PNL-4491
1-
NUREG/CR-3011
PNL-4491

Dose Projection Considerations for Emergency Conditions at Nuclear Power Plants

Prepared by G. A. Stoetzel, J. V. Ramsdell, R. W. Poeton,
D. C. Powell, A. E. Desrosiers

Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

REFERENCE COPY

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability of responsibility for any third party's use, or the results of such use, of any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

Availability of Reference Materials Cited in NRC Publications

Most documents cited in NRC publications will be available from one of the following sources:

1. The NRC Public Document Room, 1717 H Street, N.W.
Washington, DC 20555
2. The NRC/GPO Sales Program, U.S. Nuclear Regulatory Commission,
Washington, DC 20555
3. The National Technical Information Service, Springfield, VA 22161

Although the listing that follows represents the majority of documents cited in NRC publications, it is not intended to be exhaustive.

Referenced documents available for inspection and copying for a fee from the NRC Public Document Room include NRC correspondence and internal NRC memoranda; NRC Office of Inspection and Enforcement bulletins, circulars, information notices, inspection and investigation notices; Licensee Event Reports; vendor reports and correspondence; Commission papers; and applicant and licensee documents and correspondence.

The following documents in the NUREG series are available for purchase from the NRC/GPO Sales Program: formal NRC staff and contractor reports, NRC-sponsored conference proceedings, and NRC booklets and brochures. Also available are Regulatory Guides, NRC regulations in the *Code of Federal Regulations*, and *Nuclear Regulatory Commission Issuances*.

Documents available from the National Technical Information Service include NUREG series reports and technical reports prepared by other federal agencies and reports prepared by the Atomic Energy Commission, forerunner agency to the Nuclear Regulatory Commission.

Documents available from public and special technical libraries include all open literature items, such as books, journal and periodical articles, and transactions. *Federal Register* notices, federal and state legislation, and congressional reports can usually be obtained from these libraries.

Documents such as theses, dissertations, foreign reports and translations, and non-NRC conference proceedings are available for purchase from the organization sponsoring the publication cited.

Single copies of NRC draft reports are available free upon written request to the Division of Technical Information and Document Control, U.S. Nuclear Regulatory Commission, Washington, DC 20555.

Copies of industry codes and standards used in a substantive manner in the NRC regulatory process are maintained at the NRC Library, 7920 Norfolk Avenue, Bethesda, Maryland, and are available there for reference use by the public. Codes and standards are usually copyrighted and may be purchased from the originating organization or, if they are American National Standards, from the American National Standards Institute, 1430 Broadway, New York, NY 10018.

Dose Projection Considerations for Emergency Conditions at Nuclear Power Plants

Manuscript Completed: January 1983
Date Published: May 1983

Prepared by
G. A. Stoetzel, J. V. Ramsdell, R. W. Poeton,
D. C. Powell, A. E. Desrosiers

Pacific Northwest Laboratory
Richland, WA 99352

Prepared for
Division of Emergency Preparedness and Engineering Response
Office of Inspection and Enforcement
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555
NRC FIN B2311

ABSTRACT

The purpose of this report is to review the problems and issues associated with making environmental radiation dose projections during emergencies at nuclear power plants. The review is divided into three areas: source term development, characterization of atmospheric dispersion and selection of appropriate dispersion models, and development of dosimetry calculations for determining thyroid dose and whole body dose for ground level and elevated releases. A discussion of uncertainties associated with these areas is also provided.

SUMMARY

This report reviews the problems and issues associated with the preparation of environmental radiation dose projections during emergencies at nuclear power plants. This dose assessment process differs considerably from prospective assessments made during siting and licensing studies and from retrospective assessments made after a release.

The major differences among these three processes are straightforward and qualitative. Prospective analyses must rely upon assumed (i.e., "design basis") source terms, estimated or average meteorological conditions, and postulated dosimetry parameters. The timeliness of the analysis is not a constraint. Assessments during emergencies, however, must reflect the source term of the actual accident, the existing or forecast meteorological conditions, and the true demographic and dosimetric parameters that apply to the exact situation. Timeliness is essential. Retrospective studies may rely strictly upon the entire history of applicable physical measurements, employing analytical techniques without regard to timeliness.

The differences in the type of information available in each case affects the type of analysis appropriate to each case. In particular, the uncertainties associated with predicting the course of a complicated reactor evolution and the stochastic nature of atmospheric transport and dispersion limits the accuracy of emergency dose assessments.

The accuracy of the source term assessment depends upon uncertainties in the quantity and type of radioactivity released. In the case of the worst feasible accidents (e.g., PWR 2 and BWR 1, as developed in the NRC's Reactor Safety Study), the halogens and volatile solids (e.g., cesium) in the release could deliver from 90 to 98% of the total absorbed dose to the whole body as well as virtually all of the radiation dose to the thyroid. Environmental release fractions for noble gases, iodines, and cesium following releases of these radioelements from the void space and fuel matrix of a nuclear power reactor will vary widely depending on the status of reactor safety systems and containment barriers. Clearly, the 90 to 98% of the potential radiation dose to the whole body delivered by iodines and volatile solids is, a priori, quite uncertain. A source term developed generically and applied to a specific accident would introduce an uncertainty of at least a factor of 100 to 10,000 in whole body dose and a factor of 10,000 to 1,000,000 in thyroid dose. Note that these estimates of source term uncertainty do not incorporate the effects of agglomeration, plateout, deposition, or water solubility. Therefore, the stated uncertainties are not upper limit values.

Obviously, the "source term" should not be developed prior to the accident. Methods and procedures implemented during an emergency should allow the known state of major fission product barriers and engineered safety features to influence the estimate or calculation of the source term. In addition, methods and procedures should be considered for both monitored and unmonitored

releases. For a monitored release, the following concepts need to be considered in estimating the source term: radionuclide mix of noble gases and iodines, corrections for time after reactor shutdown, limitations of monitors, and methodology for estimating particulate releases. For an unmonitored release, initial source term estimates should be based on available plant parameters, plant-specific information, and data from previously calculated accident scenarios.

With respect to atmospheric dispersion (diffusion and transport) of released radioactivity, calculations performed under emergency conditions must estimate dispersion during relatively brief periods of time. The usual Gaussian formulas are relatively accurate when the diffusion estimates reference time intervals of months or years, but the accuracy of estimates for short time periods (minutes or fractions of an hour) are inherently limited because diffusion of effluents in the atmosphere is a stochastic process. The upper limit of diffusion model accuracy is estimated to be about a factor of two to three under conditions where the meteorological parameters controlling diffusion are measured near the point of release and topographic relief is minimal. Under exceptional circumstances, which include rough terrain, wake flows, over water trajectories, extremes of atmospheric stability or instability and ranges of more than 10 km, uncertainties may be as great as one to two orders-of-magnitude if standard models are used.

These uncertainty estimates refer, in general, to maximum ground-level concentrations, considering only diffusion. They do not consider other atmospheric process that affect concentrations, such as radioactive decay, dry deposition and washout by precipitation. It is also important to note that these are estimates of the uncertainty on the plume centerline; they are not estimates of uncertainty at specific points in space. This difference is significant. Estimates of uncertainty at a point in space must include uncertainty in plume position, a source of uncertainty not included in the estimates given.

Recommendations for protective action are principally determined by diffusion (i.e., magnitude of concentration) rather than by transport (i.e., location of effluent). This is fortunate because the maximum ground level concentration is the least uncertain estimator of atmospheric diffusion and an excellent estimator of maximum environmental radiation dose rate. Therefore, efforts to provide accurate emergency dose assessments should characterize the diffusion characteristics of the reactor site. These characteristics include type of diffusion equation (i.e., generally the basic Gaussian equation is used), vertical constraints on diffusion, building wake effects, and deposition and washout.

No single set of procedures for estimating transport and diffusion of airborne material is appropriate for all nuclear facilities. Each facility must consider its specific topographic setting and potential release points to create an adequate model for atmospheric dispersion.

Compared to estimates of the source term and atmospheric dispersion, dosimetry calculations are relatively insensitive to the problems of

projecting from a partial data base and the need for timeliness. Two caveats are necessary, however: the dosimetry code must be adequate for the various radioelements potentially in a release; and the method of plume shine calculation must coincide with the spatial model of atmospheric plume dispersion. Otherwise, the uncertainties associated with radiation transport and the pre-accident composition and distribution of the offsite population should not cause uncertainties of the maximum offsite impact to exceed a factor of two.

In summary, the priorities for emergency dose assessment are:

- a capability to develop an accident-specific source term
- a characterization of atmospheric transport and diffusion and selection of appropriate models
- a development of dosimetry calculations for determining thyroid dose and whole body dose for ground level and/or elevated releases
- a verification that the ensemble of models for determining source term, atmospheric dispersion, and dosimetry calculations are coordinated and produce reasonable results.

CONTENTS

ABSTRACT	iii
SUMMARY	v
1.0 INTRODUCTION.....	1.1
1.1 SOURCE TERM.....	1.1
1.2 ATMOSPHERIC DISPERSION.....	1.1
1.3 DOSIMETRY.....	1.2
2.0 SOURCE TERM.....	2.1
2.1 INTRODUCTION.....	2.1
2.2 CLARIFICATION OF TMI ACTION PLAN ITEMS.....	2.1
2.3 MODELS.....	2.2
2.3.1 Regulatory Guides 1.3 and 1.4.....	2.2
2.3.2 Reactor Safety Study (RSS).....	2.3
2.3.3 NUREG-0771 and NUREG-0772.....	2.7
2.4 POTENTIAL SOURCES OF ERROR.....	2.10
2.4.1 Radioiodine Release Fractions.....	2.11
2.4.2 Fission Product Groups.....	2.13
2.4.3 Isotopic Makeup of Radioiodine and Noble Gas Fractions...	2.13
2.5 CONCLUSIONS.....	2.15
2.5.1 Monitored Releases.....	2.15
2.5.2 Unmonitored Releases.....	2.17
2.5.3 Field Measurements.....	2.18
2.6 REFERENCES.....	2.18
3.0 ATMOSPHERIC DISPERSION (METEOROLOGY).....	3.1
3.1 INTRODUCTION.....	3.1
3.2 BASIC PROBLEMS IN EVALUATING AIRBORNE RELEASES.....	3.2

3.3	ATMOSPHERIC DISPERSION MODELS.....	3.3
3.3.1	Available Models.....	3.4
3.3.2	Model Evaluation.....	3.7
3.3.3	Model Uncertainty.....	3.11
3.4	ATMOSPHERIC TRANSPORT.....	3.13
3.4.1	Wind Field Models.....	3.15
3.4.2	Vertical Adjustment of Winds.....	3.18
3.4.3	Effective Release Height.....	3.19
3.4.4	Uncertainties in Transport Estimates.....	3.20
3.5	ATMOSPHERIC DIFFUSION AND DEPOSITION.....	3.21
3.5.1	The Basic Gaussian Diffusion Equations.....	3.22
3.5.2	Diffusion Coefficient Estimates.....	3.22
3.5.3	Vertical Constraints on Diffusion.....	3.24
3.5.4	Building Wakes.....	3.25
3.5.5	Deposition and Washout.....	3.26
3.6	REFERENCES.....	3.27
4.0	DOSIMETRY.....	4.1
4.1	INTRODUCTION.....	4.1
4.2	FEDERAL GUIDANCE.....	4.1
4.3	INTERMEDIATE DOSE CALCULATION METHODS.....	4.2
4.3.1	External Gamma Radiation Dose from Plume.....	4.3
4.3.2	Inhalation Dose to Child Thyroid.....	4.17
4.3.3	Other Dose Pathways.....	4.22
4.4	RAPID DOSE CALCULATION METHODS.....	4.24
4.4.1	External Gamma Radiation Dose from Plume.....	4.27
4.4.2	Inhalation Dose to Child Thyroid.....	4.28
4.5	REFERENCES.....	4.28
APPENDIX A - TRANSPORT AND DIFFUSION IN COMPLEX TOPOGRAPHY.....		A.1
A.1	TRANSPORT AND DIFFUSION IN A COASTAL ENVIRONMENT.....	A.1
A.1.1	Elevated Releases During the Summer.....	A.1
A.1.2	Temporal Variation of the Sea Breeze.....	A.4
A.1.3	Other Coastal Release Scenarios.....	A.9
A.1.4	Coastal Measurement Programs.....	A.13

A.2	TRANSPORT AND DIFFUSION IN COMPLEX TERRAIN.....	A.14
A.2.1	Transport Near Isolated Hills.....	A.14
A.2.2	Transport Near Two-Dimensional Features.....	A.17
A.2.3	Flow Channeling.....	A.21
A.2.4	Local Terrain-Induced Winds.....	A.23
A.2.5	Fumigation.....	A.30
A.2.6	Stagnation.....	A.30
A.2.7	Impaction and Wakes.....	A.33

FIGURES

2.1	Ratio of Thyroid Dose to External Dose for Various Iodine Release Fractions.....	2.12
2.2	Correction Factor for Noble Gas Measurements Assuming All Activity is ^{133}Xe	2.16
2.3	Correction Factor for Radioiodine Measurements Assuming All Activity is ^{131}I	2.17
A.1	Three Elevated Release Scenarios with Onshore Flow During the Summer.....	A.3
A.2	Elevated and Ground-Level Concentrations in a Sea Breeze Fumigation Condition.....	A.4
A.3	Comparison of Ground-Level Centerline Concentrations for the Scenarios Shown in Figure A.1.....	A.5
A.4	Possible Trajectory of Material Released During a Sea Breeze Event.....	A.7
A.5	Three Wintertime Coastal Elevated Release Scenarios.....	A.10
A.6	Comparison of Ground-Level Centerline Concentrations for the Winter Elevated Release Scenarios.....	A.11
A.7	Summer Scenarios for Coastal Ground-Level Releases.....	A.11
A.8	Comparison of Centerline Concentrations for the Release Scenarios in Figure A.7.....	A.12
A.9	Winter Scenarios for Coastal Ground-Level Releases.....	A.12
A.10	Comparison of Centerline Concentrations for the Release Scenario in Figure A.9.....	A.13
A.11	Location of Meteorological Measurement Programs Conducted in Coastal Regions.....	A.15
A.12	Locations of Tracer Studies Conducted in Coastal Regions.....	A.16
A.13	Streamline Flow Around and Over a Hemisphere.....	A.17
A.14	Flow Around an Isolated Mountain Heated by Solar Radiation.....	A.18
A.15	The Effect of Relative Dimensions of a Hill and Plume on Transport and Diffusion.....	A.19

A.16	Simulated Flow Visualization of the Convergence and Increase in Air Speed Rising Over a Two-Dimensional Slope.....	A.19
A.17	Effects of A Mountain Ridge on Airflow.....	A.20
A.18	Transport and Diffusion Near a Cliff.....	A.21
A.19	Three Examples of Valley Channeling the Wind.....	A.22
A.20	Effects of Surface Heating on Slope Flow.....	A.24
A.21	Diurnal Mountain-Valley Wind Cycle.....	A.25
A.22	Thermal and Wind Structure in a Valley During Morning Inversion Break-up.....	A.27
A.23	Potential Circulation Patterns in a Heated Valley Corresponding to the Conditions Described in Table A.3.....	A.28
A.24	Drainage Winds in the Snake River Basin, Idaho.....	A.30
A.25	Divergent Trajectories of Tetroons Released One Minute Apart with about 100 m Separation in Elevation.....	A.31

TABLES

2.1	Core Accident Summary.....	2.5
2.2	Non-Core Accident Summary.....	2.6
2.3	Core Melt Accidents: Fraction of Core Inventory Released.....	2.7
2.4	Source Terms for Group 4 and 5 Accidents.....	2.8
2.5	Minimum Design Parameters for Alternate Source Terms.....	2.9
2.6	Fission Product Grouping.....	2.10
2.7	Effective Whole Body Dose Commitment: Total Rems and Percent of Total Rems by Fission Product Group.....	2.14
2.8	Organ Doses from Inhaled Radioactivity: Total Rems and Percent of Total Rems by Fission Product Group	2.14
3.1	Some Public Domain B* Models and Their Capabilities and Features.....	3.5
3.2	Capabilities and Features for Emergency Response Atmospheric Transport and Diffusion Models.....	3.8
3.3	Confidence Ranges for Parameter Estimates in Atmospheric Models.....	3.13
4.1	Comparison of Dose Factors for Exposure to a Semi-Infinite Plume of Noble Gases.....	4.6
4.2	Finite-Cloud Dose Correction Factors D_C/D_∞^C	4.11
4.3	Differences Between Finite Plume Dose Factors for Straight-Line Plume vs. Sector-Averaged Plume Model-- ^{133}Xe	4.13
4.4	Listing of Dosimetry Codes for Accidental Releases.....	4.14
4.5	ICRP 23 Breathing Rate Values.....	4.18
4.6	Age-Dependent Factors Used in Calculating Thyroid Dose from Inhalation-- ^{131}I	4.19
4.7	Age-Dependent Inhalation Dose Commitment Factors for Radioiodines...	4.21
4.8	Ratio of Thyroid Dose per Unit Radioiodine Air Concentration (^{131}I) for Various Ages Versus an Adult.....	4.21
4.9	External Dose Factors from Ground Contamination.....	4.25

4.10	Age-Specific Ingestion Dose Factors to the Thyroid for Radioiodines.....	4.27
A.1	Hypothetical Wind Record for a Sea Breeze Event.....	A.6
A.2	Location and Times of Fumigation for the Example in Figure A.4.....	A.8
A.3	Valley Circulation Patterns Resulting from the Combined Effects of an Upper Level Wind and Solar Heating.....	A.29

1.0 INTRODUCTION

Offsite dose assessment during nuclear power plant emergencies is required of all facilities by Title 10 Code of Federal Regulations, Part 50.47(b)(9), which states that "adequate methods, systems and equipment for assessment and monitoring actual or potential offsite consequences of a radiological emergency are in use."

This document reviews problems and issues associated with offsite dose assessment in emergency situations. Currently, there is no federal guidance on real-time dose assessment for use in emergency response facilities (ERFs) during emergency situations. The only available federal guidance is specific to pre-operational (licensing) review or routine effluent releases.

Dose assessment methodologies generally are divided into two time frames: those used in the control room during the initial hour or two of the emergency, and those used in the emergency operations facility (EOF) or technical support center (TSC) for the duration of the emergency. The control room methodologies are generally less sophisticated than those used in the EOF, where the highest level of expertise in evaluating the consequences of environmental releases is expected to be found.

This review is divided into three major sections: source term, atmospheric dispersion and dosimetry.

1.1 SOURCE TERM

This section discusses methods for estimating both the quantity and isotopic composition of accidental radioactive material releases. Models available for estimating release fractions from a reactor are reviewed with respect to application in emergency situations. In addition, potential sources of error involved in source term estimates are reviewed, including data input assumptions and calculation methods.

1.2 ATMOSPHERIC DISPERSION

This section covers several areas. It summarizes the problems in evaluating consequences of airborne releases, discusses atmospheric processes (transport, diffusion and deposition) in relatively simple topographic settings, and includes examples of atmospheric dispersion models. Also contained in this section is an overview of the difficulties encountered during the decision-making process, and sufficient background to make the literature readily useable.

While no single set of procedures for estimating transport and diffusion of airborne material is appropriate for all nuclear facilities, a list of publicly available models developed under federally funded programs is provided as a starting point in developing site specific procedures. Also given is a

table listing potential model features and rating the importance of the features in relation to site topography and release height.

1.3 DOSIMETRY

This section reviews the models available for calculating dose to individuals offsite during an emergency situation, emphasizing methods for calculating external gamma dose to the whole body and inhalation dose to the thyroid from the plume.

Modifications to rapid dose calculations, such as radioactive decay and daughter ingrowth during plume transit, also are discussed. A listing of possible computer codes to perform dose calculations are reviewed for application in emergency situations.

2.0 SOURCE TERM

2.1 INTRODUCTION

The first step in assessing the radiological consequences of an accident is to determine the actual or potential source term. This includes the quantity and radionuclide makeup of the radioactive material released to the environment as well as its temporal variation. Once the source term is measured or estimated, meteorological and dosimetry models may be applied to the assessment. Decisions can then be made regarding appropriate emergency actions (such as sheltering and evacuation) and where to apply them. During the initial and intermediate phases of an accident, involving hours rather than days, most important are the releases of radioactive material to the atmosphere. Noble gases and halogens dominate the initial assessments of the radiological impacts, although other radionuclides may be important for intermediate or long-term considerations, depending on the severity of the accident.

Ideally, monitoring of releases during an accident would provide immediate direct information on the quantities, forms and identities of radionuclides being released. Some effluent monitors incorporate gamma ray spectrometers. However, in general, the information available is more limited. Typically, monitored systems are capable of providing measurements of total noble gas, radioiodine and particulate releases. In other cases only gross dose rate measurements of atmospheric releases are available. For unmonitored releases, even this information is lacking.

When the information is limited, the analyst must make assumptions regarding the nature of the radionuclides in the release, until onsite or off-site sample analysis can provide more exact data. Uncertainties may range over several orders of magnitude, and the challenge facing the staff of the Emergency Response Facilities is in making interim assessments based on partial information, which are reasonably conservative but still prevent unnecessary responses.

2.2 CLARIFICATION OF TMI ACTION PLAN ITEMS

A number of the requirements and commitments for improvement resulting from lessons learned at Three Mile Island (TMI) relate to post accident sampling capability, improved effluent monitoring, and effluent analysis. Commitments for improvement are included in NUREG-0737 (U.S. NRC 1980), and relate directly to the efforts at source term determination. They include:

- 1) The capability to promptly obtain reactor coolant and containment atmosphere samples. The combined time allotted for sampling and analysis should be 3 hours or less from the time a decision is made to take a sample.

- 2) The performance of continuous monitoring of high-level, environmental accident releases of radioactive noble gases from effluent release points. Monitoring shall be provided for the total range of concentrations extending from normal condition concentrations to a maximum of 10^5 $\mu\text{Ci/cc}$ (^{133}Xe). Multiple monitors are usually necessary to cover the ranges of interest. Specific accident release pathways shall be monitored. Different maximum ranges are specified for various release paths, examples of which include containment exhaust (10^5 $\mu\text{Ci/cc}$), pressurized water reactor (PWR) condenser air removal system exhaust (10^4 $\mu\text{Ci/cc}$), buildings with systems containing primary coolant or offgases, PWR steam safety valve discharge and atmospheric steam dump valve discharge (10^3 $\mu\text{Ci/cc}$), and radwaste buildings and fuel handling/storage buildings (10^2 $\mu\text{Ci/cc}$).
- 3) The capability to collect and analyze representative samples of radioactive iodines and particulates in plant gaseous effluents during and following an accident. This capability is not required for PWR secondary main steam safety valve and cleanup valve discharge lines.

Design criteria for the reactor coolant and containment atmosphere sampling capability include the assumption of fission product releases as described in Regulatory Guides 1.3 (U.S. AEC 1974a) and 1.4 (U.S. AEC 1974b). These design basis conditions may necessitate shielding or design features to reduce personnel exposure and permit analysis of samples with high initial activities. The designs are not required to consider thermal deposition of particulates, loading of detectors and sampling equipment with water vapor or condensed water, condensation with sampling, or accumulation of water in sampling lines or detection equipment.

During the accident at Three Mile Island, the large quantities of radioactive noble gases being released caused erroneously high readings on the radioiodine effluent monitoring systems. The NRC report (NUREG-0737) subsequently concluded that iodine gaseous monitors for accident conditions were impractical at that time, therefore necessitating collection and analysis of radioiodine samples. Analysis using gross gamma measurements should include provisions to minimize noble gas interference.

2.3 MODELS

This section describes available models for characterizing releases to the environment from reactor accidents. The purpose is to examine methods for making initial assessments of source terms for input into atmospheric dispersion and dosimetric calculations.

2.3.1 Regulatory Guides 1.3 and 1.4

The simplest and most commonly referenced model for source term activities released under accident conditions is found in Regulatory Guides 1.3 and 1.4 (U.S. AEC 1974a,b). These guides are used in licensing and are not useful for emergency response situations.

These guides specify releases of fission product inventory to containment for a design basis loss of coolant accident (LOCA). One hundred percent of the radioactive noble gas inventory and 25% of the radioiodines are assumed to be immediately available for leakage from the reactor containment to the environment. These source term assumptions are similar to those in TID-14844 (DiNunno et al. 1962), which is referenced in the siting criteria of 10 CFR 100. The major difference is that TID-14844 also includes a particulate release from fuel consisting of 1% of the remaining fission products.

According to Regulatory Guides 1.3 and 1.4, the primary containment should be assumed to leak at the technical specifications' leak rate. The reduction in the amount of radioactive material available for leakage (achieved by engineered safety features such as containment sprays) is to be considered on an individual-case basis. According to TID-14844, reductions of several orders of magnitude may be possible. For the design basis accidents addressed in Regulatory Guides 1.3 and 1.4, the containment is assumed to remain intact.

According to the present position of the NRC staff (U.S. NRC 1981a), the design basis accidents (DBAs) are intended to conservatively describe accident conditions. They serve as the bases for engineering design and licensing evaluations. The DBAs adopted for use are non-mechanistic, hypothetical events with accident scenarios only broadly sketched; they are not intended to substitute for realistic assessments of actual accident consequences. While the large uncertainties involved in accident fission product source terms support the use of DBA conditions in assessing design limitations, it is also clear that their unmodified application to actual accident conditions may result in erroneous consequence estimates, such as the incorrect assumption that accident consequences will always be dominated by radioiodine releases. Therefore, Regulatory Guides 1.3 and 1.4 (U.S. AEC 1974 a, b) should not be used in emergency response situations.

2.3.2 Reactor Safety Study (RSS)

The Reactor Safety Study (WASH-1400) (U.S. NRC 1975) approach to accident analysis is a mechanistic one. Specific accident sequences are analyzed in an effort to calculate radionuclide release fractions and assess the accident consequences. Fission products released are grouped into seven classes, of which two are the noble gases and the halogens. Estimates of radioactivity released to containment in the RSS are based on a review of applicable data on radioactive release, transport, and deposition within the reactor systems. Four core release terms are identified for each of the seven radionuclide classes: gap release, core melt release, vaporization release, and core steam explosion release. Cumulative fractional releases from containment are calculated for each accident sequence and for each of the radionuclide classes.

The specific accident sequences are grouped into nine PWR and five boiling water reactor (BWR) release categories. The physical processes that define each release category are described. The categories generally are

characterized by core status (meltdown or no meltdown), containment integrity and operability of engineered safety features such as containment sprays and heat-removal systems.

Table 2.1 shows the Reactor Safety Study summary of release categories and release fractions for accidents involving fission product releases from the core. The RSS summary for accidents not involving the core is shown in Table 2.2.

The difficulty with using source terms arrived at by mechanistic analyses is that they require a clear and complete understanding of the specific accident processes. During an actual accident, the sequence of events and even the status of important plant systems may not be completely understood. Projection of source terms from release fractions assumed on a mechanistic basis thus becomes very difficult, and lead to large uncertainties. Environmental release fractions for noble gases, iodines, and cesium following releases of these radioelements from the void space and fuel matrix of a reactor will vary widely dependent on the status of reactor safety systems and containment barriers (see Table 2.1). For core melt accidents, noble gas release fractions varied over two orders of magnitude while iodine release fractions varied over approximately four orders of magnitude. Therefore, a source term developed generically and applied to a specific accident can be expected to introduce an uncertainty of at least a factor of 100 to 10,000 in whole body dose. The corresponding uncertainty in absorbed dose to the thyroid is approximately a factor of 10,000 to 1,000,000. Recent work by Oak Ridge (Niemczyk and McDowell-Boyer 1982) to estimate accidental releases has concluded that the overall results regarding source terms do not differ significantly from the Reactor Safety Study results.

One method of simplifying Table 2.1 for use based on limited information would be to further group the release categories for fuel melt accidents (i.e. accidents more serious than PWR 8 and 9 or BWR 5) on mode of containment failure. On this basis, a PWR fuel melt accident with massive containment failure would be represented by RSS categories PWR 1 through 3, PWR fuel melt with large containment leakage or isolation failure by PWR 4 and 5, and PWR fuel melt with basemat melt-through by PWR 6 and 7.

For BWRs there would be two cases: fuel melt with containment failure (BWR 1 through 3) and fuel melt with isolation failure (BWR 4). Categories PWR 8-9 and BWR 5 are not included since they do not involve fuel melt.

Taking the geometric mean of the release fractions to the environment in each such grouping from Table 2.1 produces the results in Table 2.3. The geometric mean more accurately reflects the release fraction in each category than the arithmetic mean.

The actual ranges of release fractions, as shown in Table 2.1, are generally less than an order of magnitude for any particular radionuclide group within the five release categories above. The major exception is the PWR 6-7 category, representing basemat melt-through accidents. The ranges of RSS release fractions in this category are typically one to two orders of

TABLE 2.1. Core Accident Summary (Table V 2-1 from U.S. NRC 1975)

RELEASE CATEGORY	PROBABILITY PER REACTOR-YR	TIME OF RELEASE (HR)	DURATION OF RELEASE (HR)	WARNING TIME FOR EVACUATION (HR)	ELEVATION OF RELEASE (METERS)	CONTAINMENT ENERGY RELEASE (10^6 Btu/HR)	FRACTION OF CORE INVENTORY RELEASED							
							Xe-Kr	ORG. I	I	Cs Rb	Te-Sb	Ba Sr	Ru ^(a)	La ^(b)
PWR 1	9×10^{-7}	2.5	0.5	1.0	25	520	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	1×10^{-3}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR 1	1×10^{-6}	2.0	2.0	1.5	25	130	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
BWR 2	6×10^{-6}	30.0	3.0	2.0	0	30	1.0	7×10^{-3}	0.90	0.50	0.30	0.10	0.03	4×10^{-3}
BWR 3	2×10^{-5}	30.0	3.0	2.0	25	20	1.0	7×10^{-3}	0.10	0.10	0.30	0.01	0.02	3×10^{-3}
BWR 4	2×10^{-6}	5.0	2.0	2.0	25	N/A	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}
BWR 5	1×10^{-4}	3.5	5.0	N/A	150	N/A	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-14}	0	0

(a) INCLUDES Mo, Rh, Tc, Co.

(b) INCLUDES Md, Y, Ce, Pr, La, Nb, Am, Cm, Pu, Np, Zr.

TABLE 2.2. Non-Core Accident Summary (Table V 2-2 from U.S. NRC 1975)^(a)

ACCIDENT	PROBABILITY OF OCCURRENCE PER REACTOR YR	TIME OF RELEASE (HR)	DURATION OF RELEASE (HR)	ELEVATION OF RELEASE (M)	EQUIVALENT FRACTION OF CORE INVENTORY RELEASED ^(c)							
					Xe Kr	ORC. I	I Br	Cs Rb	Te	Ba Sr	Ru	La
LOSS OF COOLING IN SFSP	$<10^{-6}$ ^(b)	5	5	40	10^{-1}	7×10^{-4}	7×10^{-4}	10^{-3}	6×10^{-4}	10^{-4}	2×10^{-4}	2×10^{-5}
DROPPED SHIPPING CASK	6×10^{-7}	10	10	0	3×10^{-7}	10^{-11}	10^{-11}	1×10^{-7}	3×10^{-10}	5×10^{-11}	0	0
REFUELING ACCIDENT	10^{-3}	<1	<1	40	9×10^{-5}	4×10^{-7}	4×10^{-7}	6×10^{-9}	2×10^{-11}	3×10^{-11}	0	0
WASTE GAS STORAGE TANK RUPTURE	10^{-2}	<1	<1	0	2×10^{-4}	10^{-9}	10^{-9}	0	0	0	0	0
LIQUID WASTE STORAGE TANK RUPTURE	10^{-2}	<1	<1	0	0	8×10^{-8}	8×10^{-8}	6×10^{-8}	4×10^{-9}	5×10^{-11}	2×10^{-8}	10^{-11}
EARTHQUAKE-INDUCED LOSS OF COOLING IN SFSP WITH LOSS OF AIR COOLING SYSTEM	3×10^{-8}	5	5	0	10^{-1}	7×10^{-2}	7×10^{-2}	10^{-1}	6×10^{-2}	10^{-2}	10^{-2}	10^{-3}

(a) PWR AND BWR DESIGNS WERE EXAMINED, AND THE MORE SEVERE ACCIDENTS WERE SELECTED AS REPRESENTATIVE BOUNDS FOR BOTH.

(b) BWR ESTIMATED PROBABILITY INCLUDES CONSIDERATION OF TURBINE AND TORNADO GENERATED MISSILES.

(c) FRACTIONS OF TOTAL CORE INVENTORY 30 MINUTES AFTER SHUTDOWN.

TABLE 2.3. Core Melt Accidents: Fraction of Core Inventory Released

	Xe-Kr	Org. I	I	Cs-Rb	Te-Sb	Ba-Sr	Ru	La
PWR 1-3	0.9	6×10^{-3}	0.5	0.3	0.3	0.04	0.06	3×10^{-3}
PWR 4-5	0.4	2×10^{-3}	0.05	0.02	0.01	2×10^{-3}	1×10^{-3}	2×10^{-4}
PWR 6-7	0.04	2×10^{-4}	1×10^{-4}	9×10^{-5}	1×10^{-4}	9×10^{-6}	8×10^{-6}	1×10^{-6}
BWR 1-3	1	7×10^{-3}	0.3	0.3	0.4	0.04	0.07	4×10^{-3}
BWR 4	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}

magnitude for any particular radionuclide group. The effectiveness of containment sprays is a primary determinant of release fractions for these types of accidents.

The advantage of Table 2.3 over Table 2.1 is that it provides a ready means for making preliminary estimates of release fractions and source terms for severe accidents, based on minimal information regarding containment integrity. The release fraction should be modified in any specific accident according to the expected performance of the engineered safety features.

2.3.3 NUREG-0771 and NUREG-0772

NUREG-0771 (U. S. NRC 1982) presents a five-group classification of fuel melt accidents based on degrees of core and containment safety feature integrity as follows:

- Group 1 - Complete core melt. Early containment failure. Engineered Safety Features (ESF) are ineffective.
- Group 2 - Complete core melt. Late containment failure, or early failure with operational ESFs.
- Group 3 - Complete core melt. Containment fails by basemat melt-through. ESF systems function as designed.
- Group 4 - Partial core melt. Containment system functions. ESF systems function as designed. Dominant release pathway is via containment atmosphere.
- Group 5 - Partial core melt. Containment system functions. ESF systems function as designed. Dominant fission product release pathway is through water.

ESF in this case means Engineered Safety Features used for mitigation (rather than prevention) of fission product releases. These groupings represent serious reactor accidents in a generalized manner and provide a manageable means of categorizing accidents based on limited information.

Groups 4 and 5 represent DBA-equivalent accidents in which the containment maintains its integrity, and in this respect differ from groups 1, 2 and 3. Containment integrity will have significant impact on releases of fission products to the environment. NUREG-0771 (U.S. NRC 1982) presents alternate source terms developed for accidents in Groups 4 and 5. These source terms and their associated minimum design parameters are shown in Tables 2.4 and 2.5. The Table 2.4 source terms represent accidents less severe than those for the core melt accidents in Table 2.3. The six fission product categories used in Table 2.4 are based primarily on volatility considerations described in Table 2.6.

Similar estimates for accidents more serious than DBA-equivalent sequences are not provided in NUREG-0771 (U.S. NRC 1982). Reactor Safety Study release fractions to the environment are discussed with regard to their potentially large overpredictions of severe accident source terms. At this time, sufficient information is not available to provide a basis for more realistic estimates. Studies now underway should provide better information on the magnitude of the uncertainties in the Reactor Safety Study. In the interim, Table 2.3 provides estimates for generalized fuel melt cases.

TABLE 2.4. Source Terms for Group 4 and 5 Accidents
(Table 3.8, U.S. NRC 1982)

	Fraction of Core Inventory Released		
	<u>BWR</u>	<u>PWR</u>	<u>PWR - Ice Condenser</u>
<u>Source Term, 2-hr Duration</u>			
Noble gases	4×10^{-5}	2×10^{-5}	8×10^{-5}
Halogens	1×10^{-6}	1×10^{-6}	1×10^{-7}
Cesium	4×10^{-7}	5×10^{-7}	4×10^{-8}
Soft metals	2×10^{-7}	3×10^{-7}	2×10^{-8}
Strong metals	2×10^{-8}	2×10^{-8}	2×10^{-9}
Refractory oxides	4×10^{-10}	4×10^{-10}	4×10^{-11}
<u>Source Term, 24-hr Duration</u>			
Noble gases	1×10^{-3}	3×10^{-4}	1×10^{-3}
Halogens	3×10^{-5}	9×10^{-6}	1×10^{-5}
Cesium	2×10^{-5}	6×10^{-6}	1×10^{-5}
Soft metals	7×10^{-6}	2×10^{-6}	3×10^{-6}
Strong metals	5×10^{-7}	2×10^{-7}	4×10^{-7}
Refractory oxides	1×10^{-8}	3×10^{-9}	5×10^{-9}

TABLE 2.5. Minimum Design Parameters for Alternate Source Terms
(Table 3.9, U.S. NRC 1982)

BWR

- Mark III containment, leakage <0.5%/day
- By-pass leakage <1% of containment leakage
- Positive Main Steam Isolation Valve leakage control system required
- Emergency Core Cooling System (ECCS) recirculation leakage <1 gpm, and filtered exhaust

PWR, Large Containment

- Containment leakage <0.1%/day
- Ratio of spray flow to containment volume $>10^{-3}$ gpm/ft³
- By-pass leakage <1% of containment leakage
- ECCS recirculation leakage <1 gpm, and filtered exhaust

PWR, Ice Condenser

- Containment leakage <0.5%/day
- Ratio of spray flow to upper containment volume $>10^{-3}$ gpm/ft³
- By-pass leakage <1% of containment leakage
- Deck fan flow >2 lower volumes per hour
- ECCS recirculation leakage <1 gpm, and filtered exhaust

In NUREG-0772 (U.S. NRC 1981), fission product release fractions from fuel were developed and compared with Reactor Safety Study figures for some specific accident sequences. Good agreement was found for Cs and I releases, but significantly higher releases from fuel were estimated for Te, Sb, Ba and Sr than in the Reactor Safety Study. Because of its volatility, the iodine precursor Te could be important to overall iodine releases. Consequently, daughter product ingrowth should be included in dosimetry models.

For RSS risk-dominant accidents, NUREG-0772 concludes that sensitivity studies have shown I, Cs, Te and Ru are responsible for most of the consequences of severe reactor accidents. The report also concludes that the reduction factor of all fission products except noble gases would be greater than 100,000 in cases of severe core damage accidents (50% fuel melt) where there is no loss of containment integrity and containment safety features remain operable (see Table 2.4). NUREG-0772 focuses on low probability-high consequence core melt accidents but it could be expected that similar reduction factors would apply to less severe accidents where the containment was not damaged or bypassed.

TABLE 2.6. Fission Product Grouping (Table 3.5, U.S. NRC 1982)

- I. NOBLE GASES--Elements which are chemically inert and exist as gases under normal environmental conditions. KRYPTON, XENON.*
- II. HALOGENS--Elements which are extremely labile, do not form oxides, exist in water as soluble anions, and dissociate readily. bromine, IODINE.
- III. CESIUM--Unique because of its relatively high volatility and copious quantity.
- IV. SOFT METALS--Although not necessarily present in that form within a reactor core, these elements possess comparatively soft, low density metallic states. This is due to the presence of few electronic states capable of forming chemical bonds. These elements possess comparatively reactive oxides. zinc, gallium, germanium, arsenic, selenium, silver, cadmium, indium, tin, ANTIMONY, TELLURIUM, RUBIDIUM, STRONTIUM, BARIUM.
- V. STRONG METALS--Although not necessarily present in that form, these elements have comparatively hard, high density metallic states. In common with the last group, below, they have many available bonding electronic states and possess a diversity of stable oxides and oxyanions. ZIRCONIUM, NIOBIUM, MOLYBDENUM, TECHNETIUM, RUTHENIUM, RHODIUM, palladium.
- VI. REFRACTORY OXIDES--These elements have many bonding electronic states, but their metallic states are of only moderate density and very easily oxidized. They have very stable ionic oxides which are soluble in uranium oxide, and they form highly charged cations which have generally low water solubility. YTTRIUM, LANTHANUM, CERIUM, PRASEODYMIUM, NEODYMIUM, promethium, samarium, europium, gadolinium, terbium, dysprosium, thorium, protactinium, uranium, NEPTUNIUM, PLUTONIUM, americium, CURIUM.

* Elements listed in capitals are those identified as risk dominant in the Reactor Safety Study (U.S. NRC 1975).

2.4 POTENTIAL SOURCES OF ERROR

One of the major conclusions of the Technical Bases Report (NUREG-0772, U.S. NRC 1981b) is that the uncertainties in predicting atmospheric release source terms are very large (i.e., at least an order of magnitude). This refers to source term estimates made on a mechanistic basis with specific sequences and conditions known. Uncertainties in predictions made during the actual course of an accident will necessarily be even greater. Training of plant staff during exercises is an important means of improving the management of uncertainties during accidents. Prior thought should be given to the use

of control data in assessing the status of engineered safety features (e.g., actual filter efficiency, containment spray operability).

Various sources of errors are discussed in EPA-520/1-75-001 (U.S. EPA 1975) associated with dose calculation methods, and are divided into input data errors (e.g. release rate, release characteristics, environmental information) and calculational assumption errors (e.g. "whole body dose rate equals exposure rate"). While the magnitude of potential errors from the calculational assumptions are all less than a factor of two, the potential errors from input data are in some cases as high as a factor of 100 or more. Of these, the error factor associated with release characteristics input (e.g., iodine to noble gas ratio) is dominant. Consequently the first problem addressed with regard to dose calculations should be the types and quantities of radionuclides to be input.

2.4.1 Radioiodine Release Fractions

Given that the release is monitored in some manner (e.g. gaseous release dose rate measurements), the greatest source of error in estimating the release impact is the estimation of the radioiodine quantity included in the release. When noble gas and radioiodine release fractions are of the same order of magnitude, as is the case with DBA releases to containment, radioiodine doses to the thyroid will dominate the radiological consequences. This determines the scope of necessary protective actions and the area over which they will be applied. Using dose conversion tables from EPA-520/1-75-001 (U.S. EPA 1975) it can be seen that, at one hour after shutdown, 1 Ci/m³ of radioiodine will produce a dose to the limiting organ (child's thyroid) which is 1000 times the gamma dose from 1 Ci/m³ of noble gas. Since the thyroid Protective Action Guides are five times higher than those for whole body exposure, thyroid doses would dominate the protective action decisions for any release to the environment where the ratio of iodine to noble gas release fractions is greater than 1:200. For ratios lower than this, the consequences of errors in estimates of iodine release fractions would be minimal with regard to protective actions required, since the primary dosimetric impact would be from whole body rather than thyroid exposures.

From a protective-action standpoint, the dividing line between conditions dominated by noble gases and those dominated by radioiodines can be found when the ratio of thyroid dose to external dose (from noble gases and radioiodines) equals five. Using the computer code WRAITH (Scherpelz, Borst and Hoenes 1980) 50-year dose commitments from airborne releases can be calculated for different mixtures of noble gases and radioiodines. Using the core inventories specified in the RSS (U.S. NRC 1975) and assuming ground level release conditions and release fractions given in Regulatory Guides 1.3 and 1.4 (U.S. AEC 1974a,b), WRAITH calculations show that the ratio of thyroid to external doses from noble gases varies between 300 and 460 in the interval between 1000 and 17,500 m from the release. Figure 2.1 shows the effects of reducing the iodine release fractions by factors of 10, 100, and 1000 relative to the design basis accident conditions. Such reductions might be accomplished by Engineered Safety Features (ESFs) such as sprays and filters. It is clear

FIGURE 2.1. Ratio of Thyroid Dose to External Dose for Various Iodine Release Fractions

from Figure 2.1 that such systems must reduce iodine releases to 10^{-2} to 10^{-3} of Regulatory Guide 1.3 or 1.4 levels before thyroid dose is no longer the controlling factor for protective action considerations. Regulatory Guides 1.3 and 1.4 are used here for illustration only and are not appropriate for use in emergency response situations. The curved nature of the plots results from the fact that at relatively small distances, the thyroid dose will increase faster than the external dose. The thyroid dose is directly proportional to the ground level concentration at a given point, but the external dose from a finite cloud is the sum of contributions from all points in the cloud.

As already noted, high noble gas to iodine ratios at Three Mile Island resulted in erroneously high indications on the radioiodine monitors. The post-accident sampling and analysis capability stipulated in NUREG-0737 (U.S. NRC 1980) can help establish actual conditions and limit unnecessary actions.

2.4.2 Fission Product Groups

Significant errors may be introduced by failure to consider important groups of radionuclides in accident assessments. Noble gases and radioiodines may be the only significant concerns for some specific situations, but in others the effects of other categories of fission products (such as particulates) need to be addressed.

To illustrate this point, whole body and organ doses have been calculated for the 2 hour PWR source terms in Table 2.4 for the case of a ground level release, stability class D, a 2 m/s windspeed and a distance of 5000 meters. Internal doses resulting from the inhalation of radioactive particles and external doses received from the passing radioactive plume were calculated using the computer code WRAITH (Scherpelz, Borst and Hoenes 1980). The external doses received during residence on contaminated ground were calculated assuming a three hour residence time (Moeller, Scherpelz and Desrosiers 1981). The results of these calculations are shown in Tables 2.7 and 2.8.

From Table 2.7 it can be seen that fission products other than noble gases and iodines can contribute significantly to whole body exposure, particularly from internally deposited soft metals and cesium. Table 2.8 percentages show that soft metals are the primary contributors to organ doses to the marrow and lungs under the circumstances stated. Although the release fractions in Table 2.4 represent significant reductions in radioiodine releases relative to previous estimates, the relative magnitudes of the thyroid and whole body doses in this case make it clear that protective actions would continue to be dictated by anticipated thyroid exposures for cases where only iodine and noble gases are released. It is also apparent that should iodine releases be reduced, organ doses to the lungs might be important if particulate releases were not reduced.

2.4.3 Isotopic Makeup of Radioiodine and Noble Gas Fractions

A potential source of error in calculations involving either noble gases or radioiodines is the group of assumptions made regarding the isotopic mix

TABLE 2.7. Effective Whole Body Dose Commitment: Total Rems and Percent of Total Rems by Fission Product Group

	Percentage of Dose			Total
	Internal	External	Deposition	
Noble Gases	<0.1	78.6	0	39.9
Halogens	12.1	19.5	99.1	36.2
Cesium	27.1	0.2	0.1	7.1
Soft Metals	48.6	1.5	0.7	13.5
Strong Metals	11.8	0.2	<0.1	3.2
Refractory Oxides	0.3	<0.1	<0.1	<0.1
Total Rem	1.4×10^{-3}	2.7×10^{-3}	1.2×10^{-3}	5.3×10^{-3}

TABLE 2.8. Organ Doses from Inhaled Radioactivity: Total Rems and Percent of Total Rems by Fission Product Group

	Percentage of Dose		
	Marrow	Lungs	Thyroid
Noble Gases	0.2	0.2	---
Halogens	1.1	0.5	100
Cesium	4.6	0.1	---
Soft Metals	93.7	96.5	<0.1
Strong Metals	0.3	2.8	---
Refractory Oxides	<0.1	<0.1	---
Total Rem	1.6×10^{-2}	3.0×10^{-1}	2.0×10^{-1}

within each group. For instance, graphic methods presented in EPA-520/1-75-001 (U.S. EPA 1975) for determining radioiodine doses assume a mix of isotopes present at 4.5 hours after shutdown. This assumption results in an overestimation of thyroid doses for times shorter than 4 hours after shutdown and an underestimation for longer times. The error is relatively small ($\pm 33\%$), however, and correction factors are provided. In the case of a gap (rather than core melt) release, the higher relative concentration of ^{131}I would cause an overestimation of thyroid dose projections, but the maximum error would be 30%.

Some dosimetrists assume that all observed noble gas activity is due to ^{133}Xe and interpret the results as equivalent curies of ^{133}Xe rather than a mixture of noble gas isotopes. Using data from U.S. NRC Regulatory Guide 1.109 (U.S. NRC 1977), the whole body dose conversion factor for ^{133}Xe is

2.94×10^{-4} mrem-m³/pCi-yr (equal to 33.56 rem/hr per Ci/m³). EPA 520/1-75-001 (U.S. EPA 1975) contains dose conversion factors for noble gas mixtures at various times after shutdown. Comparison of these factors shows that noble gas dose rates will be underestimated if all noble gas activity is assumed to be ¹³³Xe. The factor by which the dose rates are underestimated decreases from approximately 15 to less than 5 in the first 12 hours following shutdown.

Similarly, measurements of iodine activity (e.g. on a sample canister) will misrepresent projected thyroid doses if all the observed activity is assumed to be due to ¹³¹I. In the absence of a spectrum analysis showing peaks for all the iodine isotopes, an assumption must be made regarding the iodine isotopic makeup. Single-channel analyses which see only the ¹³¹I contribution must factor in assumed fractions of other radioiodines in order to avoid underestimating thyroid doses. Using the inhalation dose factor for a child provided in U.S. NRC Regulatory Guide 1.109 and assuming the radioiodine mixture specified in the RSS (U.S. NRC 1975), the dose factor for the iodine mixture at shutdown can be calculated to be 8.3×10^{-4} mrem/pCi inhaled. The factors at 12 and 24 hours post shutdown are 2.0×10^{-3} and 2.5×10^{-3} mrem/pCi inhaled. Therefore, interpreting all iodine as ¹³¹I will overestimate thyroid dose by a factor that decreases from 5.3 to 1.8 over the first 24 hours after shutdown.

A simple and direct method for reducing errors resulting from changes in the isotopic makeup of the noble gas and iodine fractions is to provide charts or graphs of correction factors as a function of time after shutdown. Measurements made assuming all ¹³³Xe or all ¹³¹I could be corrected using these factors to accurately represent the isotopic mix at a specific time. Figures 2.2 and 2.3 show correction factors calculated using the dose conversion factors from Regulatory Guide 1.109 (U.S. NRC 1977). Initial isotopic mixes were taken from the RSS (U.S. NRC 1975) core inventories.

2.5 CONCLUSIONS

The following sections summarize the principal factors that should be addressed in evaluating source terms for monitored releases, unmonitored releases, and environmental measurements.

2.5.1 Monitored Releases

The ideal system for monitoring releases during emergencies should provide realtime measurements of the concentrations of individual radionuclides. In practice, some compromise must be obtained between the need to monitor the releases in realtime and the need for detailed isotopic information on the release. Monitoring methods used during accidents should be employed with an awareness of their uncertainties and implicit assumptions.

Many facilities use monitoring systems that provide individual measurements of iodine, noble gases and particulates. Separate absorbers or filters

FIGURE 2.2. Correction Factor for Noble Gas Measurements Assuming All Activity is ^{133}Xe

are used to remove the radioiodines and particulates, and the noble gases are monitored in realtime. Typically, such a system might be found in the facility's main exhaust stack. The following points need to be considered in evaluating such a system for estimating accident source terms:

- Assumptions about the mix of radionuclides in each of the separate fractions, particularly iodines and noble gases, should be stated explicitly (e.g., time-dependent changes due to differential decay or ingrowth should be accounted for).
- Any necessary corrections for radionuclide mixes, other than those for which the system is calibrated, should be provided. Corrections may be needed for time after shutdown and for the type of accident (e.g., gap release vs. core meltdown). All radionuclides need to be considered, including the effects of particulates on noble gas and radioiodine measurements.
- Criteria for judging the response limitations of iodine monitors in high noble gas concentrations should be provided. Procedures could provide estimates of the sensitivity of iodine monitors to noble gases in the sampling stream.

FIGURE 2.3. Correction Factor for Radioiodine Measurements Assuming All Activity is ^{131}I

- Particulate activity has the potential for considerable impact on whole body exposures. This effect may be relatively more important when releases of radioiodines are reduced, and is particularly sensitive to assumed residence time of individuals in contaminated areas (Moeller, Scherpelz and Desrosiers 1981).
- For major releases, consideration should be given to assessment of deposition by models or measurements.

2.5.2 Unmonitored Releases

Unmonitored releases should be estimated on the basis of previously calculated accidents, plant specific information, and known plant conditions. For instance, in the case of release of coolant without fuel damage, the most recent coolant analysis could be used to estimate the release. In some cases, direct in-plant surveys (e.g. effluent lines or containment entrances) may provide information on which to base release estimates. Shielding assessments and other information necessary for the application of such methods should be

anticipated and made available in emergency procedures. Computer-based systems, such as the Interactive Rapid Dose Assessment Model (IRDAM) (Poeton et al. 1982) can be used to provide timely estimates based on available information. As a first estimate for core damage accidents, tables or references should be available for the possible source terms (as in Section 2.3.3) and core and system data should be used to categorize the release.

Sampling and analysis capability should be in place to provide radionuclide data for input into source term estimates within 3 hours following the decision to take a sample. Methods should be provided for modifying source term estimates based on radionuclide mix information from sample analysis.

2.5.3 Field Measurements

Initial release estimates should be based on available plant parameter information. Field measurements provide important feedback relative to these estimates, but must be used with caution. Field measurements are subject to errors in sampling techniques, and even measurements properly made can be affected by spatial and temporal variations in concentrations. Integrated, rather than instantaneous, radiation measurements should be used wherever possible. Field measurement data should be examined for internal consistency and compared with known atmospheric conditions before being used to modify release estimates. Procedures for field measurements should provide methods for distinguishing between ground contamination and plume exposures and for locating the center of the plume.

2.6 REFERENCES

- DiNunno, J. J., et al., 1962. Calculation of Distance Factors for Power and Test Reactor Sites. TID-14844, U.S. Atomic Energy Commission, Washington, D.C.
- Moeller, M. P., R. I. Scherpelz and A. E. Desrosiers. 1981. The Sensitivity of Calculated Doses to Critical Assumptions for the Offsite Consequences of Nuclear Power Reactor Accidents. Presented at the American Nuclear Society Conference on Probabilistic Risk Assessment. Port Chester, New York.
- Niemczyk, S. J. and L. M. McDowell-Boyer. 1982. Interim Source Term Assumptions for Emergency Planning and Equipment Qualification. NUREG/CR-2629, ORNL/TM-8274. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Poeton, R. W., M. P. Moeller, G. J. Laughlin, and A. E. Desrosiers. 1982. Interactive Rapid Dose Assessment Model (IRDAM) for Reactor Accidents. NUREG/CR-3012, PNL-4511. Pacific Northwest Laboratory, Richland, Washington.

- Scherpelz, R. I., F. J. Borst, and G. R. Hoenes. 1980. WRAITH-A Computer Code for Calculating Internal and External Doses Resulting from an Atmospheric Release of Radioactive Material. PNL-3382, Pacific Northwest Laboratory, Richland, Washington.
- U.S. Atomic Energy Commission. 1974a. Assumptions Used for Evaluating the Potential Consequences of a Loss of Coolant Accident for Boiling Water Reactors. Regulatory Guide 1.3, U.S. Nuclear Regulatory Commission, Washington, D.C.
- U.S. Atomic Energy Commission. 1974b. Assumptions Used for Evaluating the Potential Consequences of a Loss of Coolant Accident for Pressurized Water Reactors. Regulatory Guide 1.4, U.S. Nuclear Regulatory Commission, Washington, D.C.
- U.S. Environmental Protection Agency. 1975. Manual of Protective Action Guides and Protective Actions for Nuclear Incidents. EPA-520/1-75-001, Revised June, 1979 and February, 1980, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1975. Reactor Safety Study - An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants. WASH-1400. NUREG-75/014, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1977. Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I. Regulatory Guide 1.109, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1979. Atmospheric Dispersion Models for Potential Accident Consequences Assessments at Nuclear Power Plants. Regulatory 1.145, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1980. Clarification of TMI Action Plan Requirements. NUREG-0737, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1981. Technical Bases for Estimating Fission Product Behavior During LWR Accidents. NUREG-0772, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1981. Regulatory Impact of Nuclear Reactor Accident Source Term Assumptions. NUREG-0771 (For Comment), Washington, D.C.

3.0 ATMOSPHERIC DISPERSION (METEOROLOGY)

3.1 INTRODUCTION

Many meteorological aspects of the emergency response decision-making process at nuclear facilities involve estimating the transport, diffusion, transformation and depletion of material released, or projected to be released to the atmosphere. Problems associated with making these estimates have been outlined by Van der Hoven (1981) and discussed at length in Nuclear Regulatory Commission sponsored workshops (Dabberdt et al. 1982 and Watson et al. 1982). In addition, various NRC documents, e.g., NUREG-0737 (U.S. NRC 1980c), NUREG-0696 (U.S. NRC 1981b), NUREG-0814 (U.S. NRC 1981c), and Regulatory Guides 1.23 (U.S. AEC 1972 and U.S. NRC 1981a), 1.97 (U.S. NRC 1980b) and 1.101 (NUREG-0654, U.S. NRC 1980a) provide facility operators guidance in the development of acceptable emergency response plans, facilities, and dose assessment techniques.

This section consolidates current information on and provides discussion of the atmospheric processes important in evaluating the consequences of airborne releases during emergencies. It provides guidance in identification of available/practical procedures for evaluating the problems of airborne releases. No single set of procedures for estimating transport and diffusion of airborne material is appropriate for all nuclear facilities. However, a list of publically available models developed under federally funded programs is included that may provide starting points for the development of site specific procedures for a nuclear facility. Potential model features and the importance of the features as a function of site topography and release height are also discussed.

The discussion is limited to the responsibilities of nuclear facilities and does not extend to offsite response organizations. Independent evaluations of such organizations should be consistent with evaluations of nuclear facilities. Other meteorological aspects related to the emergency such as the general weather condition that affect decisions, for example, snow or ice covered roads and blizzard conditions that may make evacuation a less desirable option than sheltering, are not discussed here.

The logical scenario associated with a radiological emergency at a nuclear facility consists of a staged response on the part of facility operators. At the onset of an abnormal event, the control room staff initiates response activities. If conditions warrant, the additional staff is called in to handle those aspects of the problem that go beyond the immediate operation of the facility. Staff with the highest level of expertise in the evaluation of the consequences of releases eventually will reside in the EOF. Therefore, the background information provided here is meant to be used in the evaluation of the response capability of the EOF. The expertise to be expected of the control room staff in the evaluation of the potential consequences of airborne releases is a limited subset of that expected in the EOF. However, given

limited meteorological information, interpretation by the control room staff should be consistent with interpretation by the EOF staff. The TSC staff is expected to have an intermediate level of expertise in these matters.

3.2 BASIC PROBLEMS IN EVALUATING AIRBORNE RELEASES

The atmospheric processes that describe the transport, diffusion, transformation and depletion of material are represented mathematically by a set of nonlinear partial differential equations. These equations include the equations of motion, the thermodynamic equations, the turbulent kinetic energy equations, etc. While the discussion does not delve into these equations in detail, it is necessary to highlight two particular problems in their solution.

The problems generally are referred to as closure and boundary condition specification. Closure means specifying as many independent equations as there are unknowns. Simplifying assumptions are required to obtain closure. If closure is not achieved, there will be more unknowns than equations, and finding a unique solution will not be possible. The problem in specifying boundary conditions is that the solution is four dimensional, having three spatial dimensions and time. With appropriate simplifications, the set of equations can be solved most easily when the boundary conditions are uniform in space (homogeneous) and unvarying in time (stationary). Solution of the equations becomes difficult (and time consuming) if the boundary conditions are either nonstationary or inhomogeneous. These two problems make estimation of temporal and spatial concentration distributions following release of material to the atmosphere significantly more difficult than estimating dose from concentration distributions.

In reality, particularly in coastal settings and complex topography, the atmosphere tends to be both nonstationary and inhomogeneous. Even the solution of a simplified but complete set of equations is unlikely to produce timely results for emergency response decisions. As a result, decisions will have to be based on a simplified subset of the equations. It is therefore incumbent upon the individual providing the atmospheric assessment to have a basic understanding of the processes involved, and to understand and convey information on both the relevance and limitations of the assessment.

Atmospheric models based on stationarity and homogeneity should provide acceptable results for assessing the short range consequences of current releases. By assuming stationarity and homogeneity it is possible to treat atmospheric transport implicitly while treating diffusion explicitly. When these assumptions are discarded, implicit treatment of transport becomes more difficult and less realistic.

The term "model" is used in general sense and may consist of one or more well defined mathematical algorithms. It may also consist of a set of tables, graphs or plume plot overlays that are used to estimate the concentrations or doses at a point in space.

3.3 ATMOSPHERIC DISPERSION MODELS

Sections 11.1.4, 11.1.8 and Appendix 2 of Regulatory Guide 1.101 (NUREG-0654) discuss assessment of potential and actual exposures and doses. Two types of atmospheric models are defined for making these estimates. Class A models are intended for initial, rapid dose estimates. These estimates are expected to be available within 15 minutes of the determination that an emergency condition exists, and are for use within the plume exposure Emergency Planning Zone (EPZ). Class B models are intended for use in the larger ingestion EPZ. Both Class A and B models are to be site specific in that they should use local meteorological data and account for the effects of topography in making diffusion estimates.

Other than the difference in areal extent of the EPZs to be covered, the primary distinction between the model classes is in treatment of the time variations of atmospheric conditions. Class A models generally treat time variations by assuming a sequence of steady state conditions without considering the transition from one state to the next. By contrast, Class B models represent nonstationary and inhomogeneous conditions explicitly.

In addition to the basic difference between model types, there are differences in the features that can be expected to be included in the models. Fewer atmospheric processes will be represented in Class A than in Class B models. Specifically, Class B models must treat deposition processes and forecast meteorological conditions. However, merely including these factors in a model will not qualify it as a Class B model. Regulatory Guide 1.101 (NUREG-0654) provides for use of Class A models for the entire ingestion EPZ until emergency response facilities are fully operational, if compensating measures are taken to account for potential errors at longer transport distances. Similarly, compensating measures are required in other elements of the response recommendations.

Extensive lists of general atmospheric transport and diffusion models are contained in reviews by Drake and Barrager (1979) and Liu (1982), and an Atomic Industrial Forum (AIF) task force (Bass and Smith 1981) has reviewed a number of models for emergency response applications. Although many of the models in these lists could serve as bases for Class A and B models at nuclear facilities, they all would require some degree of modification to make them site specific. The time required to modify models for Class A use is estimated to be "modest" by the AIF task force, and the time required to upgrade candidate models to Class B status is estimated to be six to 24 months.

The AIF task force recognized the existence of a group of models that had both Class A and Class B features. These models, labeled B*, could use all available data or could operate with data from a single site. The B* models are logical starting points for developing an emergency response model because of this flexibility. Initially a Class A model could be implemented, then as features were added it would gradually achieve Class B status. By using the same model as a basis for both Class A and Class B models, a large measure of consistency between the models could be ensured.

3.3.1 Available Models

Many B* models are available for use as a starting point in Class A and B model development. Some of the B* models have been developed in publicly sponsored work and are therefore in the public domain. Other B* models have been developed by private organizations and are available for a fee or as a service. There are no inherent differences in model quality because of the source, public or private, but the cost of obtaining a model developed with public funds is likely to be significantly less than obtaining an equivalent model developed by a private organization.

Table 3.1 lists nine atmospheric transport and diffusion models in the public domain that might serve as convenient starting points for Class A and B model development. The basic model features at the time of model documentation are listed in the table. The list in Table 3.1 is not comprehensive, but it does represent a reasonable cross-section of models.

The model capabilities and features listed may not represent the current state of the models because many of the models are in a continuing state of development. For instance, since the publication of the MESOI documentation (Ramsdell and Athey 1981), the following features and capabilities have been added to the model: elevated sources, multiple sources, and wet and dry deposition. In addition, the model has been extended to include three layers in the vertical, thus permitting some of the effects of wind shear to be incorporated in the model.

Selection of a B* model is discussed in the AIF task force report (Bass and Smith 1981). Suggested evaluation criteria are:

- model availability
- model documentation adequacy
- representation of physical processes
- meteorological input data requirements
- modeled terrain influences
- model transferability
- model transfer technology
- model portability
- human factors engineering
- model validation.

The task force report should be consulted for a detailed discussion of each of the criteria. It also contains an evaluation of seven of the models listed above using these criteria.

When a starting point has been established, it is necessary to select capabilities and features to be incorporated in the ultimate Class A and B models. Clearly, feature and capability importance are a function of the specific design of the facility and its topographic setting. For example, treatment of transport and diffusion from an elevated source may not be important if a facility does not have an elevated release pathway. Similarly,

TABLE 3.1. Some Public Domain B* Models and Their Capabilities and Features

Model	Type	Sources	Release Duration	Meteoro-logical Data	Trans-port	Diffu-sion	Mixing Layer	Recep-tors	Other Features	Reference
ATAD	A	A,D	A-E	B,D,E	A-D	A	A,C,D	B	D,E	Heffter 1980
HITTM	A	A,D	A-E	B,D,E	A-D	A	A,C,D	B	D,E	Benkovitz and Heffter 1980
MESODIF	B	A-C	A-E	A,D,E	A,B,D	A,C	A,B	A-D	B-D	Start and Wendell 1974
MESODIF-II	C	A,B,D	B-E	A,D,E	A,B	A,C,D	A,B	A,C,D	A-D	Powell et al. 1979
MESOI	B	A	A-E	A,D,E	A,B	A,C	A,C	B,C		Ramsdell and Athey 1981; Athey et al. 1981
MESONPLUME	C	A-D	C-E	A,B,D,E	A,B,E	A,C	C	B,C	B,D	Benkley and Bass 1979a
MESOPUFF	B	A-D	A-E	A,B,D,E	A,B,E	A,C,D	C,D	B-D	B-D	Benkley and Bass 1979b
MESOSCALE	B,D	A,B	A-E	A,B,E	A,C,D	A	A	C	D,E	Draxler 1979
PFPL	B,C	A,C	A-C	A,C,E	A	A,B	A,C	C	B-E	Garrett and Murphy 1981

TABLE 3.1. (contd)

KEY

<u>TYPE</u>	<u>METEOROLOGICAL DATA</u>	<u>MIXING LAYER</u>
A. Gaussian plume	A. Requires surface data	A. Uniform in space
B. Lagrangian puff	B. Requires upper air data	B. Uniform in time
C. Segmented plume	C. Limited to single station	C. Externally specified in time/space
D. K-theory	D. Used multiple station data if available.	D. Coupled with stability
<u>SOURCE</u>	E. Accomodates arbitrary station coordinates	<u>RECEPTORS</u>
A. Ground level	<u>TRANSPORT</u>	A. Polar grid
B. Elevated in mixed layer	A. Interpolated or weighted wind field	B. Rectangular grid
C. Elevated above mixing layer	B. Wind field module separable from diffusion model	C. Arbitrary receptor coordinates
D. Multiple sources	C. Explicit terrain	D. Elevated receptors permitted
<u>RELEASE DURATION</u>	D. Terrain following wind	<u>OTHER FACTORS</u>
A. <3 minutes	E. Flow around obstacles	A. Building wakes
B. 3 minutes to 1 hour	<u>DIFFUSION</u>	B. Plume rise
C. 1 hour to 24 hours	A. Use stability (turbulence) typing scheme	C. Radioactive decay
D. >24 hours	B. Can use direct turbulence measurements	D. Dry deposition
E. intermittent or variable emission	C. Temporally varying diffusion rates	E. Wet deposition
	D. Terrain included	

explicit terrain representation is not important if the topography within the ingestion pathway EPZ is essentially flat and there are no major features that could affect air flow.

Table 3.2 lists a number of potential model capabilities and features and suggests a relative importance for each as a function of general topographic setting and release height. However, the table should not be interpreted as setting Class A or Class B model requirements. Given an adaptable starting point, it should be possible to incorporate most of the features and capabilities listed in Table 3.2 within the current state-of-the-art in transport and diffusion modeling. In many cases the mathematical algorithms required are standard model components that have been used for years.

One notable and important exception to this general rule is the explicit treatment of local circulations in transport and diffusion. Appendix A discusses information available for use in developing explicit treatments for transport and diffusion in local circulations. Appendix A (Section A.1) is specifically concerned with the coastal environment, while Appendix A (Section A.2) deals with complex terrain and obstacles.

3.3.2 Model Evaluation

Atmospheric process models are limited approximations of actual processes. The large number of possible assumptions that can be made in simplifying the governing equations to develop the models and the variety of topographic settings where the models are to be applied make it impractical to define a single model that is appropriate for use in emergency response applications at all sites. Consequently, evaluating an emergency response capability requires assessment of the applicability and appropriateness of the selected atmospheric process models without the aid of a predefined standard. This discussion provides some guidance in that task, although a consensus does not exist on what constitutes a complete evaluation of models or on objective techniques for overall model evaluation.

Two recent workshops have concentrated on evaluation of atmospheric model performance (Fox 1981 and Buckner 1981). Fox distinguishes between two types of performance measures. The first called "scientific", is associated with cause and effect relationships, and requires extensive and detailed data. The second type of performance measure is "operational." It is more concerned with comparison of predictions with observed data in a specific application without undue concern for the details of the prediction. Both types of performance measures are important for evaluation of emergency response models.

TABLE 3.2. Capabilities and Features for Emergency Response Atmospheric Transport and Diffusion Models

Model Feature	Topographic Setting					
	Plains		Coast		Valley	
			Release Height			
	Ground	Elevated	Ground	Elevated	Ground	Elevated
<u>Transport</u>						
Output initial transport direction	A	A	A	A	A	A
Output initial transport speed	A	A	A	A	A	A
Temporally varying wind field	B	B	A	A	A	A
Horizontally varying wind field	C	C	B	B	B	B
Vertically varying wind field	C	B	C	B	C	B
Mass-consistent wind field	D	D	D	D	D	D
Implicit terrain representation	D	D	D	D	C	C
Explicit terrain representation	D	D	C	C	B	B
Explicit representation of local circulations	D(a)	D(a)	C(a)	C(a)	C(a)	C(a)
Use all appropriate wind data	B	B	B	B	B	B
Use observed or forecast data	C	C	B	B	B	B
<u>Diffusion</u>						
Appropriate release height	A	A	A	A	A	A

TABLE 3.2. (contd)

Model Feature	Topographic Setting					
	Plains		Coast		Valley	
			Release Height			
	Ground	Elevated	Ground	Elevated	Ground	Elevated
<u>Diffusion (contd)</u>						
Appropriate diffusion coefficients	A	A	A	A	A	A
Mixing layer depth	A	A	A	A	A	A
Plume rise	E	C	E	C	E	C
Building wakes	D	E	D	E	D	E
Fumigation	E	B	E	B	E	B
Explicit terrain representation	E	A	E	A	E	A
Temporally varying diffusion coefficients	B	B	B	B	B	B
Spatially varying diffusion coefficients	C	C	C	C	C	C
Temporally varying mixing layer depth	B	B	B	B	B	B
Spatially varying mixing layer depth	C	C	C	C	C	C
Temporally varying source term	C	C	C	C	C	C
Multiple isotopes	C	C	C	C	C	C
<u>Other</u>						
Dry/wet deposition	B(b)	C(b)	B(b)	C(b)	B(b)	C(b)
Output compatible with dose model	A	A	A	A	A	A

TABLE 3.2. (contd)

Model Feature	Topographic Setting					
	Plains		Coast		Valley	
			Release Height			
	Ground	Elevated	Ground	Elevated	Ground	Elevated
<u>Other (contd)</u>						
Graphics output	C	C	C	C	C	C
Automatic entry of onsite data	B	B	B	B	B	B
Easy entry of supplementary offsite data	C	C	C	C	C	C
Resuspension	E	E	E	E	E	E
<u>Key</u>	<u>Level of Importance</u>					
A	Should be in all models					
B	Should be in models for EOF use					
C	Nice to have					
D	May be of moderate value					
E	Limited value					

(a) May be beyond state-of-the-art for emergency response models.

(b) Should be in Class B models.

When evaluating atmospheric process models for emergency response applications, among the more important of the scientific aspects are:

- scientific basis for model assumptions
- suitability of algorithms and parameters to the specific application
- accuracy of the computational techniques
- consistency of computer codes with documentation
- consistency of models within a suite
- climatological applicability and potentially available data
- utilization of available and potentially available data
- sensitivity of models to variations in input parameters
- quality assurance applied to the codes

In addition, three areas of operational performance evaluation that are practical are:

- timeliness of model output,
- accuracy of plume transport estimates,
- accuracy of plume concentration estimates.

Several levels of models are likely to be included within an emergency response capability. The most sophisticated models would be used by the EOF staff when the EOF and all supporting instrumentation are operative. The control room and TSC staff would use less sophisticated models for their assessments. Similarly, the EOF staff should have a capability to make assessments when the facilities and instrumentation are less than fully operative. These model subsets should be consistent with the models used when all expected data are available. Model consistency can be checked by evaluating the underlying assumptions and can be demonstrated by comparing model estimates for test cases where predictions should be identical. In some cases, such as loss of meteorological data, changes in model parameterizations that result in model inconsistency may be necessary.

No set of practical atmospheric process models is or will be applicable for all meteorological conditions. The state-of-the-art in transport and diffusion modeling is not developed to the point where practical models can adequately treat transport and diffusion during periods of frontal passage, thunder storms, etc. As a result, there are periods when transport and diffusion estimates become the subjective responsibility of the nuclear facility's staff. The climatological frequency and duration of these periods should be estimated.

3.3.3 Model Uncertainty

Basically, atmospheric models predict averages. A range of variability around model estimates must be accepted as a natural consequence of our inability to completely define the state of the atmosphere at any time and to solve the full set of governing equations.

The source term is the initial source of uncertainty in estimating concentrations of material released to the atmosphere. Errors in the source term are propagated throughout all diffusion and deposition estimates. Next comes the uncertainties related to the random nature of the atmosphere. As time and spatial resolution increase, there is a corresponding increase in the uncertainty associated with any diffusion or deposition estimate. In this respect an analogy might be drawn with the Heisenberg Uncertainty Principle. The uncertainties become large when time resolution increases to averages of less than 10 or 15 minutes.

The diffusion models to be used in emergency response application must meet criteria related to timeliness of output. As a result, the models themselves are a source of uncertainty. Is the form of the model selected adequate? The basic form assumed for the discussion has been Gaussian. A Gaussian model may not be appropriate for some releases or facilities.

Assuming that the source term is known exactly and the selected model is adequate, and ignoring problems associated with temporal and spatial resolution, the remaining uncertainties can be divided into those associated with estimates at positions relative to the plume and those associated with estimates for specific geographic positions.

Sources of uncertainty in relative diffusion are:

- diffusion parameter estimates
- mixing height estimates
- release height
- wind speed.

The sources of uncertainty in diffusion parameters estimate are:

- representativeness of the turbulence characterization and measurements if Lagrangian similarity and statistical parameter models are used
- selection of a diffusion (stability) classification scheme, if used
- representativeness of data used to select a diffusion class
- accuracy of the measurement.

The sources of uncertainty in concentrations at specific positions relative to the ground are:

- uncertainty in transport
- uncertainty in relative diffusion
- uncertainty in deposition and washout.

Table 3.3 summarizes confidence intervals for most of the factors entering into transport, diffusion and deposition estimates using typical instrumentation.

In 1977, the American Meteorological Society Committee on Atmospheric Turbulence and Diffusion (American Meteorological Society 1978) estimated the upper limit of accuracy for diffusion models to be about a factor of two under conditions where the meteorological parameters controlling diffusion are measured near the point of release and where topographic relief is minimal. Under exceptional circumstances, which include rough terrain, wake flows, over water trajectories, extremes of atmospheric stability or instability and ranges of more than 10 km, uncertainties may be as great as an order-of-magnitude if standard models are used.

Use of site specific models may decrease the uncertainty. Working Group C at an NRC sponsored Workshop (Dabberdt 1982) estimated the uncertainty of site specific models to be about a factor of three under optimum daytime conditions with relatively strong winds. Greater uncertainty, approaching a factor of 10, was estimated for conditions when the wind speed decreases toward calm. A similar range of uncertainty (factor of 3 to 10) was given for nighttime, ground-level releases. The uncertainty range was extended to a factor of 100 for complex terrain. No level of uncertainty was estimated for nonstationary meteorological conditions such as sea breezes.

TABLE 3.3. Confidence Ranges for Parameter Estimates in Atmospheric Models

Wind Direction	$\pm 5^\circ$ for measured values, 40° rms error in interpolated or forecast directions
Wind Speed	± 0.5 m/s for measured values, ± 2 to 3 m/s rms error for interpolated or forecast speeds
Horizontal Diffusion Parameter	Factor of 2 or more depending on topography and technique used to estimate parameter
Vertical Diffusion Parameter	Factor of 2 or more depending on topography, stability, and technique used to estimate parameter
Dry Deposition Velocity	No better than an order of magnitude estimate if constant value assumed
Washout Ratio	No better than an order of magnitude estimate
Precipitation Rate	Factor of 2 for steady-state precipitation, more for convective precipitation
Temperature	$\pm 0.5^\circ\text{C}$ if properly exposed
Temperature Difference	$\pm 0.1^\circ\text{C}$ if properly exposed and matched sensors are used.

These uncertainty estimates are generally for maximum ground-level concentrations and consider only diffusion. They do not consider other atmospheric processes affecting concentrations, such as radioactive decay, dry deposition and washout by precipitation. It is also important to note that they are estimates of the uncertainty at the plume centerline; they are not estimates of uncertainty at specific points in space. This difference is significant. Estimates of uncertainty at a point in space must include uncertainty in plume position, a source of uncertainty not included in the estimates given.

The uncertainty associated with model estimates is also a function of averaging time. In general, uncertainty decreases with increasing averaging time. Estimates given above are associated with hourly averages. If the averaging interval is reduced to 5 or 10 minutes an additional factor of two can be added to the uncertainty (Ramsdell and Hinds 1971). Uncertainties associated with instantaneous spot estimates and observations are even larger.

3.4 ATMOSPHERIC TRANSPORT

Atmospheric dispersion is a collective term encompassing both the transport of material in the atmosphere and the diffusion of material during

transport. The two phenomena are closely related, and are considered separately as a matter of convenience. Historically the division is related to the division of fluid flow into a mean component and deviations from the mean. Generally, atmospheric transport is associated with the mean flow, while diffusion is associated with the deviations from the mean (turbulence).

Recent reviews of mathematical models of atmospheric dispersion (e.g., Drake and Barrager 1979, Hanna 1981, Bass and Smith 1981, and Liu et al. 1982) classify models in many ways. For the current application the models likely to be encountered can be generally placed into one of three groups:

- 1) straight-line Gaussian models, 2) variable trajectory Gaussian models, and 3) particle-in-cell models. These models differ in their treatment of the division between transport and diffusion. Straight-line Gaussian models concentrate on the diffusion of material; transport is treated implicitly by assuming infinite temporal and spatial persistence of the wind direction, wind speed and diffusion conditions existing at the time of release. The variable trajectory models treat the transport and diffusion separately and explicitly. Finally, the particle-in-cell models concentrate on the treatment of transport; diffusion is treated implicitly by random variations of the transporting winds for individual particles.

Straight-line Gaussian models are most appropriate for use in those aspects of facility licensing where statistical treatment of meteorological conditions is reasonable. They are also of value in making the initial transport and diffusion estimates within the plume exposure EPZ. However, their utility in this application diminishes as the distance from the facility increases. The primary deficiency of these models is their implicit treatment of transport. This treatment is not acceptable, *prima facie*, for making emergency response estimates beyond a few miles unless additional compensating measures are incorporated in the assessment methodology.

Variable trajectory Gaussian and particle-in-cell models require a wind field in their explicit treatments of transport. In general, wind fields used in variable trajectory Gaussian models tend to be two-dimensional, while three-dimensional wind fields are used in particle-in-cell models. Two-dimensional wind fields can be derived from surface wind data and adjusted to the height of release using standard meteorological relationships that are a function of surface roughness and stability. They normally assume a constant wind speed and direction throughout the vertical extent of the boundary layer. Three-dimensional wind fields require some information on upper level flow in addition to surface wind data. The remainder of the wind field is then estimated by interpolation. It also may be adjusted to fulfill physical constraints such as mass continuity. Given a suitable set of wind fields, the trajectory models assume that the position of the center-of-mass of a group of particles moves with the mean wind and that diffusion occurs as a result of fluctuations about the mean.

The accuracy of transport estimates is directly related to the accuracy of the modeled wind field. It is also a function of the accuracy of estimation of the effective release height.

3.4.1 Wind Field Models

Wind field models assume a more important role as dispersion model sophistication increases from Gaussian plume models to particle-in-cell models. Wind field models range in sophistication from the single straight-line transport models used in most nuclear facility licensing studies to approximate solutions of the full set of Navier-Stokes equations in three dimensions. Although there is essentially a continuum of models on the sophistication scale, the basic types are:

- uniform wind field
- area of influence
- empirical interpolation
- objective analysis
- simplified physics
- full physics (primitive equation)

Sophistication increases from top to bottom of the list as do computer memory, computational time and data input requirements.

Uniform wind field (UW) models are common and are used in the NRC licensing process to estimate effects of routine releases. They are described in detail by Gifford (1968) and in several regulatory guides including Regulatory Guides 1.111 (U.S. NRC 1977) and 1.145 (U.S. NRC 1979). In evaluation of the effects of an accidental release, these models are realistic only in the area where the assumption of a uniform wind field can be considered valid. At some nuclear facilities this region might extend to a distance of 15 to 20 km from the facility, while at other locations the assumption might be valid for no more than 2 or 3 km.

The data input for a transport model consists of a uniform wind field based on a single representative wind direction and speed. The direction of transport is the reciprocal of the wind direction and speed of movement of the effluent is equal to the wind speed. Thus, computational requirements of the model are minimal and can be met by hand-held calculators, simple nomograms or even look-up tables.

The limitations of UW models are obvious. Straight line transport can lead to plumes passing through mountains or other obstacles. The uniform wind field does not permit a plume trajectory to curve to follow a valley. The only curvature in trajectories results from variations in the wind field with time.

Area of influence (AI) models based on measured winds are a better, but still simple, approach to describing the wind field. Wind instruments are distributed throughout the region of interest and each is assigned an area of influence within the region. The boundaries between areas are assigned on the basis of physical insight and consideration of probable effects of topographic features. The initial plume transport conforms to the wind speed and

direction in the area of release just as it does in a UW model. However, when the plume reaches a boundary between areas it changes direction and speed so the transport conforms to the wind in the area being entered. In this way curved trajectories are possible without changing the wind field. Hinds (1970) used this approach to estimate transport times in coastal mountains in Southern California with reasonable results.

The computational requirements for this approach are quite modest. Essentially, they consist of a series of simple estimates of the distance between area boundaries and the time required to transit each area.

Transport can be estimated with an AI model using a hand calculator or nomographs. Estimating transport in this way might take several minutes, compared to a few seconds with a uniform wind field model, but the results should be more realistic.

The limitations on accuracy of an AI model are related to the number of wind measurement sites and the skill with which the area boundaries are drawn. The time required to make transport estimates is primarily related to the speed with which data can be entered into the model. Computational time should be negligible.

Empirical interpolation (EI) models are the logical extension of the AI model to estimate the wind at a large number of points within the field. There are many ways to make the desired estimates. One of the most common techniques is the weighted average interpolation scheme used by Wendell (1972). Grid point winds are determined by averaging winds from at least three measurement locations. The weight assigned in averaging is proportional to the reciprocal of the square of the distance between the grid point and the measurement location. Thus, the scheme is strictly empirical.

Typical EI model grids contain more than 100 points (10 x 10). As a result, the computational load implicit in selection or use of an interpolated wind field is more than can be accomplished by hand following an accident. On the other hand, it is well within the capability of micro- and minicomputers. The computational time required for interpolation depends upon many factors including grid size, computer and skill of the programmer. For modest grids (say 20 x 20) and typical small computers, the interpolation can be completed within a few seconds. As with all interpolation schemes, accuracy depends on the amount of data available.

MESOI (Ramsdell and Athey 1981), a trajectory dispersion model that uses Wendell's (1972) wind field model, requires fewer than 20K words of memory on a UNIVAC 1100/44 computer. Including the time required to initialize the model interactively, the model can simulate a 12 hr release in less than 5 minutes when 6 puffs are released per hour and each puff is moved and exposures are accumulated at 2 minute intervals. The model also produces timely output (<5 minutes) on a Data General Eclipse C230 minicomputer.

Goodin, McRae and Seinfeld (1979) have evaluated various methods of interpolation for use with sparse data fields. They conclude that a second

degree polynomial interpolation function computed using weights that are proportional to the inverse square of the distance between the point in question and the measurement points provides a good compromise between accuracy and computational costs. This scheme is used by Wendell (1972), Start and Wendell (1974) and Ramsdell and Athey (1981).

Objective Analysis, Simplified Physics and Full Physics Models. The next level of sophistication in wind field modeling comes with application of physical constraints to the interpolation process. Sherman (1978) and Traci et al. (1977) have developed Objective Analysis (OA) wind field models that are termed mass consistent. In these models, the continuity equation is imposed as a constraint on the wind field. As a result, they are capable of identifying features that might be missed by less sophisticated models. However, this resolution is gained at the expense of increased data requirements and computational time. Drake and Huang (1980) have outlined a different mass consistent wind field representation that may be more useful for emergency response applications than the Sherman and Traci models.

As an alternative to the AI, EI and OA approaches, wind field models have been developed by simplification of the Navier-Stokes equations. The model developed by Fosberg, Marlatt and Krupnak (1976) to provide wind fields for predicting fire behavior and evaluation of air pollution transport patterns is typical of the simplified physics (SP) models. It is a two-dimensional single layer model in which the advection terms in Navier-Stokes equations are neglected and other terms are simplified using first-order assumptions. The model starts with a uniform background wind direction and speed imposed at the top of the layer. The geostrophic wind may be assumed for this purpose. The surface wind field is then derived by successive superposition of disturbances caused by terrain, surface friction and thermal forces.

The most sophisticated wind field models are the three-dimensional full physics (FP) or primitive equation models based on the Navier-Stokes equations. The SIGMET model (Traci et al. 1977) and the model developed by Pielke (1974) are typical full physics models. These models require extensive computer resources and are slow running, even on the fastest computers. Computational times for full physics models are generally compared with "real time." SIGMET runs at about one-half real time on a CDC 7600, i.e., a 1 hour simulation requires 30 minutes of run time.

With the exception of the FP models, wind field models are diagnostic and can be used to estimate the wind field only if given existing data. This diagnostic nature of the models limits their application in predicting future developments. They can be used to estimate future plume positions only to the extent that persistence of the wind field is assumed or forecast atmospheric data are available from other sources. The assumption of persistence for more than 2 to 3 hours is questionable under normal atmospheric conditions, and in topographic settings that are conducive to local circulations (e.g., coast lines and valleys), the use of persistence beyond an hour frequently may be unrealistic. Thus, the availability of adequate forecasts must be considered in evaluation of wind field models.

3.4.2 Vertical Adjustment of Winds

The transport wind is not necessarily the wind at the height of the wind measurements or at the height for which the wind field is computed. For ground-level releases the proper transport height increases as the plume diffuses vertically upward, and for elevated releases, a transport height between the effective release height and ground level is usually appropriate. With three-dimensional wind field models the transport wind may be estimated as a function of position relatively simply by interpolation between levels; with two-dimensional wind field models the process is more involved.

Models of the vertical profile of the wind form the bases for estimating elevated winds from low-level wind data. Two profile models are commonly used. The first one is a logarithmic model, and the second is a power-law profile. The logarithmic profile with correction for atmospheric stability is better supported by boundary layer theory and is better for heights of 100 m or less. The power-law technique, with an exponent that is a function of atmospheric stability, may give better results for heights significantly greater than 100 m. In general, however, either method should yield acceptable results if employed properly.

The logarithmic wind profile for neutral atmospheric conditions is equivalent to the law-of-the-wall in fluid dynamics. In the atmosphere the effects of surface heating and atmospheric stability frequently result in departures of the actual profile from a true logarithmic form. As a result a stability correction term is generally added to the log profile. A detailed development of this relationship may be found in the literature (e.g., Lumley and Panofsky 1964).

The power-law wind profile provides a somewhat simpler method of adjusting the wind vertically. The exponent α in the relationship is a function of surface roughness and atmospheric stability, although there has been a tendency to assume $\alpha = 1/7$ for all conditions. Touma (1977) gives values for α between 1/10 and 3/10 depending on the Pasquill stability class. When both stability and surface roughness are both considered, a larger range of values results (e.g., Panofsky 1977).

The use of either adjustment technique is subject to a number of limitations. Neither technique is appropriate for adjusting low-level winds for use in estimating transport if the effective transport height is above the atmospheric mixing layer. If this type of adjustment is attempted, large errors in transport direction and speed are possible, and in some synoptic conditions may even be likely. Within the mixing layer, the adjustment techniques are strictly applicable only to the layer where wind direction is constant. Neither technique is capable of turning the wind as the influence of surface friction decreases with increasing elevation. Finally, the profile relationships are strictly derived for use with wind speeds; they are not meant for use with the magnitudes of vector components. Component magnitudes will give the same result as speeds in vertical adjustment if the power-law profile is used with a common α .

3.4.3 Effective Release Height

The previous section describes atmospheric transport assuming that the effective transport height is known. A qualitative definition of effective transport height is inherent in the three words themselves. Providing a quantitative description a priori is difficult and involves a good deal of speculation. In general, it is some height between the effective release height of the plume for elevated releases (height of the center of mass for ground-level releases) and the ground. It can be estimated following a release by comparing observed plume positions and arrival times with model predictions based on a range of assumptions of transport heights. Prior to a release or during the course of a release an arbitrary height must be elected. Hoffnagle et al. (1981) recommend using the harmonic mean wind speed between 10 m and the effective release height for transport. Considering the general uncertainty in identifying a transport height, use of the speed at an arithmetic or geometric mean height may also be considered to be reasonable. Elevated releases during extremely stable conditions within or above the mixing layer should probably be transported using the effective release height wind.

The factors affecting effective release height are the actual release height, plume rise and aerodynamic effects of structures and terrain. The importance of the first factor is self evident. There is an extensive literature base related to plume rise and numerous models are available for its estimation. There is also an extensive literature base for discussion of aerodynamic effects, but the literature tends to be concentrated on models related to simple, isolated shapes and qualitative descriptions where real structures and terrain are concerned.

Mathematically, the initial effective stack height is the algebraic sum of the stack height, plume rise and an aerodynamic wake correction. Briggs (1969, 1973 and 1975) reviews the literature on and recommends models for plume rise. Briggs (1973) and Hosker (1981) discuss correction for aerodynamic effects. Stack height and plume rise are the dominant factors in determining effective release height during low wind speed conditions, while stack height and the wake correction are dominant during high winds.

Models are available for both the plume height during its rise and for its final height. Use of a final rise model to estimate plume rise for emergency response applications is appropriate. The detail provided by using the models for the initial rise is more than is generally warranted by the transport and diffusion models in which the plume rise estimates will be used. In many cases the information needed to estimate plume rise may not be available.

External variables affecting plume rise, in addition to ambient air temperature, are wind speed at release height and atmospheric stability. The ultimate limit to plume rise may be ambient atmospheric turbulence or the temperature inversion that marks the top of the atmospheric mixing layer.

Aerodynamic corrections to effective release height for stack-induced downwash and building effects are discussed by Briggs (1973) and Hosker (1981). Stack-induced downwash is minimized by a large ratio of effluent exit velocity to wind speed. A ratio of 1.5 or greater should eliminate downwash. Hosker (1981) also summarizes the available data for releases from vents on the sides of structures.

It is appropriate to correct the effective release height as the plume is transported downwind. Regulatory Guide 1.111 provides a conservative model for reduction of plume height for straight-line Gaussian models. This technique can be generalized for use with variable trajectory models by making the correction a function of the topography directly beneath the path of the plume. Egan (1975) describes a similar, more realistic but less conservative, height correction technique. The techniques are more realistic for terrain that extends above a plume centerline than they are when the plume flows across valleys. The techniques force a plume to descend into the valley, although data presented by Hinds (1970) show a definite decrease in ground-level concentrations below the ridgelines when a plume crosses a valley from ridge-to-ridge.

3.4.4 Uncertainties in Transport Estimates

Accurate transport estimates require an accurate wind field representation and an accurate estimate of the effective transport height for the material. Thus, uncertainties in transport arise from both the wind field model and the representation of plume behavior following release.

The first source of uncertainty in transport estimates is the adequacy of the wind field model. A model can do no more than represent average or expected atmospheric conditions at a specific site. The actual conditions at the time of a release may not be average. Wind field model adequacy may be particularly difficult to establish for coastal sites and sites in complex terrain where local circulations are frequent.

Uncertainty can enter transport estimates through inadequate meteorological data input in at least two ways. The total number of meteorological measurements can be inadequate, or the data can be inadequate if measurement locations are improperly positioned. In evaluation of the adequacy of the meteorological data, all sources of readily available data should be considered. This includes: onsite data, National Weather Service data, and data from other sources with which prior arrangements have been made. The potential data base should be considered in relation to the proposed wind field model. If the two are not consistent neither can be considered adequate. The effect of unexpected reductions in the available data base on the transport and diffusion models should be considered.

Inaccuracy in the meteorological measurements is another source of uncertainty in the wind field representation used by the model. Acceptable standards for accuracy of the licensee's meteorological measurements are

discussed in Regulatory Guide 1.23. The onsite meteorological data are likely to be the most accurate data used in the dose assessment. Prior to including the data from other sources in emergency plans, accuracy and representativeness of the data should be assessed by the licensee. This assessment should include evaluation of the basic sensors, the data collection methods, instrument maintenance, and instrument exposure. In addition, the reliability of the communications link between the data source and the licensee should be considered.

Any meteorological sensor or system is likely to fail occasionally. To minimize errors in the transport estimates due to erroneous data from failed sensors, the data processing, analysis and modeling programs should screen all data for consistency and normal range. Questionable data should be flagged for further evaluation. Obviously erroneous data should be noted and deleted from further consideration. Any time data are identified as questionable, instrument performance should be re-evaluated.

There is a measure of uncertainty in transport estimates resulting from errors in the estimation of the effective transport height. These errors are probably greater for elevated releases than for ground-level releases. The uncertainties enter through problems in selecting a formulation for estimating the transport height, e.g., choosing between the effective release height and the harmonic mean height. They also enter through possible errors in computation of plume rise, downwash and aerodynamic corrections, and the effect of changes in terrain elevation. In regions where local circulations are well developed these errors could result in uncertainty of transport direction by a full 180° under some synoptic conditions. In less complex conditions, uncertainty limits may be estimated by running the transport model twice--once assuming a ground-level release, and the second time using the effective release height for transport.

In the final analysis the dose assessment team must understand the limitations of the transport model, the input meteorological data and the estimates of effective transport height. Then limitations must then be considered in light of the synoptic conditions at the time of release to arrive at an estimate of the transport uncertainties.

3.5 ATMOSPHERIC DIFFUSION AND DEPOSITION

In this section attention is shifted from transport of airborne material by the mean wind to the diffusion of material relative to a fixed position within the plume center-of-mass. The processes to be considered are the primary processes that control the time and spatial variation of concentration within plumes or puffs. These processes are related to the random fluctuations of the wind, i.e., turbulence.

While there are many solutions to the partial differential equation describing diffusion, the methods of estimating concentrations that appear most frequently in assessing airborne releases from nuclear facilities are Gaussian, K-theory and particle-in-cell (PIC) models. Of these methods, the

Gaussian models generally require least effort to use, are fastest, and are least demanding on computational resources. K-theory and PIC models tend to be more versatile in complex terrain. The Gaussian models are most likely to be encountered in emergency response applications. Thus, the discussion in this section follows a Gaussian modeling approach. Although the discussion is not oriented toward K-theory and PIC models, it is applicable to their evaluation in the sense that it highlights general problem areas in diffusion and deposition.

Deposition is included in this section because it affects airborne concentrations by depleting the material in the plume. The material removed from the plumes contaminates the surfaces and serves as the primary source for residual contamination. Deposition through both dry and wet processes is considered.

3.5.1 The Basic Gaussian Diffusion Equations

The theoretical derivation of the Gaussian diffusion equations is presented in a wide range of texts, reports, and reviews of dispersion modeling (e.g., Csanady 1973; Pasquill 1974; Drake and Barrager 1979; Hanna 1981; Bass and Smith 1981; Liu et al. 1982; Gifford 1975, and Pasquill 1975). The starting point is the diffusion equation for an instantaneous point source in still air. The temporal and spatial variations are assumed to be separable and the partial differential equation is solved accordingly.

The Gaussian diffusion parameters σ_x , σ_y , and σ_z are related to the diffusivities k_x , k_y , and k_z , respectively, by travel time.

3.5.2 Diffusion Coefficient Estimates

Atmospheric diffusion experiments have resulted in a large number of observations of the lateral diffusion of plumes under a wide variety of atmospheric and topographic conditions. There have been relatively few measurements of the actual vertical diffusion of plumes, and even fewer measurements of the longitudinal diffusion of puffs. The published vertical diffusion coefficient data are generally values derived from diffusion models using measured concentrations and lateral diffusion coefficients.

Where σ_x is needed, as in puff models, it is the usual practice to assume $\sigma_x = \sigma_y$.

The familiar Pasquill-Gifford diffusion coefficient curves generally summarize the data collected prior to 1960. These data represent measurements to distances of a few hundred meters over flat open terrain for releases of 10 minutes to a half an hour in duration. The wide scatter of the diffusion coefficients and the limited experimental conditions that these coefficients represent have been largely forgotten as the Pasquill-Gifford curves have been reproduced.

The Pasquill-Gifford curves present lateral and vertical diffusion coefficients as functions of atmospheric stability and distance from the point

of release. The relationships were initially presented graphically, without explicit discussion of their underlying mathematical form. Explicit representation of diffusion coefficients in mathematical form is necessary in diffusion models. Eimutis and Konicek (1972) provide mathematical relationships that closely approximate the Pasquill-Gifford curves, and others including: Fuquay et al. (1964), Singer and Smith (1966) and Islitzer and Slade (1968) have described essentially the same diffusion coefficient data with other, similar mathematical representations. Briggs (1973) used the early diffusion coefficient data and data collected during the 1960's to develop formulae for diffusion coefficients for both rural and urban areas. These formulae are based on data to about 10 km from the source. However, Gifford (1976) recommends their use to distances of 20 to 30 km.

Atmospheric diffusion is fundamentally related to atmospheric turbulence. In the Pasquill-Gifford approach to estimating diffusion coefficients this relationship is implicit in the variation of the diffusion coefficients with atmospheric stability. Both atmospheric turbulence and atmospheric stability are continuously variable throughout their respective ranges. The definition and use of classes is arbitrarily done as a matter of convenience in data summarization and computation.

Gifford (1976) reviews many of the stability classification schemes that have been suggested for use in estimating diffusion coefficients. These schemes include: the use of wind speed, sky cover and solar insolation (e.g., Pasquill 1961, Turner 1961 and 1964), the use of vertical temperature difference (Regulatory Guide 1.23), and standard deviations of the wind direction and elevation angle fluctuations (e.g., Cramer 1955, Islitzer 1964, and Fuquay et al. 1964).

The various stability classification schemes do not result in equivalent estimates of diffusion coefficients. The inconsistencies between classification schemes are discussed in a number of papers (Luna and Church 1972, Skaggs and Robinson 1976, DeMarrais 1978, Lalas et al. 1979, Sedefian and Bennett 1979; and Mitchell 1982). From these discussions it may be concluded that the choice of stability classification scheme frequently can make a difference of several classes when individual hourly meteorological data are considered.

Lagrangian similarity theory, summarized by Horst et al. (1979) and statistical theory discussed by Pasquill (1974), Draxler (1976), Doran et al. (1978a and 1978b), Irwin (1979), Pasquill (1979) and Horst et al. (1979) among others estimate diffusion coefficients directly from turbulence measurements. Using diffusion data from several major experiments, Horst et al. (1979) demonstrated that estimation of diffusion coefficients directly from turbulence data significantly reduces the uncertainty in the estimates when compared with the uncertainties associated with the use of stability classification schemes.

The decrease in uncertainty is especially noticeable when a classification scheme based on the vertical temperature gradient has been used to estimate the lateral diffusion coefficient. The move from use of stability classes to direct use of turbulence data in estimating diffusion coefficients has been

recommended by an American Meteorological Society workshop and panel reviewing the area (Hanna et al. 1977 and Randerson 1979).

Computation of the σ_y and σ_z for use in variable trajectory models must be done using the derivatives of σ_y and σ_z with respect to distance (or time) for all advection steps except the first or with virtual distances that are a function of plume dimensions and stability. Otherwise, the sigmas will be discontinuous when the diffusion class changes. Increasing stability would cause puffs or plume segments to contract rather than just reducing the rate of diffusion.

The derivatives of the sigmas reflect a relationship between plume dimensions and characteristic turbulence scales. In general, since analytic formulae for σ_y and σ_z generally do not involve X to the first power, the derivatives are also functions of X . Thus, when stability changes, effective or virtual travel distances should be computed for σ_y and σ_z for use in their further growth. The effective travel distances for σ_y and σ_z are not likely to be the same.

The standard diffusion curves were developed from data collected over relatively simple terrain in diffusion experiments primarily with ground-level releases. Use of these curves or their analytic representations in areas of more complex terrain or for high-level release is open to question, providing an additional source of uncertainty. Lalas et al. (1979), Weil (1979) and DeMarrais (1978) discuss this problem and suggest methods to compensate for differences in topography and release height.

Comparing σ_y and σ_z uncertainties, it should be noted that σ_y estimates are based directly on measured data. In general, estimates of σ_z are determined by measuring all other terms in a diffusion model, then solving for σ_z as the unknown. Thus, measurement errors of all the terms are transferred to σ_z . In addition, computed σ_z values may be in error due to the basic inadequacies of the diffusion model itself.

One final source of uncertainty in σ_y and σ_x results from wind speed and direction shear in the vertical. As material diffuses vertically, shear in the mean wind tends to enhance the horizontal diffusion in both lateral and longitudinal directions. Most diffusion parameter estimation schemes fail to account for this effect. As a result, if the diffusion coefficient estimates are correct near the source, they will tend to be conservative (i.e., too small) at large distances downwind if there is significant wind shear. This is particularly the case if σ_x is assumed to be equal to σ_y , because the wind speed shear enhancement rapidly dominates along-wind turbulent diffusion.

3.5.3 Vertical Constraints on Diffusion

The vertical diffusion parameterizations discussed in the last section apply specifically to material released in the atmospheric mixing layer. Vertical diffusion of material released in the mixing layer is effectively

limited by the inversion that marks the top of the layer. The depth of the mixing layer is therefore of considerable concern in the event of an airborne release of material.

The depth of the mixing layer is a function of surface thermal and roughness characteristics. During the day, the thermal characteristics are usually the dominant factor in determining the mixed layer thickness. When surface heating is the driving force of turbulence in the mixing layer, the mixing layer is frequently referred to as the convective boundary layer. At night and in stable conditions, when surface heating is reduced, turbulence is generated by surface roughness and the thickness of the boundary layer is reduced. The climatology of seasonal and diurnal variations of boundary layer thickness are discussed by Hosler (1963), Miller (1967), Holzworth (1967), Carson (1973) and others.

Ideally, the mixing layer depth should be measured directly for use in diffusion computations. Coulter (1979) compares three methods for making this measurement: temperature profiles, lidar and sodar. The overall agreement between the methods was good, although some systematic differences were found.

Mixing layer depth measurement may be ideal, but it is not currently required. However, there are techniques for estimating the mixing layer depth from surface measurement and models (e.g., Benkley and Schulman 1979; Yamada 1979; Yu 1978; Mahrt and Heald 1979 and Mahrt 1981) that can be used as alternatives to measurement. The uncertainties inherent in the use of an alternative estimation technique can be quantified and perhaps reduced by comparison with measured mixing layer depths in a limited duration measurement program.

When material is released above the mixing layer, it diffuses slowly resulting in high plume concentrations at relatively large distances from the source. The limited vertical mixing above the layer keeps the plume above ground level and sets up the potential for a condition called fumigation. Fumigation occurs when the depth of the mixing layer increases until it reaches the level of the plume. At that time the material in the plume mixes rapidly to the ground.

3.5.4 Building Wakes

When material is released from surface vents on or near buildings, the turbulence generated by the building may enhance diffusion. This effect is discussed at length by Hosker (1981). A technique for estimating concentrations downwind of buildings is given in Regulatory Guide 1.145. Unless estimates of concentration very near the building are necessary, the Regulatory Guide 1.145 treatment should be adequate. Since the building wake effect on diffusion is primarily found near the source, inclusion of a building wake correction in diffusion models to be used beyond the facility fenceline will not make a significant difference in offsite dose estimates.

3.5.5 Deposition and Washout

The atmospheric processes for depletion of material in a plume include dry deposition and washout. Dry deposition is a boundary phenomenon depending in part on the diffusing material, its concentration near the surface, atmospheric turbulence, and the characteristics of the surface. Washout, on the other hand, occurs throughout the entire volume of the plume exposed to precipitation. It depends on the nature of the material, the precipitation type and intensity, the size of the raindrops or snowflakes, and the collection efficiency of the precipitation. When these processes are included in models they are highly parameterized: dry deposition is modeled by a dry deposition velocity and washout ratio is modeled by a "wet deposition velocity." These processes are discussed at length in reviews by Sehmel (1980b) and Slinn (1978).

The dry deposition velocity is defined as the ratio of flux of material to the surface to the concentration of material just above the surface. The rate at which material is deposited is a product of a "dry deposition velocity" and the near surface concentration. The surface concentration can be determined by time integration of the deposition rate.

Sehmel's review contains an extensive list of the factors influential in dry deposition. This list includes more than 20 factors each for: micro-meteorological variables, depositing material, and the surface. As a result, a single parameterization such as deposition velocity is subject to wide variation. Sehmel (1980a) shows that the range of deposition velocities reported for iodine covers more than three orders of magnitude. Reported ranges for dry deposition velocity for other materials indicate that the range for iodine is reasonably common.

Deposition models can be divided into two general classes: source depletion and surface depletion models. Both classes consider deposition velocity to be constant. In the source depletion models, (e.g., Van der Hoven, 1968) the amount of material deposited is removed from the source term as a function of distance. Reduction of the source term artificially depletes the plume concentration throughout the full vertical extent of the plume rather than removing material from the part of the plume closest to the surface. Surface depletion models, e.g., Horst (1977), Draxler and Elliott (1977), and Overcamp (1980), have been developed to correct this deficiency.

Comparing the two model types, the surface depletion models result in lower surface level airborne concentrations and less deposition near the source. As a result, more material remains in plume. Horst (1977) indicates that the differences between the models are a function of the ratio of deposition velocity to wind speed and atmospheric stability. Differences are greatest for large values of the ratio ($\sim 10^{-2}$) and high atmospheric stability ($\sim$ Pasquill F). For either small ratios ($\sim 10^{-3}$) or unstable atmospheric conditions, the difference becomes small (10 to 35%). Improvements gained in the surface depletion model are made at the expense of increased computational

time. Horst reported that his surface depletion model took more than 20 times the computational time of the source depletion model.

Washout depletion is frequently modeled as an exponential decay by introduction of scavenging rate analogous to a radioactive decay rate. Slinn (1978) gives approximate expressions for scavenging rates of both rain and snow. The scavenging rate is only representative of a small volume of the plume. To determine the plume depletion it is necessary to integrate the product of the scavenging rate and concentration vertically through the plume. Then the resulting flux can be used to define a wet deposition velocity. Alternatively, a wet deposition velocity can be defined as the product of a washout ratio and surface precipitation rate in which the washout ratio contains the results of the vertical integration. Slinn suggests that estimates of scavenging rates be treated as order-of-magnitude estimates, and shows data from Gatz (1977) and Rosinski (1967) indicating that washout ratios are also order-of-magnitude estimates.

Dry and wet deposition velocities provide a means of comparing the relative importance of the two atmospheric depletion processes if source depletion models are assumed. The washout process is comparable to dry deposition in depleting a plume for materials with small washout ratios during light rainfall. With moderate increases in either washout ratio or rainfall rate, or both, washout becomes the more important process.

3.6 REFERENCES

- American Meteorological Society, 1978. "Accuracy of Dispersion Models," Bull. Am. Met. Soc., 59, pp. 1025-1026.
- Athey, G. F., K. J. Allwine, and J. V. Ramsdell. 1981. User's Guide to the MESOI Diffusion Model and to the Utility Programs UPDATE AND LOGRVU. PNL-3999, Pacific Northwest Laboratory, Richland, Washington.
- Bass, A and D. G. Smith, 1981. Atmospheric Dispersion Modeling for Emergency Preparedness. AIF/NESP-022, Atomic Industrial Forum, Washington, DC.
- Benkley, C. W., and A. Bass. 1979a. Development of Mesoscale Air Quality Simulation Models, Volume 2. User's Guide to MESOPLUME (Mesoscale Plume Segment) Model. EPA-600/7-80-057, Environmental Protection Agency, Washington, D.C.
- Benkley, C. W. and A. Bass. 1979b. Development of Mesoscale Air Quality Simulation Models, Volume 3. User's Guide to MESOPUFF (Mesoscale Puff) Model. EPA-600/7-80-058, Environmental Protection Agency, Washington, D.C.
- Benkley, C. W. and L. L. Schulman, 1979. "Estimating Hourly Mixing Depths from Historical Meteorological Data," J. Appl. Meteor., 18, pp. 772-780.

- Benkovitz, C. M. and J. L. Heffter. 1980. User's Guide to the Heffter Interactive-Terminal Transport Model (ARL HITTM). Informal Report BNL-27801, Brookhaven National Laboratory, Upton, New York.
- Briggs, G. A., 1969. Plume Rise, AEC Critical Review Series, TID-25075.
- Briggs, G. A., 1973. "Diffusion Estimates For Small Emissions," in Environmental Res. Lab., Air Resources Atmos. Turb. & Diffusion Lab., 1973 Annual Report, ATDL-106, USDOC-NOAA.
- Briggs, G. A., 1975. "Plume Rise Predictions," in Lectures on Air Pollution and Environmental Impact Analyses, Chapter 3, Amer. Met. Soc., Boston, MA 02108.
- Buckner, M. R. (compiler), 1981. Proceedings of the First SRL Model Validation Workshop, Hilton Head, SC. DP-1597. 128 pp.
- Busch, N. E., 1973. "On the Mechanics of Atmospheric Turbulence," in Workshop on Micrometeorology, D. A. Haugen, ed. American Meteorological Society, pp. T-65.
- Businger, J. A., 1973. "Turbulent Transfer in the Atmospheric Surface Layer," in Workshop on Micrometeorology, D. A. Haugen, Ed., American Meteorological Society, pp. 67-100.
- Carson, J. E., 1973. "The Development of a Dry Inversion-capped Convectively Unstable Boundary Layer," Quart. J. Roy. Met. Soc. 99, pp. 450-467.
- Cate, J. H. 1977. "Complex Airflow Over the Upper Snake River Plain." Presented at Joint Conference on Application of Air Pollution Meteorology, Salt Lake City, Utah.
- Coulter, R. L., 1979. "A Comparison of Three Methods for Measuring Mixing-Layer Height." J. Appl. Meteor., 18:1495-1499.
- Cramer, H. E., 1957. "A Practical Method for Estimating the Dispersal of Atmospheric Contaminants," in Proceedings of the First National Conference on Applied Meteorology. American Meteorological Society, Boston, Massachusetts.
- Csanady, G. T., 1973. Turbulent Diffusion in the Environment, D. Reidel, Dordrecht, 248 pp.
- Dabberdt, W. F., F. L. Ludwig, R. E. Ruff, S. SethuRaman, J. Tickler and A. Patrinos. 1982, Workshop on Meteorological Aspects of Emergency Response Plans For Nuclear Power Plants: Proceedings and Recommendations. Final Report, SRI Project 3689, SRI International, Menlo Park, California.
- Defant, F., 1951. "Local Winds," Compendium of Meteorology, American Meteorological Society, Boston, pp. 655-662.

- Demarrais, G. A., 1978. "Atmospheric Stability Class Determination on a 481-meter tower in Oklahoma." Atmos. Environ., 12:1957-1964.
- Dickerson, M. H., 1981. "An Overview, Current Status, and Future Plans for the DOE Atmospheric Studies in Complex Terrain (ASCOT) Program," in preprints Second Conference on Mountain Meteorology, Steamboat Springs, Colorado, pp. 10-13.
- Dickerson, M. H. and P. H. Gudiksen, 1980. "The Department of Energy's Atmospheric Studies in Complex Terrain (ASCOT) Program," in preprint volume Second Joint Conference on Applications of Air Pollution Meteorology and Second Conference on Industrial Meteorology, New Orleans, LA. pp. 469-473.
- Doran, J. C., T. W. Horst and P. W. Nickola, 1978a. "Variations in Measured Values of Lateral Diffusion Parameters," J. Appl. Meteor., 17:825-831.
- Doran, J. C., T. W. Horst and P. W. Nickola, 1978b. "Experimental Observation of the Dependence of Lateral and Vertical Dispersion Characteristics on Source Height," Atmos. Environ., 12:2259-2263.
- Drake, R. L. and J. M. Barrager, 1979. Mathematical Models for Atmospheric Pollutants, EPRI EA-1131. 5 Volumes.
- Drake, R. L., and C. H. Huang, 1980. "Mass consistent, Interpolated Wind Fields for Complex Terrain," in Proceedings of Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment, Gatlinburg, TN. CONF-801064.
- Draxler, R. R. 1976. "Determination of Atmospheric Diffusion Parameters." Atmos. Environ., 10:99-105.
- Draxler, R. R. 1979. "Modeling the Results of Two Recent Mesoscale Dispersion Experiments." Atmos. Environ., 13:1523-1523.
- Draxler, R. R. and W. P. Elliott, 1977. "Long Range Travel of Airborne Material Subjected to Dry Deposition," Atmos. Environ., 11: 35-40.
- Dunn, R. and R. Ullman, 1982. Quality Assurance for Computer Software. McGraw-Hill, New York, 351 p.
- Dyer, A. J., 1974. "A Review of Flux-Profile Relationships," Boundary-Layer Meteor. 7:363-372.
- Egan, B. A., 1975., "Turbulent Diffusion in Complex Terrain," in Lectures on Air Pollution and Environmental Impact Analyses. American Meteorological Society, Boston, MA, pp 112-135.
- Eimutis, E. C. and Konicek, M. G., 1972. "Derivations of Continuous Functions for the Lateral and Vertical Atmospheric Dispersion Coefficients," Atmos. Environ., 6:859-863.

- Fosberg, M. A., W. E. Marlatt and L. Krupnak, 1976. "Estimating Airflow Patterns Over Complex Terrain," USDA Forest Service Research Paper RM-162, 16 p.
- Fox, D. G., 1981. "Judging Air Quality Model Performance," Bull. Am. Meteorol. Soc. 62:599-609.
- Fujita, T. 1967. "Mesoscale Aspects of Orographic Influences on Flow and Precipitation Patterns." In Proceedings of the Symposium on Mountain Meteorology. No. 122, pp. 132-146, Colorado State University, Ft. Collins, Colorado.
- Fuquay, J. J., C. L. Simpson, and W. T. Hinds, 1964. "Estimates of Ground-Level Air Exposures Resulting From Protracted Emissions From 70-meter stacks at Hanford," J. Appl. Meteor. 3:761-770.
- Garrett, A. J., and C. E. Murphy, Jr. 1981. A Puff-Plume Atmospheric Deposition Model for Use at SRP in Emergency Response Situations. DP-1595, Savannah River Laboratory, Aiken, South Carolina.
- Gatz, D. F., 1977. "Scavenging Ratio Measurements in METROMEX," in Precipitation Scavenging (1974), Symposium Proceedings, ERDA Report CONF-741003, pp. 77-87.
- Gifford, F. A., 1957. "Relative Atmospheric Diffusion of Smoke Puffs." J. Meteor., 14:410-414.
- Gifford, F. A., 1968. "An Outline of Theories of Diffusion in the Lower Layers of the Atmosphere," in Meteorology and Atomic Energy - 1968. D. Slade, Ed., USAEC Report TID-24190, pp. 65-116.
- Gifford, F. A., 1975. "Atmospheric Dispersion Models for Environmental Pollution Applications." In Lectures on Air Pollution and Environmental Impact Analyses, Chapter 2, American Meteorological Society, Boston, Massachusetts.
- Gifford, F. A., 1976. "Turbulent Diffusions - Typing Schemes: A Review," Nucl. Safety, 17:68-86.
- Gifford, F. A., 1981. Comments on "Lateral Dispersion Coefficients as a Function of Averaging Time," J. Appl. Meteor., 20:213.
- Golder, D., 1972. "Relations Among Stability Parameters in the Surface Layer." Boundary Layer Meteor., 3:47-58.
- Goodin, W. R., G. J. McRae and J. H. Seinfeld, 1979, "A Comparison of Interpolation Methods for Sparse Data: Application to Wind and Concentration Fields," J. Appl. Meteor., 18:761-771.

- Hanna, S. R., G. A. Briggs, J. Deardorff, B. A. Egan, F. A. Gifford and F. Pasquill. 1977. "Meeting Review--AMS Workshop on Stability Classification Schemes and Sigma Curves - Summary of Recommendations," Bull. Amer. Meteorol. Soc., 58:1305-1309.
- Hanna, S. R., 1981. Handbook on Atmospheric Diffusion Models, ATDL Contribution File No. 81/5, prepared for the World Meteorological Organization, 66 pp.
- Heffter, J. L. 1980. "Air Resources Laboratories Atmospheric Transport and Diffusion Model (ARL-ATAD)." Air Resources Laboratories, NOAA Technical Memorandum, ERL ARL-81.
- Hewson, E. W., E. W. Bierly and G. D. Gill. 1961 "Topographic Influences on the Behavior of Stack Effluents." Proceedings of the American Power Conference 23: 358-370.
- Hinds, W. T., 1970. "Diffusion Over Coastal Mountains of Southern California," Atmos. Environ., 4:107-124.
- Hoffnagle, G. F., M. E. Smith, T. V. Crawford and T. J. Lockhart, 1981. "On-Site Meteorological Instrumentation Requirements to Characterize Diffusion From Point Sources - A Workshop 15-17 January 1980, Raleigh, N.C." Bull. Amer. Meteorol. Soc., 62 pp. 255-261.
- Holzworth, G. C., 1967. "Mixing Depths, Wind Speeds and Air Pollution Potential for Selected Locations in the United States," J. Appl. Meteor., 6:1039-1044.
- Horst, T. W., 1977. "A Surface Depletion Model for Deposition from a Gaussian Plume," Atmos. Environ., 11:41-46.
- Horst, T. W., J. C. Doran and P. W. Nickola, 1979., "Evaluation of Empirical Atmospheric Diffusion Data," NUREG/CR-1798, 150 p.
- Hosker, R. P., Jr., 1981. Methods for Estimating Wake Flow and Effluent Dispersion Near Simple Block Like Buildings, NOAA Technical Memorandum, ERL ARL-108, 138 p.
- Hosler, C. R., 1963. "Climatological Estimates of Diffusion Conditions in the United States." Nucl. Safety, 5:184-198.
- Irwin, J. S. 1979. "Estimation Plume Dispersion - A Recommended Generalized Scheme," in Preprint Volume for Fourth Symposium on Turbulence, Diffusion and Air Pollution. American Meteorological Society, Boston, Massachusetts.
- Irwin, J. S. and F. S. Binkowski, 1981. "Estimation of the Monin-Obukhov Scaling Length Using On-Site Instrumentation," Atmos. Environ., 15:1091-1094.

- Islitzer, N. F. 1965. "Program Review and Summary of Recent Accomplishments at NRTS." In Conference on AEC Meteorological Activities, May 19-22, 1964, BNL-914, Brookhaven National Laboratory, Upton, New York.
- Islitzer, N. and D. H. Slade, 1968. Meteorology and Atomic Energy - 1968, pp. 117-8. USAEC Report TID-24190. Environmental Science Services Administration.
- Jehn, K. H., 1973. A Sea Breeze Bibliography, Report No. 37, Atmospheric Sciences Group, College of Engineering, The University of Texas, Austin, TX, 51 p.
- Lalas, D. P., V. Catsoulis and M. Petrakis, 1979. "On the Consistency of Stability Classification Schemes When Applied to Non-Homogeneous Terrain," Atmos. Environ., 13:pp. 687-691.
- Lamb, B. K., A. Lorenzen and F. H. Shair, 1978. "Atmospheric Dispersion and Transport Within Coastal Regions - Part I, Tracer Study of Power Plant Emissions From the Connard Plain," Atmos. Environ., 12:pp. 2089-2100.
- Lamb, B. K., F. H. Shair and T. B. Smith, 1978. "Atmospheric Dispersion and Transport Within Coastal Regions - Part II. Tracer Study of Industrial Emissions in the California Delta Region," Atmos. Environ., 12:2101-2118.
- Liu, M. K., G. E. Moore, and H. Y. Holman, 1982. Survey of Plume Models for Atmospheric Application. EPRI EA-2243, 152 pp.
- Ludwig, F. L. and G. Byrd, 1980. "An Efficient Method for Deriving Mass-Consistent Flow Fields from Wind Observations in Rough Terrain," Atmos. Environ., 14:585-587.
- Lumley, J. A. and H. A. Panofsky, 1964. The Structure of Atmospheric Turbulence. 239 pp.
- Luna, A. E. and H. W. Church. 1972. "A Comparison of Turbulence Intensity and Stability Ratio Measurements to Pasquill Stability Classes," J. Appl. Meteor., 11:663-669.
- Lyons, W. A. and H. S. Cole, 1973. "Fumigation and Plume Trapping on the Shores of Lake Michigan During Stable Onshore Flow," J. Appl. Meteor., 12:494-510.
- Lyons, W. A., 1975. "Turbulent Diffusion and Pollutant Transport in Shoreline Environments," in Lectures on Air Pollution and Environmental Impact Analyses, American Meteorological Society, Boston, MA, pp. 136-208.
- Mahrt, L. and R. C. Heald, 1979. Comments on "Determining Height of the Nocturnal Boundary Layer," J. Appl. Meteor., 18:383.

- Mahrt, L. 1981. "Modelling the Depth of the Stable Boundary Layer," Boundary-Layer Meteor., 21:3-19.
- Mazzola, C. A. and J. W. Wilson, 1979. "Quality Assurance Aspects of a Nuclear Related Meteorological Monitoring Program," in Quality Assurance in Air Pollution Measurement, Air Pollution Control Association, pp. 332-339.
- McRae, G. J., F. H. Shair and J. H. Seinfeld, 1981. "Convective Downmixing of Plumes in a Coastal Environment," J. Appl. Meteor., 20:1312-1324.
- Meroney, R. N. J. E. Cermak, and B. T. Young, 1975. "Modeling of Atmospheric Transport and fumigation at Shoreline Sites," Boundary-Layer Meteor., 9:69-90.
- Mikkelsen, T. and I. Troen, 1981. Comments on "Lateral Dispersion Coefficients as Functions of Averaging Time," J. Appl. Meteor., 20:731-732.
- Miller, M. E., 1967. "Forecasting Afternoon Mixing Depths and Transport Wind Speeds," Mon. Wea. Rev., 95:35-44.
- Misra, P. K., 1980. "Dispersion From Tall Stacks Into a Shoreline Environment," Atmos. Environ., 14:397-400.
- Mitchell, A. E., Jr. 1982. "A Comparison of Short-Term Dispersion Estimates Resulting from Various Atmospheric Stability Classification Methods." Atmos. Environ., 16:765-773.
- Nickola, P. W. 1971. "Measurements of the Movement, Concentration and Dimensions of Clouds Resulting from Instantaneous Point Sources." J. Appl. Meteor., 10:962-973.
- Olsson, L. E., W. P. Elliott and S-I Hsu, 1973. "Marine Air Penetration in Western Oregon: An Observation Study." Mon. Wea. Rev., 101(4): pp. 356-362.
- Orgill, M. M., 1981. A Planning Guide For Future Studies, PNL-3656/ASCOT/80/4 Pacific Northwest Laboratory, Richland, WA.
- Overcamp, T. J., 1980. "A Comparison Between Surface-Corrected and Source Depletion Models for Estimating Deposition of Pollutants," in Proceedings of Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment, Gatlinburg, TN. CONF. 801064, pp. 281-288.
- Panofsky, H. A., 1977. "Wind Structure in Strong Winds Below 150 m.," Wind Engineering, 1:91-103.
- Pasquill, F., 1961. "The Estimation of Windborne Material," Meteorological Magazine, 90:33-49.

- Pasquill, F., 1974. Atmospheric Diffusion, Halstead Press, 429 pp.
- Pasquill, F., 1975. "The Dispersion of Materials in the Atmospheric Boundary Layer - The Basis for Generalization," in Lectures on Air Pollution and Environmental Impact Analyses, Chapter I, Amer. Met. Soc., Boston, MA 02108.
- Pasquill, F., 1979. "Atmospheric Dispersion Modeling," J. Air Poll. Control Assoc., 29:117-119.
- Pielke, R. A., 1974. "A Three-Dimensional Numerical Model of the Sea Breezes Over South Florida," Mon. Wea. Rev., 102:115-139.
- Powell, D. C., H. L. Wegley and T. D. Fox, 1979. "Mesodif-II: A variable Trajectory Plume Segment Model to Assess Ground Level Air Concentrations and Deposition of Effluent Releases From Nuclear Power Facilities," NUREG/CR-0523, USNRC, Washington, D.C.
- Ramsdell, J. V. and W. T. Hinds, 1971. "Concentration Fluctuations and Peak-to-Mean Concentration Ratios in Plumes From a Ground-Level Continuous Point Source." Atmos. Environ., 5:483-495.
- Ramsdell, J. V. and G. F. Athey, 1981. MESOI: An Interactive Lagrangian Trajectory Puff Diffusion Model, PNL-3998, Pacific Northwest Laboratory, Richland, WA.
- Randerson, D. 1979. "Review Panel on Sigma Computations," Bull. Amer. Meteor. Soc., 60:682-683.
- Raynor, G. S., P. Michael, R. M. Brown and S. Sethu Raman, 1975. "Studies of Atmospheric Diffusion From a Nearshore Oceanic Site," J. Appl. Meteor., 14:1080-1094.
- Raynor, G. S., S. Sethu Raman and R. M. Brown, 1979. "Formation and Characteristics of Coastal Internal Boundary Layers During Onshore Flows," Boundary-Layer Meteor., 16:487-514.
- Raynor, G. S., P. Michael and S. Sethu Raman, 1979. Recommendations for Meteorological Measurement Programs and Atmospheric Diffusion Prediction Methods for Use at Coastal Nuclear Reactor Sites, NUREG/CR-0936. USNRC, Washington, DC.
- Raynor, G. S., P. Michael and S. Sethu Raman, 1980. "Meteorological Measurement Methods and Diffusion Models for Use at Coastal Nuclear Reactor Sites," Nucl. Safety, 21:749-765.
- Rosinski, J., 1967. "Insoluble Particles in Hail and Rain," J. Appl. Meteor., 6, 1966-1974.
- Rowe, R. D., 1981. Comments "On Lateral Dispersion Coefficients as Functions of Averaging Time," J. Appl. Meteor., 20:728-730.

- Scorer, R. S., 1952. "Mountain-Gap Winds; A Study of Surface wind at Gibraltar," Quart. J. R. Met. Soc., 78:53-61; 462-463.
- Scorer, R. S., 1955. "Theory of Airflow Over Mountains: IV - Separation of Flow From the Surface," Quart. J. R. Met. Soc., 81:340-350.
- Sedefian, L. and E. Bennett, 1980. "A Comparison of Turbulence Classification Schemes," Atmos. Environ., 14:741-750.
- Sehmel, G. A., 1980a. "Literature Ranges of Dry Deposition Velocities for Gases," in Pacific Northwest Laboratory Annual Report for 1979 to the DOE Assistant Secretary for Environment, Part 3, PNL-3300, Pacific Northwest Laboratory, Richland, WA.
- Sehmel, G. A., 1980b. "Particle and Gas Dry Deposition: A Review," Atmos. Environ., 14:983-1011.
- Sehmel, G. A. and W. H. Hodgson, 1980. "A Model for Predicting Dry Deposition of Particles and Gases to Environmental Surfaces," in Implications of the Clean Air Act Amendments of 1977 and Energy Considerations for Air Pollution Control. Symposium Series No. 196, Vol. 76, pp. 218-230, American Institute of Chemical Engineers, New York.
- Shearer, D. L. and R. J. Kaleel, 1982. Critical Review of Studies on Atmospheric Dispersion in Coastal Regions. NUREG/CR-2754.
- Sheih, C. M., 1980. "On Lateral Dispersion Coefficients as Functions of Averaging Time," J. Appl. Meteor., 19:557-561.
- Sheih, C. M., 1981a. "Reply," J. Appl. Meteor., 20:213-214.
- Sheih, C. M., 1981b. "Reply," J. Appl. Meteor., 20:730.
- Sherman, C. A., 1978. "A Mass-Consistent Model Complex Terrain," J. Appl. Meteor., 17:312-319.
- Singer, I. A. and M. E. Smith, 1966. "Atmospheric Dispersion at Brookhaven National Laboratory," Int. J. Air Water Poll., 10:125-135.
- Skaggs, D. L., and E. Robinson. 1976. "A Comparison of Methods for Estimating Atmospheric Stability and Diffusion Coefficients," J. Air Poll. Cont. Assoc., 26:888-891.
- Slinn, W. G. N., 1978. "Parameterizations for Resuspension and for Wet and Dry Deposition of Particles and Gases for Use in Radiation Dose Calculations," Nucl. Safety, 19, 205-219.
- Start, G. E., and L. L. Wendell, 1974. Regional Effluent Calculations Considering Spatial and Temporal Meteorological Variations, NOAA Technical Memorandum ERL ARL-44, Air Resources Laboratories, Idaho Falls, Idaho.

- Start G. E., C. R. Dickson and L. L. Wendell, 1975. "Diffusion in a Canyon Within Rough Mountainous Terrain," J. Appl. Meteor., 14:333-346.
- Start, G. E., C. R. Dickson and N. R. Ricks. 1974. "Effluent Dilutions Over Mountainous Terrain and Within Mountain Canyons," presented at Symposium on Atmospheric Diffusion and Air Pollution, Santa Barbara, California. Sponsored by American Meteorological Society, pp. 226-232.
- Touma, J. S., 1977. "Dependence of the Wind Profile Power Law on Stability for Various Locations," J. Air. Poll. Control Assoc., 27, pp. 863-866.
- Traci, R. M., G. T. Phillips, P. C. Patnaik, and B. E. Freeman, 1977. "Development of a Wind Energy Site Selection Methodology," RLO/2440-11, 205 p.
- Turner, D. B., 1961. "Relationships Between 24-Hour Mean Air Quality Measurements and Meteorological Factors in Nashville, Tenn." J. Air Poll. Control Assoc., 11:483-489.
- Turner, D. B., 1964. "A Diffusion Model for an Urban Area," J. Appl. Meteor., 3:83-91.
- U.S. Atomic Energy Commission, 1972. "Onsite Meteorological Programs," Regulatory Guide 1.23, USNRC, Washington, DC.
- U.S. Environmental Protection Agency, 1980. Guidelines for Determination of Good Engineering Practice Stack Height, Environmental Protection Agency Office of Air Quality, Planning and Standards Report No. EPA-450/4-80-023 (draft), 84 p.
- U.S. Nuclear Regulatory Commission, 1977. "Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases From Light-Water-Cooled Reactors," Regulatory Guide 1.111 Revision 1, USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission, 1979. "Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants," Regulatory Guide 1.145, (Draft for Comment), USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission, 1980a. Criteria for Preparation and Evaluation of Radiological Emergency Response Plans and Preparedness in Support of Nuclear Power Plants, Regulatory Guide 1.101 (NUREG-0654 Rev. 1), USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission, 1980b. "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following An Accident," Regulatory Guide 1.97, Rev. 2, USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission, 1980c. Clarification of TMI Action Plan Requirements, NUREG-0737, USNRC, Washington, DC.

- U.S. Nuclear Regulatory Commission, 1981a. Meteorological Measurement Programs for Nuclear Power Plants, Proposed Revision 1 to Regulatory Guide T.23, USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission, 1981b. Functional Criteria For Emergency Response Facilities, NUREG-0696, USNRC, Washington, DC.
- U.S. Nuclear Regulatory Commission. 1981c. Methodology for Evaluation of Emergency Response Facilities. NUREG-0814, USNRC, Washington, D.C.
- Van der Hoven, I. A., 1967. "Atmospheric Transport and Diffusion at Coastal Sites," Nucl. Safety, 8:490-499.
- Van der Hoven, I. A., 1968. "Deposition of Particles and Gases," Meteorology and Atomic Energy, 1968, (O. Slade, Ed.), pp. 202-208, USAEC, TID-24190.
- Van der Hoven, I. A., 1981. Meteorological Considerations in the Development of a Real-Time Atmospheric Dispersion Model for Reactor Effluent Exposure Pathway, NUREG/CR-2584, USNRC, Washington, DC.
- Van Dop, H., R. Steinkist and F.T.M. Neinwstadt, 1979. "Revised Estimates for Continuous Shoreline Fumigation," J. Appl. Meteor., 18:133-137.
- Venkatram, A., 1980. "Estimating the Monin-Obukhov Length in the Stable Boundary Layer for Dispersion Calculations," Boundary-Layer Meteor., 19:481-485.
- Wanta, R. C., and W. P. Lowry, 1976. "Airflow Through Rough Terrain and Built-up Areas," In Air Pollution, 3rd. Ed., Ed. A. C. Stern, Vol. 1, 8: 386-390. Academic Press, San Francisco, California.
- Watson, E. C., ed., 1982. Proceedings of the Workshop on Environmental Assessment, Sponsored by the U. S. Nuclear Regulatory Commission, NUREG/CP-0025.
- Weil, J. C., 1979. "Applicability of Stability Classification Schemes and Associated Parameters to Dispersion of Tall Stack Plumes in Maryland," Atmos. Environ., 13:819-831.
- Wendell, L. L., 1972. "Mesoscale Wind fields and Transport Estimates Determined From a Network of Wind Towers," Mon. Wea. Rev., 100:565-578.
- Wendell, L. L., 1973. "Some Influences of Regional Boundary Layer Flow on Atmospheric Transport and Dispersion," presented at Second Joint Conference on Sensing of Environmental Pollutants, Washington, DC. Sponsored by Instrument Society of America, p. 271-278.
- Whiteman, C. D., 1982. "Breakup of Temperature Inversions in Deep Mountain Valleys: Part I. Observations," J. Appl. Meteor., 21:270-289.

- Whiteman, C. D. and T. B. McKee, 1982. "Breakup of Temperature Inversions in Deep Mountain Valleys: Part II. Thermodynamic Model." J. Appl. Meteor., 21:290-302.
- Wilkins, E. M., 1956. "Effects of Topography on Winds and Diffusion Conditions at the National Reactor Testing Station," J. Air Poll. Control Assoc. 6(1): 14-16.
- Yamada, T., 1979. "Prediction of the Nocturnal Surface Inversion Height," J. Appl. Meteor., 18:526-531.
- Yu, T., 1978. "Determining Height of the Nocturnal Boundary Layer," J. Appl. Meteor., 17:28-33.

4.0 DOSIMETRY

4.1 INTRODUCTION

The preceding two sections on source term and atmospheric dispersion have reviewed methods for estimating radionuclide release rates during an accident, and the subsequent transport and diffusion of releases in the environment. This section reviews methodologies for calculating offsite dose rates and doses from known radionuclide concentrations at downwind receptor locations. These offsite concentrations can be obtained either from estimates using release information and current meteorological conditions or by field measurement techniques.

Compared to estimates of the source term and atmospheric dispersion, dosimetry calculations are relatively insensitive to the problems of projecting from a partial data base and the need for timeliness. Two caveats are necessary, however: the dosimetry code must be capable of handling the various radioelements potentially in a release; and the method of plume shine calculation must coincide with the spatial model of atmospheric plume dispersion. Otherwise, the uncertainties associated with radiation transport and the pre-accident composition and distribution of the offsite population should not cause uncertainties of the maximum offsite impact to exceed a factor of two.

The review concentrates on doses received in the plume emergency planning zone (EPZ) including external gamma radiation dose to the whole body and inhalation dose to the thyroid from the passing plume. Methods for rapidly calculating and projecting the above doses are critical, as these calculations will help determine what protective actions may be necessary. Doses received from other pathways such as external gamma dose from ground contamination, inhalation dose from resuspended radioactive material, and ingestion doses are not discussed in detail. Such doses would be less significant than doses from the passing plume during the first hours following a release of radioactivity.

The first topic of discussion is applicable federal guidance on offsite dose calculation methods. Reviews of rapid and intermediate dose calculation methods are presented next. Rapid calculation methods are intended for use in the control room during approximately the first hour of an accident while intermediate methods are generally more sophisticated and are intended for use in the EOF and TSC once established. Reviews of dose calculation methods include discussions of mathematical models and computer codes for calculating external gamma dose to the whole-body and inhalation dose to the thyroid from the passing plume. A variety of different models are reviewed with a discussion of the advantages and disadvantages of each model.

4.2 FEDERAL GUIDANCE

Federal guidance was provided in Di Nunno et al. (1962) for calculating doses in the exclusion area and low population zone. Dose calculation methods

were presented for inhalation dose to the critical organ and external gamma radiation dose from the passing plume. These calculations are required by 10 CFR 100 (Reactor Site Criteria) as a part of the licensing process for a reactor.

Regulatory Guides 1.3 (U.S. AEC 1974a) and 1.4 (U.S. AEC 1974b) provide assumptions to be used in evaluating the potential radiological consequences of a loss of coolant accident (LOCA) for boiling water reactors (BWRs) and pressurized water reactors (PWRs). This evaluation is required of each applicant for a construction permit or operating license in accordance with Section 50.34 of 10 CFR 50. Equations for calculating external whole body dose from the plume using a semi-infinite cloud model (see Section 4.3.1.1) are provided in the two regulatory guides. In addition, iodine dose conversion factors found in Internal Commission on Radiological Protection (ICRP) Publication 2 (1959) are recommended for use in calculating inhalation dose to the thyroid.

Federal guidance also has been provided in Regulatory Guide 1.109 (U.S. NRC 1977a), NUREG-0172 (Hoenes and Soldat 1977), and NUREG-0133 (Boegli et al., 1978) on acceptable methodologies for estimating radiation dose due to release of radioactive materials in effluents. This guidance is concerned with implementing of requirements in 10 CFR 50, Appendix I, "Numerical Guides for Design Objectives and Limiting Conditions for Operation to Meet the Criterion 'As Low As is Reasonably Achievable' for Radioactive Material in Light-Water-Cooled Nuclear Power Reactor Effluents". Regulatory Guide 1.109 (U.S. NRC 1977a) provides guidance to the licensee on mathematical models acceptable to NRC staff for calculating external gamma dose from contaminated air and inhalation dose to the thyroid. Although Regulatory Guide 1.109 was written for calculating doses from routine effluent releases, some of the calculational methods are applicable to accident releases as discussed in Section 4.3. NUREG-0172 (Hoenes and Soldat 1977) provides updated information on calculating inhalation and ingestion doses. NUREG-0133 (Boegli et al. 1978) represents the most recent federal guidance on calculating offsite doses from routine reactor effluents, and uses methodology outlined in Regulatory Guide 1.109.

To date, no explicit federal guidance has been provided on dose calculation methods to be used in the event of an accidental release at a nuclear power plant. All the studies reviewed above are for specific licensing actions or routine effluent releases.

4.3 INTERMEDIATE DOSE CALCULATION METHODS

Intermediate dose calculation methods would be used in the EOF and TSC. These methods require more rigorous modeling and the capability to include a broader release spectrum of radionuclides than a rapid dose calculation method. In addition, use of a computer is essential.

4.3.1 External Gamma Radiation Dose from Plume

Methods for calculating external gamma radiation dose from a passing plume are based on the type of release. For a ground-level release, a semi-infinite plume model is generally conservative (Dabberdt et al. 1982, Healy and Baker 1968, U.S. NRC 1977a). For an elevated release, a finite plume model is generally recommended (Dabberdt et al. 1982, Healy and Baker 1968, and U.S. NRC 1977a). A finite plume model also could be used for a ground-level release, if more realistic results are desired.

Among the factors to consider when determining whether a release is elevated or ground-level are stack height, temperature of the release, velocity of the release, windspeed, and nearby building and terrain effects. Regulatory Guides 1.3, 1.4 and 1.145 (U.S. NRC 1979) which were developed for accidental releases, consider a release to be elevated if the release point is greater than 2 1/2 times the height of any structure close enough to affect plume dispersion. All other releases are considered to be at ground-level. Regulatory Guide 1.111 (U.S. NRC 1977b) identifies a release as elevated if the release height is higher than twice that of any adjacent solid structure. This guidance was developed for routine effluent releases. Regulatory Guide 1.109 suggests using the finite plume model (indicative of an elevated release) when the release occurs from a free-standing stack over 80 m high. The methods discussed above were developed for specific licensing actions or for generic application to routine releases; they are not necessarily applicable to an accidental release. Since accidental release conditions cannot be determined a priori, the type of release should be determined on a case by case basis during an accident situation.

4.3.1.1 Ground-Level Release

For a ground-level release, Regulatory Guides 1.3, 1.4, and 1.109 and Dabberdt et al. (1982) recommend using the semi-infinite plume model for calculating external gamma radiation dose from the passing plume for ground-level releases. Use of this model requires a plume to be at or near the ground and plume dimensions to be large compared to the mean freepath of gamma radiation in air. Therefore, the plume is assumed to have a uniform concentration and to be of semi-infinite dimensions (bounded by the ground plane). Gamma radiation dose rate is proportional to the average radionuclide concentration in air and can be calculated by multiplying the average concentration by a dose conversion factor.

The basic expression for the gamma dose rate at the surface of the body from radionuclide, i , using the semi-infinite plume assumption is:

$$D_{\gamma i}(0) = 0.23 f_{\gamma i} \bar{E}_{\gamma i} X_i \quad (1)$$

where

$D_Y(o)$ = gamma dose equivalent rate at the surface of the body from radionuclide, i (rem/sec)

$f_{\gamma i}$ = stopping power of tissue relative to air for the gamma energy, assumed to be a constant at 1.11 (Healy and Baker 1968)

$E_{\gamma i}$ = effective gamma energy released per disintegration of radionuclide i , (MeV/dis)

x_i = concentration of radionuclide, i , in the plume at the receptor location (Ci/m³)

0.23 = conversion factor

$$= (0.5) \frac{\left(1.6 \times 10^{-6} \frac{\text{ergs}}{\text{MeV}}\right) \left(3.7 \times 10^{10} \frac{\text{dis}}{\text{Ci sec}}\right)}{(1293 \text{ g/m}^3) (100 \text{ ergs/g-rad})}$$

$$= 0.23 \frac{\text{rad dis m}^3}{\text{MeV Ci sec}}$$

Equation (1) was originally derived by Healy and Baker (1968) and used as a basis for calculations in Regulatory Guide 1.109.

Using a semi-infinite plume model for calculating external gamma doses from a ground-level release will overestimate doses near the release point particularly under stable atmospheric conditions. Correction factors should be developed for use under these conditions.

Several modifications to Equation (1) are necessary to obtain a more accurate method of calculating external gamma dose. They include:

- calculation of dose at a depth of 5 cm of tissue, which is effectively whole-body dose
- calculation of radioactive decay during plume transit
- calculation of daughter product ingrowth during plume transit.

The calculation of the 5-cm depth dose should always be incorporated in calculations of external gamma dose from a plume. However, there are situations where ignoring radioactive decay and daughter product ingrowth during plume transit will not significantly affect results. Radioactive decay during plume transit would not need to be considered for a noble gas release in which there was a long holdup time (>24 hr) prior to an environmental release. In

this situation short-lived noble gas radionuclides ($^{85\text{m}}\text{Kr}$, ^{87}Kr , ^{88}Kr , $^{135\text{m}}\text{Xe}$) would decay to insignificant levels. The main contributor to external dose becomes ^{133}Xe ($t_{1/2} = 127$ hr), which would decay insignificantly over a transit time of several hours.

To obtain the 5-cm depth dose, Equation (1) is multiplied by a buildup factor and an exponential attenuation factor as indicated below:

$$D_{\gamma i}(5) = D_{\gamma i}(0) [1 + \mu_g \Delta x] e^{-\mu_g \Delta x} \quad (2)$$

where

$D_{\gamma i}(5)$ = gamma dose equivalent rate to tissue from nuclide i after attenuation by 5-cm of tissue (rem/sec)

$D_{\gamma i}(0)$ = gamma dose equivalent rate at the surface of the body from nuclide, i (rem/sec)

μ_g = linear energy attenuation coefficient in tissue for photons of initial energy E_{γ} (cm^{-1})

$\Delta x = 5$ cm

The calculation of a 5-cm depth dose for a given radionuclide i is usually included in a precalculated dose factor (DF_i). The dose factor in units of mrem/hr per $\mu\text{Ci}/\text{m}^3$ can then be multiplied by the radionuclide concentration at the receptor location to give a dose rate:

$$D_{\gamma i}(5) = x_i DF_i \quad (3)$$

A comparison of dose factors for noble gas radionuclides from selected references is presented in Table 4.1. Differences in dose factors among the references for a given radionuclide partly are due to the use of different values for effective gamma energy released per disintegration ($\bar{E}_{\gamma i}$). Gamma energies and abundance data were taken from Martin (1973), Meek and Gilbert (1970), and Kocher (1977).

The impact of these dose factor differences can best be seen by considering a specific accident scenario. The following noble gas inventory would be released for a WASH-1400 PWR-2 Accident (U.S. NRC 1975):

^{85}Kr	$= 5.0 \times 10^5$ Ci
$^{85\text{m}}\text{Kr}$	$= 1.5 \times 10^7$ Ci
^{87}Kr	$= 1.1 \times 10^7$ Ci
^{88}Kr	$= 3.3 \times 10^7$ Ci
^{133}Xe	$= 1.5 \times 10^8$ Ci
^{135}Xe	$= 2.5 \times 10^7$ Ci

TABLE 4.1. Comparison of Dose Factors for Exposure to a Semi-Infinite Plume of Noble Gases (mrem/hr per $\mu\text{Ci}/\text{m}^3$)

Nuclide	Regulatory Guide 1.109 (U.S. NRC 1977a)	WASH-1400 (U.S. NRC 1975)	Kocher (1980a)	Scherpelz, Borst and Hoenes (1980)
$^{83\text{m}}\text{Kr}$	8.63×10^{-6}	---	4.62×10^{-5}	2.00×10^{-8}
$^{85\text{m}}\text{Kr}$	1.34×10^{-1}	1.31×10^{-1}	1.03×10^{-1}	1.27×10^{-1}
^{85}Kr	1.84×10^{-3}	1.71×10^{-3}	1.40×10^{-3}	1.97×10^{-3}
^{87}Kr	6.76×10^{-1}	6.52×10^{-1}	5.32×10^{-1}	7.22×10^{-1}
^{88}Kr	1.68	1.68	1.35	1.68
^{89}Kr	1.89	---	1.26	1.59
^{90}Kr	1.78	---	8.47×10^{-1}	3.11
$^{131\text{m}}\text{Xe}$	1.04×10^{-2}	---	5.62×10^{-3}	---
$^{133\text{m}}\text{Xe}$	2.87×10^{-2}	---	1.93×10^{-2}	2.69×10^{-2}
^{133}Xe	3.36×10^{-2}	3.26×10^{-2}	2.17×10^{-2}	2.90×10^{-2}
$^{135\text{m}}\text{Xe}$	3.56×10^{-1}	---	2.69×10^{-1}	3.80×10^{-1}
^{135}Xe	2.07×10^{-1}	2.04×10^{-1}	1.61×10^{-1}	2.06×10^{-1}
^{137}Xe	1.62×10^{-1}	---	1.16×10^{-1}	---
^{138}Xe	1.01	---	7.53×10^{-1}	---
^{41}Ar	1.01	---	8.50×10^{-1}	4.03×10^{-1}

The noble gas radionuclides considered were those determined to significantly contribute to dose based on a number of parameters including quantity of nuclide, release fraction, radioactive half-life, emitted radiation type and energy, and chemical characterization (U.S. NRC 1975). Assuming a PWR-2 nuclide mixture for a unit concentration ($1 \mu\text{Ci}/\text{m}^3$) of noble gases at a receptor location, the following dose rates were calculated using dose factors from Table 4.1:

- Regulatory Guide 1.109 (U.S. NRC 1977a) 3.2×10^{-1} mrem/hr
- WASH-1400 (U.S. NRC 1975) 3.2×10^{-1} mrem/hr
- Kocher (1980a) 2.5×10^{-1} mrem/hr
- Scherpelz, Borst and Hoenes (1980) 3.2×10^{-1} mrem/hr

For this accident scenario, dose rates varied by approximately 30% depending on which dose factors were used. Under accident conditions, the variation in dose factors in Table 4.1 would not be a significant concern.

The second modification to the basic semi-infinite plume expression involves accounting for radioactive decay during plume transit to the downwind receptor location. This can be done by modifying the x_i term in Equation (3) to:

$$x_i^D = x_i \exp \left(- \frac{\lambda_i r}{\bar{u}} \right) \quad (4)$$

where

x_i^D = concentration of radionuclide, i , at the downwind receptor location corrected for decay ($\mu\text{Ci}/\text{m}^3$)

λ_i = decay constant for nuclide, i (sec^{-1})

r = distance from the release point to the receptor (m)

$\bar{u}$ = average wind speed (m/sec)

In most calculation methods, radioactive decay is accounted for in the atmospheric dispersion model and expressed as:

$$Q_i^D = Q_i \exp \left(- \frac{\lambda_i r}{\bar{u}} \right) \quad (5)$$

where

Q_i^D = quantity of nuclide, i , in the release corrected for radioactive decay (Ci)

Q_i = quantity of nuclide, i , in initial release (Ci)

The final modification to be considered is daughter ingrowth during plume transit. For every parent nuclide, i , in the release, production of each daughter, j , can be calculated by (Bateman 1910):

$$x_j'(r) = x_{0i} \prod_{k=2}^n \lambda_k^r f_k^r \sum_{\ell=1}^n \frac{e^{-\lambda_\ell^r t_r(r)}}{\prod_{\substack{p=1 \\ p \neq \ell}}^n (\lambda_p^r - \lambda_\ell^r)} \quad (6)$$

where

- f_k^r = the fraction of nuclide (k-1) decays which produce nuclide k,
 $x_j'(r)$ = concentration of nuclide j at receptor location corrected for production from each parent nuclide i ($\mu\text{Ci}/\text{m}^3$)
 x_{0i} = concentration of parent nuclide i at receptor location ($\mu\text{Ci}/\text{m}^3$)
 λ_k^r = radioactive decay constant for nuclide k (d^{-1})
 λ_ℓ^r = radioactive decay constant for nuclide ℓ (d^{-1})
 λ_p^r = radioactive decay constant for nuclide P (d^{-1})
 $t_r(r)$ = transit time for plume to travel from release site to range r (d)
 $= \frac{r}{86400 \bar{u}}$ [$\bar{u}$ = windspeed (m/sec)]
 $[r = \text{range (m)}]$

Similar to radioactive decay corrections, daughter ingrowth is usually accounted for in the atmospheric dispersion model such that $x_j'(r)$ and x_{0i} become $Q_j'(r)$ and Q_{0i} , respectively. Where $Q_j'(r)$ is the amount released corrected for daughter ingrowth during plume transit. The concentration of nuclide i at the receptor location (x_i^T) is a sum of the initial concentration of nuclide i in the release corrected for radioactive decay (x_i^0) and the concentration of nuclide i produced from parent nuclides (x_i^P) as expressed below:

$$x_i^T = x_i^0 + x_i^P \quad (7)$$

A simpler means of dealing with Bateman equations has been described by Hamawi (1971) and Scherpelz and Desrosiers (1981). The final expression for calculating dose rate for a ground-level release using a semi-infinite plume model would be:

$$\dot{D}_Y^T(5) = \sum_i x_i^T \cdot DF_i \quad (8)$$

where

$\dot{D}_Y^T(5)$ = gamma dose rate to whole body from all radionuclides in plume at the receptor location (mrem/hr)

x_i^T = concentration of nuclide i at receptor location corrected for radioactive decay and daughter ingrowth during plume transit ($\mu\text{Ci}/\text{m}^3$)

DF_i = dose factor for nuclide i ($\frac{\text{mrem/hr}}{\mu\text{Ci}/\text{m}^3}$)

Equation (8) considers all modification factors (5-cm depth dose, radioactive decay and daughter ingrowth during plume transit) and sums the dose rates from all radionuclides in the plume at the receptor location.

An optional modification to the basic semi-infinite plume expression is the calculation of a dose reduction or shielding factor to account for shielding provided by residential structures. Several studies have reported estimates for the reduction in external penetrating radiation dose by sheltering (Aldrich et al. 1978a, Aldrich et al. 1978b, and Burson et al. 1975). Estimates are reported in terms of a shielding factor (SF) which is the ratio of the dose received inside the structure to the dose that would be received outside the structure. Shielding factors are highly dependent on the type of structure. Burson et al. (1975) have developed average SFs which consider the public to inhabit a variety of structures (i.e., brick homes, wood homes, homes with and without basements). They report an average SF range of 0.5 to 0.75 for airborne radionuclides and 0.08 to 0.5 for ground contamination. The lower range values are for a typical variety of structures in the Northeast, which generally have basements, while the higher range values are typical for the Southwest and Pacific coast, where there are more structures without basements.

Kocher (1980b) has developed a model to estimate dose reduction factors for external photon exposure for airborne nuclides using a point-kernel integration method. If more rigorous shielding factor calculations are needed, such a model could be incorporated into the extended dose calculational model. The output of such a model should include both shielded and unshielded doses.

Shielding factors are generally used in the calculation of population dose as in Regulatory Guide 1.109. These factors would also be appropriate for use in calculating dose to emergency workers at known work locations. Their use is not generally recommended for calculating offsite dose to the maximum individual during an emergency; as there is no way to assure that all individuals are indoors even if they have been so notified by authorities.

The discussion thus far on ground-level releases has dealt with calculation of dose rates. During an emergency situation, projected doses would be compared to Environmental Protection Agency (EPA) Protective Action Guides (PAG) (U.S. EPA 1975) in order to determine what protective actions would be recommended. Knowing the duration of the release or the projected duration of exposure, the dose rate integral can be evaluated. If the duration of release cannot be estimated, then the reactor operator should have default values of the release duration to fall back on. Default values may be based on available plant parameters at the time of the accident (e.g., containment high-range radiation monitor readings, temperature or pressure readings in containment). Another method for determining dose (when neither exposure time or total radionuclide release are known) is presented in U.S. EPA (1975). Exposure starts at a particular site when the plume arrives, and ends with a wind direction change or a termination of the release. The EPA suggests the exposure period conservatively could be assumed equal to the 99% probable maximum duration of wind direction persistence for that site and for the existing atmospheric stability conditions.

4.3.1.2 Elevated Release

A method for determining whether a release is elevated was presented in the introduction to Section 4.3.1. A finite plume model is the method-of-choice for calculating external dose from an overhead plume (elevated release) and can also be used for calculating external dose from a ground-level release. Such a model should be used when the plume dimensions are on the order of the mean free path of gamma radiation or smaller. Consideration is given to the spatial distribution of radionuclide concentrations when using a finite plume model, therefore, the interface with the meteorological transport and diffusion model is important.

Finite plume calculations should take into account the same modification factors as semi-infinite calculations to include 5-cm depth dose, radioactive decay during plume transit, and daughter ingrowth during plume transit. As discussed in Section 4.3.1.1 there are situations when consideration of radioactive decay and daughter ingrowth during plume transit are not necessary. In addition, procedures for determining integrated dose from a dose rate at a receptor location would be similar for finite and semi-infinite plume calculations.

Most finite plume models involve a numerical integration technique. A partial list of studies using this technique are Healy and Baker (1968), Regulatory Guide 1.109 (U.S. NRC 1977a), WASH-1400 (U.S. NRC 1975), EPA-Protective Action Guidance Document (U.S. EPA 1975), Lahti, Hubner and Golden (1981), Scherpelz, Borst and Hoenes (1980), and Streng, Watson and Houston (1975). A second type of finite plume model is a concentric cylinder set (CCS) cloud gamma dose model (Arras 1981).

Numerical Integration Methods

Numerical integration methods in Regulatory Guide 1.109, WASH-1400, and the EPA-Protective Action Guidance document are based on methods from unpublished work of Gamertsfelder in Healy and Baker (1968). The Regulatory Guide 1.109 model is a vertically finite sector-averaged Gaussian plume model developed for constant, chronic releases. Equations used to calculate dose rate to air from the elevated cloud at a receptor location are presented in Appendix E of Regulatory Guide 1.109.

The WASH-1400 study and the EPA-Protective Action Guidance document use finite plume correction factors from Healy and Baker (1968) for calculating external gamma dose from elevated releases. The correction factors are a ratio of dose from a finite plume to dose from a semi-infinite plume of uniform concentration. The factors in Table 4.2 were developed for a spherical cloud of uniform concentration. Correction factors for 0.7 MeV gammas (Table 4.2) are expressed as a function of the vertical dispersion coefficient (σ_z) and the elevation of the plume centerline above the surface (h_p). Using Table 4.2, finite plume doses can be calculated by first calculating the dose

TABLE 4.2. Finite-Cloud Dose Correction Factors $\left(\frac{n_c}{n_\infty}\right)$ (a,b)

Vertical Dispersion Coefficient (σ_z) meters	Ratio of Plume Height (h_e) to Vertical Dispersion Coefficient (σ_z)					
	0	1	2	3	4	5
3	0.020	0.018	0.011	0.066	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1000	0.951	0.600	0.130	0.011	0.001	0.001

(a) Data from Healy and Baker (1968).

$$(b) \frac{D_c}{D_\infty} = \frac{\text{dose using finite plume model}}{\text{dose using semi-infinite plume model}}$$

at the receptor location using a semi-infinite plume model and multiplying by the appropriate correction factor based on values of σ_z and h_e . These correction factors are relatively energy independent. Over a gamma energy range of 0.1 MeV to 2 MeV, the factors vary by a maximum of a factor of two (Healy and Baker 1968).

Garrett and Murphy (1981) use a numerical integration technique in conjunction with a real-time atmospheric dispersion model. The atmospheric dispersion model can simulate either an instantaneous (puff) or continuous (plume) release. Two assumptions are made to simplify the calculations, a) material is assumed to be released instantaneously and b) cloud size is assumed to be constant during the period that dose is accumulated at the downwind receptor. The finite plume model is based on a line source concept where the total dose is a summation of doses from an infinite number of line sources. Numerical integrations can be performed at every designated time interval or at every 12th time-interval in an effort to cut down computing time and cost. If the latter option is chosen, doses at the intervening time-intervals are estimated based on the assumption that dose will decrease in proportion to the inverse of the distance from the release. This type of estimate is conservative but never overestimates dose by more than ~50%.

Another numerical integration technique is a three-dimensional point kernel method. Equations used for such a method are presented in Streng, Watson and Houston (1975), Scherpelz, Borst and Hoenes (1980), and Lahti, Hubner and Golden (1981).

Other Methods

Arras (1981) has developed a concentric cylinder set (CCS) cloud gamma dose model to estimate external gamma doses from an elevated release. The model was developed primarily to estimate doses from irregular clouds and requires no computer for its use. The CCS model was found to agree to within 30% of other published models when identical input parameters could be used (Arras 1981).

The NRC has developed precalculated dose relationships for ^{85}Kr , ^{87}Kr , ^{88}Kr , ^{89}Kr , ^{133}Xe , ^{135}Xe , ^{137}Xe , ^{138}Xe and ^{41}Ar using the finite plume methodology in Regulatory Guide 1.109. The relationships are presented as nomograms and regression equations. Knowing wind speed, stability class, and distance to the receptor location, dose in mrem/Ci released can be determined. These nomograms and equations are discussed briefly in Dabberdt et al. (1982) and are documented in U.S. NRC (1983).

Considerations When Choosing Finite Plume Model

There are a number of items that need to be considered when trying to choose an appropriate model for finite plume calculations. As mentioned earlier, consideration must be given to the spatial distribution of radionuclide concentrations as determined by atmospheric dispersion models. Lahti, Hubner and Golden (1981) calculated finite cloud gamma dose factors (kernels) for the straight-line Gaussian plume model and the Gaussian sector-averaged model. Dose factors for the sector-averaged dispersion model were found to be significantly lower than for the straight-line dispersion model at the loci of the plume centerline (see Table 4.3). This is particularly true for the more stable atmospheric classes at greater distances from the release point.

Usage of numerical integration techniques, such as described in Regulatory Guide 1.109, Garrett and Murphy (1981), Streng, Watson and Houston (1975), and Scherpelz, Borst and Hoenes (1980) will give the most exact results for finite plume calculations. However, if computer availability or operating cost is prohibitive for the rather timely numerical integration calculations, then alternate methods can be used with reasonable accuracy. Alternate methods include using dose correction factors (Healy and Baker 1968), modified numerical integration technique (Garrett and Murphy 1981), the concentric cylinder set cloud gamma dose model (Arras 1981), finite cloud gamma dose factors (Lahti, Hubner, and Golden 1981), and the nomograms developed by U.S. NRC (1983).

TABLE 4.3. Differences Between Finite Plume Dose Factors for Straight-Line Plume vs. Sector-Averaged Plume Model-- ^{133}Xe (a)

Stability Class	Straight-Line Plume Factors vs. Sector-Averaged Plume Factors (% Greater) (b)					
	Distance Downwind (m)					
	400 (1/4 mi)	800 (1/2 mi)	1,609 (1 mi)	3,218 (2 mi)	8,045 (5 mi)	16,090 (10 mi)
A	12	16	20	23	28	32
B	16	27	34	41	49	56
C	18	41	57	69	83	95
D	21	53	97	127	154	173
E	24	66	140	206	256	284
F	26	77	182	300	404	453
G	27	84	217	402	613	714

(a) Data taken from Lahti, Hubner and Golden (1981).

(b) Similar relationships were observed for other noble gas nuclides.

4.3.1.3 Computer Codes

Table 4.4 is a listing of some existing computer codes for calculating external dose (from air and ground contamination), inhalation dose, and ingestion dose from accidental releases. The following references were used in compiling Table 4.4: Strenge, Watson and Droppo (1976), Hoffman et al. (1977), Mosier et al. (1980), Owen et al. (1979), SAI (1981), and ANS (1982). Atmospheric transport models are included in approximately 70% of the codes. These transport models should be reviewed carefully for applicability in a real-time accident situation.

Approximately 70% of the codes listed in Table 4.4 will calculate external gamma dose from a passing plume. A review of all of the codes is beyond the scope of this report, but two codes, the NRC's RADPUR code (Dabberdt et al. 1982) and WRAITH (Scherpelz, Borst and Hoenes 1980), are reviewed in detail. In addition, several other codes appropriate for calculating external gamma dose from the plume are briefly discussed.

RADPUR

The RADPUR code contains subroutines for handling atmospheric dispersion (calculating χ/Q values) as well as for calculating external gamma dose using either semi-infinite or finite plume models. It can and should be modified by

TABLE 4.4. Listing of Dosimetry Codes for Accidental Releases

Code	Atmos. Tran. Model	External Plume	External Ground	Inhala- tion	Inges- tion	Reference
ACRA-II	x	x		x		Stallman and Kam 1973; McGill et al. 1976
AERIN				x	x	Voilleque 1968; Voilleque 1970
AIRWAY	x	x	x	x	x	Rider and Beal 1977
CEDRIC				x	x	Clarke 1972
COMRADEX I,II, III,IV	x	x		x		Willis et al. 1970; Specht et al. 1975a; Otter and Connors 1975; Specht et al. 1975b;
CRAC 2	x	x	x	x	x	Ritchie et al. 1981
DACRIN	x			x		Houston et al. 1974
EERIE	x	x		x		MacDonald 1971
ERGAM		x				Cooper 1976; Garrett and Murphy 1981
EXGAM		x				Steyn and Kim 1966
EXREM III		x	x			Trubey and Kaye 1973; Killough and McKay 1976
GADOSE/DOOSET	x	x		x		Lee et al. 1966
INDOS 2,3	x			x		ThyKier-Nielsen 1974; Killough and Rohwer 1974

TABLE 4.4. (contd)

Code	Atmos. Tran. Model	External Plume	External Ground	Inhala- tion	Inges- tion	Reference
INREM-I,II				x	x	Turner et al. 1968; Killough et al. 1975; Killough et al. 1978
MO 142	x	x		x		Eckert 1964
NURSE-1	x	x	x	x		Couchman et al. 1964
PLUME	x	x		x		Binford 1967
RACER	x	x				Streng et al. 1971
RADOS	x	x				Cooper 1967
RADPUR	x	x		x		Dabberdt et al. 1982; U.S. NRC 1982
RISC	x			x		Anno et al. 1963
RSAC-2	x	x	x	x		Wenzel 1974
SUBDOS	x	x				Streng et al. 1975
TIRION	x	x	x	x		Kaiser 1976
WRAITH	x	x		x		Scherpelz et al. 1980
YIELDS				x	x	Chester 1974

the user to include site-specific information if available. Such information would include building sizes, distances to the exclusion boundary in each sector, and terrain features. This discussion will concentrate on the external dosimetry models. The following is a list of the code's subroutines:

- REDMET--reads in the meteorological data

- ADJWND--employs a model that corrects the wind speed to the appropriate elevation
- FRACTN--determines whether the plume should be considered elevated or ground-level
- GX00--calculates the x/Q at the centerline of the elevated plume
- EX00--calculates the ground-level x/Q for an elevated plume
- RISE--estimates the momentum rise from a circular stack
- IOOSE--calculates the child-thyroid inhalation dose (most restrictive age group) from ^{131}I through ^{135}I
- DOSEAR--calculates the noble gas doses with corrections for radioactive decay and daughter build-up during plume transit
- DINT--performs numerical integration over the plume for finite cloud doses.

The code can be simplified for certain accident situations. For example, for a ground-level release, subroutines FRACTN, EX00, RISE, and DINT (which deal with elevated releases) can be deleted.

RADPUR uses Regulatory Guide 1.111 (U.S. NRC 1977h) guidance for determining if the release should be considered ground level or elevated. This guidance considers a release to be elevated if the release height is greater than twice the height of any adjacent solid structure. For a ground-level release, RADPUR uses a semi-infinite plume model to calculate external gamma dose to the whole body. The model follows the methodology outlined in Section 4.3.1.1, including consideration of all modification factors -- 5-cm depth dose, radioactive decay during plume transit, and daughter ingrowth during plume transit. Semi-infinite cloud gamma whole-body dose factors were obtained from Regulatory Guide 1.109 for 14 noble gas nuclides (^{83}mKr , ^{85}mKr , ^{85}Kr , ^{87}Kr , ^{88}Kr , ^{89}Kr , ^{131}mXe , ^{133}mXe , ^{133}Xe , ^{135}mXe , ^{137}Xe , ^{138}Xe , and ^{41}Ar). In addition daughter production from the following nuclides were considered: ^{88}Rb , ^{89}Rb , ^{138}Cs , ^{139}Cs , ^{139}Xe , and ^{139}Ba . RADPUR also includes semi-infinite cloud beta air-dose factors, beta skin-dose factors, and gamma air-dose factors.

For an elevated release, RADPUR uses the finite plume model developed in Regulatory Guide 1.109, Appendix F, and Hamawi (1976). The model considers all appropriate modification factors for the 14 noble gas nuclides listed previously.

The code calculates external gamma doses for both the sector average concentration and the plume centerline concentration using either the semi-infinite or finite plume model.

WRAITH

The WRAITH computer code (Scherpelz, Borst and Hoenes 1980) provides an atmospheric dispersion model in addition to calculating both external gamma whole body dose and inhalation dose from the passing plume. The atmospheric dispersion model is a bivariate straight-line Gaussian distribution type with Pasquill values for standard deviations. Dispersion calculations can be corrected for plume meander, building wake effects, plume rise, and plume depletion by dry deposition.

External gamma doses to the whole body are calculated using either a semi-infinite plume model or a finite plume model. The user is responsible for selecting the model based on release conditions. The semi-infinite plume model follows methodology outlined in Section 4.3.1.1 and includes all the modification factors. Semi-infinite plume gamma dose factors to the whole body for 297 radionuclides are found in WRAITH.

As mentioned in Section 4.3.1.2, WRAITH uses a "finite plume" three-dimensional point kernel numerical integration technique for calculating external gamma doses from an elevated release. Equations used in these calculations can be found in Scherpelz, Borst and Hoenes (1980). Such calculations involve relatively long computer times (e.g., 10 to 55 sec per calculation on the UNIVAC 1100/44).

Other Codes

RSAC-2 (Wenzel 1974) and TIRION (Kaiser 1976) will calculate external gamma dose using either a semi-infinite or finite plume model in a manner similar to RADPUR and WRAITH. Several other codes including ACRA-II (Stallman and Kam 1973), COMRADEX-IV (Specht et al. 1975b), ERGAM (Cooper 1976; and Garrett and Murphy 1981), EXGAM (Steyn and Kim 1966), and SUBDOSA (Streng et al. 1975) calculate external dose with a finite plume model. Two codes, AIRWAY (Rider and Beal 1977) and EXREM-III (Trubey and Kaye 1973) use only a semi-infinite plume model. These codes are not appropriate for an elevated release (overhead plume) unless dose correction factors, as discussed in Section 4.3.1.2, are applied. The computer code, CRAC-2 (Ritchie et al. 1981), uses finite plume dose correction factors.

4.3.2 Inhalation Dose to Child Thyroid

Inhalation of radioiodines and particulates are of major concern during plume passage because inhaled or ingested radioiodines concentrate in the thyroid. Several factors need to be known to compute the inhalation dose to the thyroid. These factors include: 1) air concentration of radioactive material at a downwind receptor location (χ) in Ci/m³; 2) breathing rate (BR) in m³/hr; and 3) dose factor (DF) in rem/Ci inhaled. The rate at which inhalation dose commitment is received is a product of these three factors.

$$D_{ia}(r) = x_i(r) BR_a DF_{ia} \quad (9)$$

where

$D_{ia}(r)$ = dose commitment rate from nuclide, i , to the thyroid of an individual in age group, a , at receptor location, r (mrem/hr of exposure)

$x_i(r)$ = concentration of nuclide, i , at receptor location r (Ci/m³)

BR_a = breathing rate for individuals in age group a (m³/hr)

DF_{ia} = inhalation dose factor from nuclide, i , to an individual in age group a (mrem/Ci inhaled)

The concentration term in Equation (9) should be corrected for radioactive decay and daughter ingrowth during plume transit. When calculating thyroid dose, daughter ingrowth need not be considered if only radioiodines are in the release. However, if tellurium (Te) is present, ingrowth should be considered. An optional internal dose reduction factor would be appropriate for calculating population dose but is not recommended for calculating dose to the maximum individual as discussed in Section 4.3.1.1. Kocher (1980b) provides a methodology for calculating such factors. Breathing rates are specified in ICRP Report 23 (1975) and shown in Table 4.5. Dose factors for radionuclides of interest can be calculated using lung deposition and clearance models in ICRP Report 2 (1959) or Morrow (1966) and ICRP (1972)--Task Group Lung Model. Inhalation dose factors are dependent on age. Age-dependent parameters include thyroid mass, fractional uptake of I by the thyroid, effective half-life in the thyroid, breathing rate and energy absorbed in the thyroid per disintegration of radioiodine (see Table 4.6).

When considering more than one radioisotope of iodine, the dose commitment rate equation becomes a summation of all radionuclides available for inhalation:

$$D_a^T(r) = BR_a \sum_i x_i(r) DF_{ia} \quad (10)$$

TABLE 4.5. ICRP 23 Breathing Rate Values

	Breathing Rates (m ³ /hr)				
	Adult (Man)	Adult (Woman)	Child (10 yr)	Infant (1 yr)	Newborn
Resting	0.45	0.36	0.29	0.09	0.03
Light Activity	1.20	1.14	0.78	0.25	0.09

TABLE 4.6. Age-Dependent Factors Used in Calculating Thyroid Dose from Inhalation-- ^{131}I

Age (yr)	Thyroid Mass (g)	f_a (a)	T_e (b) (days)	ϵ (c) (MeV/dis)	Breathing Rate (m^3/hr)
<u>NUREG-0172 (Hoenes and Soldat 1977) and Regulatory Guide 1.109 (U.S. NRC 1977)</u>					
1	2	0.23	5.7	0.2180	0.23 (0.16) ^(f)
4	5	0.23	5.7	0.2250	0.29 (0.42)
14	15	0.23	6.9	0.2330	0.56 (0.91)
Adult	20	0.23	7.4	0.2360	0.89 (0.91)
<u>U.S. EPA (1975)</u>					
Newborn	1	0.23	5.7	0.19	0.09
1	1.8	0.13	6.2	0.19	0.25
5	3.6	0.13	6.2	0.19	0.47
10	7.4	0.13	7.3	0.19	0.79
15	12.1	0.13	7.3	0.20	1.2
Adult	16	0.13	7.3	0.20	1.2
<u>WASH-1400 (U.S. NRC 1975)</u>					
Newborn	1	(d)	(d)	(d)	0.04
1	1.8	↓	↓	↓	0.16
5	3.6	↓	↓	↓	0.40
10	7.4	↓	↓	↓	0.62
Adult	16	↓	↓	↓	0.96
<u>Dunning and Schwarz (1981)^(e)</u>					
Newborn	1.4	0.47	5.3	(d)	(d)
Child (0.5 to 2 yr)	2.3	0.39	5.0	↓	↓
Adolescent (6 to 16 yr)	6.7	0.47	6.9	↓	↓
Adult (>18 yr)	18.3	0.19	7.3	↓	↓

(a) f_a = fractional uptake of iodine by the thyroid.

(b) T_e = effective half-life in thyroid.

(c) ϵ = energy absorbed in thyroid per disintegration of radioiodine atom.

(d) Not available.

(e) All values represent mean values.

(f) Values in parentheses are breathing rates used in Regulatory Guide 1.109

4.3.2.1 Lung Models

As previously mentioned, the two basic models for calculating respiratory system deposition and clearance are the initial lung model (ICRP 1959) and the Task Group Lung Model (TGLM) (Morrow 1966; ICRP 1972). Dose factors in NUREG-0172 (Hoenes and Soldat 1977) were calculated using ICRP (1959) methodology while WASH-1400 (U.S. NRC 1975) and U.S. EPA (1975) used the TGLM. Streng et al. (1978) briefly reviewed the two models. The authors concluded that for inhalation of particulate material, dose calculations should be based on the TGLM, as that model was developed to handle particulates. For vapors and gases, use of the initial lung model would be more appropriate unless information is available on deposition characteristics of the material involved.

4.3.2.2 Calculation of Inhalation Dose Factors

In addition to the lung model used, age-dependent parameters affect the calculation of dose factors. These factors include thyroid mass, fractional uptake of iodine by the thyroid, effective half-life in thyroid, energy absorbed in thyroid per disintegration of radioiodine atom, and breathing rate. Breathing rate is generally not considered in the calculation of inhalation dose factor (see Equation 10).

Table 4.6 is a partial listing of age-dependent factors used in calculating dose factors from several references (Hoenes and Soldat 1977; U.S. NRC 1975; U.S. NRC 1977; U.S. EPA 1975; and Dunning and Schwarz 1981). Variability of age-dependent parameters as shown in Table 4.6 in conjunction with usage of different lung models contributes to the differences in inhalation dose factors to the thyroid presented in Table 4.7. As was mentioned previously, NUREG-0172 (Hoenes and Soldat 1977) and Regulatory Guide 1.109 used the initial ICRP lung model while U.S. EPA (1975) and WASH-1400 (U.S. NRC 1975) used the TGLM. Direct comparisons of dose factors for each age group are difficult because age groups are not consistent among the references. However, where groups could be compared, values were found to vary by less than a factor of two for ^{131}I . Such differences are not significant enough to choose one method over the other.

4.3.2.3 Dose Calculations

From Equation (10), inhalation dose to the thyroid is found to be a product of a breathing rate and an inhalation dose factor. Table 4.8 presents data on the ratio of thyroid dose per unit ^{131}I air concentration for several age groups. Other radioiodines (^{132}I , ^{133}I , ^{134}I , ^{135}I) would show similar relationships. These ratios indicate that a newborn to 5-year-old child would receive up to twice the thyroid dose received by an adult from inhalation of the same concentration during plume passage. Therefore, inhalation doses to the child thyroid should be calculated unless young children are absent from the affected population.

TABLE 4.7. Age-Dependent Inhalation Dose Commitment Factors for Radioiodines (mrem/pCi inhaled).

Age (yr)	Nuclide				
	¹³¹ I	¹³² I	¹³³ I	¹³⁴ I	¹³⁵ I
NUREG-0172 (Hoenes and Soldat 1977) and Regulatory Guide 1.109 (U.S. NRC 1977)					
Infant	1.06×10^{-2}	1.21×10^{-4}	2.54×10^{-3}	3.18×10^{-5}	4.97×10^{-4}
4	4.39×10^{-3}	5.23×10^{-5}	1.04×10^{-3}	1.37×10^{-5}	2.14×10^{-4}
14	1.83×10^{-3}	1.89×10^{-5}	3.65×10^{-4}	4.94×10^{-6}	7.76×10^{-5}
Adult	1.49×10^{-3}	1.43×10^{-5}	2.69×10^{-4}	3.73×10^{-6}	5.60×10^{-5}
U.S. EPA (1975)					
Newborn	1.8×10^{-2}	8.8×10^{-4}	6.0×10^{-3}	4.4×10^{-4}	1.8×10^{-3}
1	6.2×10^{-3}	2.8×10^{-4}	1.9×10^{-3}	1.4×10^{-4}	5.7×10^{-4}
5	3.1×10^{-3}	1.4×10^{-4}	1.0×10^{-3}	7.2×10^{-5}	3.0×10^{-4}
10	1.8×10^{-3}	7.3×10^{-5}	5.0×10^{-4}	3.5×10^{-5}	1.5×10^{-4}
15	1.2×10^{-3}	4.4×10^{-5}	2.9×10^{-4}	2.2×10^{-5}	9.4×10^{-5}
Adult	8.8×10^{-4}	3.3×10^{-5}	2.3×10^{-4}	1.7×10^{-5}	7.0×10^{-5}
WASH-1400 (U.S. NRC 1975)					
1	5.9×10^{-3}	3.6×10^{-5}	9.7×10^{-4}	5.9×10^{-6}	2.4×10^{-4}
5	5.1×10^{-3}	3.0×10^{-5}	8.3×10^{-4}	5.1×10^{-6}	2.0×10^{-4}
10	2.6×10^{-3}	1.6×10^{-5}	4.3×10^{-4}	2.6×10^{-6}	1.1×10^{-4}
Adult	1.1×10^{-3}	6.6×10^{-6}	1.8×10^{-4}	1.1×10^{-6}	4.4×10^{-5}

TABLE 4.8. Ratio of Thyroid Dose per Unit Radioiodine Air Concentration (¹³¹I) for Various Ages Versus an Adult

Age	U.S. EPA (1975)	WASH-1400 (U.S. NRC 1975)	NUREG-0172 (Hoenes and Soldat 1977) and Regulatory Guide 1.109 (U.S. NRC 1977)
Newborn	1.6	---	---
1	1.5	0.9	2.0
4	---	---	1.0
5	1.4	1.9	---
10	1.4	1.6	---
14	---	---	1.0
15	1.3	---	---
Adult	1.0	1.0	1.0

4.3.2.4 Computer Codes

Numerous computer codes are available to calculate inhalation doses from a passing plume (see Table 4.4). While a review of all the inhalation codes in Table 4.4 is beyond the scope of this document, several codes to be briefly discussed include the NRC's RADPUR code (Dabberdt et al. 1982), AERIN (Voilleque 1970), DACRIN (Houston, Streng and Watson 1974), WRAITH (Scherpelz, Borst and Hoenes 1980), RSAC-2 (Wenzel 1974), and INREM-II (Killough et al. 1978). These codes are examples of appropriate intermediate dose calculational methods.

The RADPUR code calculates inhalation dose to the child thyroid as expressed in Equation (10). The subroutine IDOSE calculates inhalation dose to the child thyroid. Inhalation dose factors were taken from NUREG-0172 for the following radioiodines: ^{131}I , ^{132}I , ^{133}I , ^{134}I , and ^{135}I . ICRP 2 (1959) methodology was used in calculating the dose factors. A child's breathing rate of $3700 \text{ m}^3/\text{yr}$ ($0.42 \text{ m}^3/\text{hr}$) was used as derived from Regulatory Guide 1.109 (U.S. NRC 1977).

The computer codes AERIN, DACRIN, INREM-II, RSAC-2, and WRAITH are based on the ICRP TGLM. These codes are more extensive than RADPUR as they are capable of calculating inhalation doses to various organs from a whole spectrum of nuclides, not just inhalation dose to the thyroid from radioiodines. One of these codes would be needed if fission products other than noble gases and radioiodines were released, or modifications would have to be made to RADPUR.

4.3.3 Other Dose Pathways

Dabberdt et al. (1982) recommended that whole body gamma dose from ground contamination and ingestion dose from contaminated milk be determined during the intermediate time period (1 hr to 1 day) after an accidental release. These calculations may be included as part of the intermediate dose calculation methods, however, it should be emphasized that calculation of doses from the plume take precedence. Dabberdt et al. (1982) did not recommend calculation of inhalation doses from resuspended material or ingestion doses from contaminated crops or water supplies during the immediate or intermediate time frame of response.

4.3.3.1 Whole Body Gamma Dose from Ground Contamination

The basic model for calculating whole body gamma dose from ground contamination considers the surface as an infinite plane of negligible thickness with a uniform contamination distribution. For purposes of this discussion, it is assumed that levels of ground contamination are known either by estimates based on deposition mechanisms or by field measurements.

The basic equation for calculating external dose rate from ground contamination is:

$$D^T = \sum_i C_i DF_i \quad (11)$$

where

D^T = total dose rate for all nuclides

C_i = concentration of nuclide, i , on ground surface (pCi/m²)

DF_i = whole-body dose factor for nuclide, i (mrem/hr / pCi/m²)

Dose factors have been calculated by a number of authors as reviewed in Hoffman et al. (1977). Table 4.9 is a comparison of dose rates from two references (U.S. NRC 1977a and Kocher 1980a). These dose factors would be appropriate to use in the intermediate dose calculation method.

Several computer codes are available to calculate external gamma dose from ground contamination, including AIRWAY (Rider and Beal 1977), CRAC 2 (Ritchie et al. 1981), RSAC-2 (Wenzel 1974), and EXREM III (Trubey and Kaye 1973).

Shielding factors may be considered as an optional modification to Equation (11). For example, Regulatory Guide 1.109 recommends a residential shielding and occupancy factor of 0.5. Kocher (1980b) presents a model which could be used to determine shielding factors from residential units.

4.3.3.2 Ingestion Dose from Contaminated Milk

To calculate ingestion dose from contaminated milk, the concentration of radioiodines in the milk needs to be determined. This can be accomplished by direct measurement of milk or estimations based on the concentration of radioiodines in the animals' feed and feed intakes of the animal. Regulatory Guide 1.109 (U.S. NRC 1977a) provides a method for calculating nuclide concentrations in milk.

Knowing the level of milk contamination, dose commitment rate to an individual's thyroid can be found by using the following equation:

$$D_a^T = \sum_i C_i \cdot U_a \cdot DF_{ia} \quad (12)$$

where

D_a^T = dose commitment rate for age group a from all nuclides in milk (mrem/hr)

C_i = concentration of nuclide i in milk (pCi/l)

U_a = consumption rate of individual in age group a (l/hr)

DF_{ia} = ingestion dose factor for nuclide i and an individual in age group, a (mrem/pCi)

As with inhalation doses from the plume, thyroid doses to the most sensitive age groups (children) should be calculated. Age-specific consumption factors can be found in Regulatory Guide 1.109. Dose factors for all age groups can be found in NUREG-0172 (Hoenes and Soldat 1977) and are listed in Table 4.10.

4.4 RAPID DOSE CALCULATION METHODS

Rapid dose calculation methods are intended for use in the control room during approximately the first hour of an accident until the TSC and EOF are activated. As outlined by Dabberdt et al. (1982), rapid methods should consider external gamma doses and inhalation doses to the thyroid from the passing plume. Such calculation methods should be simple, to allow usage by individuals with a minimum knowledge of dose assessment. Examples of these methods include hand calculations, nomograms, isopleths, calculators, and microcomputers.

This section provides a brief discussion of dosimetry models that could be used in the rapid dose calculation method, but this is only part of the rapid dose assessment model. Other parts include source term and atmospheric dispersion determination. Specific determinations would include:

- ground-level or elevated release
- atmospheric stability class
- radioactive release rate
- composition of release (are radioiodines present?)
- time interval from reactor shutdown to initial release
- duration of the release.

IRDAM (Interactive Rapid Dose Assessment Model) (Poeton et al. 1982) is an example of a model which considers the above factors.

TABLE 4.9. External Dose Factors from Ground Contamination
(mrem/hr/pCi/m²)

Radionuclide	Regulatory Guide	
	1.109 (U.S. NRC 1977)	Kocher (1980a)(a)
²⁴ Na	2.5 x 10 ⁻⁸	6.14 x 10 ⁻⁸
⁵¹ Cr	2.2 x 10 ⁻¹⁰	8.50 x 10 ⁻¹⁰
⁵⁴ Mn	5.8 x 10 ⁻⁹	1.61 x 10 ⁻⁸
⁵⁶ Mn	1.1 x 10 ⁻⁸	2.90 x 10 ⁻⁸
⁵⁹ Fe	8.0 x 10 ⁻⁹	2.11 x 10 ⁻⁸
⁵⁸ Co	7.0 x 10 ⁻⁹	1.91 x 10 ⁻⁸
⁶⁰ Co	1.7 x 10 ⁻⁸	4.38 x 10 ⁻⁸
⁶⁵ Ni	3.7 x 10 ⁻⁹	9.46 x 10 ⁻⁹
⁶⁴ Cu	1.5 x 10 ⁻⁹	4.12 x 10 ⁻⁹
⁶⁵ Zn	4.0 x 10 ⁻⁹	1.12 x 10 ⁻⁸
⁸³ Br	6.4 x 10 ⁻¹¹	1.53 x 10 ⁻¹⁰
⁸⁴ Br	1.2 x 10 ⁻⁸	2.77 x 10 ⁻⁸
⁸⁶ Rb	6.3 x 10 ⁻¹⁰	1.71 x 10 ⁻⁹
⁸⁸ Rb	3.5 x 10 ⁻⁹	1.05 x 10 ⁻⁸
⁸⁹ Rb	1.5 x 10 ⁻⁸	3.53 x 10 ⁻⁸
⁸⁹ Sr	5.6 x 10 ⁻¹³	2.56 x 10 ⁻¹²
⁹¹ Sr	7.1 x 10 ⁻⁹	1.30 x 10 ⁻⁸
⁹² Sr	9.0 x 10 ⁻⁹	2.31 x 10 ⁻⁸
⁹⁰ Y	2.2 x 10 ⁻¹²	2.76 x 10 ⁻¹³
^{91m} Y	3.8 x 10 ⁻⁹	1.08 x 10 ⁻⁸
⁹¹ Y	2.4 x 10 ⁻¹¹	6.38 x 10 ⁻¹¹
⁹² Y	1.6 x 10 ⁻⁹	4.60 x 10 ⁻⁹
⁹³ Y	5.7 x 10 ⁻¹⁰	1.58 x 10 ⁻⁹
⁹⁵ Zr	5.0 x 10 ⁻⁹	1.43 x 10 ⁻⁸
⁹⁷ Zr	5.5 x 10 ⁻⁹	3.30 x 10 ⁻⁹
⁹⁵ Nb	5.1 x 10 ⁻⁹	1.47 x 10 ⁻⁸
⁹⁹ Mo	1.9 x 10 ⁻⁹	3.25 x 10 ⁻⁹
^{99m} Tc	9.6 x 10 ⁻¹⁰	2.90 x 10 ⁻⁹
¹⁰¹ Tc	2.7 x 10 ⁻⁹	7.10 x 10 ⁻⁹

TABLE 4.9. (contd)

Radionuclide	Regulatory Guide	
	1.109 (U.S. NRC 1977)	Kocher (1980a) ^(a)
¹⁰³ Ru	3.6×10^{-9}	9.63×10^{-9}
¹⁰⁵ Ru	4.5×10^{-9}	1.55×10^{-8}
¹⁰⁶ Ru	1.5×10^{-9}	---
^{110m} Ag	1.8×10^{-8}	5.15×10^{-8}
^{125m} Te	3.5×10^{-11}	1.51×10^{-9}
^{127m} Te	1.1×10^{-12}	4.62×10^{-10}
¹²⁷ Te	1.1×10^{-11}	1.01×10^{-10}
^{129m} Te	7.7×10^{-10}	9.28×10^{-10}
¹²⁹ Te	7.1×10^{-10}	1.32×10^{-9}
^{131m} Te	8.4×10^{-9}	2.73×10^{-8}
¹³¹ Te	2.2×10^{-9}	8.49×10^{-9}
¹³² Te	1.7×10^{-9}	5.57×10^{-9}
¹³⁰ I	1.4×10^{-8}	4.21×10^{-8}
¹³¹ I	2.8×10^{-9}	8.03×10^{-9}
¹³² I	1.7×10^{-8}	4.35×10^{-8}
¹³³ I	3.7×10^{-9}	1.22×10^{-8}
¹³⁴ I	1.6×10^{-8}	4.89×10^{-8}
¹³⁵ I	1.2×10^{-8}	2.73×10^{-8}
¹³⁴ Cs	1.2×10^{-8}	3.03×10^{-8}
¹³⁶ Cs	1.5×10^{-8}	4.10×10^{-8}
¹³⁷ Cs	4.2×10^{-9}	---
¹³⁸ Cs	2.1×10^{-8}	4.00×10^{-8}
¹³⁹ Ba	2.4×10^{-9}	8.33×10^{-10}
¹⁴⁰ Ba	2.1×10^{-9}	3.39×10^{-9}
¹⁴¹ Ba	4.3×10^{-9}	1.63×10^{-8}
¹⁴² Ba	7.9×10^{-9}	1.96×10^{-8}
¹⁴⁰ La	1.5×10^{-8}	3.93×10^{-8}
¹⁴² La	1.5×10^{-8}	4.25×10^{-8}
¹⁴¹ Ce	5.5×10^{-10}	1.77×10^{-9}
¹⁴³ Ce	2.2×10^{-9}	6.27×10^{-9}

TABLE 4.9. (contd)

Radionuclide	Regulatory Guide 1.109 (U.S. NRC 1977)	Kocher (1980a) ^(a)
¹⁴⁴ Ce	3.2×10^{-10}	5.19×10^{-10}
¹⁴⁴ Pr	2.0×10^{-10}	5.30×10^{-10}
¹⁴⁷ Nd	1.0×10^{-9}	3.24×10^{-9}
¹⁸⁷ W	3.1×10^{-9}	9.83×10^{-9}
²³⁹ Np	9.5×10^{-10}	5.34×10^{-9}

(a) Kocher (1980a) presents dose factors for additional nuclides - 240 total.

TABLE 4.10. Age-Specific Ingestion Dose Factors to the Thyroid for Radioiodines^(a)

Age Group	Nuclide (mrem/pCi ingested)				
	¹³¹ I	¹³² I	¹³³ I	¹³⁴ I	¹³⁵ I
Infant	1.39×10^{-2}	1.58×10^{-4}	3.31×10^{-3}	4.15×10^{-5}	6.49×10^{-4}
Child (4 yr)	5.72×10^{-3}	6.82×10^{-5}	1.36×10^{-3}	1.79×10^{-5}	2.79×10^{-4}
Teenager (14 yr)	2.39×10^{-3}	2.46×10^{-5}	4.76×10^{-4}	6.45×10^{-6}	1.01×10^{-4}
Adult	1.95×10^{-3}	1.90×10^{-5}	3.63×10^{-4}	4.99×10^{-6}	7.65×10^{-5}

(a) Data from NUREG-0172 (Hoenes and Soldat 1977).

4.4.1 External Gamma Radiation Dose from Plume

When calculating external gamma dose from the plume using a rapid calculation model, a reliable dose estimate can be obtained by considering only a few critical noble gas nuclides. In WASH-1400 (U.S. NRC 1975), for example, only the following noble gas nuclides were considered: ^{85m}Kr, ⁸⁵Kr, ⁸⁷Kr, ⁸⁸Kr, ¹³³Xe, and ¹³⁵Xe. Another way of handling the noble gas mixture in a release would be to consider all activity to be ¹³³Xe and apply correction factors for time after shutdown to determine dose (see Figure 2.2, Section 2.4.3).

Similar to intermediate dose calculation methods, semi-infinite plume considerations should be used for a ground-level release while finite plume considerations should be used for an elevated release. Semi-infinite plume dose factors discussed in Section 4.3.1.1 (Table 4.1) would be appropriate. Radioactive releases should also be corrected for radioactive decay during plume transit. Finite plume considerations could be handled using finite plume correction factors developed by Healy and Baker (1968) or the method of Lahti, Hubner and Golden (1981) as reviewed in Section 4.3.1.2 of this document. Numerical integration techniques requiring relatively long computer times (U.S. NRC 1977a; Scherpelz, Borst and Hoenes 1980) would not be appropriate for a rapid dose calculational method. Nomograms developed by the NRC (U.S. NRC 1983) using finite plume methodology from Regulatory Guide 1.109 (U.S. NRC 1977a) would be appropriate for calculating external gamma dose.

4.4.2 Inhalation Dose to Child Thyroid

Calculation of inhalation dose to a child's thyroid can be accomplished using Equation (10) in Section 4.3.2. The dose calculation could consider a mixture of several radioiodine nuclides (e.g., ^{131}I , ^{132}I , ^{133}I , ^{134}I , ^{135}I) or consider all activity to be ^{131}I and apply a correction factor for time after shutdown (see Figure 2.3, Section 2.4.3). Dose factors and breathing rates used for the rapid dose calculation method would be the same as those in Section 4.3.2.

4.5 REFERENCES

- Aldrich, D. C. and J. D. Johnson, 1978a. Public Protection Strategies for Potential Nuclear Reactor Accidents: Sheltering Concepts with Existing Public and Private Structures. SAND-77-1725, Massachusetts Institution of Technology, Cambridge, Massachusetts.
- Aldrich, D. C., P. E. McGrath, N. C. Rasmussen. 1978b. Examination of Off-site Radiological Emergency Measures for Nuclear Reactor Accidents Involving Core Melt. SAND 78-0454, Sandia Laboratories, Albuquerque, New Mexico.
- American Nuclear Society and the Institute of Electrical and Electronics Engineers. 1982. PRA Procedures Guide - A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants. NUREG/CR-2300, Vol. 2, Rev. 1, Review Draft, Washington, D.C.
- Anno, G. H., T. P. Wilcos and J. K. Witthaus. 1963. "RISC: Radiological Inhalation Safety Code for IBM 7090." Trans. Amer. Nucl. Soc. 6, pp. 106-107.
- Arras, J. M. 1981. Concentric Cylinder Set Model for Estimating Dose from Gamma-Emitting Cloud. AFRRITN 81-1, Armed Forces Radiobiology Research Institute, Bethesda, Maryland.

- Bateman, H. 1910. "The Solution of a System of Differential Equations Occurring in the Theory of Radioactive Transformations." Proc. Cambridge Phil. Soc. 15, p. 423.
- Binford, F. T., J. Barish, and F. B. K. Kam. 1967. Estimation of Radiation Doses Following a Reactor Accident. ORNL-4086, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Boegli, J. S., R. R. Bellamy, W. L. Britz, and R. L. Waterfield. 1978. Preparation of Radiological Effluent Technical Specifications for Nuclear Power Plants. NUREG-0133, U.S. Nuclear Regulatory Commission, Washington, D.C.
- Burson, Z. G. and A. E. Profio. 1975. Structure Shielding from Cloud and Fallout Gamma Ray Sources for Assessing the Consequences of Reactor Accidents. EGG-1183-1670, EG&G, Inc., Las Vegas, Nevada.
- Chester, R. O. 1974. Biological Dose and Radiological Activity from Nuclear Reactor or Nuclear Weapon Fission Products. ORNL-4996, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Clarke, R. H. 1972. Multi-Compartment Model for Studying the Dose-Intake Relationship for Radioactive Isotopes. RD/B/M2291, Central Electricity Generating Board.
- Cooper, R. E. 1967. RADOS, A Code to Estimate Gamma Dose from a Cloud of Radioactive Gases. DP-1098, Savannah River Laboratory, Aiken, South Carolina.
- Cooper, R. E. 1976. "A Computer Code to Provide Emergency Response Capabilities to Estimate Whole Body Gamma Dose." In Savannah River Laboratory Environmental Transport and Effects Research Annual Report, FY-1975. DP-1412, pp. 40-41, Savannah River Laboratory, Aiken, South Carolina.
- Couchman, M. L., A. W. DeAgazio, and Y. S. Kim. 1964. NURSE-1-A Nuclear Rocket Safety Evaluation Code for the Control Data 3600. NUS-180, Nuclear Utility Services, Inc., Rockville, Maryland.
- Dabberdt, W. F., et al. 1982. Workshop on Meteorological Aspects of Emergency Response Plans for Nuclear Power Plants: Proceedings and Recommendations. Final Report, SRI Project 3689, SRI International, Menlo Park, California.
- Di Nunno, J. J., F. D. Anderson, R. E. Baker, and R. L. Waterfield. 1962. Calculation of Distance Factors for Power and Test Reactor Sites. TID-14844, U.S. Atomic Energy Commission, Washington, D.C.
- Dunning, D. E., Jr. and G. Schwarz. 1981. "Variability of Human Thyroid Characteristics and Estimates of Dose from Ingested ^{131}I ." Health Physic J. 40, pp. 661-675.

- Eckert, R. J. 1964. A FORTRAN Program for the Calculation of the Potential Hazards from an Accidental Fission-Product Release-M0142. WAPD-TM-348, Bettis Atomic Power Laboratory, West Mifflin, Pennsylvania.
- Garrett, A. J. and C. E. Murphy, Jr. 1981. A Puff-Plume Atmospheric Deposition Model for Use at SRP in Emergency Response Situations. DP-1595, E. I. duPont de Nemours & Co., Savannah River Laboratory, Aiken, South Carolina.
- Hamawi, J. M. 1971. "A Useful Recurrence Formula for the Equations of Radioactive Decay." Nucl. Tech. 11, pp. 84-88.
- Hamawi, J. M. 1976. A Method for Computing the Gamma-Dose Integrals I_1 and I_2 for the Finite-Cloud Sector-Average Model. YAEC-1105, Yankee Atomic Electric Company, Framingham, Massachusetts.
- Healy, J. W. and R. E. Baker. 1968. "Radioactive Cloud Dose Calculations." In Meteorology and Atomic Energy 1968. Ed. D. H. Slade, U.S. Atomic Energy Commission, Washington, D.C.
- Hoenes, G. R. and Soldat, J. K. 1977. Age-Specific Radiation Dose Commitment Factors for a One-Year Chronic Intake. NUREG-0172, Pacific Northwest Laboratory, Richland, Washington.
- Hoffman, F. O., C. W. Miller, D. L. Shaeffer, and C. T. Garten, Jr. 1977. "Computer Codes for the Assessment of Radionuclides Released to the Environment." Nuclear Safety 18(3), pp. 343-354.
- Houston, J. R., D. L. Streng, and E. C. Watson. 1974. DACRIN: A Computer Program for Calculating Organ Dose from Acute or Chronic Radionuclide Inhalation. BNWL-B-389, Pacific Northwest Laboratory, Richland, Washington.
- International Commission on Radiological Protection. 1959. Report of Committee II on Permissible Dose for Internal Radiation. Publication 2, Pergamon Press.
- International Commission on Radiological Protection. 1972. The Metabolism of Compounds of Plutonium and Other Actinides. Publication 19, Pergamon Press, New York, New York.
- International Commission on Radiological Protection. 1975. Report of the Task Group on Reference Man. Report No-23, Pergamon Press, Oxford, United Kingdom.
- Kaiser, G. D. 1976. A Guide to the Use of TIRION - A Computer Program for the Calculation of the Consequences of Releasing Radioactive Material to the Atmosphere. SRD-R-62, Safety and Reliability Directorate, United Kingdom Atomic Energy Authority, Wigshaw Lane, Calceith, Watlington, Lancashire, United Kingdom.
- Killough, G. G. and P. S. Rohwer. 1974. INDOS-Conservational Computer Codes to Implement ICRP-10-10A Models for Estimation of Internal Radiation Dose to

- Man. ORNL-4916, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Killough, G. G., P. S. Rohwer, and W. D. Turner. 1975. INREM: A FORTRAN Code Which Implements ICRP 2 Models of Internal Radiation Dose to Man. ORNL-5003. Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Killough, G. G. and G. R. McKay. 1976. A Methodology for Calculating Radiation Doses from Radioactivity Released to the Environment. USERDA Report ORNL-4992, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Killough, G. G. et al. 1978. INREM II: A Computer Implementation of Recent Models for Estimating the Dose Equivalent to Organs of Man from an Inhaled or Ingested Radionuclide. NUREG/CR-0114, ORNL/NUREG/TM-84, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Kocher, D. C. 1977. Nuclear Decay Data for Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities. ORNL/NUREG/TM-102, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Kocher, D. C. 1980a. "Dose Rate Conversion Factors for External Exposure to Photon and Electron Radiation from Radionuclides Occurring in Routine Releases from Nuclear Fuel Cycle Facilities." Health Physics J., Vol. 38, pp. 543-621.
- Kocher, D. C. 1980b. Effects of Indoor Residence on Radiation Doses from Routine Releases of Radionuclides to the Atmosphere. Nucl. Tech. Vol 48, pp. 171-179, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Lahti, G. P., R. S. Hubner and J. C. Golden. 1981. "Assessment of γ -Ray Exposures Due to Finite Plumes." Health Physics J., Vol. 41, pp. 319-340.
- Lee, R., J. Mack, and D. B. Sedgley. 1966. GADOSE and DOSET: Programs to Calculate Environmental Consequences of Radioactivity Release. USAEC Report GA-6511, General Atomic, San Diego, California.
- MacDonald, H. F. 1971. "Assessment of Environmental Hazards Following Nuclear Reactor Accidents," in Rapid Methods for Measuring Radioactivity in the Environment. Symposium Proceedings, STI/PUB/289, pp. 43-54, International Atomic Energy Agency, Vienna, Austria.
- Martin, M. J. 1973. Radioactive Atoms, Supplement I. ORNL-4923, U.S. Atomic Energy Commission, Washington, D.C.
- McGill, B., B. F. Maskewitz, C. M. Anthony, H. E. Commolander, and H. R. Hendrickson. 1976. Abstracts of Digital Computer Code Packages Assembled by the Radiation Shielding Information Center. ORNL/RSIC-13, Vol. IV, Oak Ridge National Laboratory, Oak Ridge Tennessee.
- Meek, M. E. and R. S. Gilbert. 1970. Summary of Gamma and Beta Energy and Intensity Data. NEDO-12037.

- Morrow, P. E. 1966. "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract." Health Physics J., Vol. 12, p. 173.
- Mosier, J. E., et al. 1980. Low-Level Waste Management: A Compilation of Models and Monitoring Techniques. ORNL/SUB-79/13617/2, Prepared by Science Applications, Inc., Oak Ridge, Tennessee, for Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Otter, J. M. and P. A. Conners. 1975. Description of the COMRADEX - III Code. U.S. NRC Report TI-001-130-053, Atomics International, Canoga Park, California.
- Owen, P. T., N. S. Dailey, C. A. Johnson, and F. M. Martin (eds). 1979. An Inventory of Environmental Impact Models Related to Energy Technologies. ORNL/EIS-147, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Poeton, R. W., M. P. Moeller, G. J. Laughlin and A. E. Desrosiers. 1982. Interactive Rapid Dose Assessment Model (IRDAM) for Reactor Accidents. NUREG/CR-3012, PNL-4511. Pacific Northwest Laboratory, Richland, Washington.
- Rider, J. L. and S. K. Beal. 1977. Model to Estimate the Local Radiation Doses to Man from the Atmospheric Release of Radionuclides (LWBR Development Program). WAPD-TM-1273, Bettis Atomic Power Lab., West Mifflin, Pennsylvania.
- Ritchie, L. T., J. D. Johnson and R. M. Blond. 1981. Calculation of Reactor Accident Consequences, Version 2. SAND81-1994, (NUREG/CR-2324), Sandia National Laboratories, Albuquerque, New Mexico.
- Scherpelz, R. I., F. J. Borst, and G. R. Hoenes. 1980. WRAITH - A Computer Code which Calculates Internal and External Doses Resulting from Atmospheric Releases of Radioactive Material. PNL-3382, Pacific Northwest Laboratory, Richland, Washington.
- Scherpelz, R. I. and A. E. Desrosiers. 1981. "A Modification to a Recurrence Formula for Linear First-Order Equation." Health Physics J., Vol. 40, pp. 905-907.
- Science Applications, Inc. 1981. Tabulation of Waste Isolation Computer Models. ONWI-78, Office of Nuclear Waste Isolation, Battelle Memorial Institute, Columbus, Ohio.
- Specht, E. R., C. Martin, J. Otter and R. Hart. 1975a. Description of COMRADEX-II Code. U.S. AEC Report TI-001-130-048, Atomics International, Canoga Park, California.
- Specht, E. R., J. M. Otter, and R. S. Hart. 1975b. Description of the Containment and Meteorology of Environmental Radiation Exposure (COMRADEX-II) Code. N707TI 130047, Rockwell International, Canoga Park, California.

- Stallman, F. W., and F. B. K. Kam. 1973. ACRA - A Computer Program for the Estimation of Radiation Doses Caused by a Hypothetical Reactor Accident. ORNL-TM-4082, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- Steyn, J. J. and Y. S. Kim. 1966. Users Manual for the Code EXGAM: A Code to Calculate Gamma Photon Dose from an Airborne Radioactive Release. U.S. AEC Report NUS-329, NUS Corporation, Rockville, Maryland.
- Streng, D. L., M. M. Hendrickson, and E. C. Watson. 1971. RACER - A Computer Program for Calculating Potential External Dose from Airborne Fission Products Following Postulated Reactor Accidents. BNWL-B-69, Battelle, Pacific Northwest Laboratories, Richland, Washington.
- Streng, D. L., E. C. Watson, and J. R. Houston. 1975. SUBDOS - A Computer Program for Calculating External Doses from Accidental Atmospheric Release of Radionuclides. BNWL-B-351, Pacific Northwest Laboratory, Richland, Washington.
- Streng, D. L., E. C. Watson, and J. G. Droppo. 1976. Review of Calculational Models and Computer Codes for Environmental Dose Assessment of Radioactive Releases. BNWL-B-454, Pacific Northwest Laboratory, Richland, Washington.
- Streng, D. L. et al. 1978. A Review of Methodology for Accident Consequence Assessment. PNL-2633, Pacific Northwest Laboratory, Richland, Washington.
- Thyker-Nielsen, S. 1974. Models for Calculation of External Gamma Doses and Inhalation Doses from Releases of Radioactive Isotopes to the Atmosphere. RISO-M-1725, Danish Atomic Energy Commission, Risoe Research Establishment (in Danish).
- Trubey, D. K. and S. V. Kaye. 1973. The EXREM III Computer Code for Estimating External Radiation Doses to Populations from Environmental Releases. U.S. AEC Report ORNL-TM-4322, Oak Ridge National Laboratory, Oak Ridge Tennessee.
- Turner, W. D., S. V. Kaye, and P. S. Rohwer. 1968. EXREM and INREM Computer Codes for Estimating Radiation Dose to Populations from Construction of a Sea-Level Canal with Nuclear Explosives. USAEC Report CTC-8, Oak Ridge National Laboratory, Oak Ridge, Tennessee.
- U.S. Atomic Energy Commission. 1974a. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Boiling Water Reactors. Regulatory Guide 1.3, Washington, D.C.
- U.S. Atomic Energy Commission. 1974b. Assumptions Used for Evaluating the Potential Radiological Consequences of a Loss of Coolant Accident for Pressurized Water Reactors. Regulatory Guide 1.4, Washington, D.C.

- U.S. Environmental Protection Agency. 1975. Manual of Protective Action Guides and Protective Actions for Nuclear Incidents. EPA-520/1-75-001, Revised June 1979 and February 1980, Environmental Protection Agency, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1977a. Calculation of Annual Doses to Man from Routine Releases of Reactor Effluents for the Purpose of Evaluating Compliance with 10 CFR Part 50, Appendix I. Regulatory Guide 1.109, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1977b. Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors. Regulatory Guide 1.111, Washington D.C.
- U.S. Nuclear Regulatory Commission. 1975. Reactor Safety Study, Appendix VI - Calculation of Reactor Accident Consequences. WASH-1400, Appendix D, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1979. Atmospheric Dispersion Models for Potential Accident Consequence Assessments at Nuclear Power Plants. Regulatory Guide 1.145, Washington, D.C.
- U.S. Nuclear Regulatory Commission. 1983. Nomograms for Evaluation of Doses from a Finite Cloud. NUREG-0851, Washington, D.C.
- Voilleque, P. G. 1968. Calculation of Organ and Tissue Burdens and Doses Resulting from an Acute Exposure to a Radioactive Aerosol/Using the ICRP Task Group Report on the Human Respiratory Tract. U.S. AEC Report IDO-12067, Idaho Operations Office, Idaho Falls, Idaho.
- Voilleque, P. G. 1970. "AERIN, A Code for Acute Aerosol Inhalation Exposure Calculations." Health Physics J., Vol. 19, pp. 427-432.
- Wenzel, D. R. 1974. "A Computer Code to Calculate Doses Resulting from Release of Radionuclides to the Atmosphere." Presented at Health Physics Society Annual Meeting, Houston, Texas, July 7-11.
- Willis, C. A., G. A. Spangler, and W. A. Rhoades. 1970. "A New Technique for Reactor Siting Dose Calculations." Health Physics J., Vol. 19, pp. 47-54.

APPENDIX A

TRANSPORT AND DIFFUSION
IN COMPLEX TOPOGRAPHY

TRANSPORT AND DIFFUSION IN COMPLEX TOPOGRAPHY

Transport and diffusion of airborne releases in complex topography settings including coastal and valley locations are discussed in this appendix.

A.1 TRANSPORT AND DIFFUSION IN A COASTAL ENVIRONMENT

A large percentage of the nuclear facilities in the United States are located in coastal environments because of the requirement for cooling water. As a result, the problems associated with assessing atmospheric transport and diffusion in this environment require specific attention. In simplistic terms the coastal environment can be characterized as consisting of coincident changes in surface roughness, thermal and moisture characteristics. These changes frequently induce local circulations, particularly if the coast or shore line is associated with a relatively large body of water. The sea breeze (lake breeze) has received a good deal of attention in the scientific literature. For example, Jehn (1973)^(a) lists 545 references appearing between 1664 and 1973 in his bibliography. Of these references, 157 have appeared since 1959.

A quick review of the current literature indicates no reduction in the rate at which new material is appearing. The trend of subject matter in the recent literature is divided between numerical and physical modeling of the atmospheric processes and applied studies related directly to atmospheric diffusion. A number of summaries of the material on transport and diffusion in the coastal environment have been published. Among these, the summaries by Lyons (1975), Raynor, Michael and SethuRaman (1979 and 1980), and Shearer and Kaleel (1982) are particularly appropriate to emergency response applications. The Shearer and Kaleel summary lists 232 references including many project reports that are not widely publicized.

A.1.1 Elevated Releases During the Summer

In general, the coastal environment diffusion problem given the most attention is onshore flow with an elevated release when the land surface is warmer than the water. Figure A.1 illustrates three possible scenarios. In each scenario the wind is blowing from left to right and the water surface is cooler and smoother than the land. Dashed lines indicate the internal boundary layers (IBL). However, it should be remembered that the internal boundary layer is in reality a zone. In Figure A.1(a) the release is occurring entirely within the IBL. This case is essentially no different than an inland release under similar atmospheric conditions. There may be some restriction to vertical diffusion at the top of the IBL, but the restriction is similar to that which occurs at the top of the mixing layer defined by normal inversions.

(a) All references in this appendix can be found in Section 3.0's reference section.

In the scenario in Figure A.1(b), the release occurs at the coast, above the IBL. The initial diffusion takes place in the stable atmospheric conditions associated with air over the water. At some point downwind, the IBL reaches the plume level and material in the plume mixes rapidly to the ground. Van der Hoven (1967) suggests that diffusion in this case is similar to diffusion under conditions of inversion break-up that are responsible for fumigation. Lyons and Cole (1973); Meroney et al. (1975); Van Dop et al. (1979); Misra (1980) and McRae et al. (1981) give continuous plume models for use in estimating concentrations in this scenario. Van der Hoven (1967) also suggests that the height of the IBL is approximately proportional to the overland fetch raised to the $1/2$ power. Raynor et al. (1975) present a model of IBL growth in which the IBL is a function of not only fetch to $1/2$ power, but also to wind speed to the -1 power, land-sea temperature difference to the $1/2$ power and the stability of the air over the water to the $-1/2$ power. The model of Misra avoids the problem of specification of IBL height.

In the third scenario, Figure A.1(c), the release occurs in the unstable air over the land, but before the plume diffuses to ground level it encounters the stable air over the water. There the diffusion rate is significantly reduced. Finally, the plume encounters unstable air in an IBL as it passes over land some distance downwind. The primary difference between the second and third scenarios is the length of plume travel in the stable air.

Figure A.2 shows the elevated and ground-level centerline concentration as a function of distance from the source. This figure shows the concentration as a function of time for a fixed distance downwind as the mixing layer increased in depth. Here airborne material is transported to an intersection with the IBL.

The centerline, ground-level concentrations for the three scenarios are qualitatively compared in Figure A.3. Scenario (a) gives the greatest maximum concentration, with the position of the maximum closer to the stack than for the other scenarios. The maximum for (b) is somewhat lower than for (a) because of the initial diffusion that takes place prior to encountering the unstable air in the IBL. The initially slow diffusion that causes the maximum to be lower in this case is also responsible for (b) having higher concentrations than (a) beyond the (b) concentration maximum. The comparison can be extended to include (c) without modification.

Mathematically, the comparison in Figure A.3 can be explained using the elevated Gaussian plume model. At the point of maximum ground-level concentrations, the vertical diffusion parameters will be about equal in the three scenarios. However, because of the increasing travel distances to the maxima from (a) to (b) to (c), the horizontal diffusion parameters will increase from one scenario to the next. As a result, the concentration maxima will decrease. Beyond the maxima, the ground-level concentrations can be considered inversely proportional to the product of the horizontal and vertical diffusion parameters, and the exponential term that compensates for plume height can be neglected. The growth rate of the diffusion parameters is

(c)

(b)

(a)

FIGURE A.1. Three Elevated Release Scenarios with Onshore Flow During the Summer

FIGURE A.2. Elevated and Ground-Level Concentrations in a Sea Breeze Fumigation Condition

a function of downwind distance and atmospheric stability. It is greatest in unstable atmospheric conditions and least in stable conditions. As a result, the longer the plume travels in stable atmospheric conditions, the longer it takes for the product of the diffusion parameters to reach a magnitude associated with a specified concentration level.

A.1.2 Temporal Variation of the Sea Breeze

Up to this point diffusion in the coastal environment has been considered independent of transport. Implicitly the assumption is that wind direction is constant in both time and space. That assumption is appropriate if the ground-level concentration as a function of downwind distance in the plume is of interest. If the position of the maximum ground-level concentration, the time at which a release will intersect the IBL, or any number of other related concerns is of interest, the implicit transport assumption is no longer

FIGURE A.3. Comparison of Ground-Level Centerline Concentrations for the Scenarios Shown in Figure A.1

tenable. The sea breeze is typically a nonstationary phenomenon in which both wind direction and speed are functions of time.

To illustrate the importance of considering the time variation, consider the following example: the scenario is a north-south oriented coast with water to the west and land to the east during the summer. Therefore, stable air can be assumed over the water and unstable air during the day over the land. In the absence of a dominant synoptic weather situation, the 12 hour sequence of wind observations in Table A.1 might be recorded at a location near the coast. To simplify the example, assume that these winds are representative for the air over land and over water, and consider the diffusion and transport of material released at the beginning of each hour throughout the day. The diffusion can be represented by the appropriate scenario in Figure A.1. Figure A.4 shows trajectories for the material released at each time. The solid line represents the coast, and the dashed line represents the ground-level projection of position of the intersection of the elevated plume and the IBL. The numbers along the trajectories are times associated with the leading edge of the plume.

TABLE A.1. Hypothetical Wind Record for a Sea Breeze Event

Time	Wind Direction	Wind Speed
0700	140	2
0800	160	2
0900	180	2
1000	210	3
1100	240	4
1200	260	5
1300	270	5
1400	280	5
1500	300	4
1600	320	3
1700	340	3
1800	360	2
1900	020	2

If a release occurred at the first two starting times being considered, the initial plume travel would be over water and the plume would finally intersect the IBL well north of the release point. We have essentially scenario (c) from Figure A.1. Delaying the release shifts us to scenario (b), and more importantly causes the point of intersection with the IBL to move south, closer to the source. During the middle of the day, the wind direction carries material directly inland, and the distance to the point of the ground-level concentration maximum is at a minimum. As the afternoon progresses, the wind continues to veer, ultimately carrying material off-shore. Such diffusion conditions are represented graphically in Figure A.1 (Scenario C).

To further explore the consequences of this type of wind variation on diffusion and transport, we have listed the time, position and total distance traveled to the IBL intersection for releases beginning each hour as listed in Table A.2. Material released between 0700 and 1100 hr would arrive at the ground between 1030 and 1130 hr, appearing to ground-level observers almost as though it had been released from an off-shore line source that increased in strength from north to south. For this reason, the duration of a high-level concentration at any point would be relatively short. By contrast, observers positioned under a plume released from 1200 to 1400 hr could correctly perceive that they were beneath the plume from a single point source. They would have a significantly larger exposure to the high concentrations than the observers to the north, because the lateral motion of the plume during this period is significantly slower than during the earlier period. Finally,

FIGURE A.4. Possible Trajectory of Material Released During a Sea Breeze Event

TABLE A.2. Location and Times of Fumigation for the Example in Figure A.4

<u>Release Time</u>	<u>Time of Intersection with IBL</u>	<u>Direction and Distance (km) IBL Intersection</u>	<u>Total Distance Traveled (km)</u>
0700	1130	008/32.8	39.6
0800	1108	010/24.8	27.1
0900	1048	015/15.8	16.2
1000	1050	030/9.0	9.0
1100	1123	060/5.4	5.4
1200	1214	080/4.7	4.7
1300	1314	090/4.3	4.3
1400	1416	100/4.7	4.7
1500	1521	120/5.4	5.4
1600	1640	140/7.2	7.2
1700	---	---	---
1800	---	---	---
1900	---	---	---

observers farther south would again undergo short periods of high exposure during the later portion of the afternoon as the wind direction continued to veer.

Having considered a realistic description of diffusion and transport, consider how the straight-line Gaussian plume might be misapplied. A release prior to 1000 hr would not be expected to affect the area onshore because the winds prior to that time are either offshore or along the coast. Releases between 1000 and 1600 hr would be reasonably well treated, provided that only the position and time of arrival of the plume at the point of maximum concentration were to be estimated. Total exposures would be overestimated, if persistence were assumed and the release extended more than an hour. For releases after 1600 hr, the position and arrival time of the plume at some point on the land cannot be predicted from the wind at the point and time of release.

As might be expected, actual conditions along a coastline are more complex than indicted in the preceding example. Raynor et al. (1979) indicate that the wind direction tends to change as the coastline is crossed, unless the offshore wind is essentially perpendicular to the coast. If the wind approaches the coast at an oblique angle, the direction shifts as the coast line is crossed, leaving it more nearly perpendicular. The diffusion data

collected in many coastal diffusion experiments, e.g., Lamb, Lorenzen and Shair (1978) and Lamb, Shair and Smith (1978), provide further evidence of the inadequacy of simple models that relegate transport to an implicit treatment.

A.1.3 Other Coastal Release Scenarios

Concerns related to coastal diffusion and transport are not limited to the elevated release scenarios so far discussed. Those scenarios are primarily summer scenarios. Briefly consider three additional sets of scenarios: "winter" elevated release scenarios that parallel the "summer" scenarios, then "summer" and "winter" ground-level release scenarios.

In Figure A.5, the wind is again blowing from left to right. This time, however, the water is warmer than the land surface. The cooler land tends to stabilize the air as it flows inland, thus reducing the turbulence and vertical diffusion rate. The increased stability is countered, at least partially, by the increased land roughness. In Figure A.5(a) the release is within the IBL. As a result, it behaves as would be expected of releases in other, non-coastal locations with similar meteorological conditions. In Figure A.5(b) the release occurs in the relatively unstable air still under the influence of the water. When the plume intersects the IBL, the rate of vertical diffusion in the lower portion of the plume decreases due to the increased atmospheric stability within the IBL. As a result of the initial diffusion in the relatively unstable air, the plume reaches the ground sooner in Figure A.5(b) than it does in Figure A.5(a). In the final "winter" scenario, Figure A.5(c), the release takes place in the stable air over land. Shortly, the plume encounters the unstable air over the water and mixes to the surface. It then continues downwind until it intersects another body of land. If the initial over-land fetch is sufficiently short, the plume in Figure A.5(c) will reach the ground sooner than the plumes in either Figure A.5(a) or Figure A.5(b).

The centerline, ground-level concentrations for the "winter" scenarios are qualitatively compared in Figure A.6. In these scenarios, going from (a) to (b) to (c) increases the magnitude of the maximum concentrations and reduces the ground-level centerline concentrations beyond the maxima. This is opposite of the changes taking place in the "summer" scenarios.

The ground-level release scenarios are illustrated in Figures A.7 through A.10. In these scenarios the source is over land. As a result, there are just two cases. In the first case, the release takes place within the IBL during an onshore flow. In the second case the flow is offshore and the concern is about the concentration when the plume returns to land.

Figure A.7 deals with "summer" conditions where the land is warmer than the water and the air over the land tends to be unstable. The release in Figure A.7(a) behaves as a release at inland sites. In Figure A.7(b), however, after an initial period of relatively rapid vertical diffusion, the plume

FIGURE A.5. Three Wintertime Coastal Elevated Release Scenarios

encounters the stable air over the water and the vertical diffusion rate slows. Relatively rapid vertical diffusion resumes when the plume returns to land. The relative centerline concentrations in these two cases are shown qualitatively in Figure A.8.

FIGURE A.6. Comparison of Ground-Level Centerline Concentrations for the Winter Elevated Release Scenarios

FIGURE A.7. Summer Scenarios for Coastal Ground-Level Releases

FIGURE A.8. Comparison of Centerline Concentrations for the Release Scenarios in Figure A.7

FIGURE A.9. Winter Scenarios for Coastal Ground-Level Releases

FIGURE A.10. Comparison of Centerline Concentrations for the Release Scenario in Figure A.9

"Winter" scenarios for ground-level releases in a coastal environment are illustrated in Figure A.9. In Figure A.9(a) the release takes place in relatively stable air over land and diffuses in those conditions. The release in Figure A.9(b) takes place over land, but the vertical diffusion is enhanced when the plume encounters the moist, unstable air over the water. Figure A.10 shows the effects of the enhanced vertical diffusion.

Comparing Figures A.8 and A.10 with Figures A.4 and A.6, it can be seen that the effects of specific scenarios are different for ground-level releases than for elevated releases. For elevated releases, changing the scenario changes the magnitude and position of the maximum concentration. On the other hand, changing the scenario for ground-level releases does not change the maximum concentration. It only changes the distances required to realize a given concentration reduction.

A.1.4 Coastal Measurement Programs

The simplistic outline of coastal transport and diffusion given above, results from an attempt to generalize from many rather specific sources of diffusion data and modeling studies. When it comes to evaluating the consequences of a release at a specific location, this general picture should be augmented with any directly applicable information. There is a good bit of relevant information for several coastal regions around the United States. The areas for which this information is most abundant are: the California coast from Los Angeles north to the San Francisco Bay area, the Great Lakes region, the north Atlantic coast particularly along New Jersey, New York and

lower New England, the Florida Atlantic coast, and the Texas coast along the Gulf of Mexico. Figures A.11 and A.12 show the locations of measurement programs identified by Shearer and Kaleel (1982).

A.2 TRANSPORT AND DIFFUSION IN COMPLEX TERRAIN

The discussion now moves to topographic settings that include valleys and ridges. The coastal environment previously discussed was sufficiently complex that it was treated by assuming long straight coastlines and ignoring topographical features frequently associated with coasts such as bluffs and inland hills and mountains. In this section similar simplifications will be made. In general, discussion will be limited to isolated topographic features, i.e., individual hills, bluffs, valleys and gorges. The primary issues associated with transport and diffusion in complex terrain can be illustrated using this approach and can provide some insight into transport and diffusion in real terrain, where more detailed study is needed for a quantitative evaluation.

A large portion of the current research in atmospheric transport and diffusion is directed toward complex terrain problems. Orgill (1981) compiled an extensive summary of the work in this area through 1979 for use in planning Department of Energy multi-laboratory complex terrain research programs, which go by the acronym ASCOT (Atmospheric Studies in Complex Terrain). Dickerson and Gudiksen (1980) describe the overall ASCOT program and Dickerson (1981) describes its current status. Orgill's summary lists 362 references for the section on "Terrain-Induced Airflow Phenomena," and 169 references for the section on "Plume or Pollutant Transport and Diffusion in Complex Land Forms." It forms the basis for the material presented here. For a more detailed discussion of the material, refer to Orgill's report or to his references. Appropriate references to the primary information sources are included in this section.

Following Orgill, the major areas of concern related to atmospheric processes in complex terrain are: streamline displacement, channeling, local terrain-induced winds, stagnation in basins and valleys, impaction of elevated plumes on terrain, fumigation and effects of flow deformation and wakes on plumes.

A.2.1 Transport Near Isolated Hills

Flow around geometric shapes that might represent isolated terrain features has been studied in great detail using mathematical models such as potential flow theory and in-wind tunnels. A hemisphere can be assumed to represent an isolated hill. Figure A.13 shows typical streamlines flowing over and around the hill. Low wind speeds will be found on the windward and leeward sides of the hill, and areas of higher speed will be found on the top and cross-wind sides of the hill where there is convergence of the distorted flow. Figure A.14 shows the same general features as shown in Figure A.13 but for a more realistic shape.

FIGURE A.11. Location of Meteorological Measurement Programs Conducted in Coastal Regions (Shearer and Kaleel 1982)

FIGURE A.12. Locations of Tracer Studies Conducted in Coastal Regions
(Shearer and Kaleel 1982)

FIGURE A.13. Streamline Flow Around and Over a Hemisphere

The effect of an isolated hill on transport and diffusion depends, to a large extent, on the relative sizes of the hill and the plume. If a release occurs sufficiently close to the hill that the horizontal and vertical dimensions of the plume are small compared with the dimensions of the hill, the primary effect should be a displacement of the plume. If the dimensions of the plume and hill are approximately equal, two possibilities are apparent. In the first possibility, the plume may be diverted around the hill as in the previous case. The second possibility arises if the wind is nearly directly toward the hill. In this case, the plume may split as it approaches the region of flow divergence just upwind of the hill. Finally, if the plume dimensions are large compared with those of the hill, the hill will have little effect on the plume. These possibilities are illustrated in Figure A.15. The ease of qualitatively defining them belies the practical difficulties in selecting the appropriate case and making a quantitative estimate of the effect.

A.2.2 Transport Near Two-Dimensional Features

Flow over two-dimensional features such as long cylinders and prisms also has been studied in detail. These shapes when perpendicular to the flow are somewhat analogous to cliffs and mountain ridges. They tend to block the flow, and as a result air is forced up and over them. The convergence of the air as it rises causes it to speed up. Figure A.16 illustrates these features as might be shown through flow visualization techniques in a wind tunnel. Figure A.17 shows the effects of blocking to be expected in real terrain.

FIGURE A.14. Flow Around an Isolated Mountain Heated by Solar Radiation (Orgill 1981, adapted from Scorer 1955 and Fujita 1967)

FIGURE A.15. The Effect of Relative Dimensions of a Hill and Plume on Transport and Diffusion

FIGURE A.16. Simulated Flow Visualization of the Convergence and Increase in Air Speed Rising Over a Two-Dimensional Slope

FIGURE A.17. Effects of a Mountain Ridge on Airflow (Orgill 1981)

The rising air on the windward side of the mountain range corresponds to the rising air in the wind tunnel example. However, Figure A.17 indicates three additional effects: funneling air through passes in the range, causing stagnation of low-level air on the windward side of the mountain, and diverting the flow. Funneling the air through the passes will be discussed shortly.

Atmospheric conditions favorable to stagnation on the windward side of the ridge are: a mixing layer depth less than the height of the mountains, stable conditions in the mixing layer, and low wind speeds. Under these conditions, treatment of plume transport becomes difficult. Considerable mixing of the air may occur within the stagnant zone without any true transport occurring. With somewhat higher wind speeds than are associated with stagnation, there can be a deflection of the horizontal near surface wind

approaching the ridge. This is particularly true where the length of the ridge is not long enough for the ridge to be considered a two-dimensional feature.

Hewson, Bierly and Gill (1961) illustrate the potential effects of cliffs on plume transport for the case in which the wind is toward the cliff. In unstable atmospheric conditions the flow tends to rise while being deflected. In stable conditions, the vertical motion of the air is limited and the primary effect of the cliff is to deflect of the plume. These two conditions are illustrated in Figure A.18. Of course, the difference between the release height and the height of the cliff plays an important role in determining the extent of the effect, as does the distance from the release to the cliff.

A.2.3 Flow Channeling

There are many ways in which wind channeling can occur, three of which are illustrated in Figure A.19. Figure A.19(a) represents a mountain pass or gorge. Figure A.19(b) depicts the modification of upper level winds by a valley or canyon, and Figure A.19(c) shows the convergence of the flow where two valleys meet. The mountain pass situation is similar to air flow through

FIGURE A.18. Transport and Diffusion Near a Cliff (Orgill 1981, adapted from Hewson, Bierly and Gill 1961)

FIGURE A.19. Three Examples of Valley Channeling the Wind (adapted from Orgill 1981)

a venturi. Bernoulli's Theorem can be used to estimate the change in flow as the air passes through the gap. The direction of the flow and the speed depend, in part, on the large scale wind, the temperature and pressure gradients across the pass, and on the heights of inversion or stable layers on either side of the pass. Olsson, Elliott and Hsu (1973) and Scorer (1952) among others discuss the conditions that are necessary for flow through a pass to exist. Although the pass is shown as straight in Figure A.19, that is not a necessary configuration. It should also be noted that significant wind through the pass can be generated by pressure and temperature differences, even when there are light winds on the windward side of the pass.

Analysis of the channeling in the second case is more complex. Insight into the potential magnitude of the flow induced in the valley cannot be gained through a mathematical formulation as neat as Bernoulli's Theorem. Conceptually, however, the induced flow should be a function of: the angular

difference between the upper level wind direction and the valley orientation, and the atmospheric stability and height difference between the ridges on the sides of the valley.

The third example of channeling considers the convergence of air flows from two valleys. Assuming the air flows are contained within the valleys, the equation for conservation of mass can be used to relate the inflow and outflow wind speeds. Use of this equation requires estimates of the cross-sectional areas of the valley at the inflow and outflow points. More realistic estimates of the flow can be made if sufficient information is available by using Bernoulli's Theorem.

Where valleys converge or a single valley curves there may be a tendency for the air to follow preferred paths over the ground. Specifically, conservation of vorticity and momentum may tend to cause a curved jet along the outer side of the curve, while the air along the inside of the curve moves relatively slowly.

A.2.4 Local Terrain-Induced Winds

The third area of terrain effects primarily related to atmospheric transport is that of local terrain-induced winds. These winds are associated with the diurnal variation of surface heating. As a result, they tend to follow a regular diurnal cycle in the absence of overriding synoptic influences. The two types of topographic features that give rise to local winds are adjacent land and water masses, and sloping terrain. We have already discussed the land-sea breeze; now we will discuss various slope (mountain-valley) flows. The primary driving force for these flows is the density change that occurs in air as it is heated or cooled.

The basic process responsible for these thermally induced local winds is illustrated in Figure A.20. The upper frame represents the daytime condition. Solar radiation warms the slopes, which in turn, warms the layer of air in contact with the surface. The decrease in density of the warmed air starts the air moving up the slope where it continues to warm. To compensate for the ascending air along the slope, there must be descending air somewhere. In a valley, the descending air may be in the center of the valley or along an unheated slope. The nighttime condition is illustrated in the lower frame. As the surface of the slope cools due to long-wave terrestrial radiation, the temperature of the air layer next to the surface cools faster than the air farther from the surface. This cooling results in increased density for the surface layer air, and descending motion along the slope.

Defant (1951) presents a classic picture of mountain-valley circulations, which is included in Orgill's summary (1981). This picture, shown in Figure A.21 follows the mountain-valley circulation through a full diurnal cycle. The cycle starts at sunrise (A) with general down-valley flow indicated by the black arrows and the onset of up-slope flow indicated by the white arrows. By mid-morning (B) the slope winds become the dominant flow feature. As heating continues, an up-valley wind begins to develop and the role of the up-slope

SURFACE HEATING - UPSLOPE FLOW

RADIATION COOLING - DOWNSLOPE

FIGURE A.20. Effects of Surface Heating on Slope Flow (Orgill 1981)

FIGURE A.21. Diurnal Mountain-Valley Wind Cycle (Defant 1951 and Orgill 1981)

winds diminishes (C). In late afternoon (D), the up-slope winds cease and the primary flow is up the valley. The remainder of the cycle is essentially a mirror image of the diurnal cycle to this point. When the slopes enter the shadows in early evening (E), down-slope flow starts. This flow tends to counter the valley wind. In late evening the valley wind stops and the primary circulation is due to the down-slope flow. Eventually, in the middle of the night (G), the mountain wind develops. Finally, the down-slope flow ceases, leaving just the mountain wind (H). This condition persists until early morning when the surface heating starts the cycle over. This picture is based upon observations indicating the diurnal temperature range in mountain valleys is larger than in open plains. In the mid-day, valley temperatures

tend to be higher than plains temperatures, and at night they tend to be lower. Thus, these temperature differences also contribute to the diurnal wind variation.

Whiteman (1982) and Whiteman and McKee (1982) have examined the details of the morning transition in the mountain-valley circulation. Whiteman (1982) presents an analysis of observations of temperature and wind profiles in several valleys in the Colorado Rocky Mountains. The morning change in winds is related to the break-up of the nocturnal temperature inversion. Figure A.22 shows typical conditions in the middle of the break-up period. The thermal stratification, shown in the upper portion of the figure, has several layers. Next to the surface there is a convective boundary layer (CBL) developing as a result of surface heating. Immediately above the CBL is a stable layer containing the remnants of the nighttime inversion. It is overlain by a neutral layer, and finally there is the slightly stable layer that represents the free atmosphere. Associated with each of these thermal layers is a characteristic wind regime. The up-floor and up-slope winds are contained within the CBL, and up-incline winds are found within the neutral layer. The nighttime down-valley winds persist within the stable core, and the gradient wind is found in the free atmosphere.

Problems associated with estimating plume transport during the morning inversion break-up period are immediately obvious. From Defant's (1951) description it might be expected that the break-up and wind transition take place rather rapidly. However, Whiteman's (1982) observations indicate the transition typically takes from 3.5 to 5 hours to complete, with an average of about 4.5 hours. And in one of Whiteman's observation periods, when the ground was snow covered, the transition did not go to completion.

Transition mechanisms include both a deepening of the CBL and descent of the bottom of the elevated neutral layer. When the ground is wet or covered with snow, the development of the CBL may be delayed or inhibited. Two of Whiteman's cases followed this pattern. In a third case, on a summer morning, the inversion break-up resulted from growth of the CBL without descent of the bottom of the upper neutral layer. In the remaining 18 cases, both mechanisms were operative. Typical values for the rate of increase in the CBL depth and descent of the bottom of the upper neutral layer were found to be 70 m hr^{-1} and 80 m hr^{-1} , respectively. Whiteman and McKee (1982) discuss the thermodynamics of the mechanisms.

With differential heating of the sides of valley and different orientations of the upper level wind possible, local circulations within the valley are possible. Wanta and Lowry (1976) have cataloged several of the potential local circulation patterns. Six of these patterns are illustrated in Figure A.23. The conditions associated with the patterns are listed in Table A.3. As with most of the information on local circulations in complex terrain, these patterns should be considered as qualitative descriptions, and should be verified if they are likely to have a significant effect on transport at a specific location.

FIGURE A.22. Thermal and Wind Structure in a Valley During Morning Inversion Break-up (Whiteman 1982)

FIGURE A.23. Potential Circulation Patterns in a Heated Valley Corresponding to the Conditions Described in Table A.3. Regions where thermal and mechanical circulations reinforce each other are indicated by +, where they counter each other by -. (From Orgill 1981, adapted from Wanta and Lowry 1976)

TABLE A.3. Valley Circulation Patterns Resulting from the Combined Effects of an Upper Level Wind and Solar Heating (from Orgill 1981, adapted from Wanta and Lowry 1976)

<u>Wind Direction Relative to Ridge</u>	<u>Ridge Orientation</u>	<u>Time</u>	<u>Resulting Flow</u>
Parallel	East-West	Day	South-facing slope is heated. Single Helix.
Parallel	East-West	Night	Downslope flow on both slopes. Double Helix.
Parallel	North-South	Day	Up-slope flow on both heated slopes. Double Helix.
Parallel	North-South	Night	Downslope flow on both slopes. Double Helix.
Perpendicular	East-West	Day	South-facing slope is heated. North wind--stationary eddy fills valley. South wind--eddy suppressed, flow without separation.
Perpendicular	East-West	Night	Indefinite flow--extreme stagnation in valley bottom.
Perpendicular	North-South	Day	Upslope flow on both heated slopes--stationary eddy one-half of the valley.
Perpendicular	North-South	Night	Indefinite flow--extreme stagnation in valley bottom.

In Figures A.21 through A.23, the valleys have been drawn as relatively narrow. Lest we be tempted to conclude that the local circulations in question are found only in narrow valleys, Figure A.24 illustrates a well documented drainage flow in the Snake River Basin in Idaho (Wilkins 1956, Wendell 1972, and Cate 1977). The width of the basin is about 60 miles. Figure A.25, from Wendell (1973), shows what can happen to atmospheric transport when the drainage flow occurs. The trajectories in the figure represent the paths of two tetroons (constant level balloons) released one minute apart with about 100 m vertical separation. It is important to know that the conditions are such that widely divergent trajectories of released material are possible in the event of an accident. This knowledge should be based upon a combination of climatological information and current meteorological data. It also presupposes a good bit of meteorological understanding by the individual making the meteorological assessment at the time of the accident.

FIGURE A.24. Drainage Winds in the Snake River Basin, Idaho (Orgill 1981)

A.2.5 Fumigation

The fumigation process has been discussed in Section A.1.1. Since its characterization and treatment in complex terrain is not significantly different than in the other situations, it will not be discussed further.

A.2.6 Stagnation

Stagnation is defined as the state of the atmosphere when the wind speed approaches zero and the direction is ill-defined for relatively long periods. The primary problems associated with stagnation are the small initial dilution that occurs as material is released and the poorly defined transport direction. In licensing nuclear facilities, these problems are treated by assigning wind speeds below anemometer threshold an arbitrary speed and distributing the directions in proportion to the frequency of occurrence of directions during higher wind speeds. This is a satisfactory approach for licensing, but it is not appropriate when an accident release is about to occur or has already occurred. In this case, it is important to use any available information to estimate the segment of the population most likely to be exposed, and to estimate the level of exposure.

The licensing treatment of low wind speed conditions is the direct result of mathematical problems associated with allowing the wind speed to approach zero in the denominator of the continuous plume equation. This is not a fundamental problem, however, if the Gaussian plume model is discarded. One

FIGURE A.25. Divergent Trajectories of Tetroons Released One Minute Apart with about 100 m Separation in Elevation (Wendell 1973)

relatively simple approach that reasonably treats the stagnation problem is use of a Gaussian puff model. A second problem of historical rather than fundamental origin is also apparent. That problem is associated with the specification of the values for the diffusion parameters σ_x , σ_y and σ_z . The historical origin of the problem comes from routine specification of values

for these parameters as functions of travel distance. If the air is stagnant, how can there be a travel distance and how can these parameters be defined? Lower limits can be placed on the magnitude of the product of the parameters. To identify the lower limit consider the thermodynamic laws that control the atmosphere. They will only allow the atmosphere to concentrate an effluent through processes such as gravitational settling and redistribution by precipitation. In a practical sense, they will not permit the atmosphere to compress the effluent, thereby increasing its concentration. Thus, the release time and flow rate define a minimum volume for the effluent. In this case the flow rate is for the stack, vent or other path by which the effluent reaches the atmosphere.

Returning to consideration of stagnation and wind speed, the transformation leading to the Gaussian plume equation involved the mean components of the wind in a Cartesian coordinate system. Both positive and negative values are acceptable for component speeds. Thus, assuming that a component mean is zero is not equivalent to assuming that the component speed is zero at all times during the averaging period. Also, in many, if not most, cases of calm winds, the wind is not really calm. It is just below the instrument response threshold. Therefore, it is reasonable to consider or allow some diffusion even though there is little or no transport. This can be accomplished by treating the diffusion parameters σ_x , σ_y and σ_z as functions of time since release rather than as functions of distance from the source. Treatment of diffusion as a time-dependent process rather than a distance-dependent process is an old concept. Diffusion theory is generally developed in terms of time rather than distance; it is only when the continuous plume model is derived that the diffusion parameters are made a function of distance. Development of diffusion theory as a function of time is found in many places (e.g., Gifford 1968, Csanady 1973 and Pasquill 1974). The relationship between diffusion parameters and time is discussed in papers by Gifford (1957), Fuquay, Simpson and Hinds (1964), Nickola (1971) and in a recent paper by Sheih (1980) with the ensuing comments and replies (Gifford 1981, Sheih 1981a, Rowe 1981, Sheih 1981b and Mikkelsen and Troen 1981) and elsewhere.

With the diffusion parameters determined as a function of time, the puff diffusion equation may be used to estimate the concentration at a particular instant following the release regardless of wind speed. However, it is unlikely that the integration to obtain an estimate of the total exposure to time T following release can be done in closed form. However, the integration can be performed numerically and still produce a timely estimate.

Assuming that a release can be represented as a single puff is reasonable for short duration releases, that is for releases of perhaps 15 minutes' duration. For longer releases, the release should be modeled as a series of puffs. To estimate concentrations and exposures when more than one puff is used to simulate a release, it is necessary to sum the contributions of all puffs.

Clearly the conceptual treatment of diffusion in stagnant conditions is tractable. The basic problems are in the selection of diffusion parameters and in prediction of the direction of motion of the material when the wind picks up. There is a need for further work on the definition of the time-dependent diffusion parameters at low wind speeds. This definition might be provided by diffusion experiments, or by special turbulence measurements made with sensitive instruments during low wind speed conditions.

Near calm winds provide an opportunity to monitor the release onsite, and they provide more time for the public to take protective action. To take maximum advantage of these opportunities it is necessary to estimate the time that the wind will pick up and the direction of motion of the material when the wind picks up. While these estimates may be best made by a professional forecaster, it is possible to develop objective forecasting techniques that could be used by a health physicist with a moderate amount of training. Objective forecast aids might use current meteorological conditions and climatological data on local circulations to make the estimates. The forecast aids can be developed from routinely collected data or from data obtained in a relatively short (compared to the life of the facility) meteorological study.

A.2.7 Impaction and Wakes

The problem of impaction is essentially one of estimating the position and concentration at touchdown of an elevated plume in complex terrain. It involves both transport and diffusion. Given the airflow possibilities discussed earlier in this section and in the previous section, the problem of predicting the location of touchdown may be difficult. The problem of estimating the concentration at touchdown may be somewhat easier.

Regulatory Guide 1.111 treats impaction by assuming straight-line transport directly into topographic features. The concentration at the point of impaction is then the axial concentration in the elevated plume just prior to impaction. Clearly, these assumptions give a conservative estimate of the maximum ground-level concentration. Distortion of the air as it flows over and around topographic features will reduce the concentrations as the plume approaches the surface. Improved estimates of the impact location require better transport models, while less conservative, more realistic concentration estimates can be made within the existing model.

Egan (1975) briefly describes what appears to be a more realistic model for flow over topographic features. If the feature is lower than the effective plume height, the effective height is reduced by one half the height of the feature. If the elevation of the topographic feature is greater than the effective plume height, the plume height is reduced by a factor of two. These plume height corrections are used in place of the Regulatory Guide 1.111 correction procedure in which each increase in terrain elevation is subtracted directly from the plume height until the plume is at ground-level. Egan also discusses corrections to be applied to the diffusion parameters as a result of flow deformation and acceleration.

Complex terrain diffusion tests (Start, Dickson and Wendell 1975, and Start, Dickson and Ricks 1974) support Egan's diffusion parameter corrections. Data from these experiments show significantly enhanced diffusion in comparison with expectations based on the Pasquill-Gifford stability class. The reductions in concentration were greatest in stable conditions. For class F conditions, average concentration reductions were more than an order of magnitude, while for classes C and D, average reductions in concentration were typically a factor of two to a factor of four.

In his summary of available field data, Egan questions whether "very low diffusion rates" should be expected. This question arises because: 1) nocturnal inversions tend to produce drainage winds that produce mechanical turbulence, 2) topographic-induced flow distortions produce shears that contribute to turbulence and also decrease concentrations through divergence and 3) stable thermal stratification is associated with a number of other flow features that enhance diffusion such as waves and rotors.

The effects of wakes has been discussed in relation to transport. If an obstacle is of the same scale as a plume or larger, the wake of the obstacle may enhance the diffusion as shown in Figures A.14 and A.15. If it is smaller than the plume, it will not affect the diffusion.

Position of the source in relation to the obstacle is an important consideration. The point of release is commonly assumed to be upwind of the obstacle, in which case the preceding discussion is appropriate. If, however, the release takes place immediately downwind of the obstacle, the situation is more complex. The flow at the release point may be counter to the overall flow and highly variable. Another possibility is that the air in the wake may be nearly calm. If a facility is located in the vicinity of topographic features that could affect transport and diffusion, special studies may be required to evaluate those effects for each wind direction.

NUREG/CR-0311
PNL-4491
RH

DISTRIBUTION

No. of
Copies

OFFSITE

205	U.S. Nuclear Regulatory Commission Division of Technical Information and Document Control 7920 Norfolk Avenue Bethesda, MD 20014
20	Barry Zalcmn Emergency Preparedness Development Branch U.S. Nuclear Regulatory Commission Washington, D.C. 20555

ONSITE

50	<u>Pacific Northwest Laboratory</u> A. E. Desrosiers W. A. Glass E. E. Hickey J. L. Kenoyer G. J. Laughlin G. F. Martin J. B. Martin M. A. McLean R. W. Poeton D. C. Powell J. V. Ramsdell R. I. Scherpelz J. M. Selby D. L. Streng G. A. Stoetzel (27) W. V. Thomas C. M. Unruh Technical Information (5) Publishing Coordination (2)
----	---

NRC FORM 335 (7-77)		U.S. NUCLEAR REGULATORY COMMISSION BIBLIOGRAPHIC DATA SHEET		1. REPORT NUMBER (Assigned by DDC) NUREG/CR-3011	
4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Dose Projection Considerations for Emergency Conditions at Nuclear Power Plants				2. (Leave blank)	
7. AUTHOR(S) GA Stoetzel, AE Desrosiers, RW Poeton, JV Ramsdell, DC Powell				3. RECIPIENT'S ACCESSION NO.	
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Pacific Northwest Laboratory P. O. Box 999 Richland, WA 99352				5. DATE REPORT COMPLETED MONTH January YEAR 1983	
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Emergency Preparedness and Engineering Response Office of Inspection and Enforcement U.S. Nuclear Regulatory Commission Washington, D. C. 20555				DATE REPORT ISSUED MONTH May YEAR 1983	
				6. (Leave blank)	
				8. (Leave blank)	
				10. PROJECT/TASK/WORK UNIT NO.	
				11. CONTRACT NO. FIN B2311	
13. TYPE OF REPORT			PERIOD COVERED (Inclusive dates)		
15. SUPPLEMENTARY NOTES				14. (Leave blank)	
16. ABSTRACT (200 words or less) Review of the problems and issues associated with developing capabilities for and making environmental radiation dose projections during emergencies at nuclear power plants. The review is divided into three areas: source term development, characterization of atmospheric dispersion and selection of appropriate dispersion models, and development of dosimetry calculations for determining thyroid dose and whole body dose for ground level and elevated releases. Uncertainties associated with these areas are discussed.					
17. KEY WORDS AND DOCUMENT ANALYSIS Emergency Preparedness Incident Response Radiological Protection Dose Projection			17a DESCRIPTORS		
17b. IDENTIFIERS/OPEN-ENDED TERMS					
18. AVAILABILITY STATEMENT Unlimited			19. SECURITY CLASS (This report) Unclassified		21. NO. OF PAGES
			20. SECURITY CLASS (This page) Unclassified		22. PRICE \$