dose to the thyroid by simply locating the ordinate of the appropriate t_a line at the projected inhalation time t_e . For any different thyroid dose the iodine concentration can be scaled linearly. For example, if the plume arrival time at a given location were about 4 hours and the projected exposure time were also 4 hours, the radioiodine concentration which would deliver a 5 rem thyroid inhalation dose to a child would be equal to approximately 2×10^{-6} Ci/m³ of air.

Figure 4.2 can also be used to project thyroid doses based on radioiodine concentrations estimated from containment release rate and meteorological conditions at the time of the accident. However, figure 4.2 should not be used to project inhalation doses from single iodine isotopes because in its derivation a five component mixture of radioiodines has been assumed. For that purpose, the dose conversion factors listed in table 3.6 may be used (multiplied by 3.6×10^3 to convert units of time from seconds to hours). Similarly, figure 4.2 would not be suitable for projecting thyroid dose if the release occurred from a reactor that had been shut down for a period such that the shorter-lived isotopes of iodine had decayed. In such a case, the dose conversion factor for iodine-131 from table 3.6 would be more appropriate.

The ratio of iodine concentration to the semi-infinite cloud gamma dose rate from iodines and noble gases, RIG^m , which was discussed in section 2.2.2, is presented in table 4.6 as a function of time after reactor shutdown and iodine release fraction. The increase of RIG^m with time is due to the decay of the short-lived but energetic (in gamma energy) Kr-88, I-132, and I-134.

The values in table 4.6 indicate that the ratio of iodine concentration to semi-infinite cloud gamma dose rate from both noble gases and iodines varies from approximately 6×10^{-4} at shutdown to 1.3×10^{-3} at 12.5 hours. For an iodine release fraction equal to 0.25, this ratio varies from approximately 4×10^{-4} to 9×10^{-4} over a 12.5 hour period after shutdown.

Figure 4.3 presents a graph of projected thyroid dose as a function of the projected time period of exposure and either the radioiodine concentration or the gamma dose rate in air. The relationship between thyroid dose and radioiodine concentration was established by selecting the 5 rem line from figure 4.2 which corresponds to a 4 hour period after reactor shutdown at which exposure is assumed to begin. This line was chosen because over an inhalation period of 12 hours, all the other lines are within a ± 33 percent range of the 4 hour line. For different thyroid doses, the iodine concentration has been scaled linearly. For concentration

Table 4.6. Ratio of iodine concentration to total iodine and noble gas gamma dose rate as a function of iodine release fraction and time after shutdown $\left(\frac{\text{Ci/m}^3}{\text{rem/hr}}\right)$

Iodine Release Fraction	Time after Shutdown							
	0.0 (hr)	1.5 (hr)	2.5 (hr)	3.5 (hr)	4.5 (hr)	6.5 (hr)	12.5 (hr)	
	Iodine concentration to γ dose rate ratio $\left(\frac{\text{Ci/m}^3}{\text{rem/hr}}\right)$							
1.0	6.0E-04	6.9E-04	7.6E-04	8.4E-04	9.1E-04	1.0E-03	1.3E-03	
0.5	5.1E-04	5.6E-04	6.2E-04	6.8E-04	7.4E-04	8.5E-04	1.1E-03	
0.25	4.0E-04	4.1E-04	4.5E-04	4.9E-04	5.4E-04	6.4E-04	8.8E-04	
0.1	2.4E-04	2.3E-04	2.5E-04	2.7E-04	3.0E-04	3.6E-04	5.2E-04	
0.05	1.5E-04	1.3E-04	1.4E-04	1.6E-04	1.7E-04	2.1E-04	3.1E-04	
0.025	8.2E-05	7.1E-05	7.6E-05	8.4E-05	9.3E-05	1.1E-04	1.7E-04	
0.01	3.5E-05	3.0E-05	3.2E-05	3.5E-05	3.9E-05	4.8E-05	7.5E-05	
0.005	1.8E-05	1.5E-05	1.6E-05	1.8E-05	2.0E-05	2.4E-05	3.8E-05	
0.0025	9.1E-06	7.6E-06	8.2E-06	9.0E-06	1.0E-05	1.2E-05	1.9E-05	
0.001	3.7E-06	3.1E-06	3.3E-06	3.6E-06	4.0E-06	4.9E-06	7.8E-06	
0.0005	1.8E-06	1.5E-06	1.6E-06	1.8E-06	2.0E-06	2.5E-06	3.9E-06	
0.00025	9.2E-07	7.7E-07	8.2E-07	9.1E-07	1.0E-06	1.2E-06	2.0E-06	
0.0001	3.7E-07	3.1E-07	3.3E-07	3.6E-07	4.0E-07	5.0E-07	7.8E-07	

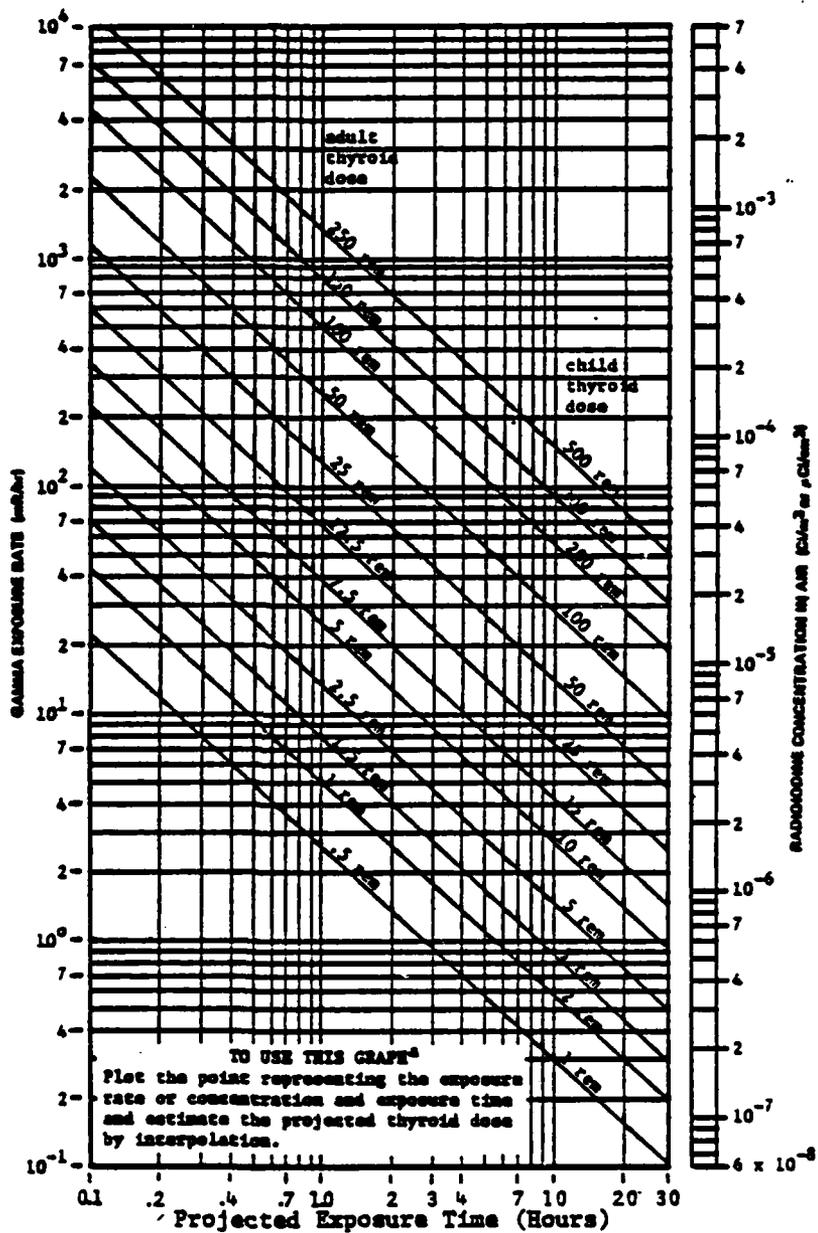


FIGURE 4.3 PROJECTED THYROID DOSE AS A FUNCTION OF EITHER GAMMA EXPOSURE RATE, OR RADIONUCLIDE CONCENTRATION IN AIR AND THE PROJECTED EXPOSURE TIME.

* THIS GRAPH SHOULD BE USED IN CONJUNCTION WITH FIGURES 4.4 AND 4.5.

measurements made less than 4 hours after reactor shutdown, figure 4.3 will slightly overestimate the thyroid dose; and for measurements made more than 4 hours after reactor shutdown, the dose will be underestimated. Figure 4.4 provides an indication of the error involved. The ordinate of this figure provides a correction factor.

Because of shifts in wind direction, it is unlikely that thyroid inhalation doses would be projected for time periods beyond the range considered in table 4.3. However, for those instances when that range might be exceeded, the lines have been extended from 0.1 to 30 hours in figure 4.3.

The adult thyroid inhalation doses which have been indicated in figure 4.3 have been obtained by dividing the newborn infant doses by a factor of two, in accordance with discussion in section 3.2.5 of this Appendix. The use of the same factor for I-131 as for the other iodine isotopes (see table 3.6) introduces an error in the adult dose of at most 25 percent, which is well within the uncertainty range of the overall dose projection method.

As discussed previously, the iodine release fraction would depend on the functional status of the engineered safety systems, and significant fractions of the core inventory of radioiodines would be expected to be released to the environment only in the most severe types of accidents. However, if, for the purpose of

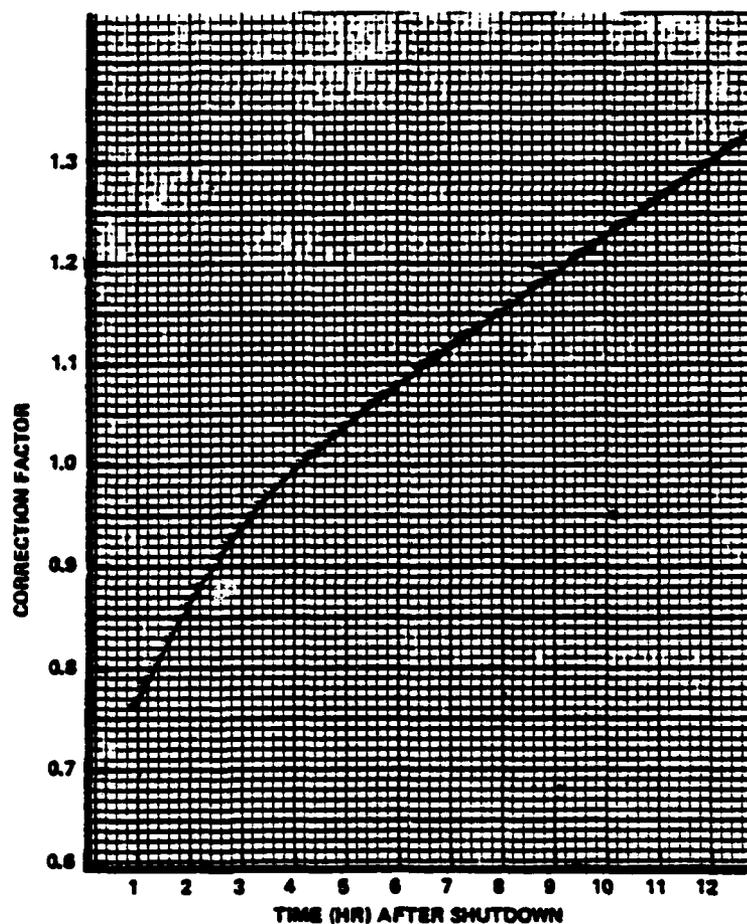


FIGURE 4.4 CORRECTION FACTORS FOR THYROID INHALATION DOSE AS A FUNCTION OF TIME AFTER REACTOR SHUTDOWN THAT RADIOIODINE CONCENTRATION IS MEASURED.

analysis, a 0.25 iodine release fraction is assumed⁵, then table 4.6 indicates that over a time period of 12.5 hours after reactor shutdown the ratio of iodine concentration to cloud gamma dose rate is equal to $6 \times 10^{-4} \pm 50$ percent $\left(\frac{\text{Ci/m}^3}{\text{rem/hr}}\right)$. This ratio has been used to establish the functional dependence of thyroid inhalation dose on the gamma exposure rate in air, in $\mu\text{rem/hr}$, as indicated in figure 4.3.

Since the relationship between gamma exposure rate in air and thyroid inhalation dose in figure 4.3 is based on the semi-infinite cloud assumption, the use of gamma exposure rate from a finite cloud to estimate thyroid dose by means of figure 4.3 will tend to underestimate the thyroid dose. To compensate for this effect, the measured cloud gamma exposure rate should be multiplied by the finite plume correction factor plotted in figure 4.5 before being applied in figure 4.3 to estimate projected thyroid dose. This factor, which has been plotted as a function of distance from reactor and atmospheric stability class, is equal to the ratio of gamma exposure rate from an infinite cloud to that from a finite cloud, as discussed in section 2.2.3 of this Appendix. The finite cloud correction factor may also be used to reduce the whole body gamma dose from a given noble gas concentration which has been

⁵These assumptions are in agreement with AEC guidance (4,5) on assumptions that may be used in evaluating the radiological consequences of an accident at a light water cooled nuclear power facility.

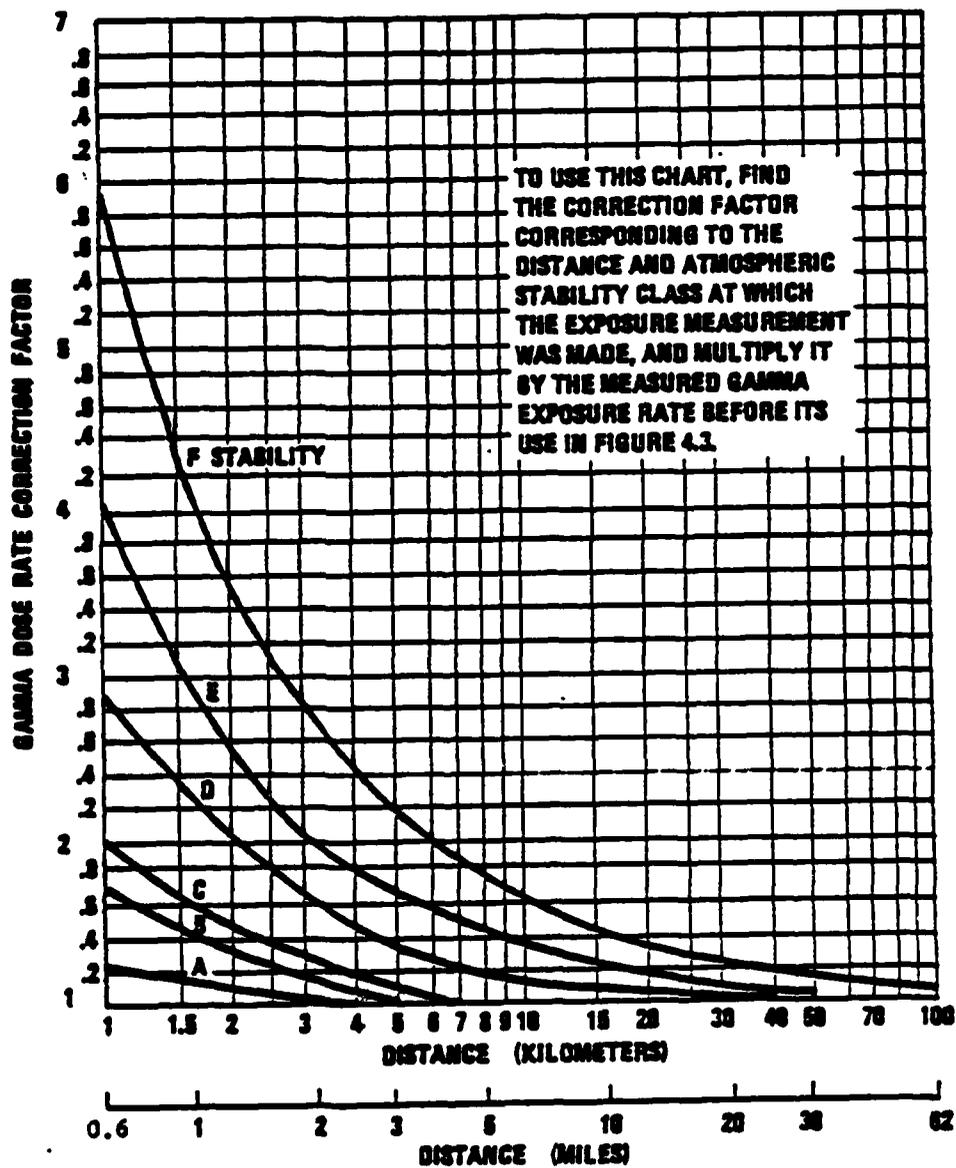


FIGURE 4.5 GAMMA EXPOSURE RATE FINITE CLOUD CORRECTION FACTOR

Revised 6/80

estimated by means of figure 4.1. To do this, the estimated whole body dose should be divided by the finite cloud correction factor. Obviously, whole body dose projections based on measurements of gamma exposure rate in air should not be modified.

In the development of figure 4.3, the iodine release fraction was assumed to be 0.25, and the noble gas release fraction was assumed to be 1.0. This corresponds to an iodine to noble gas ratio of about 0.3.

For accidents in which the iodine release fraction or the iodine to noble gas ratio is known to be different from that which has been assumed in preparation of figure 4.3, a second multiplicative correction factor could be used to correct the thyroid inhalation doses projected on the basis of measurements of gamma dose rate in air and figure 4.3. This correction factor has been plotted in figure 4.6 as a function of the ratio of iodine to noble gas activities⁶, and has been obtained by dividing the ratio of iodine concentration to gamma dose rate at iodine release fraction equal to 0.25 by the ratio of iodine concentration to gamma dose rate at other iodine release fractions. The iodine release correction factor varies by at most 25 percent over the 12.5 hour time period after reactor shutdown, and its value at 4.5 hours has been selected for figure 4.6.

⁶Table 4.2 indicates that over a 12.5 hour period after reactor shutdown, the iodine to noble gas activity ratio = 1.3 x iodine release fraction.

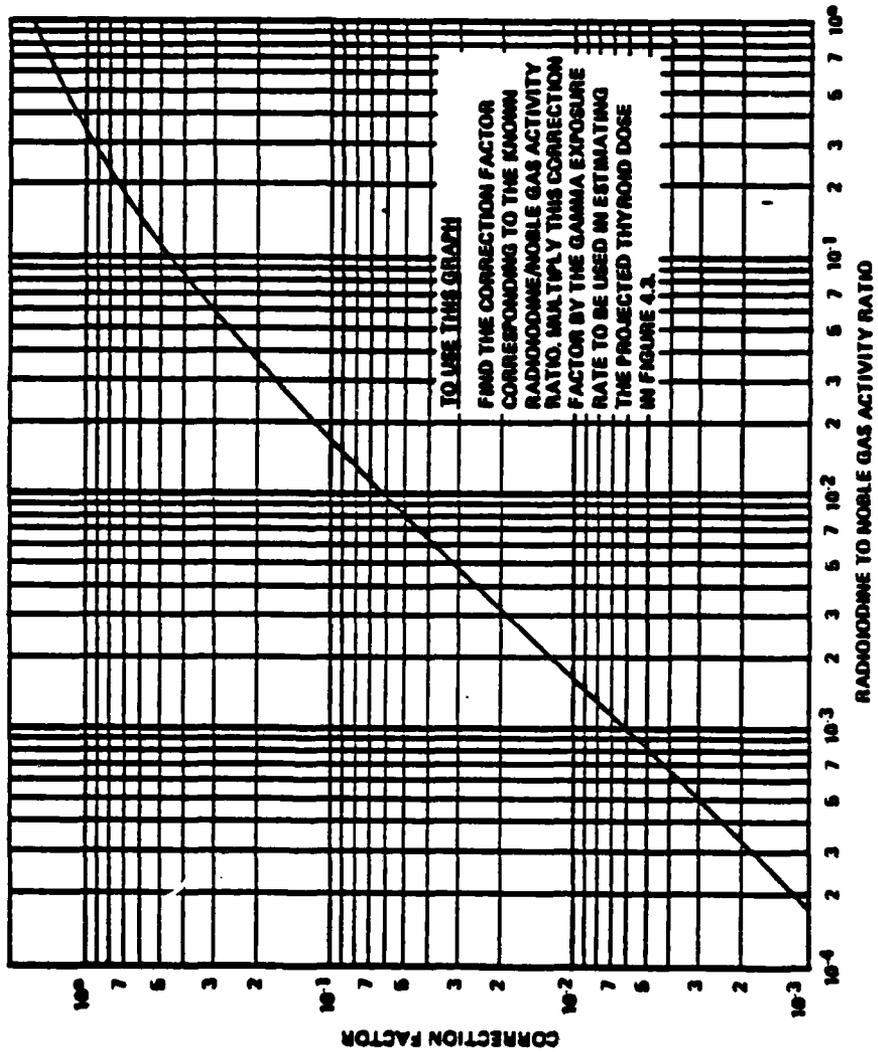


FIGURE 4.6 RADIOIODINE RELEASE CORRECTION FACTOR

5.0 Accuracy of Dose Projection Methods

The calculational methods that have been presented are intended for use in estimating projected population dose from exposure to the plume. These dose projections would be needed very quickly following collection of the data on which the calculations would be based. Therefore, numerous assumptions have been made to reduce the need for collection of different types of data, and with each assumption, the potential exists for introduction of error. Several correction factor curves have been provided to reduce the error for cases where data might be available to determine these factors.

In addition to errors associated with calculational assumptions, there is a potential for major errors in the data used as a basis for the calculations. Both types of errors are considered.

5.1 Calculational Errors Associated with Release Rate Assumptions

It has been assumed that the release will be continuous and at a constant rate. No calculational error would result from this assumption if the release actually occurred in this manner. However, there are an infinite number of release rate characteristics that could occur. This introduces a potential error in the input data which will be discussed later.

5.2 Calculational Errors Associated with Assumptions on Release Characteristics

Methods have been provided for projecting dose to both the thyroid and to the whole body based on two different types of data. One type of data would be gross airborne concentrations, and the other would be gamma exposure rate measurements. Data on concentration could be from either environmental measurements or from calculations based on release rates, distance, meteorological conditions, and windspeed.

5.2.1 Errors in Whole Body Dose

If whole body dose projections are based on gamma exposure rate measurements, the only assumption affecting calculational error would be that of setting exposure rate equal to dose rate, which is conservative, by a factor of about 1.33.

If the exposure rate is based on noble gas concentrations, a possible calculational error factor of ± 0.6 over a time period of 1 to 12.5 hours after shutdown may be encountered because of changes in the composition of the plume resulting from depletion of the shorter-lived isotopes from radioactive decay.

The whole body gamma exposure rate associated with an airborne concentration of noble gases and iodines as shown in figure 4.3 was provided to permit the use of gamma exposure rate measurements to estimate projected thyroid dose from inhalation of radioiodines. It was not intended for estimating gamma exposure rate from gross

concentration measurements or calculations. However, by appropriate use of correction factors provided in figures 4.4, 4.5, and 4.6, one could estimate exposure rate from gross concentration data. The error associated with the calculations would be primarily associated with the accuracy of the data used to obtain correction factors and not with assumptions regarding mixtures of iodines and noble gases in the release.

An additional consideration for whole body dose would be the contribution from particulate materials. Based on information in reference (32), airborne particulate materials would contribute about 20 percent of the external dose from the plume with the remaining being contributed by iodines and noble gases. This could cause the whole body dose projections based on concentrations of iodines and noble gases in air to be about 20 percent low.

5.2.2 Errors in Thyroid Dose

Two methods of projecting thyroid inhalation dose are provided. One method uses gross iodine concentration as a basis, and the other uses gamma exposure rate data as a basis.

The relative abundance of the different isotopes of iodine changes as a function of time after shutdown which changes the dose conversion factor. If the correction factor curves are used to correct this error, there should not be significant error associated with changing characteristics due to decay of short-lived isotopes

prior to start of exposure. However, a gap release as opposed to a core melt release could cause the iodine mix to have a relative concentration of iodine-131 higher than assumed due to the decay of short-lived isotopes during the process of leaching from the fuel pellets to the gaps. This could cause thyroid dose projections from gap releases to be underestimated by a maximum of about 30 percent.

The use of gamma exposure rate measurements to project thyroid dose requires assumptions regarding the characteristics of the release, and if the characteristics are different than assumed, the resulting dose estimates could include large errors. This would not be the preferred data base for estimating thyroid dose but could be used if iodine concentration data were not available. To reduce the error involved, correction factor charts for isotopic composition have been included as figures 4.4 and 4.6. If data are available to permit determination of these correction factors, the only significant errors should be a possible 30 percent underestimate associated with a gap release as discussed above and a possible 20 percent overestimate from particulate material contribution to gamma exposure rate.

5.3 Errors Associated with Input Data

Data will be collected under pressure of emergency conditions, and the associated errors may severely affect the accuracy of dose projection. Errors caused by inaccurate data relating to (1)

environmental levels as a function of time, (2) the duration of exposure, or (3) the radiological characteristics of the release could seriously affect the dose projection results. Additional errors can be associated with information on windspeed and direction, atmospheric stability, precipitation, and with interpretation of instrumentation readings.

5.3.1 Duration of Exposure

To project dose based on concentrations or exposure rates, it is always necessary to know the duration of exposure. It has been assumed for purposes of these calculations that this parameter will be known, when in fact the duration might range from a value of zero due to errors in wind direction data or to a value equal to the duration of release if wind direction is persistent in the predicted direction. The resulting error in the projected dose could be either positive or negative and would be proportional to the error in the estimated duration except as affected by the changes in concentration as a function of time. It is not possible to put bounds on this source of error.

5.3.2 Errors in Release Rate Data

The release rate could have many different characteristics due to pressure transients caused by changes in the core conditions, operation of engineered safeguards, or changes in containment integrity. These conditions could introduce one or more orders of magnitude errors in the projected dose depending on whether the data

forming the basis for dose projection were obtained from a high or low point in the transient. This error could be reduced by frequent updating of data.

5.3.3 Errors in Data on Release Characteristics

If gamma dose rates are used to estimate projected thyroid inhalation doses, correction factor curves are provided which utilize the relative amounts of iodines and noble gases in the release. If the data are not available to permit use of these correction factors, errors could be introduced in projected thyroid doses ranging from a factor of 2 too low to a factor of 100 or more too high.

5.3.4 Errors in Environmental Measurements and Information

Environmental information would include gamma radiation exposure rate, airborne concentrations of radioactive material, atmospheric stability class, windspeed, and predicted meteorological conditions.

Measurements of exposure rates and concentrations would be representative of a particular location at a particular time, and they may not represent either the average or maximum conditions at that location. Levels at a particular location will change as a function of time depending on wind direction stability, localized dispersion conditions, and fluctuations in release rate. No limits can be assigned to the errors associated with such measurements, but they could easily vary over 1 or more orders of magnitude.

5.4 Summary

A summary of the potential errors associated with dose projection methods presented here is provided in table 5.1. The potential error factors are values that could be divided into the calculated dose to get the true dose. Due to the many unknowns associated with input data and information, it is not possible to assign limits to the potential errors. However, it is apparent that the potential errors associated with inaccurate input data overwhelm those associated with calculational assumptions, and therefore, further refinement of assumptions does not appear to be necessary.

Table 5.1. Estimated errors associated with dose calculation methods

Calculational Assumptions		Input Data	
Assumption	Potential Error Factor	Type of Data	Potential Error Factor
Whole body dose rate equals exposure rate	1.33	Duration of exposure estimates	unknown
Whole body dose rate from noble gas concentration is not a function of the mixture over a 1 to 12 hr period	±0.6 ²	Release rate	0.1 to 10 more or less
		Release characteristics	.5 to 100 more or less
Whole body dose rate from mixture of noble gases and iodines is not influenced by particulates in the plume	1 to 0.8	Environmental measurements and information	0.01 to 100 more or less
Thyroid dose will not be influenced by a concentration enriched in I-131	1 to 0.7		

²The use of these projection methods for noble gases which had decayed for weeks to months (as might be the case for accidental releases from waste gas decay tanks) could cause overestimates of the whole body dose by a factor of 10 or more.

REFERENCES

- (1) INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. ICRU Report 19. Radiation Quantities and Units. International Commission on Radiation Units and Measurements, Washington, D.C. 20014 (July 1, 1971).
- (2) RICHARDSON, A. C. B. "The Historic Development of Concepts of Radiation Dose Commitment." Environmental Protection Agency, Office of Radiation Programs, Washington, D.C. 20460. Published in the Proceedings of the Eighth Midyear Topical Symposium of the Health Physics Society (October 1974).
- (3) U.S. ENVIRONMENTAL PROTECTION AGENCY. 40 CFR 190, Environmental Radiation Protection Requirements for Normal Operations of Activities in the Uranium Fuel Cycle, Final Environmental Statement. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C. 20460 (November 1976).
- (4) U.S. ATOMIC ENERGY COMMISSION. Regulatory Guide 1.3. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors. Directorate of Regulatory Standards, Nuclear Regulatory Commission, Washington, D.C. 20555 (June 1973).
- (5) U.S. ATOMIC ENERGY COMMISSION. Regulatory Guide 1.4. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors. Directorate of Regulatory Standards, Nuclear Regulatory Commission, Washington, D.C. 20555 (June 1973).
- (6) D. SLADE, ed. "Meteorology and Atomic Energy - 1968," U.S. AEC Report TID-24190. Environmental Science Services Administration, Air Resources Labs (July 1968).
- (7) U.S. NUCLEAR REGULATORY COMMISSION. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, WASH-1400 (NUREG-75/014), Appendix VI, Calculation of Reactor Accident Consequences. Nuclear Regulatory Commission, Washington, D.C. 20555 (October 1975).
- (8) RICHARDSON, L. C. "User's Manual for the Fortran Version of RSAC - A Radiological Safety Analysis Computer Program," IDO-17261, AEC Research and Development Report, Mathematics and Computers, Health and Safety, TID-4500 (June 1968).

- (9) ANNO, G. H. AND M. A. DORE. The Effectiveness of Sheltering as a Protective Measure Against Nuclear Accidents Involving Gaseous Releases. Pacific-Sierra Research Corporation, prepared for the U.S. Environmental Protection Agency, Contract No. 68-01-3223 (December 1975).
- (10) ENGLAND, T. R. AND R. E. SCHEFTER. "ENDF/B-IV Fission-Product Files: Summary of Major Nuclide Data," Los Alamos Scientific Laboratory of the University of California, National Technical Information Service. Springfield, Virginia 22151 (October 1975).
- (11) INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. "Report of the Task Group on Reference Man," ICRP Publication 23, Pergamon Press, New York (1975).
- (12) FISHER, K. D. AND C. J. CARR. "Iodine in Foods; Chemical Methodology and Sources of Iodine in the Human Diet." Contract No. FDA 71-294 prepared for Division of Nutrition, Bureau of Foods, FDA. Federation of American Societies of Experimental Biology, Bethesda, Maryland (1974).
- (13) BERSON, S. A. "Pathways of Iodine Metabolism," American Journal of Medicine, 20:653-668 (1956).
- (14) ODDIE, T. H., D. A. FISHER, W. M. MCCONAHEY, AND C. S. THOMPSON. "Iodine Intake in the United States: A Reassessment," J. Clin. Endocrinol., 30:659-665 (1970).
- (15) GRAYSON, R. R. "Factors Which Influence the Radioactive Iodine Thyroid Uptake Test," American Journal of Medicine, 28:397-415 (1960).
- (16) BLUM, M. AND R. CHANDRA. "Lower Normal Values for ^{131}I Thyroid Uptake Not Related to the Ingestion of White Bread," Journal of Nuclear Medicine, 12:743-745 (1970).
- (17) CAPLAN, R. H. AND R. KUJAK. "Thyroid Uptake of Radioactive Iodine: A Reevaluation," J. American Medicine Association, 215:916-918 (1971).
- (18) ALAZRAKI, N. P., S. E. HALPERN, AND W. L. ASHBURN. "A Reevaluation of ^{131}I Thyroid Uptake," Radiol. 105:611-614 (1972).

- (19) BERNARD, J. D., R. A. McDONALD, AND H. A. NESMITH. "New Normal Ranges for the Radioiodine Uptake Study," *Journal of Nuclear Medicine*, 11:449-451 (1970).
- (20) FITTMAN, J. A., JR., G. E. DAILEY, III, AND R. J. BESCHI. "Changing Normal Values for Thyroidal Radioiodine Uptake," *New England Journal of Medicine*, 280:1431-1434 (1969).
- (21) GHAKHEMANT, G. G., P. B. HOFFER, B. E. OFFENHEIM, AND A. GOTTSCHALK. "New Normal Values for Thyroid Uptake of Radioactive Iodine," *Journal of American Medical Association*, 217:337-339 (1971).
- (22) HARVEY, W. C., D. T. KOPP, AND W. W. BOVIE. "Further Observations on the Normal Radioactive Iodine Uptake," *Journal of Nuclear Medicine*, 13:548-550 (1972).
- (23) KARHAUSEN, L., et al. "Iodine Metabolism in Children and Adolescents in an Area of the Community," AEC-tr-7481, U.S. Atomic Energy Commission, Office of Information Services (1974).
- (24) FISHER, D. A., T. H. ODDIE, AND J. C. BURROUGHS. "Thyroidal Radioiodine Uptake Rate Measurement in Infants," *American Journal Diseases of Children*, 103:42-53 (1962).
- (25) IL'IN, L. A., G. V. ARKHANGEL'SKAYA, YU. O. KONSTANTINOV, AND I. A. LIKHAREV. "Radioactive Iodine in the Problem of Radiation Safety," Atomizdat, Moscow, 1972, AEC-tr-7536, U.S. Atomic Energy Commission, Office of Information Services (1974).
- (26) WELLMAN, H. N., J. G. KERELAKES, AND B. M. BRANSON. "Total- and Partial-Body Counting of Children for Radiopharmaceutical Dosimetry Data," pp. 133-156 in *Medical Radionuclides Radiation Dose and Effects*, R. J. Cloutier, C. L. Edwards, and W. S. Snyder, editors, AEC Symposium Series #20, U.S. Atomic Energy Commission, Division of Technical Information (1970).
- (27) INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. "Report of Committee II on Permissible Dose for Internal Radiation," ICRP Publication 2, Pergamon Press, New York (1959).
- (28) WELLMAN, L. T. AND F. C. VON DER LAGE. "Radionuclide Decay Schemes and Nuclear Parameters for Use in Radiation-Dose Estimation," MIRD Pamphlet No. 10. Society of Nuclear Medicine (September 1975).

- (29) U.S. DEPARTMENT OF HEALTH, EDUCATION AND WELFARE.
"Radiological Health Handbook." U.S. Public Health Service
(January 1970).
- (30) FORD, M. R. AND W. S. SNYDER. "Variation of Absorbed Fraction
with Shape and Size of the Thyroid," Health Physics Division
Annual Progress Report for Period Ending July 31, 1975.
Oak Ridge National Laboratory, ORNL-5046 (September 1975).
- (31) U.S. ENVIRONMENTAL PROTECTION AGENCY. "Environmental Analysis
of the Uranium Fuel Cycle, Part II - Nuclear Power Reactors."
Office of Radiation Programs, U.S. Environmental Protection
Agency (November 1973).
- (32) WALL, I. B., et al. "Overview of the Reactor Safety Study
Consequence Model," NUREG-0340. U.S. Nuclear Regulatory
Commission, Washington, D.C. 20555 (October 1977).