EXAMINATION OF OFFSITE RADIOLOGICAL EMERGENCY PROTECTIVE MEASURES FOR NUCLEAR REACTOR ACCIDENTS INVOLVING CORE MELT

by

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S.B., Massachusetts Institute of Technology (1974)
S.M., Massachusetts Institute of Technology (1976)

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DAVID C. ALDRICH

Submitted to the Department of Nuclear Engineering on March 3, 1978 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

ABSTRACT

Evacuation, sheltering followed by population relocation, and iodine prophylaxis are evaluated as offsite public protective measures in response to nuclear reactor accidents involving core-melt. Evaluations were conducted using a modified version of the Reactor Safety Study consequence model. Models representing each measure were developed and are discussed. Potential PWR core-melt radioactive material releases are separated into two categories, "Melt-through" and "Atmospheric," based upon the mode of containment failure. Protective measures are examined and compared for each category in terms of projected doses to the whole body and thyroid. Measures for "Atmospheric" accidents are also examined in terms of their influence on the occurrence of public health effects.

For "Melt-through" accidents, few, if any, early public health effects are likely, and doses in excess of Protective Action Guides (PAGs) are "confined" to areas within 10 miles of the reactor. Evacuation appears to provide the largest reduction in whole body dose for this category. However, sheltering, particularly when basements are readily available, may be an acceptable alternative. Both evacuation and iodine prophylaxis can substantially reduce the dose to the thyroid.

For "Atmospheric" accidents, PAGs are likely to be exceeded at very large distances, and significant numbers of early public health effects are possible. However, most early fatalities occur within 10 miles of the reactor. Within 5 miles, evacuation appears to be more effective than sheltering in reducing the number of early health effects. Beyond 5 miles, this distinction is less, or not, apparent. Within 10 miles, early health effects are strongly influenced by the speed and efficiency with which protective measures are implemented. Outside of 10 miles, they are not. The projected total number of thyroid nodules is not substantially reduced unless iodine prophylaxis is administered over very large areas (distances).

The qualitative effects of weather conditions on the above conclusions are also briefly discussed.
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Section 1
Introduction

In the unlikely event of a nuclear reactor accident leading to an atmospheric release of significant quantities of radioactive material, the offsite populace may be subject to substantial radiation exposure. To limit the public risk from these potential accidents, published Federal guidance [1] recommends that state and local governments assume legal authority and responsibility for the formulation and implementation of offsite radiological emergency response plans in areas surrounding nuclear facilities. Public utilities that operate nuclear power reactors are required to include within their corporate emergency plans provisions for participation with local authorities in the response to radiological emergencies [1]. Effective mitigation of radiation exposure of the general public, and therefore the consequences of such exposure, is of prime concern to those responsible for radiological emergency planning and response, and requires the timely implementation of appropriate response actions. The design of appropriate response actions, however, demands some knowledge of the relative merits of measures* available for the protection of the public, the time available and resources required to implement such measures, and

*Protective "measures" and "actions" are used interchangeably in this text.
the distance or area within which they should be employed. In order to provide this information, this study was undertaken to evaluate, in terms of public radiation exposure and health effects, the relative merits of possible offsite emergency phase protective measures. Evaluations of such measures were conducted using the consequence model of the Reactor Safety Study [2], with some revision for the modeling of protective actions. This report describes the methodology used in performing this analysis, and presents the observations and conclusions obtained from the study.

Three emergency phase protective measures have been examined and compared in this study: evacuation, sheltering followed by population relocation, and iodine prophylaxis. Emergency phase protective measures are those actions that might be implemented either before or shortly (within approximately 1 day) after the release of radioactive material. The primary objective of implementing these actions is to limit the public risk from: (1) exposure to external penetrating radiation from the passing cloud of radioactive material (cloud); (2) exposure to external penetrating radiation from radionuclides deposited on the ground and other surfaces during cloud passage (ground); and (3) the radionuclides inhaled during passage of the cloud (inhalation). Evacuation, which is an expeditious movement of the near-site populace to avoid exposure to the passing cloud, is currently given considerable attention as a potential protective measure in
most radiological emergency planning within the United States. However, recent studies [3,4,5] support the view that it is desirable to consider alternative or supplemental strategies to evacuation; for example, population sheltering followed by the selective relocation of affected persons. Available evidence [6] also suggests some potential benefits of iodine prophylaxis, i.e., reduced thyroid dose and subsequent health effects, if it is administered either prior to or shortly after exposure to airborne radioiodines. Actions such as the control of access to the affected area surrounding the reactor, and post emergency phase or recovery measures such as the decontamination of persons and land, or the interdiction of land, crops, milk or water supplies have not been addressed in this study.

Although a considerable body of data exists that relates to the effectiveness of evacuation, sheltering, and iodine prophylaxis as protective measures in specific circumstances, little information is available that is of broad practical use to those responsible for emergency response planning for reactor accidents. A recently reported study [4,5] provided some useful information in the form of estimated dose reduction factors achieved by sheltering and evacuation as a function of a number of timing and other physical parameters. However, that study considered only the release of noble gases and radioiodines from a potential reactor accident rather than a realistic set of accident conditions in which other
radioisotopes (in gas, vapor and particulate form) would be released as well. Also, the methodology used is applicable only to the situation of invariant weather conditions after the release, does not consider the possibility of precipitation, and permits only the prediction of dose reductions rather than offsite consequence reductions.* For these reasons, the results of that study are of limited value as guidance for the formulation of radiological emergency response plans. The mathematical techniques (including variant weather following the release, the possibility of precipitation at any time during or following the release, the calculation of offsite consequences, etc...) and the substantial data base contained in the consequence model of the Reactor Safety Study [2] provide a vehicle for performing a more thorough and meaningful analysis of the relative merits of protective actions for more realistic reactor accident situations.

The Reactor Safety Study [7] concluded that the public risk from nuclear reactor accidents was dominated by core-melt, or "Class 9," accidents. Because of the extremely low probability of these events,** it has generally not been considered appropriate to develop emergency response plans

*The importance of these omissions and assumptions are discussed in subsection 2.4.

**From its detailed evaluation of two reactor power plants, the Reactor Safety Study [7] estimated the probability of a core-melt accident to be approximately 1 in 20,000 (5 x 10^-5) per reactor-year.
specifically for accidents of this type [8]. However, state and local planning authorities are encouraged by federal guidance to develop response plans with breadth and versatility, and to give some consideration to core-melt accidents to determine whether their plans could be readily expanded to cope with them, if one were to occur [8]. Events of less severity than core-melt accidents would have marginal offsite impacts unless very unique and unfavorable weather conditions exist at the time of the release. For these reasons, this study has focused entirely on evaluating the effectiveness of protective measures for core-melt accident releases.

The intent of this study is to provide state and local government emergency preparedness organizations with an improved basis for the planning of protective measures in the environs of light water nuclear power reactors. Advance knowledge of the relative merits of possible protective measures, the distances to which or areas within which they might be required, and the time available to implement them should help to minimize offsite consequences if a serious reactor accident were to occur. However, appropriate protective measures cannot be determined solely on the basis of potential dose or consequence reductions. The specific response planned should be a function of local population locations with respect to available roads, means of communication, etc., and the measures actually implemented would depend on the type of accident, the resources available for the
implementation of the measures, the public risk that their implementation may entail, and other local constraints at the time of the accident such as weather conditions. The information presented in this report when coupled with these latter considerations provides a substantially improved basis for the design of appropriate emergency response actions.

The succeeding sections of this report describe the approach used and the results obtained in this study. Section 2 briefly reviews (1) the nature of the hazards posed by nuclear reactor accidents, (2) the federal guidance presently available for radiological emergency response planning in the United States, and (3) the studies relating to the effectiveness of radiological emergency response actions that have been previously performed. Section 3 describes the methodology used in this study, the categories of reactor accidents established for the study, and the criteria by which the protective measures are compared. Section 4 outlines the assumptions and data employed in modeling the radiological emergency protective measures examined in this study. Section 5 presents the results of this examination, and discusses briefly how these results might change as a function of easily observable weather conditions at the time of the release. Finally, Section 6 summarizes the study and restates its principal conclusions.
Section 2
Nuclear Reactor Accidents and Radiological Emergency Response

2.1 Introduction

This section briefly reviews (1) the nature of the hazards posed by possible nuclear reactor accidents, (2) current federal guidance for radiological emergency response planning in the United States, and (3) previous studies that evaluated the effectiveness of radiological emergency response actions. The intent in this section is to present sufficient material to familiarize the reader with these topics. This material is not, in general, needed for an understanding of the remainder of this report. However, the Reactor Safety Study accident categories presented in Figure 2.1 and the concept of Protective Action Guides (PAGs), discussed in subsection 2.3 are referred to in latter sections.

2.2 Nature of Hazards from Nuclear Reactor Accidents

Potential accidents at nuclear power reactors differ from those at conventional electric power generating stations because of the possibility of a release to the environment of significant quantities of radioactive material [7,9]. The potential range of reactor accidents extends from events of moderate frequency (anticipated operational occurrences), leading to no significant release from the facility, to extremely low probability, high consequence events ("Class 9"
or core-melt accidents). Large inventories of radioactive material are contained in irradiated uranium dioxide fuel located within the reactor core and the spent fuel storage pools of present-day light water reactors (LWRs). This irradiated fuel contains a large number of different fission product isotopes as well as many actinides produced as a result of successive neutron captures and decays in the heavy metal elements initially present within the fuel. Additional, although comparatively minor, sources of radioactive material are produced by neutron activation of reactor coolant and structural materials. The bulk (approximately 98%) of the radioactive material contained in irradiated fuel elements will remain in those elements unless the fuel is severely overheated or melted [7]. Therefore, only reactor accidents in which the fuel is subject to these conditions have the potential to release large quantities of radioactive material to the environment. The emphasis of nuclear power plant safety design is primarily directed at preventing such accidents and mitigating the potential consequences should an accident occur.

Fuel overheating within the reactor core can result from either the loss of reactor coolant within the core (LOCA),* or transient events in which the core heat generation rate becomes larger than the heat removal capability of the reactor cooling system. All commercial nuclear power reactors are

*Loss of coolant accident.
equipped with engineered safety features (ESFs) to reduce the probability of core melting if either a LOCA or transient event were to occur. ESFs are also designed to reduce the amount of radioactive material released to the environment in the event of a reactor accident. The functions that these safety systems perform include reactor shutdown, emergency core cooling, post-accident removal of radioactive material and heat from the containment atmosphere, and the maintenance of containment integrity.

If severe core overheating or melting and loss of containment integrity* were to occur due to the failure of one or more ESFs following a LOCA or transient event, significant quantities of radioactive material could be released to the atmosphere. The release of this material constitutes a potentially serious hazard to man. As the released cloud of radionuclides is carried from the site by the wind, atmospheric diffusion and turbulence effects will continually act to disperse the contaminants at a rate dependent upon the wind speed, thermal stability, and local topography. The processes of radioactive decay and deposition will also act to reduce airborne concentrations. The populace downwind of the reactor site could potentially be subject to radiation exposure from: (1) airborne radionuclides in the passing cloud;

*Containment failure may result from either inadequate isolation of containment openings or penetrations, a reactor vessel steam explosion, hydrogen burning, overpressure, or melt-through of the containment vessel by molten fuel (see subsection 3.3).
(2) radionuclides deposited on the ground and other surfaces as the cloud passes; (3) inhalation of radionuclides in the passing cloud; (4) inhalation of resuspended nuclides and (5) ingestion of contaminated crops, milk, and water. Radiation exposure from radionuclides in the passing cloud is generally termed early exposure and is of relatively short duration (hours). Exposure to radioactive material deposited out of the cloud, termed chronic exposure, is potentially of much longer duration (years) unless direct actions such as evacuation, interdiction, or decontamination are taken. Furthermore, unless rain or some other form of precipitation occurs during or shortly after the release,* the quantity of radioactive material deposited in a given area would generally represent only a small fraction of the material present in the passing cloud. Therefore, the instantaneous dose rate for chronic exposure (but not necessarily the total dose) would be significantly lower than that for early exposure.

Exposure to radioactive material released during a reactor accident may result in public health effects of three types: early and continuing somatic effects, late somatic effects, and genetic effects. Early and continuing somatic effects would occur within days to weeks after the exposure period and include the early illnesses and mortalities that are usually observed after large acute doses

*The occurrence of rain or other precipitation can result in the deposition of a large fraction of the material present in the cloud at a given point.
of radiation. These effects are primarily associated with individual whole body doses of 100 rem or more, and would thus be limited to individuals exposed in the immediate vicinity of the reactor. Late somatic effects include latent cancer fatalities and morbidities and are typically observed between 2 to 30 years after exposure. Genetic effects are observed in the descendants of exposed individuals rather than in the exposed individuals themselves. In contrast to early somatic effects, both latent cancers and genetic effects are random phenomena whose probability of occurrence for a given individual is a function of the dose received by that individual. Consequently, these effects may be observed at long distances from the reactor where a small dose might still be received by large numbers of people. Radiological health effects are discussed in detail in Appendix VI of the Reactor Safety Study [2].

Reactor accidents in which large quantities of radioactive material are released might also result in serious economic consequences. Deposition of radionuclides from the cloud of radioactive material may require the impoundment of contaminated crops, milk and water supplies, the interdiction of land, and the decontamination of land and buildings. Economic costs might also result from the loss of production and earnings in areas affected by the accident and from the implementation of emergency protective measures.

A quantitative assessment of the hazards or public risk associated with the U.S. commercial nuclear power industry
was performed by the Reactor Safety Study [7]. The study identified those potential reactor accident sequences that could lead to the release of significant quantities of radioactive material to the environment. The probability of these accident sequences was determined to be very small, and the study concluded that the hazard or public risk from reactor accidents was dominated by those accidents in which core-melting takes place. The core-related accident sequences identified were grouped into a series of release categories for PWR and BWR reactors based upon characteristics of the postulated release. These categories are presented in Table 2.1 along with their estimated probabilities of occurrence per year of reactor operation, release magnitudes, and other parameters that characterize the release. PWR categories 1 through 7 and BWR categories 1 through 4 represent accident sequences in which core melting occurs. Accidents in PWR 8 and 9 and BWR 5 are less severe and do not involve melting of the core. The time of release is the time interval between the initiation of the hypothetical accident and the release of radioactive material from the containment structure to the atmosphere. The duration of release is the period of time during which radioactive material is emitted to the atmosphere. The warning time for evacuation is the projected time interval between awareness of impending core-melt and the release of radioactive material from the containment building. For those accidents in which core-melting does not occur,
Table 2.1 Summary of Release Categories Representing Hypothetical Nuclear Reactor Accidents (from Ref. 2)

| Release Category | Probability (reactor-yr)
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR 1</td>
<td>$9 \times 10^{-7}$ (a)</td>
</tr>
<tr>
<td>PWR 2</td>
<td>$8 \times 10^{-6}$</td>
</tr>
<tr>
<td>PWR 3</td>
<td>$4 \times 10^{-6}$</td>
</tr>
<tr>
<td>PWR 4</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>PWR 5</td>
<td>$7 \times 10^{-7}$</td>
</tr>
<tr>
<td>PWR 6</td>
<td>$6 \times 10^{-6}$</td>
</tr>
<tr>
<td>PWR 7</td>
<td>$4 \times 10^{-6}$</td>
</tr>
<tr>
<td>PWR 8</td>
<td>$4 \times 10^{-5}$</td>
</tr>
<tr>
<td>PWR 9</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>BWR 1</td>
<td>$1 \times 10^{-6}$</td>
</tr>
<tr>
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<tr>
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<td>BWR 4</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>BWR 5</td>
<td>$1 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time of Release Duration Warning Time Elevation</th>
<th>Energy Release</th>
<th>Ne-Kr</th>
<th>Organic I</th>
<th>(b)</th>
<th>Ca-48</th>
<th>Sr-90</th>
<th>Ba-140</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR 1</td>
<td>2.5</td>
<td>0.5</td>
<td>1.0</td>
<td>25</td>
<td>20 and 520 (e)</td>
<td>0.9</td>
<td>6 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 2</td>
<td>2.5</td>
<td>0.5</td>
<td>1.0</td>
<td>0</td>
<td>170</td>
<td>0.9</td>
<td>7 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 3</td>
<td>5.0</td>
<td>1.5</td>
<td>2.0</td>
<td>0</td>
<td>6</td>
<td>0.8</td>
<td>6 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 4</td>
<td>2.0</td>
<td>3.0</td>
<td>2.0</td>
<td>0</td>
<td>1</td>
<td>0.6</td>
<td>2 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 5</td>
<td>2.0</td>
<td>4.0</td>
<td>1.0</td>
<td>0</td>
<td>0.3</td>
<td>0.3</td>
<td>2 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 6</td>
<td>12.0</td>
<td>10.0</td>
<td>1.0</td>
<td>0</td>
<td>N/A</td>
<td>0.3</td>
<td>2 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 7</td>
<td>2.0</td>
<td>10.0</td>
<td>1.0</td>
<td>0</td>
<td>N/A</td>
<td>6 x 10^{-3}</td>
<td>2 x 10^{-3}</td>
</tr>
<tr>
<td>PWR 8</td>
<td>0.5</td>
<td>0.5</td>
<td>N/A(f)</td>
<td>0</td>
<td>N/A</td>
<td>2 x 10^{-3}</td>
<td>5 x 10^{-6}</td>
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<td>PWR 9</td>
<td>0.4</td>
<td>0.4</td>
<td>N/A</td>
<td>0</td>
<td>N/A</td>
<td>3 x 10^{-6}</td>
<td>2 x 10^{-9}</td>
</tr>
</tbody>
</table>

(a) Background on the isotope groups and release mechanisms is presented in Appendix VII.
(b) Organic iodine is combined with elemental iodines in the calculations. Any error is negligible since its release fraction is relatively small for all large release categories.
(c) Includes Ru, Rh, Co, Mo, Tc.
(d) Includes Y, La, Sr, Mo, Ca, Fr, Hg, Np, Pu, Am, Cm.
(e) Accident sequences within PWR 1 category have two distinct energy releases that affect consequences. PWR 1 category is subdivided into PWR 1A with a probability of $4 \times 10^{-7}$ per reactor-year and 20 x 10$^6$ Btu/hr and PWR 1B with a probability of $5 \times 10^{-7}$ per reactor-year and 520 x 10$^6$ Btu/hr.
(f) Not applicable.
(g) A 10 meter elevation is used in place of zero representing the mid-point of a potential containment break. Any impact on the results would be slight and conservative.
there is no projected warning time. Finally, the height of release and the energy content of the released plume strongly influence the height to which the plume rises and thus the exposure to persons near the site.

2.3 Current Federal Guidance for Radiological Emergency Response Planning

The legal authority and responsibility of state and local governments for offsite radiological emergency response is recognized in Appendix E to 10 CFR Part 50 [1]. Although neither the Nuclear Regulatory Commission (NRC) nor any other federal agency has statutory authority over state and local organizations with respect to the development of radiological emergency preparedness programs, an inter-agency program was established to provide response planning guidance and related training to state and local government authorities [10]. Participating federal agencies include the NRC, which exercises the lead role in this activity, and the U.S. Environmental Protection Agency (EPA) which assumes responsibility for establishing Protective Action Guides (PAGs) and recommending appropriate protective actions that can be taken by governmental authorities. A number of guidance documents have been published by these and other agencies for use by state and local authorities [11,12,13,14].

Protective Action Guides (PAGs) for whole body and thyroid exposure to accidental airborne releases have been promulgated by the EPA [12]. PAGs were established as
guidance to limit public radiation exposure in the event of an airborne release to levels such that no detectable early biological effects would be produced in the most sensitive population group (pregnant women, children) and to reduce the risk of longterm health effects from this exposure. A PAG is defined as the projected dose* to an individual in the general public which warrants the initiation of emergency protective actions, and, as such, is a trigger value to aid in decisions to implement these actions.** PAGs range from 1 to 5 rem for whole body exposure and from 5 to 25 rem for projected dose to the thyroid. For each organ, the lower value of the range should be used if there are no major local constraints to providing protection at that level, particularly for sensitive populations. However, if local constraints make the lower values impractical to follow, in no case should the higher value be exceeded in determining the need for protective action. The determination of what emergency protective measures should be implemented in any given accident situation must be based on the actual conditions that exist and/or that are projected at the time of the accident.

*The projected dose is the dose that would be received by the individual within a few days following the release if no protective actions are taken [12].

**Note that a PAG does not imply an acceptable level of risk. It is used only in an effort to minimize the risk from an event which is occurring or has already occurred. A PAG should not be used as a reason for stopping actions underway which, if carried to completion, could result in significant reductions in dose to the general public [12].
Present federal guidance [8,11,12,13,14] recommends that a range of reactor accidents with a broad spectrum of release characteristics (compositions, magnitudes and timings) be used as a basis for developing emergency response plans. However, there has been a great deal of confusion as to what accidents this range should include. A resolution was passed at the 1976 annual meeting of the Conference of (State) Radiation Control Program Directors requesting the federal government to clarify their recommendation [8]. In response to this resolution, the NRC and EPA formed a special Task Force on Emergency Planning with the goal of providing a clearer definition of the types of radiological accidents for which state and local governments should develop emergency plans and preparedness programs. The recommendations of the Task Force, which present planning basis guidance in terms of the size of the planning area (distance) and time and radiological characteristics of releases for which offsite organizations should be prepared, have recently been released in a draft report* [8]. After considering a number of issues related to the types of potential accidents (including "Class 9" or core-melt accidents), the report suggests that two uniform Protective Action Zones (PAZs) about each nuclear facility be adopted for the purpose of emergency planning: one for

*The report is supplemental to the emergency planning guidance already published by the NRC and EPA.
the short-term "plume exposure pathway"* and one for the "ingestion exposure pathway." For the plume exposure pathway, the Task Force recommends a single PAZ approximately 10 miles in radius within which evacuation or sheltering may be appropriate protective measures. For the ingestion exposure pathway, the Task Force recommends a PAZ approximately 50 miles in radius. These recommendations are for planning purposes only and do not imply that actions would have to be taken throughout the PAZ or that actions should either be extended to or limited to PAZ boundaries during an actual emergency situation.

2.4 Previous Studies of Radiological Emergency Protective Measures

A considerable body of data exists which describes the effectiveness of evacuation, sheltering, and iodine prophylaxis in specific circumstances. This data is employed to a large extent in the modeling of the protective measures in this study. However, very little information is available that is of immediate practical value to those responsible for developing and implementing radiological emergency response programs.

An analysis was recently performed by Anno and Dore [4] to estimate the effectiveness of sheltering following a release of gaseous fission products from a nuclear power plant.

*Plume exposure pathway includes exposure due to (1) the passing cloud, (2) ground deposited radionuclides within a few days of the release and (3) inhalation of radionuclides from the passing cloud.
reactor. Their work focused broadly on what were deemed to be the essential general characteristics and parameters of structures available to the public for sheltering. Sheltering effectiveness was presented in terms of dose reduction factors (DRFs) which are the ratio of the dose received while sheltered to the dose that would be received outdoors. DRF estimates for both whole body and thyroid doses were presented as a function of source release characteristics, assumed structure parameters, and various timing scenarios. The composition and relative proportions of radionuclides (krypton, xenon, and iodine) in the release were defined assuming a design basis accident (DBA). Shelter characteristics considered included structural shielding against radiation as a function of building size, gaseous fission product ingress, and shelter air turnover or ventilation rate. Temporal parameters investigated included source release time and time spent in the shelter structure. The sensitivity of sheltering effectiveness to these parameters was discussed.

A further analysis by Anno and Dore [5] compared the effectiveness of evacuation and sheltering in terms of respective DRF values, using a common time frame for the variation of timing parameters. Estimates of sheltering were based on their previous work. Evacuation effectiveness estimates were based on a simple model that considered the possible exposure time increments over a time frame determined by the source release and cloud exposure duration, the
estimated time of cloud arrival, and information and proce-
dural delay times before evacuation. A transit period was
included during which shielding by an appropriate vehicle
(automobile or bus) was assumed. The advantages of employing
combinations of emergency protective measures were also dis-
cussed.

For several reasons, the analysis performed by Anno
and Dore [4,5] is of limited practical use as guidance for
the formulation of emergency response plans. These limita-
tions are either a result of the simplistic methodology used
in the work or the limited range of situations considered.
Their study considers only the release of noble gases and
radioiodines from a single class of potential reactor acci-
dents rather than from a realistic set of accidents in which
other radioisotopes (in gas, vapor, and particulate form)
would be released as well. The atmospheric behavior (deposi-
tion) of these additional radionuclides are in general not
similar to those addressed by Anno and Dore and may alter
the relative effectiveness of the measures investigated. The
methodology used in their work is strictly applicable only
to the situation of invariant meteorology* after the release
and did not address the possibility of precipitation. Preci-
pitation is important because of its efficiency in removing
particulate and some gaseous materials from the air, and
could drastically alter the relative fraction of dose received
from a particular exposure mode (inhalation, cloud, ground)
and, therefore, the efficacy of a particular protective action. Finally, the results of the Anno and Dore work are exhibited only as potential dose reductions (DRFs) to the whole body and thyroid, with no consideration given to the potential consequences that are to be avoided or reduced. For accidents in which very large quantities of radioactive material are released, emergency response actions might be directed specifically towards limiting the occurrence of illnesses and fatalities, and an evaluation of the relative effectiveness of response measures in terms of these consequences is desirable.

*Weather conditions generally change over a period of several hours. It has been demonstrated that the use of invariant meteorology following a release results in significantly different dose and consequence predictions than does the use of time varying weather data [3].
Section 3
Approach, Assumptions and Methodology

3.1 General Approach

The effectiveness of emergency protective measures are examined and compared, in terms of offsite radiation exposures and subsequent public health effects, using the consequence model of the Reactor Safety Study [2]. A brief outline and description of the model as developed in the Reactor Safety Study is presented in subsection 3.2 of this report. For use in this study, the original model was revised slightly to reflect the different protective measures examined. Justification for and a description of these revisions are included in Section 4 on the modeling of radiological emergency protective measures.

For reasons outlined in the introduction to this report, the effectiveness of response actions are evaluated for core-melt accident releases only. The range of core-melt releases is separated into two "response" categories for PWR accidents, PWR "Melt-Through" and "Atmospheric," and protective measures are examined in terms of these groupings. The categorization is based on the predicted containment failure mode and is described in subsection 3.3 of this report. The criteria by which protective measures are examined and compared are discussed in subsection 3.4. To reduce the required time and cost of computation, BWR accidents are not dealt with.
specifically in this analysis. However, the information and conclusions presented for PWRs would be qualitatively applicable for BWRs as well, given a similar mode of containment failure.

Several simplifications are made in this study to facilitate the analysis and to allow the presentation of results and conclusions in a concise and easily interpretable manner. The information presented does not correspond to any particular reactor site. Nevertheless, whenever possible, data is provided to allow emergency planning authorities to adapt this information to their specific site or local. A uniform population density of 100 persons per square mile is assumed in all calculations of public health effects. The impacts of real, or site-specific, population distributions on conclusions drawn from these calculations are discussed in Section 5. Projected radiation exposures for downwind individuals are independent of population distribution. Additionally, all calculations performed in this study utilize meteorological data taken from a single reactor site. Site-to-site variations in meteorological histories in the United States have been shown to have little effect on the distribution for the expected number of public health effects when a large number of weather sequences are used [3], and this simplification should not be significant.
3.2 Consequence Model of the Reactor Safety Study

The consequence model of the Reactor Safety Study describes the progression of the cloud of radioactive material released from the containment structure during and following a reactor accident, and predicts its interaction with and influence on man [2,3,15]. A schematic outline of the calculational steps taken in the model is presented in Figure 3.1. The engineering analyses performed in the Reactor Safety Study provide an estimate of accident probabilities and release magnitudes that are used as input to the consequence model. Given these estimates, a standard Gaussian dispersion model is used to calculate ground level airborne concentrations of radioactive material downwind of the reactor site. Weather data are input to the dispersion model in the form of hourly recordings of wind speed, thermal stability, and precipitation occurrence for a one-year period at seven selected reactor sites.* The wind direction, however, is assumed to be invariant during and following the release. Radionuclide concentrations within the cloud are depleted by deposition (both wet and dry) and radioactive decay, and ground contamination is calculated for downwind distances.

Hourly weather recordings were used to account for weather variations during the progression of the accident.**

*The seven reactor sites were chosen to be representative of all reactor sites with respect to the variability of climatic and topographic features.

**The use of invariant meteorology during the accident progression results in significantly different consequence predictions than when using time varying weather data, and was found to be inadequate for risk calculations [3].
Figure 3.1 Schematic Outline of Reactor Safety Study Consequence Model (from Ref. 15).
Beginning at a selected hour within the year's data, the dispersion model uses the subsequent sequential meteorological conditions to predict the dispersion and transport of the released cloud of radioactive material. Hourly recordings are incorporated to describe the changing pattern of dispersion until all of the released radioactive material (excluding the noble gases) has been deposited. By using a stratified sampling technique* on the year's data, a frequency distribution of estimated consequences may be produced.

The consequence model uses the calculated airborne and ground radionuclide concentrations to estimate the public's exposure to external penetrating radiation from (1) airborne radionuclides in the cloud and (2) radionuclides deposited out of the cloud, and internal radiation from (1) radionuclides inhaled directly from the passing cloud, (2) inhaled resuspended radionuclides, and (3) the ingestion of contaminated food and milk. Radiation exposure from sources external to the body is calculated for time periods over which individuals are exposed to those sources, while the exposure from sources internal to the body is calculated over the remaining life of the exposed individual.

*In order to ensure complete coverage of diurnal, seasonal, and four-day weather cycles, starting times are selected every four days with a thirteen hour shift. In this manner, each hour of the day is represented in 24 samples, and a total of ninety-one samples are obtained from one year's data.
The Reactor Safety Study consequence model allows the input of either site specific or assumed population data as a function of distance from the reactor site. A simple evacuation model was incorporated, based on a statistical analysis of evacuation data assembled by the U.S. Environmental Protection Agency [16]. All individuals within 25 miles of the reactor were assumed to evacuate radially outward from the site immediately upon warning with an effective speed of either 0, 1.2, or 7 miles per hour. This current study incorporates a revised treatment of public evacuation as well as models representing sheltering, relocation and iodine prophylaxis. These models are described in Section 4 of this report.

Based on the calculated radiation exposure to downwind individuals, the consequence model estimates the number of public health effects that would result from the accidental release. Early and continuing morbidities and fatalities, late somatic fatalities, and thyroid and genetic effects may be computed. Early and continuing fatalities are estimated on the basis of exposure to the bone marrow, lung and gastrointestinal tract, and are observed within one year of the exposure period. Bone marrow damage is the dominant contributor to this effect. In both the Reactor Safety Study and this study, early fatalities are calculated based on an LD$_{50/60}$* of 510 rads to the bone marrow, which

*The dose that would be lethal to 50 percent of the population within 60 days.
presumes supportive medical treatment of the exposed individual [2]. Early morbidities (injuries) are defined as those illnesses requiring medical attention or hospital treatment, and are observed primarily as incidences of respiratory impairment. Thyroid effects that may be computed include the occurrence of benign and malignant thyroid nodules.

The consequence model also incorporates an economic model to estimate the potential extent of property damage associated with the release of radioactive material. The total dollar cost of the accident is estimated as the sum of (1) the evacuation cost, (2) the value of condemned crops and milk, (3) the cost of decontaminating land and structures, (4) the cost of interdicting land and structures, and (5) the loss of income during the period of relocation and temporary unemployment.

3.3 Emergency Response Categories for Core-Melt Accidents

Potential core-melt accidents, depending on the particular accident sequence, may result in a wide range of radioactive material releases of varying release magnitudes, compositions and timings over which the relative merits of emergency response actions may vary substantially. Therefore, for the planning of these response actions, some estimate is required of what information about a projected release will be available to responsible authorities for decision making.
at the time of the emergency. The Reactor Safety Study [7] grouped the spectrum of potential core-melt accidents into seven release categories for the PWR and four for the BWR. Estimates of probability per reactor-year, release magnitudes, timing values and other parameters that characterize these release categories were presented in Table 2.1. Because of the lack of complete understanding of the physical processes associated with core-melting and the resulting release of radioactive material to the environment, there is a large degree of uncertainty and overlap in these groupings. It is therefore unlikely that a particular accident progression could be easily categorized at the time of the accident as a PWR 4, for instance, as opposed to a PWR 3 or 5. Nevertheless, there are several potential sources of information which could quickly provide some indication of the severity of a release shortly before or after it has occurred. These sources include in-plant monitoring devices for temperature, pressure and radioactivity, engineered safeguard instrumentation, and site (outside containment) radiation surveys and fixed monitoring devices. Therefore, for the purpose of this study, it has been assumed that there would be sufficient information readily available during the accident progression to classify the accident into one of two "response" categories for emergency response purposes.

Because containment failure mode is an important and observable mechanistic factor in determining consequences,
it was chosen as the criterion by which accidents were grouped into the two "response" categories. Tables 3.1 and 3.3 list the dominant accident sequences for each of the PWR and BWR core-melt release categories defined in the Reactor Safety Study. The accident sequence symbols found in these tables are defined in Tables 3.2 and 3.4. PWR 6 and 7 are clearly dominated by accident sequences involving containment failure by containment vessel melt-through. PWR 1-5, on the other hand, consist of accidents in which containment failure occurs directly to the atmosphere as a result of either inadequate isolation of containment openings or penetrations, a reactor vessel steam explosion, hydrogen burning or overpressure. Therefore, in this study, PWR core-melt accidents are categorized as either a PWR "Melt-through" release (PWR 6 and 7) or a PWR "Atmospheric" release (PWR 1-5). These two categories are comprised of the Reactor Safety Study release categories from which they are defined, each weighted by its respective probability as calculated in the Reactor Safety Study. Summing the appropriate probabilities as listed in Table 2.1 suggests probabilities of $4.6 \times 10^{-5}$ per reactor-year for the PWR "Melt-through" category and $1.4 \times 10^{-5}$ per reactor-year for the PWR "Atmospheric" category. Although a large degree of uncertainty is associated with these numbers, they do indicate that the likelihoods of the two "response" categories defined here are roughly comparable. Therefore, if core-melt accidents
Table 3.1 Dominant Accident Sequences versus PWR Core-Melt Release Categories (from Ref. 7, Appendix V)

<table>
<thead>
<tr>
<th>RELEASE CATEGORIES</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>AR-9 1.10-10</td>
<td>AR-9 1.10-9</td>
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<tr>
<td>A Probabilities</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V Probabilities</td>
<td>6x10-7</td>
<td>6x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
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<tr>
<td>TRANSIENT EVENT - T</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T Probabilities</td>
<td>3x10-7</td>
<td>3x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
<td>4x10-6</td>
</tr>
</tbody>
</table>

(1) SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORY

| MEDIAN (50% VALUE) | 4x10-7 | 6x10-6 | 4x10-6 | 6x10-6 | 6x10-6 | 6x10-6 | 4x10-6 |
| LOWER BOUND (25% VALUE) | 4x10-6 | 6x10-7 | 6x10-7 | 6x10-7 | 6x10-6 | 6x10-6 | 4x10-6 |
| UPPER BOUND (75% VALUE) | 4x10-6 | 6x10-5 | 4x10-5 | 6x10-5 | 6x10-5 | 6x10-5 | 6x10-5 |

41
TABLE 3.2 Key to PWR Accident Sequence Symbols

A - Intermediate to large LOCA.

B - Failure of electric power to ESFs.

B' - Failure to recover either onsite or offsite electric power within about 1 to 3 hours following an initiating transient which is a loss of offsite AC power.

C - Failure of the containment spray injection system.

D - Failure of the emergency core cooling injection system.

F - Failure of the containment spray recirculation system.

G - Failure of the containment heat removal system.

H - Failure of the emergency core cooling recirculation system.

K - Failure of the reactor protection system.

L - Failure of the secondary system steam relief valves and the auxiliary feedwater system.

M - Failure of the secondary system steam relief valves and the power conversion system.

Q - Failure of the primary system safety relief valves to reclose after opening.

R - Massive rupture of the reactor vessel.

S_1 - A small LOCA with an equivalent diameter of about 2-6 inches.

S_2 - A small LOCA with an equivalent diameter of about 1/2 to 2 inches.

T - Transient event.

V - LPIS check valve failure.

α - Containment rupture due to a reactor vessel steam explosion.

β - Containment failure resulting from inadequate isolation of containment openings and penetrations.

γ - Containment failure due to hydrogen burning.

δ - Containment failure due to overpressure.

ε - Containment vessel melt-through.
Table 3.3 Dominant Accident Sequences versus BWR Core-Melt Release Categories (from Ref. 7, Appendix V)

<table>
<thead>
<tr>
<th>RELEASE CATEGORIES</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
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</thead>
<tbody>
<tr>
<td>LARGE LOCA DOMINANT ACCIDENT SEQUENCES (A)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A Probabilities</td>
<td>$8 \times 10^{-8}$</td>
<td>$6 \times 10^{-8}$</td>
<td>$2 \times 10^{-7}$</td>
<td>$2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$S_2$ Probabilities</td>
<td>$1 \times 10^{-8}$</td>
<td>$9 \times 10^{-9}$</td>
<td>$2 \times 10^{-7}$</td>
<td>$2 \times 10^{-8}$</td>
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<td>TRANSIENT DOMINANT ACCIDENT SEQUENCES (T)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>T Probabilities</td>
<td>$1 \times 10^{-6}$</td>
<td>$6 \times 10^{-6}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>PRESSURE VESSEL RUPTURE ACCIDENTS (R)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>R Probabilities</td>
<td>$2 \times 10^{-9}$</td>
<td>$2 \times 10^{-8}$</td>
<td>$1 \times 10^{-7}$</td>
<td>$1 \times 10^{-8}$</td>
</tr>
<tr>
<td>SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORIES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MEDIAN (50% VALUE)</td>
<td>$1 \times 10^{-6}$</td>
<td>$6 \times 10^{-6}$</td>
<td>$2 \times 10^{-5}$</td>
<td>$2 \times 10^{-6}$</td>
</tr>
<tr>
<td>LOWER BOUND (34 VALUE)</td>
<td>$1 \times 10^{-7}$</td>
<td>$2 \times 10^{-6}$</td>
<td>$5 \times 10^{-6}$</td>
<td>$5 \times 10^{-7}$</td>
</tr>
<tr>
<td>UPPER BOUND (95% VALUE)</td>
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<td>$3 \times 10^{-5}$</td>
<td>$8 \times 10^{-5}$</td>
<td>$1 \times 10^{-5}$</td>
</tr>
</tbody>
</table>
Table 3.4 Key to BWR Accident Sequence Symbols

A - Rupture of reactor coolant boundary with an equivalent
diameter of greater than six inches.

C - Failure of the reactor protection system.

E - Failure of emergency core cooling injection.

G - Failure of containment isolation to limit leakage to less
than 100 volume percent per day.

H - Failure of core spray recirculation system.

I - Failure of low pressure recirculation system.

J - Failure of high pressure service water system.

Q - Failure of normal feedwater system to provide core
make-up water.

R - Reactor vessel rupture event.

S₁- Small pipe break with an equivalent diameter of about
2-6 inches.

S₂- Small pipe break with an equivalent diameter of about
1/2 - 2 inches.

T - Transient event.

U - Failure of HPCI or RCIC to provide core make-up water.

V - Failure of low pressure ECCS to provide core make-up water.

W - Failure to remove residual core heat.

α - Containment failure due to steam explosion in vessel.

β - Containment failure due to steam explosion in containment.

γ - Containment failure due to overpressure - release through
reactor building.

γ' - Containment failure due to overpressure - release
direct to atmosphere.

δ - Containment isolation failure in drywell.

ε - Containment isolation failure in wetwell.
are to be addressed in planning for emergency response, there is no a priori reason to disregard either category based on probabilistic grounds. Because release characteristics are greatly influenced by the containment failure mode, radioactive material releases from accidents within either of these two response categories will in general have similar features. As indicated in Table 2.1, PWR 6 and 7, comprising the "Melt-through" category, have a relatively long time after the initiation of the accident before the release occurs (10-12 hours), long "continuous" release durations (10 hours), and relatively small fractions of core radioisotope inventories released. In contrast, PWR 1-5, comprising the "Atmospheric" category, have short times after the initiation of the accident before the release occurs (2-5 hours), short "puff" release durations (0.5-4 hours), and larger release fractions of core radioisotopes inventories.

Although this study has not dealt specifically with BWR reactor accidents in the evaluation of emergency protective measures, a categorization based on containment failure mode similar to that described above for the PWR is possible for BWR core-melt accident progressions. For the specific BWR design investigated in the Reactor Safety Study, the probability of containment failure by containment vessel melt-through is essentially zero, i.e., the containment will always fail directly to the atmosphere. As indicated by Table 3.3, BWR 4 is dominated by accident sequences involving containment
isolation failure in either the drywell or wetwell, whereas BWR 1-3 are dominated by accidents in which the containment fails from either a steam explosion in the reactor vessel or containment, or from overpressure resulting in release through the reactor building or directly to the atmosphere. Containment failure by containment vessel melt-through may be more probable for other BWR designs, depending on the particular containment structure employed.

3.4 Criteria for Examination and Comparison of Protective Measures

Protective measures are examined in this study in terms of the early radiation exposure received by the public and, where appropriate, the subsequent public health effects as well. Because PAGs have been established for the whole body and thyroid (see subsection 2.2), projected doses to these organs in particular have been used in this analysis. Whole body and thyroid doses are presented for PWR "Melt-through" and "Atmospheric" releases as a function of distance from the reactor and the protective measures implemented.

Relatively small fractions of core radioisotope inventories would be released to the atmosphere by accidents in the "Melt-through" category, and the resulting doses downwind of the reactor are estimated to be generally quite low. For this type of release, the expected number of public health effects is therefore low, if not zero, and the efficacy of protective measures are evaluated only in terms
of projected dose levels. In contrast, PWR "Atmospheric" accidents may result in the release of very large fractions of core radioisotope inventories to the atmosphere, extremely high doses to individuals downwind of the reactor, and significant numbers of public health effects of all types. Protective measures for this type of release are therefore evaluated both in terms of resulting health effects and projected doses. Evacuation and sheltering are compared in terms of projected early fatalities and injuries. Iodine prophylaxis, which acts specifically to reduce the dose to the thyroid, is examined in terms of the occurrence of thyroid nodules. Late somatic fatalities and genetic effects have not been addressed in this study.*

*These effects would be due in large part to chronic exposure and would, in most cases, occur predominantly at very large distances from the reactor. They therefore would generally be little affected by emergency phase protective actions taken in areas near the reactor.
Section 4

Modeling of Radiological Emergency Protective Measures

4.1 Introduction

To evaluate and compare the merits of evacuation, sheltering and iodine prophylaxis as potential radiological emergency protective measures, mathematical representations of each measure were developed for use in the consequence model of the Reactor Safety Study. The representations for evacuation and sheltering are based on work documented in three technical reports [17,18,19] which were written as part of this study and are included as appendices to this report. A brief discussion of the nature of the protective measures investigated and a description of the models used to represent them are presented here. The relative risks, difficulties and costs associated with the measures are discussed in the literature [6,12,16].

4.2 Sheltering and Population Relocation

For the purpose of this study, sheltering is defined as the deliberate action by the public to take advantage of the protection against radiation exposure afforded by remaining indoors, away from doors and windows, during and after the passage of the cloud of radioactive material. The shielding inherent in normally inhabited structures offers some degree of protection against external penetrating radiation from
airborne and surface deposited radionuclides. Furthermore, the exclusion of a significant amount of airborne radioactive material from the interior of a structure, either by natural effects or by certain ventilation strategies, can reduce the amount of inhaled radionuclides as well. Population relocation* is a post-accident measure designed to limit radiation exposure from radionuclides deposited on the ground and other surfaces. In many instances, exposure from this source would, in a relatively short time, result in a dose much greater than the dose from the other exposure pathways.

The potential of sheltering and relocation strategies for limiting dose from exposure to radiation from airborne and surface deposited radionuclides is discussed in Appendix A. Estimates made by Burson and Profio [20] of shelter effectiveness for specific building types are presented. The estimates indicated (1) the wide range of potential shielding factors** afforded by normally inhabited structures, and (2) that basements of both homes and larger buildings offer very effective shielding against external

*Relocation is essentially a post-accident evacuation of persons in affected areas. Because it is a post-accident response, it can be implemented in a more selective manner than an immediate evacuation.

**The shielding provided by a structure against external penetrating radiation from airborne or surface deposited radionuclides is expressed 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.
penetrating radiation from ground contamination. Therefore, the efficacy of a sheltering strategy would depend to a large extent on the type of structures the public inhabits and the degree to which basements are available and utilized. Three generic sheltering/relocation strategies are identified and discussed, and representative shielding factors for use in modeling each of these strategies are recommended. The three generic strategies are (1) population relocation only (no specific sheltering response initiated), (2) sheltering at location followed by relocation, and (3) preferential sheltering followed by relocation. If no specific sheltering response is implemented (strategy (1) above), persons are assumed to continue their normal activities until they are relocated at some post-accident time. Because a large fraction of the public is located indoors most of the time anyway, some degree of radiation shielding will be afforded the public as a whole by this strategy.* Additional protection could be achieved by implementing a strategy of sheltering at location (strategy (2) above). In this strategy, persons are directed to remain indoors at their present location, or to move indoors if they are outside, preferably occupying basements if

*This protection was recognized in the Reactor Safety Study [2] and was used there to calculate health effects for populations located at distances greater than that assumed for evacuation. Note, however, that this protection applies to the public only in an average sense; by virtue of their normal activities some persons will be outdoors during the radiation exposure incident and will receive little if any benefit from structural shielding.
they are available. Even further benefit might be derived from employing preferential sheltering locations (strategy (3) above); for example, directing people to those neighboring homes with basements or to nearby large buildings such as schools, public office buildings or public fallout shelters.

Representative shielding factors for each of the foregoing strategies are also suggested in Appendix A. The shielding factors estimated by Burson and Profio [20] may be used to evaluate preferential sheltering in specific building types. Average* shielding factors of 0.75 for exposure to airborne radionuclides (cloud) and 0.33 for exposure to ground contamination (ground) are recommended for the strategy in which no specific sheltering response is employed (i.e., the public continues its normal activities). The range of protection offered by the strategy of sheltering at location is represented by two sets of average "cloud" and "ground" shielding factors; (0.5, 0.08) and (0.75, 0.33). The range reflects regional differences in the frequency of brick and wood homes and of homes with basements, as well as temporal differences in building occupancy. The lower end of the

*Average shielding factors were established by permuting the Burson and Profio estimates and regional data on the mix of structures inhabited by the public. Note that the use of average shielding factors for the assessment of radiological consequences results in the assignment of average doses to all individuals within a given area rather than the distribution of doses that would actually occur due to the variation in shielding protection afforded individuals. The adequacy of this simplification is discussed in Appendix A.
shielding factor range,* (0.5, 0.08), corresponds to regions such as the Northeast where a large fraction of homes have basements. Shielding factors at the upper end of the range, (0.75, 0.33), correspond to areas such as the Southwest or Pacific Coast where most homes do not have basements.**

Average shielding factor sets for other geographic regions and for several assumed building occupancy distributions are also provided in Appendix A.

To estimate the potential effectiveness of sheltering in reducing the amount of radionuclides inhaled, a multi-compartment ventilation model was developed for the calculation of airborne radioactive material concentrations internal to structures. This model is described in Appendix B along with the sensitivity of the model to parameters and protection strategies. Using "best estimate" values for the parameters, the model indicates that sheltered individuals will inhale roughly 35 percent less radionuclides than if they were outside during the passage of the cloud. Larger reductions are possible if the ventilation rate (air turnover rate) is reduced either by tighter building construction or by the sealing of openings in the structure. Further analysis indicated that the strategy of opening doors and windows, turning on ventilating systems, etc., in an attempt to

*The lower the SF, the greater the protection.

**These shielding factors, (0.75, 0.33), were chosen to be the same as the values for "normal activity" discussed earlier [17].
"air-out" the structure after the cloud of radioactive material has passed will most likely not contribute significantly to reducing the amount of inhaled radionuclides unless very low ventilation rates during cloud passage are achieved.

In the model of sheltering and population relocation used in this study, shelter-access by the public is assumed to be completed prior to the arrival of the cloud of radioactive material,* and persons are assumed to remain sheltered until relocated. During an actual accident situation, sheltered individuals in affected areas would be exposed to ground contamination while sheltered (with shielding provided by the structure) and while being relocated (with less, if any, shielding depending on the transport mode). However, throughout this analysis, exposure to ground and surface deposited radionuclides (ground contamination) is presented in terms of effective exposure times assumed to occur only while sheltered,** i.e., people are assumed to receive no specific exposure while relocating. Effective exposure

*If this cannot be accomplished, the effectiveness (dose reduction) diminishes almost linearly with increasing outside exposure time [4].

**For example, an effective exposure time of 6 hours while sheltered (with SF for ground contamination = 0.2) might, in fact, be due to 4 hours of exposure while sheltered (with SF = 0.2) and 1/2 hour exposure while relocating (with SF = 0.8).
periods of 6, *12, and 24 hours to ground contamination are assumed. Results for other exposure times are easily constructed from the results provided. Individuals located outdoors** are assigned shielding factors of 1.0 (cloud) and 0.7 (ground) (see Appendix A) and 1 day of effective exposure to ground contamination. Persons outside sheltered or evacuated areas are assumed to continue their normal activities and are assigned averaged shielding factors of 0.75 (cloud) and 0.33 (ground). The effective exposure period to ground contamination for these individuals is also limited to 1-day. Shielding factors for sheltered individuals are assumed to be either (0.5, 0.08)*** or (0.75, 0.33),**** covering the range of average shielding factors discussed above. Throughout this study, the breathing rate assumed is 2.66 x 10^{-4} m^3/s,***** regardless of the protective measures implemented,

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*Because some exposure would be received while relocating (with little shielding), and it would take some time to determine affected areas and initiate a relocation, 6 hours was chosen as a practical lower limit for effective exposure time.

**If no specific sheltering response is initiated, the largest doses will be received by individuals located outdoors. The doses calculated for these individuals therefore represent "worst case" conditions.

***(Cloud, ground). Lower end of average SF range corresponding to areas with large fractions of homes with basements.

****(Cloud, ground). Upper end of average SF range corresponding to areas with few basements.

*****The average breathing rate for standard man averaged over 24 hours [21].
and individuals either located indoors or sheltered are assumed to inhale 35 percent less radionuclides than if they were outside during the passage of the cloud [18]. Results for situations in which other shielding factors or inhalation dose reductions apply are easily constructed from information presented in Section 5.

4.3 Evacuation

As indicated in Table 2.1, there would be one to several hours' warning of a significant release of radioactive material, and, depending on the windspeed following the release, several more hours might pass before the radioactive cloud reached a particular population group. Because of this available time, evacuation is given considerable attention as a public protective measure in most current radiological emergency preparedness programs in the United States. It is potentially the most effective method of avoiding radiation exposure, and can provide essentially total protection if completed prior to arrival of the cloud.*

The modeling of public evacuation as a protective measure for reactor accidents is discussed in Appendix C to this report. A simple evacuation model, based on a statistical analysis of evacuation data gathered by the EPA [16], was included in the consequence model of the

*The risk of death or injury due to evacuation by private automobile in response to disaster or accident situations has been shown to be small [16].
Reactor Safety Study [2] for use in the calculation of public risks from reactor accidents. However, for reasons which are discussed in the appendix, that model is inadequate for use in evaluating evacuation as a radiological emergency response. Therefore, a revised model of public evacuation was developed for this purpose. The revised treatment incorporates a delay time before public movement, followed by evacuation radially away from the reactor at a higher constant speed than previously assumed in the Reactor Safety Study evacuation model. Both the delay time and evacuation speed are required as input to the model, and different shielding factors are allowed while persons are stationary and in transit. All persons within the designated evacuation area are assumed to move as a group with the same delay time and speed, and no consideration is given to the possibility of a nonparticipating segment of the population. This latter assumption results in upper bound estimates of evacuation effectiveness, given a specific delay time and speed.* As detailed in the appendix, the revised model also calculates more realistic exposure durations to airborne and ground deposited radionuclides than the evacuation model used in the Reactor Safety Study.

As explained in Appendix C, the evacuation data gathered by the EPA contains sufficient information for the estimation

*The evacuation effectiveness would decrease linearly with an increasing nonparticipating fraction of the population. In actual evacuations, Civil Defense personnel have observed a nonparticipating minority of approximately 5% [16].
of delay times before evacuation if a specific speed while in transit is assumed. Transit speeds of 10 miles per hour and greater have been recorded during actual evacuation events [16], and do not seem unreasonable, except perhaps in densely populated areas. As demonstrated in Appendix C, the radiation exposure of evacuating persons is relatively insensitive to assumed speeds greater than 10 mph. Therefore, the speed of evacuation is assumed to be a constant 10 miles per hour throughout this analysis. The EPA data is analyzed in Appendix C, assuming speeds of 10 mph and higher, to estimate representative evacuation delay times. The mean, 15 percent level* and 85 percent level** delay times are shown to be approximately 3, 1 and 5 hours, respectively, and were chosen for use in this study.*** During the delay period, persons are assumed to be unaware of the accident and to continue their normal activities. Shielding factors appropriate for normal activity, 0.75 (cloud) and 0.33 (ground), are assumed for this period, and persons located in buildings are assumed to inhale 35 percent less radionuclides than if they were outdoors [18]. During the transit period, shielding

*15% of evacuations for which data is available had delay times of approximately 1 hour or less.

**85% of evacuations for which data is available had delay times of approximately 5 hours or less.

***The assumed delay times begin immediately upon warning at the plant of the impending release. For example, if the warning time is 1 hour and the delay time is 3 hours, persons begin evacuating 2 hours after the release begins at the reactor.
factors of 1.0 (cloud) and 0.5 (ground) are assumed. Persons are evacuated within distances from the reactor of either 5, 10, 15 or 25 miles* and all persons outside the evacuated area have assumed SF's (0.75, 0.33) and are exposed to ground contamination for 1 day.

4.4 Iodine Prophylaxis

A number of chemical compounds can be ingested before or shortly after inhalation of radioactive material to inhibit the biological assimilation of inhaled radio- nuclides [22]. Of these, the administration of stable iodine has received the most attention, and is the only measure examined in this study. Chemical agents capable of reducing the uptake of radioactive strontium and cesium are potentially attractive as well, but require more detailed study in living organisms before an acceptable prophylactic program for the general public can be suggested [22].

Stable iodine has received more attention as a chemical prophylactic agent than other elements because inhaled radioiodine presents the most serious hazard under many accident conditions. Because iodine and iodine compounds are normally quite volatile [6], a sizeable fraction of core radioiodine inventories can be released to the atmosphere. Radioiodine also presents a major hazard because of its unique biological

*Persons are assumed in all cases to evacuate to a distance 5 miles beyond the evacuated area before they are removed from the problem (see Appendix C).
effects [6]. Inhaled radioiodine is quickly absorbed into
the blood stream and collects preferentially in the thyroid.
Because it is eliminated from the thyroid with a relatively
long, 138 day, biological half-life, that single organ
receives the largest dose from inhaled radioiodines [22].
Thyroid effects* that may result from this exposure are docu-
mented in reference [6].

If body fluids are saturated with stable iodine before
exposure to radioiodine, the ultimate absorption of radio-
active iodine isotopes by the thyroid is greatly reduced [6].
In this condition, uptake of radioiodine by the thyroid is
said to be blocked. For most individuals, after a short-
term exposure, the majority of radioiodine uptake by the
thyroid occurs within 12 hours, and is essentially complete
with 24 hours [6]. Therefore, the initial administration
of a blocking agent will be of some value even as long
as 24 hours after the exposure period.** However, essen-
tially complete (99 percent or greater) curtailment of the
uptake of radioiodines requires that stable iodine be
administered shortly before or almost immediately after
the initiation of exposure [23]. A block of 50 percent is

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*Acute effects include thyroiditis induced about two weeks
after exposure and hypothyroidism occurring within 3 to 6
months. Continuing and late effects include hypothyroidism
arising after several years, adenomatous and fibrous
nodules, and thyroid cancer.

**Iodine prophylaxis protects only against irradiation of
the thyroid gland. It should therefore be viewed as a
supplement to other protective measures, and will not
necessarily be able to replace them.
attainable only during the first 3 or 4 hours [6]. For releases of long duration, and therefore prolonged exposure to radioiodides, iodine prophylactic measures will be useful at any time during the exposure.

Chemical compounds of stable iodine that could be used as blocking agents include potassium iodide, potassium iodate, calcium iodate and pentacalcium orthoperiodate [6]. Radiological emergency plans in Great Britain call for iodine prophylaxis using 100 milligram tablets of potassium iodate. However, only potassium iodide and sodium iodide are currently approved for human consumption in the United States by the Food and Drug Administration (FDA). Various studies [23,24] have established that for adequate suppression an initial dose of 130 mg of potassium iodide per day is required (equivalent to 100 mg of iodide). Continued administration of this daily dose appears to maintain an essentially complete block [6].

To evaluate the effectiveness of iodine prophylaxis in limiting the consequences of a reactor accident, reduction factors have been applied to the thyroid dose from inhaled radioiodines. For example, if stable iodine is administered shortly before or immediately after the release of radioactive material begins, reduction factors of 0.01 or less might be used (99% or greater dose reduction).*

*An average reduction factor of 0.05 (95% reduction) was assumed in most of this analysis to allow for the fact that same individuals may not receive or take the potassium iodide tablet.
Results for other reduction factors are easily constructed from the results provided. The dose to the thyroid from external radiation sources, radioiodines in organs other than the thyroid, and other inhaled radionuclides are unaffected by these factors.
Section 5
Examination and Comparison of Protective Measures

5.1 Introduction

Evacuation, sheltering and iodine prophylaxis are examined and compared in this section as potential radiological emergency protective measures. The approach and modeling assumptions used in performing this analysis were described in earlier sections. Protective measures are evaluated as a function of distance from the reactor for PWR "Melt-through" accidents (PWR 6 and 7) in subsection 5.2 and for PWR "Atmospheric" accidents (PWR 1-5) in subsection 5.3. The effects of easily observable weather conditions on the relative effectiveness of response measures are briefly discussed in subsection 5.4.

Protective measures are examined for both PWR "Melt-through" and PWR "Atmospheric" accidents in terms of projected doses* to the whole body and thyroid.** Given a release in one of those categories, the probability of

*Projected dose is defined for this study as the sum of the doses due to: (1) exposure to the passing cloud of radioactive material; (2) exposure to ground contamination while in the affected area; and (3) internal exposure received during the first year from inhaled radionuclides. As such, the projected dose will depend on the protective measures implemented. Note that this definition of projected dose differs from that used by the EPA [12] (see subsection 2.3).

**Iodine prophylaxis, which acts specifically to reduce the dose to the thyroid, is evaluated only in terms of projected dose to that organ.
exceeding PAGs, and the mean* and 95 percent level** projected doses are presented as a function of distance from the reactor for each of those organs. The cloud, ground and inhalation components of the mean projected dose to each organ are also presented. The inhalation component of the projected thyroid dose is further divided into components due to the inhalation of radioiodines and the inhalation of radionuclides other than iodine. The effectiveness of protective measures for the PWR "Atmospheric" release category are also evaluated in terms of expected numbers of public health effects.

Because of the uncertainties imposed by the calculational techniques, assumptions and limited data employed in the consequence model of the Reactor Safety Study, and the simple modeling of protective measures performed in this study, there is a considerable degree of uncertainty associated with the absolute results (projected doses and public health effects) presented for specific protective actions in this report. Specific sources of uncertainty

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*91 stratified weather sequences were used to calculate a frequency distribution of projected dose (see subsection 3.2). The mean projected dose presented is the mean of this distribution.

**Given that an accident in a particular category occurs, there is a 0.95 probability that the resulting dose at a given distance will be less than the value indicated on the 95 percent level curve.
include (1) the release magnitudes, probabilities* and physical characteristics assumed, (2) the modeling of atmospheric dispersion (including the input meteorological data) and cloud depletion, (3) the dosimetry modeling, and (4) the dose-response criteria used for the calculation of health effects. Because of the complex nature of the calculations performed, the absolute uncertainties involved are difficult to ascertain. Based on the judgement of the Reactor Safety Study [2], approximate uncertainties were estimated to be represented by factors of 1/4 and 4 on calculated early fatalities and injuries, and by factors of 1/3 and 3 on thyroid nodules.** However, the relative uncertainties associated with the comparison of results for protective measures in this study should be much smaller. The sources of uncertainty listed above will, in large part, cancel out when results are compared. However, when two different types of protective strategies are compared,

*All results presented in this study are conditional on the occurrence of either a PWR "Melt-Through" or PWR "Atmospheric" accident. The absolute probability of occurrence (and uncertainties in that probability) for accidents in either of these categories is therefore immaterial to this work. However, uncertainties in the relative probabilities of the Reactor Safety Study release categories comprising the "Melt-Through" and "Atmospheric" categories (see subsection 3.3) will contribute uncertainty to the results presented here.

**The quoted uncertainties indicate only the general degree to which results are influenced, and should not be taken as representing absolute limits. Note that uncertainties for predicted doses will be less than the factors above because uncertainties in the dose-response criteria will not be involved.
such as evacuation and sheltering, the uncertainties due to
the modeling of the protective measures will in general not
cancel. Therefore, based on the authors' judgements, the
approximate relative uncertainties associated with the com-
parison of different protective measures in this study (in
terms of either projected doses or health effects) are
estimated to be represented by a factor of 2. For example,
if the projected doses at a given distance for an evacuation
and a sheltering strategy (or an evacuation and an iodine
prophylaxis strategy, etc.) differ by more than a factor
of 2, the difference may be considered significant. This
factor is presented only as a qualitative guide to the
reader for use in interpreting the results presented in
this section. For strategies of a single type, the
relative uncertainty factors would be much closer to 1.

Finally, much of the information and observations
presented in this section are independent of a specific
site population distribution. Situations in which this is
not the case are noted, and the effect of specific population
distributions on the information presented is discussed.

5.2 PWR "Melt-through" Response Category (PWR 6 and 7)

PWR "Melt-through" accidents would result in the
release of relatively small fractions of core radioisotope
inventories to the atmosphere. Projected doses downwind of
the release point are therefore generally low compared to
threshold levels for early health effects, and few, if any, early fatalities or injuries are likely. Emergency phase response planning and actions for this type of accident should therefore be primarily directed towards limiting the dose to those individuals located in areas where PAGs will be, or are likely to be, exceeded. Figure 5.1 shows the probabilities of exceeding thyroid and whole body PAGs versus distance from the reactor, conditional on the occurrence of a PWR "Melt-through" release. The probabilities are calculated for an individual located outdoors, and are presented for both lower and upper PAG levels for each organ. It is evident from these results that, for all practical purposes, projected doses in excess of PAGs are confined to areas within 10 miles of the reactor for this type of accident, and in most cases, to areas considerably closer.

Mean and 95 percent level projected doses to the whole body, conditional on a PWR "Melt-through" release, are compared for evacuation and sheltering measures as a function of distance from the reactor in Figures 5.2 and 5.3. Curve A in each figure represents the dose to an individual located outdoors during passage of the cloud of radioactive material, with exposure to radionuclides deposited on the ground limited to 1 day. Curves B and C represent the range of "average" projected dose if sheltering measures are implemented and effective exposure* to ground contamination

*See subsection 4.2 for an explanation of effective exposure.
Figure 5.1 Conditional Probability of Exceeding Thyroid and Whole Body Protective Action Guides (PAGs) Versus Distance for an Individual Located Outdoors.\textsuperscript{a}

Probabilities are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

\textsuperscript{a}Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.

\textsuperscript{b}Whole body (thyroid) dose calculated includes: external dose to the whole body (thyroid) due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the whole body (thyroid) from inhaled radionuclides within 1 year.
Figure 5.2 Conditional Mean Projected Whole Body Dose Versus Distance for Sheltering and Evacuation Strategies. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

Curve A Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.

Curve C Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.

Curve D Evacuation, 5 hour delay time, 10 MPH.

Curve E Evacuation, 3 hour delay time, 10 MPH.
Figure 5.3  Conditional 95% Level Whole Body Dose Versus Distance for Sheltering and Evacuation Strategies. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

Curve A  Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B  Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.

Curve C  Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.

Curve D  Evacuation, 5 hour delay time, 10 MPH.

Curve E  Evacuation, 3 hour delay time, 10 MPH.
is limited to 6 hours. Projected doses if the public is evacuated with a speed of 10 miles per hour after delay times of 5 and 3 hours are shown by curves D and E, respectively.* If the delay time can be reduced to 1 hour or less, projected doses are close to 0 at all distances. Figure 5.4 displays the cloud, ground and inhalation components of the mean projected whole body dose to an individual located outdoors.** The total dose curve in this figure is the same as curve A in Figure 5.2. Using the component curves presented, curves representing projected whole body dose as a function of distance can be constructed for any sheltering strategy or for any type of structure by assuming the appropriate shielding factors, reduction in dose due to inhaled radionuclides, and time of exposure to ground contamination. For example, curve C of Figure 5.2, for sheltering with shielding factors (0.5, 0.08), 6 hours of exposure to ground contamination, and a reduction factor of 0.65 for dose due to inhaled radionuclides, can be constructed in the following manner. First, multiply the inhalation component curve by the 0.65 reduction factor for dose due to inhaled radionuclides. Then multiply the

---

*The dose received by evacuating persons while stationary and in transit is assigned to the distance at which they were initially located.

**The cloud component curve drops off less rapidly than the ground component curve because, as radionuclides are deposited from the cloud, the fractional concentration of noble gases in the cloud (which are not deposited) increases with distance.
Figure 5.4 Components of Mean Projected Whole Body Dose Versus Distance for an Individual Located Outdoors. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

aThe total dose calculated includes: external dose to the whole body due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the whole body from inhaled radionuclides within one year. SF's (1.0, 0.7).

bWhole body dose due to the passing cloud. SF = 1.0.

cWhole body dose due to 1-day exposure to radionuclides on ground. SF = 0.7.

dWhole body dose due to inhaled radionuclides within one year.
cloud component curve by the assumed shielding factor of 0.5 for airborne radionuclides. Finally, multiply the
ground component curve by the ratio of the assumed to out-
doors shielding factors for ground deposited radionuclides
(0.08/0.7 in this example) and then by the desired fraction
of exposure time to ground contamination* (6 hours/24 hours
in this example). The summation of these revised component
curves will result in the desired curve C.

Figures 5.5 and 5.6 compare mean and 95% level pro-
jected doses to the thyroid for the PWR "Melt-through"
category as a function of distance from the reactor and
the protective measures implemented. As in the previous
figures, curve A represents the dose received by an
individual located outdoors and exposed to ground contamina-
tion for 1 day. Curves B and D show the projected doses
for evacuation with a speed of 10 miles per hour and delay
times of 5 and 3 hours, respectively. Again, if the delay
time is reduced to 1 hour or less, the projected dose is
nearly 0 at all distances. Curve C represents the projected
dose when both sheltering and iodine prophylaxis** are
implemented. The shielding factors assumed for this
strategy correspond to the low end of the sheltering range,
and exposure to ground contamination is limited to 6 hours.

*For all practical purposes, ground dose may be assumed to be linear with exposure time for times less than several days.

**Iodine prophylaxis is assumed here to result in 95% reduction in dose to the thyroid from inhaled radioiodines.
Figure 5.5 Conditional Mean Projected Thyroid Dose Versus Distance for Various Protective Strategies. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

Curve A Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B Evacuation, 5 hour delay time, 10 MPH.

Curve C Sheltering and 95% effective iodine prophylaxis. SF's (0.5, 0.08). 6-hour exposure to radionuclides on ground.

Curve D Evacuation, 3 hour delay time, 10 MPH.
Figure 5.6 Conditional 95% Level Projected Thyroid Dose Versus Distance for Various Protective Strategies. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

Curve A  Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B  Evacuation, 5 hour delay time, 10 MPH.

Curve C  Sheltering and 95% effective iodine prophylaxis. SF's (0.5, 0.08). 6-hour exposure to radionuclides on ground.

Curve D  Evacuation, 3 hour delay time, 10 MPH.
The components of the mean projected thyroid dose for an individual located outdoors are presented in Figure 5.7. Again, the total dose curve is the same as curve A in Figure 5.5. The fractional contribution to total dose by each component remains approximately constant for all releases within this category and as a function of distance from the reactor: inhaled radioiodines account for roughly 85%, inhaled non-iodines 12%, ground 3%, and cloud 1%. As illustrated for the projected whole body dose curves, these components may be used to construct projected thyroid dose versus distance curves for any combination of assumed sheltering and iodine prophylaxis measures. The cloud and ground components should be treated as previously described, and the inhaled non-iodine component should be multiplied by the desired reduction factor for dose due to inhaled radionuclides. The component due to the inhaled radioiodines should be multiplied by both this reduction factor and the assumed reduction due to iodine prophylaxis. Summing the revised components will result in the desired curve.

Several observations can be made from the preceding figures for the PWR "Melt-through" category. First, evacuation, even with delay times of 5 hours or longer, appears to provide larger reductions in whole body dose than sheltering. This is due, in large part, to the fact that the release duration assumed is very long (10 hours), and that
Figure 5.7 Components of Mean Projected Thyroid Dose Versus Distance for an Individual Located Outdoors. Projected Doses are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

The total dose calculated includes: external dose to the thyroid due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the thyroid from inhaled radionuclides within one year. SF's (1.0, 0.7).

Thyroid dose due to inhaled radioiodines within one year.

Thyroid dose due to inhaled radioisotopes other than iodine within one year.

Thyroid dose due to 1-day exposure to radionuclides on ground. SF = 0.7.

Thyroid dose due to the passing cloud. SF = 1.0.
evacuated persons therefore will avoid exposure to a significant portion of the cloud even with a relatively long delay time. Projected doses will be more sensitive to evacuation delay time for releases of shorter duration or for releases in which the concentration of radionuclides peaks early in the release. Regardless, if people can be evacuated with small delay times, they will avoid exposure to most, if not all, of the cloud and will receive correspondingly lower doses. However, sheltering also offers significant dose reductions, particularly in areas with a large number of basements, and may offer an acceptable alternative to evacuation. For releases of long duration, responsible authorities face uncertainties due to the possibility of wind shifts and varying weather conditions. Either evacuation or sheltering of all individuals within a given radius of the reactor, or some combination of the two protective measures might be appropriate. Figure 5.7 indicates that the projected dose to the thyroid is dominated by the dose due to the inhalation of radioiodines. Sheltering by itself, unless a very large reduction in the quantity of radionuclides inhaled can be achieved,* does not offer significant reductions to this dose.** However, iodine prophylaxis, if administered in sufficient time, or evacuation

*See Appendix B.

**The assumed reduction factor for dose due to inhaled radio- nuclides of 0.65 in this study results in approximately a 35 percent reduction in thyroid dose.
with small delay times both offer substantial reductions in the dose to the thyroid.

5.3 PWR "Atmospheric" Response Category (PWR 1-5)

In contrast to the PWR "Melt-through" response category discussed in the previous subsection, PWR "Atmospheric" accidents could result in the release of large fractions of core radioisotope inventories to the atmosphere and radiation doses to individuals downwind in excess of threshold levels for early health effects. The probabilities of exceeding thyroid and whole body PAGs, conditional on this type of release, are shown in Figure 5.8 as a function of distance from the reactor. As in the previous subsection, the probabilities are calculated for a person located outdoors and are displayed for both the lower and upper PAG levels for each organ. The figure indicates that both whole body and thyroid PAGs are likely to be exceeded at very large distances* from the reactor (and correspondingly over very large areas) if a PWR "Atmospheric" accident were to occur. Doses in excess of threshold levels for early health effects

*Caution must be used in interpreting the large distances indicated. The Reactor Safety Study consequence model assumes an invariant wind direction following the release of radioactive material. However, because of the time required by the cloud to travel large distances, it is likely that the wind direction will, in fact, shift and that the predicted dose levels would not be observed at the reported radial distance. Rather, the distance applies more closely to the trajectory of the released cloud.
Figure 5.8 Conditional Probability of Exceeding Thyroid and Whole Body Protective Action Guides (PAGs) Versus Distance for an Individual Located Outdoors.\textsuperscript{a} Probabilities are Conditional on a PWR "Atmospheric" Release (PWR I-5).

\textsuperscript{a}Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.

\textsuperscript{b}Whole body (thyroid) dose calculated includes: external dose to the whole body (thyroid) due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the whole body (thyroid) from inhaled radionuclides within 1 year.
are confined to smaller areas much closer to the reactor, however. Therefore, in the unlikely event that an accident of this magnitude were to occur, responsible authorities might choose to direct their available resources towards limiting the life- and injury-threatening doses to individuals in areas close to the reactor. If sufficient resources are available, protective measures might also be implemented for individuals at larger distances for whom PAGs are, or are likely to be, exceeded. However, because of the travel time required by the cloud, there will be more time for the assessment of dose levels and likely impacts and the initiation of protective measures at these larger distances. For these reasons, protective measures for the PWR "Atmospheric" category of accidents are evaluated in this subsection in terms of impact on projected early fatalities and early injuries as well as in terms of projected doses to the whole body and thyroid.

Mean and 95% level projected whole body doses, conditional on a PWR "Atmospheric" release, are compared as a function of distance for evacuation and sheltering in Figures 5.9 and 5.10. Curve A in each figure represents the dose that would be received by an individual located outdoors during passage of the cloud of radioactive material and exposed to ground contamination for 1 day. Curves B and D cover the range of projected "average" whole body doses for sheltering with exposure to ground contamination
Figure 5.9  Conditional Mean Projected Whole Body Dose Versus Distance for Sheltering and Evacuation Strategies. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

Curve A Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.

Curve C Evacuation, 5 hour delay time, 10 MPH.

Curve D Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.

Curve E Evacuation, 3 hour delay time, 10 MPH.
Figure 5.10  Conditional 95% Level Projected Whole Body Dose Versus Distance for Sheltering and Evacuation Strategies. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

Curve A  Individual located outdoors without protection. SF's (1.0, 0.7).  1-day exposure to radionuclides on ground.

Curve B  Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.

Curve C  Evacuation, 5 hour delay time, 10 MPH.

Curve D  Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.

Curve E  Evacuation, 3 hour delay time, 10 MPH.
limited to 6 hours. Projected doses for evacuation with delay times of 5 and 3 hours and a speed of 10 miles per hour are shown by curves C and E, respectively. As noted in the previous subsection, if the delay time is reduced to 1 hour or less, and an evacuation speed of 10 MPH (or greater) is achieved, evacuating persons are likely to escape interaction with the cloud, and projected doses are nearly 0 at all distances. The cloud, ground and inhalation components of the mean whole body dose projected for an individual located outdoors (curve A in Figure 5.9) are presented in Figure 5.11. The ground component clearly dominates the other two. Again, these component curves can be used to construct approximate mean whole body dose versus distance curves for sheltering strategies other than those presented.

Figures 5.12 and 5.13 compare mean and 95% level projected doses to the thyroid as a function of distance from the reactor and the protective measures implemented. Again, curve A represents the projected dose to the thyroid of an individual located outdoors during passage of the cloud of radioactive material and exposed to ground contamination for 1 day. Projected thyroid doses for evacuation with delay times of 5 and 3 hours and an evacuation speed of 10 miles per hour are shown as curves B and C, respectively. Curve D represents the projected dose when both sheltering and iodine prophylaxis* are implemented. Figure 5.14

*Iodine prophylaxis is assumed here to result in a 95% reduction in thyroid dose due to inhaled radioiodines.
Components of Mean Projected Whole Body Dose versus Distance for an Individual Located Outdoors. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

Components of Mean Projected Whole Body Dose (REM) Given a PWR Atmospheric Release (PWR 1-5)

![Graph showing components of mean projected whole body dose versus distance](image)

**Figure 5.11** Components of Mean Projected Whole Body Dose Versus Distance for an Individual Located Outdoors. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

- **a** The total dose calculated includes: external dose to the whole body due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the whole body from inhaled radionuclides within one year. SF's (1.0, 0.7).
- **b** Whole body dose due to the passing cloud. SF = 1.0.
- **c** Whole body dose from 1-day exposure to radionuclides on ground.
- **d** Whole body dose from inhaled radionuclides within one year.
Conditional Mean Projected Thyroid Dose Versus Distance for Various Protective Strategies. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

Curve A Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B Evacuation, 5 hour delay time, 10 MPH.

Curve C Evacuation, 3 hour delay time, 10 MPH.

Curve D Sheltering and 95% effective iodine prophylaxis. SF's (0.5, 0.08). 6-hour exposure to radionuclides on ground.
Figure 5.13 Conditional 95% Level Projected Thyroid Dose Versus Distance for Various Protective Strategies. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

Curve A Individual located outdoors without protection. SF's (1.0, 0.7). 1-day exposure to radionuclides on ground.

Curve B Evacuation, 5 hour delay time, 10 MPH.

Curve C Evacuation, 3 hour delay time, 10 MPH.

Curve D Sheltering and 95% effective iodine prophylaxis. SF's (0.5, 0.08). 6-hour exposure to radionuclides on ground.
Components of Mean Projected Thyroid Dose Versus Distance for an Individual Located Outdoors. Projected Doses are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

- **a** The total dose calculated includes: external dose to the thyroid due to the passing cloud and 1-day exposure to radionuclides on ground, and the dose to the thyroid from inhaled radionuclides within one year. SF's (1.0, 0.7).
- **b** Dose to the thyroid from inhaled radiiodines within one year.
- **c** Dose to the thyroid from inhaled radioisotopes other than iodine within one year.
- **d** Dose to the thyroid from 1-day exposure to radionuclides on ground. SF = 0.7.
- **e** Dose to the thyroid due to the passing cloud. SF = 1.0.
exhibits the components of the mean projected thyroid dose for an individual located outdoors. Again, approximate mean projected thyroid dose curves for any particular sheltering or iodine prophylaxis strategy may be constructed using these components.

Several observations can be made from the information presented for PWR "Atmospheric" accidents. If no immediate protective actions are implemented, projected whole body doses in excess of threshold levels for early health effects are possible out to significant distances from the reactor. For an individual located outdoors and exposed to ground contamination for 1 day, mean projected whole body doses exceed 100 rem to approximately 10 miles. The 95% level whole body dose to the same individual exceeds 100 rem to distances beyond 30 miles. Both evacuation and sheltering are shown to result in significant reductions in projected dose to the whole body. Even so, however, whole body doses for the response strategies shown may still exceed threshold levels for early health effects in some areas. For sheltering with optimum average shielding factors, (0.5, 0.08), and 6 hours of exposure to ground contamination, the mean and 95% level doses drop below 100 rem at approximately 2 and 8 miles,
respectively. Corresponding distances for evacuation* with a 3 hour delay time are 1 and 6 miles. For evacuation with a 1 hour delay (not shown on figures), persons most likely escape interaction with the cloud of radioactive material, and projected doses are nearly 0.

The projected doses to the thyroid for PWR "Atmospheric" releases pose a serious threat to that organ for individuals out to significant distances. The thyroid dose is again dominated by the dose due to inhaled radioiodines, as indicated in Figure 5.14. Note, however, that for the previous PWR "Melt-through" release category, evacuation after a 3, or even 5, hour delay time provided very large reductions in thyroid dose because of the very long release durations for that type of release. For the "Atmospheric" accidents, however, release durations are much shorter and evacuation does not provide as much protection. Sheltering by itself, unless the quantity of radionuclides inhaled can be substantially reduced [18], will also not provide much protection. Only iodine prophylaxis (or evacuation with very small delay times) can provide large reductions in the projected dose to the thyroid.

*Note that the dose curves for evacuation drop off more rapidly than those for sheltering. For a given sheltering strategy, the assumed period of exposure to ground contamination is constant for all individuals, regardless of distance from the reactor. For evacuation, however, all individuals have the same assumed delay time. Therefore, because the travel time required by the cloud to reach individuals increases with their distance from the reactor, interaction times and corresponding doses fall off rapidly with distance.
Projected numbers of early public health effects, conditional on a PWR "Atmospheric" release, are presented in Table 5.1 for selected sheltering/relocation strategies. The mean and 95% level numbers* of early fatalities and early injuries were calculated assuming a uniform population density of 100 persons per square mile. The response strategies listed differ in terms of the radial distance within which the population is sheltered, the assumed period of exposure to ground contamination, and the shielding factors assumed. For example, if the population within 15 miles of the reactor is sheltered with average shielding factors (0.5, 0.08), and exposed to ground contamination for 1 day (i.e., strategy 4 in Table 5.1), the projected mean numbers of early fatalities and early injuries for a PWR "Atmospheric" release are 17 and 120, respectively. The corresponding 95% level numbers of early fatalities and early injuries are 77 and 530. No immediate protective actions are implemented in strategy 1, as listed in Table 5.1, and normal activity shielding factors, (0.75, 0.33), and 1 day of exposure to ground contamination are assumed. In the remaining strategies, persons within the selected distance of either 5, 10, 15, 25 or 50 miles are sheltered.** The assumed

*The numbers represent either the mean or 95% level total number of early fatalities or early injuries that occur both within and outside the sheltered area.

**As explained in Section 4 of this report, all strategies assumed the "normal activity" shielding factors, (0.75, 0.33), and 1 day of exposure to ground contamination for persons outside the sheltering area.

<table>
<thead>
<tr>
<th>Sheltering/Relocation Strategy&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Early Fatalities Mean</th>
<th>95% Level&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Early Injuries Mean</th>
<th>95% Level&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. No immediate protective action, SF's&lt;sup&gt;c&lt;/sup&gt; (0.75, 0.33), 1-day exposure to radionuclides on ground.</td>
<td>72</td>
<td>370</td>
<td>230</td>
<td>770</td>
</tr>
<tr>
<td>2. Sheltering of population within 5 miles, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.</td>
<td>35</td>
<td>300</td>
<td>200</td>
<td>760</td>
</tr>
<tr>
<td>3. Sheltering of population within 10 miles, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.</td>
<td>20</td>
<td>91</td>
<td>140</td>
<td>610</td>
</tr>
<tr>
<td>4. Sheltering of population within 15 miles, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.</td>
<td>17</td>
<td>77</td>
<td>120</td>
<td>530</td>
</tr>
<tr>
<td>5. Sheltering of population within 25 miles, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.</td>
<td>12</td>
<td>67</td>
<td>67</td>
<td>260</td>
</tr>
<tr>
<td>6. Sheltering of population within 25 miles, SF's (0.75, 0.33), 12-hour exposure to radionuclides on ground.</td>
<td>34</td>
<td>170</td>
<td>130</td>
<td>460</td>
</tr>
<tr>
<td>7. Sheltering of population within 25 miles, SF's (0.5, 0.08), 12-hour exposure to radionuclides on ground.</td>
<td>6</td>
<td>35</td>
<td>51</td>
<td>170</td>
</tr>
<tr>
<td>8. Sheltering of population within 5 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.</td>
<td>38</td>
<td>310</td>
<td>200</td>
<td>750</td>
</tr>
<tr>
<td>9. Sheltering of population within 5 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.</td>
<td>29</td>
<td>240</td>
<td>190</td>
<td>720</td>
</tr>
</tbody>
</table>

<sup>a</sup>For persons outside the sheltering area, all strategies assume SF's (0.75, 0.33) and 1-day exposure to radionuclides on ground.

<sup>b</sup>95% of the time a PWR "Atmospheric" accident occurs, the number of early fatalities (early injuries) will be less than the 95% level.

<sup>c</sup>Shielding factors (airborne radionuclides, ground contamination).
<table>
<thead>
<tr>
<th>Sheltering/Relocation Strategy&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Early Fatalities</th>
<th>Early Injuries</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>10. Sheltering of population within 10 miles, SF's&lt;sup&gt;c&lt;/sup&gt; (0.75, 0.33), 6-hour exposure to radionuclides on ground.</td>
<td>23 120</td>
<td>150 630</td>
<td></td>
</tr>
<tr>
<td>11. Sheltering of population within 10 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.</td>
<td>11 24</td>
<td>120 570</td>
<td></td>
</tr>
<tr>
<td>12. Sheltering of population within 15 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.</td>
<td>20 100</td>
<td>130 540</td>
<td></td>
</tr>
<tr>
<td>13. Sheltering of population within 15 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.</td>
<td>8 17</td>
<td>96 530</td>
<td></td>
</tr>
<tr>
<td>14. Sheltering of population within 25 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.</td>
<td>15 87</td>
<td>81 280</td>
<td></td>
</tr>
<tr>
<td>15. Sheltering of population within 25 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.</td>
<td>3 16</td>
<td>42 150</td>
<td></td>
</tr>
<tr>
<td>16. Sheltering of population within 50 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.</td>
<td>15 87</td>
<td>64 250</td>
<td></td>
</tr>
<tr>
<td>17. Sheltering of population within 50 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.</td>
<td>3 16</td>
<td>25 100</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup>For persons outside the sheltering area, all strategies assume SF's (0.75, 0.33) and 1-day exposure to radionuclides on ground.

<sup>b</sup>95% of the time a PWR "Atmospheric" accident occurs, the number of early fatalities (early injuries) will be less than the 95% level.

<sup>c</sup>Shielding factors (airborne radionuclides, ground contamination).
shielding factors are either (0.75, 0.33),* corresponding to regions with small fractions of homes with basements, or (0.5, 0.08), which are representative of regions in which most homes have basements. Assumed periods of exposure to ground contamination are either 6, 12, or 24 hours (1 day). As detailed earlier in this section, mean projected whole body and thyroid dose curves for sheltering with any shielding factors and ground contamination exposure durations are easily constructed from the information presented. However, although rough estimates can be made,** there is no corresponding method for deriving projected public health effects for sheltering strategies with shielding factors or exposure periods to ground contamination other than those above.

A similar table of projected numbers of early public health effects for selected evacuation strategies is presented in Table 5.2. Again, the mean and 95% level numbers

*Note that because the upper end of the range of shielding factors for sheltering, (0.75, 0.33), was chosen to be the same as the "normal activity" shielding factors (assumed for persons outside the sheltering radius), any strategy of sheltering with these shielding factors and 1 day of exposure to ground contamination will have projected health effects identical to strategy 1 in Table 5.1.

**Mean projected early fatalities and early injuries appear to be roughly linear as a function of assumed times of exposure to ground contamination between 6 and 24 hours. For example, assuming a linear relationship between strategies 5 and 15 in Table 5.1, the estimated mean numbers of early fatalities and early injuries for sheltering of the population within 25 miles, SF's (0.5, 0.08), and 12-hour exposure to radionuclides on ground would be 6 and 50. The corresponding actual numbers, as calculated for strategy 7, are 6 and 51, respectively.
Table 5.2 Projected Numbers of Early Health Effects for Evacuation Strategies, Conditional on a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed.

<table>
<thead>
<tr>
<th>Evacuation Strategy</th>
<th>Early Fatalities</th>
<th>Early Injuries</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean 95% Level</td>
<td>Mean 95% Level</td>
</tr>
<tr>
<td>1. Evacuation of population within 5 miles. 1 hour delay time. 10 mph.</td>
<td>26 220</td>
<td>160 670</td>
</tr>
<tr>
<td>2. Evacuation of population within 5 miles. 3 hour delay time. 10 mph.</td>
<td>28 240</td>
<td>170 720</td>
</tr>
<tr>
<td>3. Evacuation of population within 5 miles. 5 hour delay time. 10 mph.</td>
<td>31 280</td>
<td>180 720</td>
</tr>
<tr>
<td>4. Evacuation of population within 10 miles. 1 hour delay time. 10 mph.</td>
<td>8 0</td>
<td>92 550</td>
</tr>
<tr>
<td>5. Evacuation of population within 10 miles. 3 hour delay time. 10 mph.</td>
<td>10 22</td>
<td>110 570</td>
</tr>
<tr>
<td>6. Evacuation of population within 10 miles. 5 hour delay time. 10 mph.</td>
<td>13 52</td>
<td>120 580</td>
</tr>
<tr>
<td>7. Evacuation of population within 15 miles. 1 hour delay time. 10 mph.</td>
<td>5 0</td>
<td>68 420</td>
</tr>
<tr>
<td>8. Evacuation of population within 15 miles. 3 hour delay time. 10 mph.</td>
<td>8 18</td>
<td>86 460</td>
</tr>
<tr>
<td>9. Evacuation of population within 15 miles. 5 hour delay time. 10 mph.</td>
<td>11 41</td>
<td>97 480</td>
</tr>
<tr>
<td>10. Evacuation of population within 25 miles. 1 hour delay time. 10 mph.</td>
<td>0 0</td>
<td>17 23</td>
</tr>
<tr>
<td>11. Evacuation of population within 25 miles. 3 hour delay time. 10 mph.</td>
<td>3 16</td>
<td>38 130</td>
</tr>
<tr>
<td>12. Evacuation of population within 25 miles. 5 hour delay time. 10 mph.</td>
<td>6 36</td>
<td>50 160</td>
</tr>
</tbody>
</table>

*For persons outside the evacuated area, all strategies assume SF's (0.75, 0.33) and 1-day exposure to radionuclides on ground.

*95% of the time a PWR "Atmospheric" accident occurs, the number of early fatalities (early injuries) will be less than the 95% level.
shown are conditional on a PWR "Atmospheric" release and were calculated assuming a uniform population density of 100 persons per square mile. The response strategies listed in this table vary in terms of the distance within which the population is evacuated, and the assumed delay time before evacuation. Distances are either 5, 10, 15, or 25 miles, and delay times are 1, 3 or 5 hours. The assumed evacuation speed for all strategies is 10 miles per hour.

The projected public health effects presented in Table 5.1 and 5.2 can be used to further examine and compare the effectiveness of sheltering and evacuation as protective measures for PWR "Atmospheric" accidents. In Figures 5.15 and 5.16, the mean number of projected early fatalities and early injuries for sheltering strategies in which the period of exposure to ground contamination is 6 hours are plotted as a function of the radial distance inside of which the population is sheltered (sheltering distance). A sheltering distance of 0 miles implies that no immediate protective actions are implemented. Similar plots for the 95% level projected numbers of early fatalities and injuries are presented as Figures 5.17 and 5.18. Curves are included in each figure for the upper and lower ends of the assumed shielding factor range. It is important to remember that the results presented in these figures are valid only for the assumed uniform population density of 100 persons per square mile. The absolute scales and shapes of similar curves for a specific site would
Figure 5.15  Mean Number of Projected Early Fatalities Versus Distance Within Which Population is Sheltered, Given a PWR "Atmospheric Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed. Exposure to Radionuclides on Ground is 6 Hours.

 shielding factors (airborne radionuclides, ground contamination).
Figure 5.16  Mean Number of Projected Early Injuries Versus Distance Within Which Population is Sheltered, Given a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed. Exposure to Radionuclides on Ground is 6 Hours.

\[ S F's^a (0.75, 0.33) \]

\[ S F's^a (0.5, 0.08) \]

\[ ^a \text{Shielding factors (airborne radionuclides, ground contamination).} \]
Figure 5.17 95% Level\(^b\) Number of Projected Early Fatalities Versus Distance Within Which Population is Sheltered, Given a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed. Exposure to Radionuclides on Ground is 6 Hours.

\(^a\)Shielding factors (airborne radionuclides, ground contamination).

\(^b\)95% of the time a PWR "Atmospheric" accident occurs, the number of early fatalities will be less than the 95% level.
Figure 5.18 95% Level\textsuperscript{b} Number of Projected Early Injuries Versus Distance Within Which Population is Sheltered, Given a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed. Exposure to Radionuclides on Ground is 6 Hours.

\textsuperscript{a}Shielding factors (airborne radionuclides, ground contamination).

\textsuperscript{b}95\% of the time a PWR "Atmospheric" accident occurs, the number of early injuries will be less than the 95\% level.
depend strongly on the actual population distribution surrounding that site.* Nevertheless, several important general observations can be obtained from the figures at hand. First, as indicated in Figure 5.15, for a uniform population density, the reduction in the mean number of projected early fatalities afforded by an incremental increase in sheltering distance decreases with distance from the reactor. This would be expected since, as shown in the projected dose curves earlier, individuals at distances closer to the reactor are more likely to receive doses in excess of threshold levels for early health effects. Sheltering of individuals within 10 miles of the reactor greatly reduces the projected numbers of fatalities. Sheltering from 10 to 25 miles results in a somewhat smaller reduction, and no reduction is afforded by sheltering beyond 25 miles. Figure 5.16 illustrates similar behavior for projected early injuries, except that, with lower threshold levels than for early fatalities, they are more likely to occur at larger distances from the reactor. Figure 5.17 indicates that the 95% level number of projected early fatalities is not significantly reduced by sheltering beyond 10 miles. Similarly, as indicated in Figure 5.18, the 95% level of projected early injuries is not significantly reduced.

*For example, if a uniform population density of 50 rather than 100 persons per square mile was assumed, all projected numbers (scale) would be reduced by a factor of two. If a nonuniform distribution with a large population center between 10 and 15 miles was assumed, the projected numbers of public health effects would drop off rapidly as the sheltering distance is extended from 10 to 15 miles.
reduced by sheltering beyond 25 miles. Similar curves could be drawn from the information in Table 5.2 showing projected health effects for evacuation strategies as a function of the distance within which the population is evacuated. They would illustrate qualitatively the same behavior, and have not been included here.

The projected numbers of early public health effects presented in Tables 5.1 and 5.2 can be further used to compare the effectiveness of evacuation and sheltering for PWR "Atmospheric" accidents. As explained earlier in this section, if the population within a given distance is evacuated with 1 hour of delay, projected doses to the evacuated population are essentially 0, and no early public health effects will occur within that distance. Therefore, all early fatalities and early injuries that are projected in Table 5.2 for evacuation strategies with a 1 hour delay time must occur outside the assumed evacuation radius. Knowing this, the mean numbers of early health effects projected in selected radial intervals surrounding the reactor can be determined for each of the evacuation and
sheltering strategies investigated.*

Estimated mean numbers of projected early fatalities and injuries within radial intervals from 0 to 5, 5 to 10, 10 to 15 and 15 to 25 miles are compared for selected evacuation and sheltering strategies in Figures 5.19 and 5.20.** Seven strategies are included, as defined in the key to these figures. Strategy 1 assumes that no immediate protective actions are taken. 2, 3 and 4 are selected sheltering strategies, as noted. Strategies 3 and 4 represent sheltering for regions in which a large fraction of homes have basements. Effective exposure durations to ground contamination for these two strategies are 1 day and 6 hours, respectively. Strategy 2 represents

*The mean number of early fatalities occurring in selected radial intervals can be determined in the following manner. For example, if no immediate protective actions are taken (strategy 1, Table 5.1), the mean total number of early fatalities is 72. However, if, instead, the population within 5 miles is evacuated with a 1 hour delay (strategy 1, Table 5.2), the number is reduced to 26. The difference between these numbers, 46, must equal the mean number of early fatalities that occur in the interval from 0 to 5 miles when no immediate protective actions are taken. Conversely, 26 is the mean number that occur outside of 5 miles. Similarly, if the population within 5 miles is sheltered with SF's (0.5, 0.08) and 1 day of exposure to ground contamination (strategy 2, Table 5.1), the mean total number of early fatalities is 35. We have already shown that 26 of these must occur outside of 5 miles. Therefore (35-26) or 9 is the mean number of early fatalities that occur in the interval from 0 to 5 miles when this strategy is implemented.

**The number of early health effects indicated for a particular radial interval and protective strategy assumes that the strategy noted is implemented for all persons in that interval, and is independent of whatever strategies are implemented for persons in other radial intervals.
Mean Number of Projected Early Fatalities Within Selected Radial Intervals for Evacuation and Sheltering Strategies, Given a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed.

Key:
1. No immediate protective action, SF's\(^a\) (0.75, 0.33), 1-day exposure to radionuclides on ground.
2. Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.
3. Sheltering, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.
4. Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.
5. Evacuation, 5 hour delay time, 10 MPH.
6. Evacuation, 3 hour delay time, 10 MPH.
7. Evacuation, 1 hour delay time, 10 MPH.

\(^a\)Shielding factors (aribrone radionuclides, ground contamination).
Figure 5.20  Mean Number of Projected Early Injuries Within Selected Radial Intervals for Evacuation and Sheltering Strategies, Given a PWR "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed.

Key:
1. No immediate protective action, SF's\(^a\) (0.75, 0.33), 1-day exposure to radionuclides on ground.
2. Sheltering, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.
3. Sheltering, SF's (0.5, 0.08), 1-day exposure to radionuclides on ground.
4. Sheltering, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.
5. Evacuation, 5 hour delay time, 10 MPH.
6. Evacuation, 3 hour delay time, 10 MPH.
7. Evacuation, 1 hour delay time, 10 MPH.

\(^a\)Shielding factors (airborne radionuclides, ground contamination).
sheltering for regions in which most homes do not have basements, with 6 hours of effective exposure to ground contamination.* Strategies 5, 6 and 7 represent evacuation with 5, 3 and 1 hours of delay time, respectively. The results presented for each of the selected radial intervals in Figures 5.19 and 5.20 assume a uniform population density of 100 persons per square mile. The corresponding number of projected public health effects for any particular site would depend on the actual population distribution surrounding the site.** Nevertheless, the relative comparison of numbers for the strategies indicated is nearly independent of the population distribution within a given interval, and the observations made here should be appropriate regardless of the population at a specific site.

Several important observations can be made concerning PWR "Atmospheric" accidents from results presented in Figures 5.19 and 5.20. As shown and discussed earlier in this subsection, most early fatalities resulting from

*Sheltering with SP's (0.75, 0.33) and 1-day exposure to ground contamination is the same as strategy 1 in Figures 5.19 and 5.20.

**The mean number of early public health effects within the selected radial intervals can be estimated for actual site population distributions using the information presented in Figures 5.19 and 5.20. For example, if the average site population density in a downwind sector between 0 and 5 miles (number of people between 0 and 5 miles/sector area from 0 to 5 miles) is 25 persons per square mile, then all results presented for that interval would be reduced by approximately a factor of 4. The fact that the actual population within the sector is not uniformly distributed will in general not significantly affect the number of health effects that occur.
these accidents are projected to occur within approximately 10 miles of the reactor, while early injuries are likely out to somewhat larger distances.* Within 5 miles of the reactor, evacuation** appears to be more effective in reducing the number of early health effects than sheltering, as long as the delay time is kept sufficiently small. This distinction is not as apparent in the 5 to 10 mile interval, where, if basements are widely available and the effective exposure time to ground contamination can be reduced to sufficient levels (strategy 4), sheltering may be as effective as evacuation with relatively small delay times. Throughout both of the intervals from 0 to 10 miles, the importance of a rapid and efficient implementation of either evacuation or sheltering is evident (small delay times for evacuation, small ground exposure times for sheltering). Note that evacuation** with delay times of 1 hour or less will reduce the projected number of early public health effects to 0 in any radial interval, and will always be the most effective measure for a severe accident, if it can be achieved. In the intervals beyond 10 miles, there is little apparent distinction between the effectiveness of evacuation and sheltering strategies in terms of projected early fatalities or injuries. The mean

*Projected early fatalities and injuries in the 15 to 25 mile interval are higher than for the 10-15 mile interval because the interval is twice as wide.

**Note that all results presented for evacuation assume that there is no nonparticipating segment of the population, and are thus upper bound estimates. (See Section 4.3.)
number of early fatalities is 0 in both of these intervals, and projected early injuries, although not 0, are greatly reduced for each of the protective strategies investigated. In general, therefore, although protective actions may be required for areas outside of 10 miles, the occurrence of early health effects will be little affected by the actual measures used and how rapidly or efficiently they are implemented.

Finally, to further evaluate the efficacy of iodine prophylaxis as a response action for PWR "Atmospheric" accidents, the projected number of thyroid nodules (benign and malignant)* resulting from early exposure of the thyroid was also calculated. Assuming a uniform population density of 100 persons per square mile, the mean number of thyroid nodules is approximately 4000 if no immediate protective actions are implemented.** Of these, only roughly 25 percent occur within 25 miles of the reactor (7 percent occur within 10 miles). The remaining nodules are distributed approximately as follows: 20 percent occur between 25 and 50 miles, 25 percent occur between 50 and 100 miles, and 30 percent occur at distances greater than 100 miles.*** The immediate

*Roughly 40% of the thyroid nodules would be malignant (cancerous) [2].

** The corresponding 95% level number of thyroid nodules is approximately 8000.

***The approximate mean number of persons affected by the radioactive cloud in each of these distance intervals, assuming 100 persons per square mile, is as follows: 1200 within 10 miles, 7200 within 25 miles, 20,000 between 25 and 50 miles, 75,000 between 50 and 100 miles, and more than 107 at distances greater than 100 miles.
administration of stable iodine* to persons within any of these distance intervals would reduce the projected mean number of nodules in those areas by approximately 75%.

However, unless iodine prophylaxis is administered over very large areas (distances), and correspondingly to very large numbers of people, the total number of thyroid nodules expected for this type of accident will not be substantially reduced.

5.4 Influence of Weather Conditions

The preceding curves for whole body and thyroid dose versus distances were established using a stratified sampling technique on one year of meteorological data,** and represent projected doses averaged over many weather conditions. The actual dose versus distance relationships for any particular accident would depend strongly on the weather conditions that exist during and following the release, and may differ significantly from the curves above. The wind velocity profile from ground level to the top of the plume determines the direction of transport and the initial volume of air into which the contaminant is diluted. Wind speed, thermal stability, and underlying characteristics of the surrounding terrain all effect the rate of dispersal of contaminants.

*99% reduction of thyroid dose due to inhaled radioiodines, no evacuation or sheltering.

**See subsection 3.2 of this report.
in the atmosphere. Rain or other forms of precipitation can rapidly deposit significant fractions of particulates and some gaseous materials from the airborne cloud, resulting in areas with highly concentrated ground contamination.* If a major accident at a nuclear power plant were to occur, it is likely that at least some general information about current local weather conditions would be readily available for use in deciding what protective actions, if any, should be implemented. It is therefore of interest, and seems appropriate, to briefly examine the manner in which the projected dose varies as a function of easily observable weather conditions at the time of the release, and how these variations might influence the relative effectiveness of protective measures.

The weather data included in the Reactor Safety Study consequence model contains hourly recordings of wind speed, thermal stability and the occurrence of precipitation** (see subsection 3.2). Some qualitative effects of these variables on the projected dose curves are examined in Figures 5.21 through 5.26. In each of these figures, whole body

*The effects of weather on the atmospheric dispersion and deposition of contaminants are further discussed in reference [2].

**Although wind direction data is not included specifically in the consequence model, it would be of great importance to authorities responsible for the implementation of protective measures. Note also that the occurrence of precipitation, windspeed and thermal stability are not independent of one another, and that joint frequency distributions of these variables for selected sites are presented in reference [2].
Comparison of Mean Accidents in Which Exist at the Start Located Outdoors, and Release (PWR 1-5). Projected Whole Body Dose Versus Distance for Precipitation and No Precipitation Conditions of Release. Projected Doses are for an Individual and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\( a \) Accidents in which it is precipitating (rain or snow) at the start of release.

\( b \) Accidents in which it is not precipitating (rain or snow) at the start of release.

\( c \) Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
Comparison of 95% Level Projected Whole Body Dose Versus Distance for Accidents in Which Precipitation\textsuperscript{a} and No Precipitation\textsuperscript{b} Conditions Exist at the Start of Release. Projected Doses are for an Individual Located Outdoors,\textsuperscript{c} and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\textsuperscript{a}Accidents in which it is precipitating (rain or snow) at the start of release.

\textsuperscript{b}Accidents in which it is not precipitating (rain or snow) at the start of release.

\textsuperscript{c}Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
Comparison of Mean Projected Whole Body Dose Versus Distance for Accidents in Which High Wind\(^a\) and Low Wind\(^b\) Conditions Exist at the Start of the Release. Projected Doses are for an Individual Located Outdoors,\(^c\) and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\(^a\)Accidents in which the windspeed is greater than 10 MPH at the start of release.

\(^b\)Accidents in which the windspeed is less than 5 MPH at the start of release.

\(^c\)Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
Comparison of 95% Level Projected Whole Body Dose Versus Distance for Accidents in Which High Wind\(^a\) and Low Wind\(^b\) Conditions Exist at the Start of Release. Projected Doses are for an Individual Located Outdoors,\(^c\) and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\(^{a}\)Accidents in which the windspeed is greater than 10 MPH at the start of release.

\(^{b}\)Accidents in which the windspeed is less than 5 MPH at the start of release.

\(^{c}\)Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
Comparison of Mean Projected Whole Body Dose Versus Distance for Accidents that Begin During the Day\textsuperscript{a} and Night.\textsuperscript{b} Projected Doses are for an Individual Located Outdoors,\textsuperscript{c} and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\textsuperscript{a}Accidents in which the release starts between 7:00 a.m. and 7:00 p.m.

\textsuperscript{b}Accidents in which the release starts between 7:00 p.m. and 7:00 a.m.

\textsuperscript{c}Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
Comparison of 95% Level Projected Whole Body Dose Versus Distance for Accidents that Begin During the Day\(^a\) and Night\(^b\). Projected Doses are for an Individual Located Outdoors\(^c\) and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

\(^a\)Accidents in which the release starts between 7:00 a.m. and 7:00 p.m.
\(^b\)Accidents in which the release starts between 7:00 p.m. and 7:00 a.m.
\(^c\)Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.
dose versus distance curves for an individual located outdoors, and conditional on the occurrence of a PWR "Atmospheric" release, are presented for observable weather conditions at the start of release. For example, the curves labeled PRECIPITATION in Figures 5.21 and 5.22 represent the mean and 95\% level dose for accidents in which there is precipitation at the reactor site during the start of the release. The curves were established by randomly selecting 91 accident start times in which there is precipitation from the 8760 hourly recordings available in one year's meteorological data. Weather data for these and succeeding hours were used to calculate the atmospheric dispersion of the cloud as explained in subsection 3.2. No consideration was given in the selection process to whether or not the precipitation continued in subsequent hours. Similarly, the curves labeled NO PRECIPITATION represent accidents in which there is no precipitation when the release begins.* Dose curves are also compared for high (>10 mph) and low (>5 mph) wind speeds at the start of the release and for releases that begin during the day (7 a.m. to 7 p.m.) and night (7 p.m. to 7 a.m.) in Figures 5.23 through 5.26. The comparison of day and night doses predominantly reflects differences in the average thermal stability for those hours: nighttime tends to have much more stable conditions [2]. Although

*Note, however, that precipitation may begin in the hour(s) following the start of release. The apparent increase in dose at short distances in the NO PRECIPITATION curves occurs for this reason.
Figures 5.21 through 5.26 exhibit only projected whole body doses for an individual located outdoors, and are conditional on a PWR "Atmospheric" release, the illustrated effects of weather conditions would be qualitatively similar for other types of accident releases, doses to other organs, and for situations in which protective actions are implemented, as well.

Figures 5.21 and 5.22 indicate that the dose received by individuals in affected areas near the reactor (within approximately 10 miles) is likely to be considerably higher if there is precipitation at the start of release than if there is not. This is due to the high ground concentrations that result from the rapid deposition of radioactive material from the cloud. Response actions* which act to minimize the period of effective exposure to ground contamination might therefore become of increased relative importance in precipitation situations. The PRECIPITATION dose curves eventually drop below the NO PRECIPITATION curves at some distance because a large fraction of the radioactive material has been deposited from the cloud.

Figures 5.23 and 5.24 illustrate that, in general, projected doses at a given distance will decrease with increasing wind speed. Higher wind speeds are associated with improved dispersion conditions and provide a larger initial volume of

*Note that precipitation, or local conditions associated with its occurrence, may be an impediment or constraint to rapid evacuation or relocation.
air in which the released radioactive material is diluted. However, high wind speeds would also result in reduced transport times for the cloud to reach a given population group, allowing less time before evacuating persons would be overtaken by the cloud.

Finally, Figures 5.25 and 5.26 compare the projected doses for releases that begin during the day and night. Because of the more unstable, and thus better dispersion, conditions that generally exist during the day, projected doses for daytime releases tend to be somewhat lower than for those that begin at night. Figures 5.25 and 5.26 illustrate this for distances beyond approximately 5 miles. Projected doses for daytime releases are somewhat higher than for those at night within this distance because of plume rise effects. Because of the large energy content of the cloud released from some accidents within the PWR "Atmospheric" category, significant plume rises is expected for both day and nighttime releases [2].* However, the increased dispersion during daytime hours results in the cloud more rapidly reaching ground level, and thus higher doses at distances close to the reactor.

*Negligible plume rise is expected for PWR "Melt-Through" releases.
Section 6
Summary and Conclusions

This study was undertaken to evaluate, in terms of public radiation exposure and health effects, the relative merits of possible offsite emergency phase protective measures for response to nuclear reactor accidents involving core-melt. Three types of protective measures have been examined and compared: evacuation, sheltering followed by population relocation, and iodine prophylaxis. Evaluations of such measures were conducted using the consequence model of the Reactor Safety Study, with some revision for the modeling of the protective measures examined. Models representing each measure have been developed as part of this study [17,18,19], and were discussed in Section 4.

The potential range of core-melt releases was separated into two categories for PWR accidents, PWR "Melt-through" and "Atmospheric," based on the predicted mode of containment failure. Protective measures have been examined for each of these categories in terms of projected doses to the whole body and thyroid as a function of distance from the reactor. Because of the more severe hazard posed by accidents in the "Atmospheric" category, protective measures for that type of release were examined in terms of their impact on the occurrence of public health effects as well. Although BWR accidents were not dealt with specifically in this work, the
information and conclusions presented for PWRs are qualitatively applicable for BWRs as well, given a similar containment failure mode.

Several important conclusions about the relative effectiveness of the protective measures examined, the distances to which or areas within which they might be required, and the time available for their implementation, can be drawn from the results provided by this analysis. Projected doses for accidents in the PWR "Melt-through" category are generally low compared to threshold levels for early health effects, and few, if any, early fatalities or injuries are likely. Furthermore, projected whole body and thyroid doses in excess of Protective Action Guides (PAGs) for those organs are, for all practical purposes, confined to areas within 10 miles of the reactor. Emergency phase response planning for this type of accident should therefore be primarily directed towards limiting the dose to those individuals located within that distance. For persons at any distance, evacuation, even with delay times of 5 hours or longer, appears to provide larger reductions in projected whole body dose than sheltering. This is due, in large part, to the fact that the release duration assumed for the "Melt-through" category is very long (10 hours), and that evacuated persons will therefore avoid exposure to a significant portion of the cloud even with a relatively long delay time. However, sheltering, particularly in areas where most homes have basements, also
offers substantial reductions in whole body dose, and may offer an acceptable alternative to evacuation. Iodine prophylaxis, if administered in sufficient time, and evacuation with small delay times both offer substantial reductions in the projected dose to the thyroid for PWR "Melt-through" accidents.

In contrast to the "Melt-through" category, PWR "Atmospheric" accidents could result in the occurrence of significant numbers of early fatalities and injuries. Both whole body and thyroid PAGs are likely to be exceeded at very large distances from the reactor, and correspondingly over very large areas. However, doses in excess of threshold levels for early health effects are confined to areas much closer to the reactor. Therefore, if an accident of this type should occur, responsible authorities might choose to concentrate their immediately available resources on limiting the life- and injury-threatening doses to individuals in those closer areas.* Most early fatalities are projected to occur within approximately 10 miles of the reactor, while early injuries are likely out to somewhat larger distances. Within 5 miles of the reactor, evacuation appears to be more effective than sheltering in reducing the number of early health effects, as long as the delay time and nonparticipating fraction of the population can be kept sufficiently

*Then, if sufficient resources are available, protective measures might also be implemented for individuals at larger distances for whom PAGs are, or are likely to be, exceeded.
small. Between 5 and 10 miles, this distinction is not as apparent, and sheltering in areas where basements are widely available (followed by rapid relocation) may be as effective as evacuation with relatively small delay times. For all affected areas within approximately 10 miles of the reactor, the speed and efficiency with which either evacuation or sheltering and relocation are implemented strongly influence the number of projected early health effects. For areas beyond 10 miles, there is little apparent distinction between the effectiveness of evacuation and sheltering strategies in terms of projected early fatalities or injuries. Therefore, although protective actions may be required for individuals located in areas further than 10 miles from the reactor for an "Atmospheric" release, the actual measures used, and how rapidly or efficiently they are implemented, will not strongly influence the number of projected early health effects. Because of the large thyroid doses projected for PWR "Atmospheric" accidents, the number of thyroid nodules resulting from early exposure of that organ was also estimated in this analysis. The immediate administration of stable iodine to persons in areas at any distance from the reactor was shown to reduce the number of nodules in those areas by roughly 75 percent. However, unless iodine prophylaxis is administered over very large areas (distances), and correspondingly to very large numbers of people, the total number of thyroid nodules projected for this type of accident will not be
substantially reduced. Finally, the qualitative effects of weather conditions on the conclusions above were briefly discussed in subsection 5.4. Projected whole body doses to individuals in affected areas near the reactor were shown to be considerably higher if there is precipitation at the start of release than if there is not. Projected doses were also shown to decrease with increasing wind speed, and to be generally lower for daytime releases than for those that begin at night.
REFERENCES

1. Code of Federal Regulations, Title 10, Part 50, Appendix E.


Appendix A

Sheltering Concepts with Existing Public and Private Structures
PUBLIC PROTECTION STRATEGIES FOR
POTENTIAL NUCLEAR REACTOR ACCIDENTS:
SHELTERING CONCEPTS WITH EXISTING
PUBLIC AND PRIVATE STRUCTURES

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Abstract

Three generic sheltering/relocation strategies are identified and discussed. They are (1) population relocation only (no specific sheltering response initiated), (2) sheltering at location followed by relocation, and (3) preferential sheltering followed by relocation. Shielding factors representative of these strategies are calculated, and the adequacy of using average shielding factors for the calculation of public health effects is discussed.
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</table>
I. INTRODUCTION

If an accident should occur at a nuclear power reactor resulting in inadequate cooling of the fuel and subsequent loss of clad integrity, there is a possibility of release to the atmosphere of significant quantities of radioactive material. As a result of such a release the public may receive early radiation doses* through three exposure modes. These include: (1) exposure to external penetrating radiation as the radioactive material cloud passes; (2) exposure to external penetrating radiation from radionuclides deposited on the ground and other surfaces during cloud passage; and, (3) exposure due to radionuclides inhaled during passage of the cloud. Because of the internal retention of inhaled radionuclides, this latter pathway also leads to a radiation dose delivered to the individual continually during the remaining years of his life.

Protection strategies to limit or mitigate the radiation exposure and therefore the consequences of such exposure, to the general public are of prime concern to those responsible for radiological emergency planning and response. Two important elements of any protection strategy are public acceptance of, and the ability to implement, the measures proposed. There has been considerable discussion of evacuation, which is an expeditious movement of people to avoid exposure to the passing cloud, as a possible...

*Early radiation dose is that dose received within the first few days following the accident.
protective measure. A simple evacuation model was, in fact, included in the consequence model developed for the Reactor Safety Study [1]. Our studies support the view that it is desirable to consider alternative or supplemental strategies to evacuation that include population sheltering followed by the selective relocation of affected persons [2]. The shielding inherent in building structures can afford protection against exposure to the external sources of radiation cited above. Furthermore, the exclusion of a significant amount of airborne radioactive material from the interior of a structure, either by natural effects or by certain ventilation strategies, could reduce the amount of radionuclides inhaled as well [3]. Therefore, for the purposes of this report, sheltering is defined as a deliberate action by the public to take advantage of the inherent radiation shielding available in normally inhabited structures by remaining indoors, away from doors and windows, during and after the passage of the cloud of released radioactive material. Population relocation is a post-accident action designed to limit radiation exposure from ground contamination.

This report discusses the potential of sheltering and relocation strategies for limiting the dose from the two external radiation pathways described above. Estimates of shelter effectiveness are presented for specific building types. Three generic sheltering/relocation strategies are identified and average shielding factors representative of these strategies are calculated. These shielding factors reflect regional differences in the relative numbers of brick and wood homes and of homes with basements, as well as temporal differences in building occupancy. The effectiveness
of sheltering/relocation strategies in terms of limiting public health effects will be considered in subsequent papers.

II. BACKGROUND

The shielding from airborne and surface deposited radionuclides afforded by conventional building structures is well understood and discussed in the literature [1,4]. The shielding effectiveness of a structure is expressed 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. Burson and Profio [4] have made estimates of shielding for several distinct building types using currently available shielding technology. Their estimates of representative shielding factors for airborne radionuclides, assuming a semi-infinite cloud of gamma emitting material surrounding the structure, are summarized in Table 1. The energy of the gamma ray assumed in the calculations is characteristic of what might be expected from a reactor accident. A summary of the shielding factors that they suggest for radio-
uclides deposited on the ground and other surfaces (walls and roof of the structure), assuming uniform deposition around the structure, is presented in Table 2.

III. SHELTERING/RELOCATION STRATEGIES

The estimates of Burson and Profio [4] presented in Tables 1 and 2 indicate (1) the wide range of potential shielding factors afforded by normally inhabited structures, and (2) that basements of both homes and larger buildings offer very effective shielding against radiation. Therefore, the efficacy of a sheltering strategy depends to a large extent on the type of structures the public inhabits.

*The shielding factor is often referred to in the literature as the reduction factor.
<table>
<thead>
<tr>
<th>Structure or Location</th>
<th>Shielding Factor (a)</th>
<th>Representative Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Vehicles</td>
<td>1.0</td>
<td>--</td>
</tr>
<tr>
<td>Wood-frame house (b) (no basement)</td>
<td>0.9</td>
<td>--</td>
</tr>
<tr>
<td>Basement of wood house</td>
<td>0.6</td>
<td>0.1 to 0.7&lt;sup&gt;(c)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Masonry house (no basement)</td>
<td>0.6</td>
<td>0.4 to 0.7&lt;sup&gt;(c)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Basement of masonry house</td>
<td>0.4</td>
<td>0.1 to 0.5&lt;sup&gt;(c)&lt;/sup&gt;</td>
</tr>
<tr>
<td>Large office or industrial building</td>
<td>0.2</td>
<td>0.1 to 0.3&lt;sup&gt;(c,d)&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

(a) The ratio of the dose received inside the structure to the dose that would be received outside the structure.
(b) A wood frame house with brick or stone veneer is approximately equivalent to a masonry house for shielding purposes.
(c) This range is mainly due to different wall materials and different geometries.
(d) The shielding factor depends on where the personnel are located within the building (e.g., the basement or an inside room).
TABLE 2. REPRESENTATIVE SHIELDING FACTORS FOR SURFACE DEPOSITED RADIONUCLIDES (from Ref. 4)

<table>
<thead>
<tr>
<th>Structure or Location</th>
<th>Representative Shielding Factor (a)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 m above an infinite smooth surface</td>
<td>1.00</td>
<td>--</td>
</tr>
<tr>
<td>1 m above ordinary ground</td>
<td>0.70</td>
<td>0.47-0.85</td>
</tr>
<tr>
<td>1 m above center of 50-ft roadways, 50% decontaminated</td>
<td>0.55</td>
<td>0.4-0.6</td>
</tr>
</tbody>
</table>

Cars on 50-ft road:

- Road fully contaminated: 0.5, 0.4-0.7
- Road 50% decontaminated: 0.5, 0.4-0.6
- Road fully decontaminated: 0.25, 0.2-0.5

Trains:

- 0.40, 0.3-0.5

(b) Away from doors and windows.

One- and two-story wood-frame house (no basement):

- 0.4, 0.2-0.5

One- and two-story block and brick house (no basement):

- 0.2, 0.04-0.40

House basement, one or two walls fully exposed:

- 0.1, 0.03-0.15

- 0.05, 0.03-0.07

- 0.03, 0.02-0.05

Three- or four-story structures, 25000 to 10,000 ft per floor:

- 0.05, 0.01-0.08 (b)

- 0.01, 0.001-0.07 (b)

Multistory structures, >10,000 2 ft per floor:

- 0.01, 0.001-0.02 (b)

- 0.005, 0.001-0.015 (b)

(a) The ratio of dose received inside the structure to the dose that would be received outside the structure.

(b) Away from doors and windows.
as well as how long they remain there before being relocated away from ground contaminated by radioactive material.

Three generic sheltering/relocation strategies are identified here and discussed below. They are (1) population relocation only (no specific sheltering response initiated), (2) sheltering at location followed by relocation, and (3) preferential sheltering followed by relocation.

Population relocation is an action taken sometime after passage of the cloud of radioactive material to limit radiation exposure from ground contamination. Before relocation, the exposure that individuals receive from airborne and surface deposited radionuclides depends on the radiation shielding available from the particular structure they are inhabiting. Because a large percentage of the public is located indoors most of the time [5] (see Appendix A), some radiation shielding will be afforded the public even if no specific sheltering response is initiated (i.e., the public continues its normal activities; strategy (1) above). This protection was recognized in the Reactor Safety Study [1] and was used there to calculate health effects for populations located at distances greater than that assumed for evacuation. Note, however, that this protection applies to the public only in an average sense; by virtue of their normal activities some persons will be outdoors during the radiation exposure incident and will receive little if any benefit from structural shielding.

Additional protection, beyond that automatically afforded as a result of normal activities, could be achieved by initiating a sheltering strategy. One such strategy is sheltering at location (strategy (2) above) in which persons are directed to remain
indoors at their present location, or to move indoors if they are outside, preferably occupying basements if they are available. Additional benefit might be derived from a strategy of employing preferential sheltering locations (strategy (3) above); for example, directing people to those neighboring homes with basements or to nearby large buildings such as schools, public office buildings or public fallout shelters.

The time required to implement a sheltering/relocation strategy significantly influences the effectiveness of each of the response strategies discussed here. Ideally, shelter-access by the public would be accomplished prior to the arrival of the cloud of radioactive material. If this cannot be accomplished, the effectiveness (dose reduction) diminishes almost linearly with increasing outside exposure time [6]. Radiation exposure from radionuclides deposited on the ground and other surfaces continues long after cloud passage and, in many instances, in a relatively short time results in a dose much greater than the dose from the other exposure pathways. Therefore, the time interval between the cloud passage and the public relocation is also very important and should be minimized.

IV. REPRESENTATIVE SHIELDING FACTORS

In order to evaluate the three sheltering/relocation strategies identified above, shielding factors representative of each strategy must be obtained. The Burson and Profio [4] shielding factors presented in Tables 1 and 2 above may be used to evaluate preferential sheltering in specific building types; (strategy (3)). However, the remaining two strategies require some knowledge or estimate of the frequency distribution of the occupancy for various types of buildings as well as the availability and occupancy of basements.
Average shielding factors for the strategy in which no specific sheltering response is initiated (i.e., the public continues its normal activities; strategy (1)) were established in the Reactor Safety Study [1]. In that study, data on the frequency of occupancy for different building types (Appendix A), the percentage of brick housing units (Appendix B), and the Burson and Profio shielding factors (Tables 1 and 2) were permuted to obtain average shielding factors for five geographic regions* within the U.S. The average shielding factors for airborne radionuclides obtained in this manner ranged from 0.66 to 0.83 over the five regions, while those for radionuclides deposited on the ground and other surfaces ranged from 0.26 to 0.38. Both of these ranges are quite small and average values of 0.75 and 0.33, respectively, are adequate regardless of geographic region. The occupancies of different building types assumed in these calculations were averaged over a 7-day week (see Appendix A). However, the occupancy of buildings at any particular time may vary substantially from the average values; for example, at night most people will be at home, during a weekday many people will be at school or work, etc... Calculations similar to those of the Reactor Safety Study were performed using a variety of assumptions for building occupancy. Here, the average regional shielding factors for airborne radionuclides ranged from 0.64 to 0.82, while those for radionuclides deposited on the ground and other surfaces ranged from 0.28 to 0.37. These ranges indicate that the computed average shielding factors are quite insensitive to building occupancy and that the values of 0.75 for airborne

*States were grouped into regions based on the percentage of brick housing units within the state.
radionuclides and 0.33 for ground contamination are sufficient for all instances in which no specific sheltering strategy is employed.

In order to represent the strategy of deliberately sheltering persons on location (strategy (2)), average shielding factors were calculated that reflect temporal differences in the occupancy of different building types and regional differences in the relative numbers of brick and wood homes and of homes with basements. For this strategy, persons are assumed to be sheltered in basements when available to take advantage of the increased shielding that they provide. Data from the 1970 Housing Census (Appendix C) was used to estimate the fraction of homes with basements for each state and seven geographic regions.* Since no correlation is available between the frequency of basements and the type of house construction, the frequency of basements within a region was assumed to be the same for wood and brick homes. Data on the percent of brick versus wood construction (Appendix B), basement frequency, and various assumed occupancies were permuted, as in the Reactor Safety Study, using the following selected shielding factors from Tables 1 and 2 above.

**TABLE 3. SELECTED SHIELDING FACTORS FOR AIRBORNE RADIONUCLIDES**

<table>
<thead>
<tr>
<th>Type of Building</th>
<th>Shielding Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood house, no basement</td>
<td>0.9</td>
</tr>
<tr>
<td>Wood house, basement</td>
<td>0.6</td>
</tr>
<tr>
<td>Brick house, no basement</td>
<td>0.6</td>
</tr>
<tr>
<td>Brick house, basement</td>
<td>0.4</td>
</tr>
<tr>
<td>Large office or industrial building</td>
<td>0.2</td>
</tr>
<tr>
<td>Outside</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*The seven geographic regions were chosen to correspond to the seven reactor sites selected in the Reactor Safety Study [1] as being representative of the variability in climatic and topographic features. They are: Northeast, Great Lakes, Southwest, Midwest, Pacific Coast, Atlantic Coast and Southeast.
TABLE 4. SELECTED SHielding FACTORS FOR SURFACE DEPOSITED RADIonuclIDES

<table>
<thead>
<tr>
<th>Location</th>
<th>Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood house, no basement</td>
<td>0.4</td>
</tr>
<tr>
<td>Wood house, basement</td>
<td>0.05</td>
</tr>
<tr>
<td>Brick house, no basement</td>
<td>0.2</td>
</tr>
<tr>
<td>Brick house, basement</td>
<td>0.05</td>
</tr>
<tr>
<td>Large office or industrial building</td>
<td>0.02</td>
</tr>
<tr>
<td>Outside</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Locations of individuals are categorized as either (1) home, (2) school or work, and (3) commuting or outdoors.* As in the Reactor Safety Study, for the school or work category it is assumed that one-third of the people are in large offices or similar structures, and that the remaining people are in buildings having a distribution of construction types similar to that of the local single-family dwellings, i.e., the same percentage of brick buildings and buildings with basements. This assumption is believed to be conservative since government agencies (federal, state, and municipal) employ about 30% of the work force, and public buildings are usually substantial structures. No additional protection due to basement occupation is assumed for the 30% in large office or industrial buildings. This assumption has minimal impact on the resulting average shielding factors. Table 5 presents the average shielding factors calculated in each geographic region for four representative assumptions of building occupancy. Column A (78% home, 22% school school or work, 0% outside or commuting) is based on the weekly average data presented in Appendix A, assuming that all persons

*Commuting and outdoors, which were separate categories in the RSS, are combined here for simplification. Persons in this category receive shielding factors of 1.0 (cloud) and 0.7 (ground).
TABLE 5. REGIONALLY AVERAGED SHIELDING FACTORS FOR SHELTERING AT LOCATION

<table>
<thead>
<tr>
<th>Region</th>
<th>A. &quot;Weekly Average&quot;</th>
<th>B. &quot;Weekly Average w. 10% outside&quot;</th>
<th>C. &quot;Weekday&quot;</th>
<th>D. &quot;Night&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cloud</td>
<td>Ground</td>
<td>Cloud</td>
<td>Ground</td>
</tr>
<tr>
<td>1. Northeast</td>
<td>0.5</td>
<td>0.08</td>
<td>0.6</td>
<td>0.1</td>
</tr>
<tr>
<td>2. Great Lakes</td>
<td>0.6</td>
<td>0.1</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>3. Southwest</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>4. Midwest</td>
<td>0.5</td>
<td>0.09</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>5. Pacific Coast</td>
<td>0.7</td>
<td>0.3</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>6. Atlantic Coast</td>
<td>0.6</td>
<td>0.2</td>
<td>0.6</td>
<td>0.2</td>
</tr>
<tr>
<td>7. Southeast</td>
<td>0.7</td>
<td>0.2</td>
<td>0.7</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Assumed population locations:

<table>
<thead>
<tr>
<th>Home</th>
<th>School or Work</th>
<th>Commuting or Outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>78%</td>
<td>22%</td>
</tr>
<tr>
<td>B.</td>
<td>70%</td>
<td>20%</td>
</tr>
<tr>
<td>C.</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>D.</td>
<td>100%</td>
<td>0%</td>
</tr>
</tbody>
</table>

1. Shielding factors for cloud of radioactive material.
2. Shielding factors for ground and other surface deposited radionuclides.
either commuting or outdoors are moved indoors (they are assumed to occupy various building types with the same frequency as those already inside). Column B (70% home, 20% school or work, 10% outside or commuting) is similar, but assumes that 10% of the public remains outside. Columns C (40% home, 60% school or work, 0% outside or commuting) and D (100% home) employ estimates of population location for a weekday and for nighttime, respectively. Here, the average shielding factors for airborne radionuclides range from 0.5 to 0.8 and those for ground and other surface deposited radionuclides range from 0.08 to 0.3. Therefore, the range of protection offered by this sheltering strategy is well represented by two sets of "cloud" and "ground" shielding factors, (0.5, 0.08) and (0.75, 0.33), where the upper values are chosen to be the same as the "normal activity" values discussed earlier.

V. ADEQUACY OF USING AVERAGE SHIELDING FACTORS

Use of the average shielding factors described in the previous section for the assessment of radiological consequences results in the assignment of average doses to all individuals within a given area rather than the distribution of doses that would actually occur due to the variation in shielding protection afforded individuals. In other words, the average dose to the area population is calculated rather than the dose to individuals within the area. The adequacy of this simplification must be established.

The calculation of latent health effects is based on the population dose (integral of population times dose which is expressed as man-rem) rather than individual doses. Therefore,
latent health effects estimated using an average shielding factor would be identical to the results calculated using the appropriate distribution of shielding factors if a linear dose response model is assumed. However, early fatalities and early injuries are threshold effects and are calculated based on the dose to individuals. It is possible that dose values calculated using an average shielding factor may fall below a threshold level while, in fact, some members of the population have received doses in excess of this value (due to differences in the inherent shielding afforded by different building types, being outside, etc.). For this reason, the use of average shielding factors may introduce some error in the calculation of early health effects.

To estimate the potential error introduced by the assumption of average shielding factors, early health effects were calculated using several assumed shielding factor distributions (for example, 40% of population with cloud and ground SF's (0.9, 0.4), 40% with (0.6, 0.2), 10% with (0.2, 0.02) and 10% with (1.0, 0.7)) and compared to the early health effects calculated using the corresponding average shielding factors ((0.72, 0.31) in this example). Calculations were performed for a PWR2 release [1] using a stratified sample of 91 accident start times for the selection of weather during the release, meteorological data for a single reactor site, and an assumed uniform population density of 100 persons per square mile. Over the range of potential

---

\(^a\) Latent health effects estimated using an average shielding factor are nearly identical to the results calculated using the appropriate distribution of shielding factors when nonlinear dose response models are assumed.

\(^b\) Previous work has indicated that potential errors in the calculation of early effects due to the assumption of average shielding factors are more pronounced for the large release categories (PWR1 and PWR2).
shielding factors, the mean number of early fatalities calculated using the average shielding factors was 0-25% lower than the number obtained using the corresponding (and more appropriate) shielding factor distribution. The estimated peak number of early fatalities ranged from 4% higher to 20% lower when using average shielding factors. Both the mean and peak number of early injuries were only from 1-3% lower with average shielding factors.

The ranges of potential error presented above apply only for the specific release and assumptions noted, i.e., for mean values of early fatalities and injuries from 91 different accident start times. Potential errors in calculations for any specific meteorological sequence may fall outside this range. For population distributions other than uniform, e.g., a distribution peaked at a distance for which calculated doses are close to a threshold value, the discrepancy could be very much larger than is indicated above.

In conclusion, it appears that in most instances the use of average shielding factors will contribute only small errors compared to the overall uncertainties determined by all the other factors required in the consequence assessment, and therefore their use should be adequate in most situations. Nevertheless, under particular circumstances the errors introduced in the consequence assessment could be extremely large. Therefore, this possibility should be kept in mind whenever using average shielding factors, and care should be taken in interpreting results calculated using them.
VI. SUMMARY

Three generic sheltering/relocation strategies have been identified and discussed. They are (1) population relocation only (no specific sheltering response initiated), (2) sheltering at location followed by relocation, and (3) preferential sheltering followed by relocation. Shielding factors representative of these strategies have been calculated. The Burson and Profio [4] shielding factors presented in Tables 1 and 2 above may be used to calculate preferential sheltering in specific building types; (strategy (3)). Average shielding factors of 0.75 for airborne radionuclides and 0.33 for ground contamination were shown to be sufficient for instances in which no specific sheltering strategy is employed; (strategy (1)). The range of protection offered by the strategy of sheltering at location (strategy (2)) was shown to be well represented by two sets of "cloud" and "ground" shielding factors; (0.5, 0.08) and (0.75, 0.33). The range reflects regional differences in the numbers of brick and wood homes and of homes with basements, as well as temporal differences in building occupancy. The adequacy of using average shielding factors for the calculation of public health effects was discussed in section V.
REFERENCES


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APPENDIX A

Time-Use Study

The Robinson and Converse time-use study* estimated the fraction of time the public spends in various activities. Because the study selectively sampled only the adult population below 65 years of age, retired and student populations are not fully represented. However, data from the time-use study was used in the Reactor Safety Study [1] to estimate the fraction of time the population spends in various locations since (1) it gives actual measured data and (2) the student population (28% of the total population), though it might be expected to have more outdoor activity than the adult population, should be somewhat balanced by infants and retired persons (about 18% of the population), who presumably have less outside activity. Activities reported by the time-use study were categorized into four general locations; home, school or work, commuting, and outdoors. The hours per day spent at each location, or activity, averaged over a 7-day week are presented below.

<table>
<thead>
<tr>
<th>Location or Activity</th>
<th>Hours per day</th>
<th>Fraction of Total Time (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>16.6</td>
<td>69.2</td>
</tr>
<tr>
<td>School or work</td>
<td>4.7</td>
<td>19.6</td>
</tr>
<tr>
<td>Commuting</td>
<td>1.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Outdoors</td>
<td>1.5</td>
<td>6.2</td>
</tr>
</tbody>
</table>

APPENDIX B

Brick/Wood Housing Units

Data concerning the percentage of brick housing units within each state was presented in the Reactor Safety Study [1] and is repeated here. Figure B1 indicates graphically the percentages of family housing units that are brick for different parts of the country; the wide variation is conveniently categorized within five regions. Data for this figure were derived from the 1970 Census of Housing* and the 1971 FHA Homes, Data for States and Selected Areas** data book published by the Department of Housing and Urban Development (HUD). The HUD book gives statistics by state for existing single-family homes sold under the Federal Housing Administration (FHA) Section 203 program. These data show percentages of those existing (used) houses sold that have brick, stone, or concrete-block exteriors. These percentages have been assumed to be typical of all single-family houses within the state. The data were then adjusted to account for multifamily structures, which were assumed to be of heavy construction (i.e., brick). By using the housing census data on multifamily structures, the percentage of brick or equivalent housing units was estimated as follows:

\[
\text{% multifamily units} + \text{% single-family homes} \times (\text{fraction that are brick})
\]

As for the basement data in Appendix C, representative percentages of housing units that are brick were estimated for seven geographic regions: Northeast, Great Lakes, Southwest, Midwest, Pacific Coast, Atlantic Coast and Southeast. The states comprising these regions are listed in Appendix C. The


FIGURE B1. Percentage of Brick Housing Units by Region (from Ref. 1)
percentages for each state included within a region (mid-values were assumed for the ranges in Figure B1), weighted by the number of housing units in that state, were averaged to obtain the following regional percentages of brick housing units.

<table>
<thead>
<tr>
<th>Region</th>
<th>% brick housing units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>47</td>
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<tr>
<td>Great Lakes</td>
<td>36</td>
</tr>
<tr>
<td>Southwest</td>
<td>40</td>
</tr>
<tr>
<td>Midwest</td>
<td>35</td>
</tr>
<tr>
<td>Pacific Coast</td>
<td>27</td>
</tr>
<tr>
<td>Atlantic Coast</td>
<td>45</td>
</tr>
<tr>
<td>Southeast</td>
<td>59</td>
</tr>
</tbody>
</table>
APPENDIX C

Basement Data

Basement data from the 1970 U.S. Housing Census* is presented for each state in Table C1. The total number of basements in each state was divided by the number of year-round housing units to estimate the percentage of homes with basements for that state. As indicated, over 50% of U.S. homes have a basement. Also note that there is no correlation available between basements and type of house construction.

The percentages of homes with basements are typically similar for states within the same geographic area. Basement data for individual states were combined to estimate representative percentages for seven geographic regions: Northeast, Great Lakes, Southwest, Midwest, Pacific Coast, Atlantic Coast, and Southeast. The total number of basements in each region (i.e., the sum of the numbers for each state in the region) was divided by the total number of year-round housing units to estimate the percentage of homes with basements for that region. The states comprising each region, and the basement percentages calculated are listed below.

<table>
<thead>
<tr>
<th>Region</th>
<th>% homes with basements</th>
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<td>87</td>
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<tr>
<td>(Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New York, Pennsylvania, Rhode Island, Vermont and West Virginia)</td>
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</tr>
<tr>
<td>Great Lakes</td>
<td>77</td>
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<tr>
<td>(Illinois, Indiana, Michigan, Minnesota, Ohio and Wisconsin)</td>
<td></td>
</tr>
<tr>
<td>Southwest</td>
<td>13</td>
</tr>
<tr>
<td>(Arizona, California, Nevada, New Mexico, Oklahoma, Texas, Utah and Wyoming)</td>
<td></td>
</tr>
<tr>
<td>Midwest</td>
<td>71</td>
</tr>
<tr>
<td>(Colorado, Illinois, Indiana, Iowa, Kansas, Montana, Nebraska, North Dakota, South Dakota and Idaho)</td>
<td></td>
</tr>
<tr>
<td>Pacific Coast</td>
<td>23</td>
</tr>
<tr>
<td>(California, Oregon and Washington)</td>
<td></td>
</tr>
<tr>
<td>Atlantic Coast</td>
<td>51</td>
</tr>
<tr>
<td>(Connecticut, Delaware, Florida, Georgia, Maine, Maryland, Massachusetts, New Jersey, North Carolina, Rhode Island, South Carolina and Virginia)</td>
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</tr>
<tr>
<td>Southeast</td>
<td>16</td>
</tr>
<tr>
<td>(Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, South Carolina and Tennessee)</td>
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TABLE Cl. BASEMENT DATA FROM 1970 U.S. HOUSING CENSUS

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<tr>
<th>State</th>
<th>Year-round housing units</th>
<th>Basements w. basements</th>
<th>% homes</th>
<th>Year-round housing units</th>
<th>Basements w. basements</th>
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<td>Alabama</td>
<td>1,114,845</td>
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<td>R. P. Campbell</td>
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Appendix B

Multicompartment Ventilation Model for Shelters
Public Protection Strategies in the Event of a Nuclear Reactor Accident: Multicompartment Ventilation Model for Shelters

David C. Aldrich, David M. Ericson, Jr.

Prepared by Sandia Laboratories, Albuquerque, New Mexico 87115 and Livermore, California 94550 for the United States Nuclear Regulatory Commission under DOE Contract AT (29-1)-789

Printed January 1978
PUBLIC PROTECTION STRATEGIES IN THE EVENT OF A NUCLEAR REACTOR ACCIDENT: MULTICOMPARTMENT VENTILATION MODEL FOR SHELTERS

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Albuquerque, New Mexico 87115

ABSTRACT

A multicompartment ventilation model is presented for the calculation of airborne radioactive material concentrations internal to structures. The model is used to estimate the potential effectiveness of sheltering in reducing the dose due to inhaled radionuclides. The sensitivity of the model to parameter values and protection strategies is discussed. Using "best estimate" values for the model parameters, this analysis indicates that sheltered individuals receive a reduction of 35% in the dose from inhaled radionuclides. Preliminary work suggests that basements or other appropriately sealed-off rooms may provide further reductions. This analysis also indicates that the strategy of opening doors and windows, turning on ventilating systems, etc., in an attempt to "air-out" the structure after the cloud of radioactive material has passed will most likely not contribute significantly to reduction in dose due to inhaled radionuclides unless very low initial ventilation rates are achieved.
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PUBLIC PROTECTION STRATEGIES IN THE EVENT OF A NUCLEAR REACTOR ACCIDENT: MULTICOMPARTMENT VENTILATION MODEL FOR SHELTERS

I. INTRODUCTION

If an accident should occur at a nuclear power reactor that leads to inadequate cooling of the fuel, there is a possibility of release to the atmosphere of significant quantities of radioactive material. As a result of such a release the public may receive early radiation doses* through three exposure modes. These include: (1) exposure to external radiation as the cloud passes; (2) exposure to external radiation from radionuclides deposited on the ground and other surfaces during cloud passage; and, (3) internal exposure due to radionuclides inhaled from the passing cloud. This latter pathway also leads to a late time dose because of the internal retention of inhaled radionuclides.

Protection strategies to limit or mitigate the radiation exposure and the consequences of such exposure to the general public are of prime concern to those responsible for radiological emergency planning and response. A vital element of any protection strategy is public acceptance and implementation of the measures proposed. There has been considerable discussion of evacuation as a possible protective measure. A description of a simple evacuation model was, in fact, included in the consequence model developed for the Reactor Safety Study [1]. Our recent studies have supported the desirability of considering alternative or supplemental strategies.

*Early radiation dose is that due to exposure within the first few days following the accident.
to evacuation that include population sheltering. For our purpose sheltering is defined as deliberate action by the public to take advantage of the inherent radiation shielding available in normally inhabited structures by remaining indoors away from doors and windows while the radioactive cloud passes. The inherent structural shielding can afford protection against exposure to the external sources cited above. Furthermore, the exclusion of a significant amount of airborne radioactive material from the interior of a structure, either by natural effects or certain ventilation strategies, could reduce the amount of inhaled radionuclides as well.

In the consequence model of the Reactor Safety Study [1] radiation dose from inhaled radionuclides is calculated as the product of the time integrated air exposure (Ci·s/m³), the breathing rate (m³/s) and a dose conversion factor (rem/Ci inhaled). This dose is then added on an organ by organ basis to the dose obtained through the external modes to establish the early health effects associated with the postulated atmospheric release. Results in the Reactor Safety Study [1] indicate that early mortalities are primarily due to bone marrow damage to which the dose from inhaled radionuclides is only a minor contributor. One would thus not expect that reduction of the dose from inhaled radionuclides, by itself, would significantly reduce the number of early mortalities. However, under some circumstances latent health effects can be dominated by radiation dose received through inhalation of radionuclides.* Therefore, as part of the development of protection strategies it is appropriate to investigate the long and short

*With the set of postulated accident sequences in the RSS this occurs in the BWR1 and PWR1 release categories with their proportionately high Kr releases.
term benefits that will accrue from the reduction of inhaled radio-
nuclides.

This paper describes a model developed to predict the possible
dose reductions and then presents some estimates of the potential
effectiveness of a sheltering strategy in reducing the dose due to
inhaled radionuclides. The effectiveness of sheltering in reducing
the dose from external radiation will be considered in subsequent
papers.

II. BACKGROUND

Shelter or structure ventilation models for the calculation
of airborne concentration of materials internal to structures
have been discussed in the literature [2,3]. However, those
discussions have generally been concerned with a homogeneously
mixed single-compartment model of a structure. The mathematical
description of a single-compartment model is discussed in detail
in a later section of this paper. Tracer gas measurements conducted
by researchers at Princeton [4] and others [5] indicate that the
single-compartment model provides a satisfactory description of
airborne concentrations of materials in structures under some
circumstances. However, if portions of the structure are adequately
sealed off (for instance, a basement or interior room with doors
closed and taped to seal cracks, etc.), then air exchange with the
main body of the structure will occur very slowly, and the assumption
of a homogeneously mixed single-compartment will no longer be valid.
Past studies using the single-compartment model for dose reduction
calculations indicate that one of the most important parameters
of the structure is the ventilation or infiltration rate of external

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air into the interior of the structure. This infiltration rate is a function of the structure construction and the prevailing meteorological conditions, especially the wind speed. Therefore it seems probable that for any given structure the infiltration rate could vary substantially between a basement and the upper stories. Furthermore, it seems apparent that sheltering strategies will employ basements or interior rooms to take advantage of the increased protection against exposure to external radiation. Therefore, the possible differences in infiltration and concentration behavior between these "isolated" sections of a structure and the balance of the structure may lead to important differences in the dose due to inhaled radionuclides. To explore and account for this difference, a two-compartment model that considers different exterior/interior infiltration rates plus exchange between the compartments was developed. The parameter values used in the model are also discussed along with some results, including sensitivity to the parameter values and protection strategies.

III. SINGLE-COMPARTMENT MODEL

The simplest model available for the estimation of in-structure airborne radioactive material concentrations and resulting radiation dosage* employs external air infiltration into a single-compartment in which homogeneous and instantaneous mixing is assumed. This model

*The dosage is the time integral of exposure to the airborne radioactivity and has units of Ci-s/m. The product of this dosage and respiration rate (m/s) yields the total quantity of radioactive material inhaled.
can be expanded to include radioactive decay, deposition of material onto surfaces within the structure and cleanup of air by internal recirculation through appropriate filter media. A visual representation of this expanded model is shown in Figure 1.

Figure 1: Single-Compartment Model
The following definitions apply:

$C_o(t)$ - radioactive material concentration in outside air (Ci/m$^3$)

$C_i(t)$ - radioactive material concentration in inside air (Ci/m$^3$)

$Q_i$ - air flow into and out of structure (m$^3$/hr)

$Q_r$ - recirculating air flow (m$^3$/hr)

$V_i$ - structure (compartment) volume (m$^3$)

$\lambda$ - radioactive decay constant (hr$^{-1}$)

$E_r$ - efficiency of filter in recirculation loop

$D$ - deposition coefficient (hr$^{-1}$) = $v_d/h$

$v_d$ - in-structure deposition velocity (m/hr)

$h$ - compartment height (m)

$\xi$ - ingress fraction = (1 - fraction removed upon entry by impaction or "filtering" through cracks)

$t_0$ - duration of radioactive cloud passage (hr)

Employing a straightforward material balance argument the following differential equation can be derived which describes the time behavior of the radioactive material concentration within the structure.

$$\frac{dC_i(t)}{dt} = C_o(t) \xi n - C_i(t) [n + \lambda + kE_r + D] . \quad (1)$$

where: $n = Q_i/V_i$ = external air infiltration rate (volumes/hr)

$k = Q_r/V_i$ = internal air recirculation rate (volumes/hr)
Although the outside concentration \( C_0(t) \) will vary with time as the radioactive cloud passes, the solution of equation (1) for other than the most elementary expressions for \( C_0(t) \) is difficult. To simplify the analyses, \( C_0(t) \) is assumed constant at \( C_0 \) over an interval from \( t = 0 \) to \( t = t_0 \) (where \( t_0 \) is the cloud passage time).

Under this assumption, integration of equation (1) leads to the following expressions for the internal radioactive material concentration,

\[
C_1(t) = \frac{\xi n C_0}{\Sigma} \left[ 1 - e^{-\Sigma t} \right], \quad (2)
\]

for \( 0 \leq t \leq t_0 \), and

\[
C_1(t) = \frac{\xi n C_0}{\Sigma} \left[ e^{-\Sigma(t-t_0)} - e^{-\Sigma t} \right], \quad (3)
\]

for \( t \geq t_0 \) where \( \Sigma = (\gamma + D + \lambda + k \tau) \).

The dosage, \( \psi(t) \), at any time \( t \) is obtained by integrating equations 2 and 3 over \( t \). The result for \( t \leq t_0 \) is:

\[
\frac{\psi(t)}{\psi_o(t)} = \frac{\xi n}{\Sigma} \left[ 1 - \frac{1}{\Sigma t} (1 - e^{-\Sigma t}) \right], \quad (4)
\]

where \( \psi_o(t) = C_0 t \) is the dosage that would be received outside the shelter. For \( t > t_0 \) the dosage ratio is:

\[
\frac{\psi(t)}{\psi_o(t)} = \frac{\xi n}{\Sigma^2 t_o} \left[ 1 + e^{-\Sigma t} - e^{-\Sigma(t-t_0)} - e^{-\Sigma t_o} \right] + \frac{\xi n}{\Sigma} \left[ 1 - \frac{1}{\Sigma t_o} (1 - e^{-\Sigma t_o}) \right], \quad (5)
\]
IV. TWO-COMPARTMENT MODEL

To more accurately describe the airborne radioactive material concentrations within a structure having a basement as well as an upper or above ground levels, the two-compartment model shown in Figure 2 was developed. This same model can also be applied to a well-isolated interior room in a large structure. The essential difference between this model and the single compartment model is the additional compartment so that there exists the possibility of intercompartmental air exchange as well as independent exchanges of air with the surroundings. It is not necessary that the intercompartment flows $Q_b$ and $Q_{bo}$ be equal, that is, there may be a net flow in either direction. However, the following conservation relations, one for each compartment, must be satisfied.

\[ Q_i + Q_{bo} = Q_{io} + Q_b, \quad (6) \]

and

\[ Q_y + Q_b = Q_{yo} + Q_{bo}. \quad (7) \]

Figure 2. Two-Compartment Model
All terms are defined as they were previously. The additional subscripts b and y refer to the basement. Now assuming that the deposition term, D, and the ingress fraction, ξ, are the same in each compartment a material balance argument may be applied to yield the following differential equations which describe the time behavior of the radioactive material concentrations in the upper and lower compartments.

**Upper**

\[ \frac{dC_i(t)}{dt} = \frac{dC_i(t)}{dt} = C_0(t)Q_i(t) + C_i(t) \left[ Q_{io} + Q_b + Q_r + \lambda V_i - Q_r(1 - \xi) + DV_i \right] + C_b(t)Q_{bo} \]

**Lower**

\[ \frac{dC_b(t)}{dt} = C_0(t)Q_y(t) + C_i(t)Q_b(t) - C_b(t) \left[ Q_{yo} + Q_{bo} + \lambda V_b + DV_b \right] \]

Using the following definitions

\[
\begin{align*}
\eta &= \frac{Q_i}{V_i} \\
\eta &= \frac{Q_{io}}{V_i} \\
\gamma &= \frac{Q_y}{V_b} \\
\gamma &= \frac{Q_y}{V_b} \\
k &= \frac{Q_r}{V_i} \\
\beta &= \frac{Q_b}{V_i} \\
\beta &= \frac{Q_{bo}}{V_i} \\
\beta &= \frac{Q_b}{V_b} \\
\beta &= \frac{Q_{bo}}{V_b} \\
\end{align*}
\]

equations 8 and 9 may be written (with some simplification) as:
\[
\frac{dC_i(t)}{dt} = -C_i(t)\left[\eta_0 + \beta_i + \lambda + k\xi_t + D\right] + C_b(t)\beta_{io} + C_o(t)\eta_\xi
\]  
\tag{10}
\]
\[
\frac{dC_b(t)}{dt} = C_i(t)\beta_b - C_b(t)\left[\gamma_0 + \beta_{bo} + \lambda + D\right] + C_o(t)\gamma_\xi.
\tag{11}
\]

Assuming, as we did earlier, that \(C_o(t) = C_0\), a constant, from \(t = 0\) to \(t = t_0\) and that the initial concentrations of radioactive material within the shelter are zero, we can integrate equations 10 and 11 and obtain for \(0 \leq t \leq t_0\),

\[
C_i(t) = \frac{C_0 \xi}{R_1 - R_2} \left[ \frac{\eta(R_2 - A) - B\gamma}{R_1} \left(1 - e^{R_1 t}\right) + \frac{B\gamma R_1 - \eta(R_1 - A)}{R_2} \left(1 - e^{R_2 t}\right) \right],
\tag{12}
\]
\[
C_b(t) = \frac{C_0 \xi}{R_1 - R_2} \left[ \frac{R_1 - A}{B} \left(\frac{\eta(R_2 - A) - \gamma B}{R_1} \left(1 - e^{R_1 t}\right) \right) + \frac{R_2 - A}{B} \left(\frac{B\gamma R_1 - \eta(R_1 - A)}{R_2} \left(1 - e^{R_2 t}\right) \right) \right].
\tag{13}
\]

where
\[
A \equiv -(\eta_0 + \beta_i + \lambda + k\xi_t + D) \\
B \equiv \beta_{io} \\
C \equiv \beta_b \\
D \equiv -(\gamma_0 + \beta_{bo} + \lambda + D)
\]

and
\[
R_1 = \frac{(A+D) + \sqrt{(A+D)^2 - 4(AD-BC)}}{2},
\]
\[
R_2 = \frac{(A+D) - \sqrt{(A+D)^2 - 4(AD-BC)}}{2}.
\]
Similarly, for times greater than $t_o$

\[
C_j(t) = \frac{C_O \xi}{R_1 - R_2} \left[ \frac{\eta(R_2 - A) - BY}{R_1} \left( e^{R_1(t-t_o)} - e^{R_1 t} \right) \right.
+ \left. \frac{BY - \eta(R_1 - A)}{R_2} \left( e^{R_2(t-t_o)} - e^{R_2 t} \right) \right] , \tag{14}
\]

\[
C_B(t) = \frac{C_O \xi}{R_1 - R_2} \left[ \frac{R_1 - A}{B} \left( \frac{\eta(R_2 - A) - BY}{R_1} \right) e^{R_1(t-t_o)} - e^{R_1 t} \right.
+ \left. R_2 - A \left( \frac{BY - \eta(R_1 - A)}{R_2} \right) e^{R_2(t-t_o)} - e^{R_2 t} \right] . \tag{15}
\]

The dosages $\psi_j(t)$ and $\psi_B(t)$ are obtained by integrating the compartment concentration (equations 12 through 15) over time (recalling that $\psi_O(t) = C_O(t)$). The resulting dosage ratio for $0 \leq t \leq t_o$ is

\[
\frac{\psi_j(t)}{\psi_O(t)} = \frac{\xi \eta(R_2 - A) - \xi BY}{R_1(R_1 - R_2)} \left[ 1 + \frac{1}{R_1 t} \left( 1 - e^{R_1 t} \right) \right]
+ \frac{\xi BY - \xi \eta(R_1 - A)}{R_2(R_1 - R_2)} \left[ 1 + \frac{1}{R_2 t} \left( 1 - e^{R_2 t} \right) \right] , \tag{16}
\]
For times greater than $t_0$ the dosage ratio is:

$$\frac{\psi(t)}{\psi_0(t)} = \frac{\xi (R_1 - A)}{B} \left( \frac{\eta (R_2 - A) - BY}{R_1 (R_1 - R_2)} \right) \left[ 1 + \frac{1}{R_1 t} \left( 1 - e^{R_1 t} \right) \right]$$

$$+ \frac{\xi (R_2 - A)}{B} \left( \frac{BY - \eta (R_1 - A)}{R_2 (R_1 - R_2)} \right) \left[ 1 + \frac{1}{R_2 t} \left( 1 - e^{R_2 t} \right) \right] \qquad (17)$$

+ Eq. (16), with $t = t_0$.

$$\frac{\psi(t)}{\psi_0(t)} = \frac{\xi \eta (R_2 - A) - BY}{R_1 (R_1 - R_2)} \left[ \frac{1}{R_1 t_0} \left( e^{R_1 (t-t_0)} - e^{R_1 t} - 1 + e^{R_1 t_0} \right) \right]$$

$$+ \frac{\xi BY - \xi \eta (R_1 - A)}{R_2 (R_1 - R_2)} \left[ \frac{1}{R_2 t_0} \left( e^{R_2 (t-t_0)} - e^{R_2 t} - 1 + e^{R_2 t_0} \right) \right]$$

$$+ Eq. (16), \text{ with } t = t_0,$$  \quad (18)

$$\frac{\psi(t)}{\psi_0(t)} = \frac{\xi (R_1 - A)}{B} \left( \frac{\eta (R_2 - A) - BY}{R_1 (R_1 - R_2)} \right) \left[ \frac{1}{R_1 t_0} \left( e^{R_1 (t-t_0)} - e^{R_1 t} - 1 + e^{R_1 t_0} \right) \right]$$

$$+ \frac{\xi (R_2 - A)}{B} \left( \frac{BY - \eta (R_1 - A)}{R_2 (R_1 - R_2)} \right) \left[ \frac{1}{R_2 t_0} \left( e^{R_2 (t-t_0)} - e^{R_2 t} \right) \right.$$

$$\left. - 1 + e^{R_2 t_0} \right] + Eq. (17), \text{ with } t = t_0.$$

\(174\)
V. MODEL PARAMETERS

To calculate the dosages, or in this instance the ratio of inside to outside dosage, requires that appropriate values (or at least ranges of values) be established for the model parameters. For the single compartment model the essential parameters are:

- $\eta$ - the infiltration or air turnover rate
- $D$ - the deposition term
- $\lambda$ - the radioactive decay constant
- $\xi$ - the ingress fraction
- $t_0$ - the duration of cloud passage
- $k_{ef}$ - the internal recirculation rate and filter efficiency

The infiltration rate ($\eta$) depends strongly on the local meteorological conditions (particularly wind speed), the building construction (air tightness), and whether or not doors and windows are closed, air-conditioning systems are on or off, etc. Some of these considerations can be at least partially controlled in selecting a sheltering strategy.

The duration of cloud passage ($t_0$) will depend upon the prevailing meteorology as well as the initial source release duration, although to a first approximation it may be assumed equal to the release duration. The other parameters are dependent (at least partially) on the chemical and physical properties of the entering radioactive particles. Wherever possible we have presented the range over which these parameters might be expected to vary based upon research reported in the literature. In addition, we have chosen an "average" value for use in a general predictive manner.
Either of the two ventilation models presented in this paper can be used to describe a particular shelter or class of shelters using either measured or estimated parameters specific to the particular problem. The two-compartment model offers the possibility of more detailed descriptions of air flows into, out of and internal to a structure and therefore includes more air flow parameters. Unfortunately, truly representative data for most of these parameters are unavailable, and we have not been able to make positive recommendations concerning them. Nevertheless, parametric results have been obtained that indicate the added protection a basement might offer in a sheltering program.

A. Air Turnover Rate ($\eta$) [9,13]

$\eta$ is a measure of the rate of leakage of external air into a structure. In our sheltering situation, that is, windows and doors closed, external air uptake ventilating systems off, $\eta$ is due primarily to infiltration, where infiltration is the leakage of air through cracks around windows and doors, down chimneys, and through external surfaces such as walls and roof. The rate depends upon the details of the individual structure; construction, age and condition, furnace operation, topographical setting and local prevailing meteorological conditions - particularly wind speed and direction, indoor/outdoor temperature differential, and humidity [12,4]. Because of the wide variability of each of these factors, even in a fairly small geographical region, it is difficult to arrive at a single representative value for $\eta$. 

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Two calculational methods for estimating the infiltration rate in buildings (crack and air exchange methods) are presented in the ASHRAE Handbook of Fundamentals [12]. Estimates of infiltration rates under "average" conditions in residences for various types of rooms are presented in Table 1. It is not clear that the infiltration rate for the entire structure is accurately estimated by averaging the rates for the individual rooms. The assumption is sometimes made that the total infiltration for the entire building is 1/2 the sum of the infiltration into individual rooms, since air that enters rooms on the windward side will generally exit through rooms on the leeward side [12].

Measurements of infiltration rates for various residential structures have been made [20], and are summarized in Table 2. Note that \( n \) ranges from approximately 0.1 to 3 hr \(^{-1} \), the upper values being due to extreme weather conditions (high wind speeds, cold) and frequent furnace operation. Higher rates (upwards of 6-9 hr \(^{-1} \) have been measured, although they are normally due to high winds and open windows or doors. Based on building code requirements and design ventilation rates, Handley and Barton [20] suggest \( n = 2.0 \) hr \(^{-1} \) as an average rate for modern high-rise apartment complexes if all the ventilation air is from outside the building. However, if a large fraction of the internal air is recirculated, or if forced-air ventilation systems are turned off, ventilation rates could be considerably lower [3].
<table>
<thead>
<tr>
<th>Kind of Room or Building</th>
<th>Number of Air Changes Taking Place per Hour</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooms with no windows or exterior doors</td>
<td>0.5</td>
</tr>
<tr>
<td>Rooms with windows or exterior doors on one side</td>
<td>1</td>
</tr>
<tr>
<td>Rooms with windows or exterior doors on two sides</td>
<td>1.5</td>
</tr>
<tr>
<td>Rooms with windows or exterior doors on three sides</td>
<td>2</td>
</tr>
<tr>
<td>Entrance halls</td>
<td>2</td>
</tr>
</tbody>
</table>

*For rooms with weatherstripped windows or with storm sash, use two-thirds these values.
Table 2. Measured Ventilation Rates

<table>
<thead>
<tr>
<th>Type of Building</th>
<th>Measured $\eta$ (hr$^{-1}$)</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two identical modern homes, tight construction. gas heated</td>
<td>0.24 - 0.83 0.13 - 0.42</td>
<td>10 month period. Normal family activities. ASHRAE calculation methods give 0.9 hr$^{-1}$ for the gas-fueled home. ASHRAE heat loss calculation gives 1.0 hr$^{-1}$.</td>
<td>14</td>
</tr>
<tr>
<td>Ten representative electrically heated homes in Indiana. One- and two-story brick and frame homes, built over basements, crawlspaces or concrete slabs</td>
<td>0.23 - 1.14 Avg ~ 0.7</td>
<td>Unoccupied and all outside doors and windows closed. Winter. ASHRAE air change method gives 0.6 - 1.5 hr$^{-1}$.</td>
<td>15</td>
</tr>
<tr>
<td>Two well-built research homes, electric heating</td>
<td>0.33 under almost all weather conditions</td>
<td>Outer openings closed. $\eta \geq 1.5$ during operation of some appliances.</td>
<td>16</td>
</tr>
<tr>
<td>Two special research homes 1. two-story, basement, hot water heating</td>
<td>0.16 - 0.43</td>
<td>Windows and doors closed. Eight month period. Two additional homes were discussed for which $\eta = 1.5 - 3.0$ hr$^{-1}$, attributed to poor workmanship.</td>
<td>17</td>
</tr>
<tr>
<td>2. one-story, basement, gas-fueled forced warm air furnace</td>
<td>0.26 - 0.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two one-story five-room houses of insulated wood frame construction and full basements. Forced warm air heating</td>
<td>(winter) 0.25 - 0.41 0.37 - 0.63 (summer) 0.07 - 0.17 0.06 - 0.23</td>
<td>Occupied, all openings closed.</td>
<td>18</td>
</tr>
<tr>
<td>Two split-level research homes House 1 gas-fueled hot water heat</td>
<td>Avg 0.32 - 2.67 (1.2) 0.30 - 1.79 (0.84)</td>
<td>Windows and doors closed. Winter. No outdoor ventilation or exhaust fans. Calculations: House 1: Crack method 0.98, Air exchange method 0.90 hr$^{-1}$, House 2: Crack and air exchange methods 0.90 hr$^{-1}$.</td>
<td>19</td>
</tr>
<tr>
<td>House 2 gas-heated electric-heated</td>
<td>0.20 - 1.60 (0.61)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Because of the strong dependence of ventilation rate on wind speed and indoor-outdoor temperature differential, many investigators [14, 15, 16, 19] have attempted to develop empirical relationships of the form:

\[ n = A + B[\text{wind speed}] + C[\Delta T]. \]

Recent and continuing work at Princeton [4] indicates that wind and temperature effects do not act independently [i.e., their effects are not additive] and that furnace operation also has a strong effect on \( n \). For summer months, some data suggest that infiltration rates will usually range from 0.2-0.6 hr\(^{-1}\) for most houses with windows and doors closed [21]. In winter, the measured variability for the 4 year old, two-story houses studied was 0.4 to 1.5 hr\(^{-1}\). Under windy conditions \( n = 2.5 - 3.0 \) hr\(^{-1}\) is possible for older, leakier homes.

Based on the above discussion we recommend a value of \( n = 1.0 \) hr\(^{-1}\) and a range of 0.1-3.0 hr\(^{-1}\). Note that significantly smaller values of \( n \) (and hence additional protection) may be obtainable if actions are taken to more tightly seal the structure or portions of it. For instance, ventilating ducts and chimneys could be stuffed or covered, and cracks around windows and doors could be sealed with tape or moist paper.

B. Deposition Term (D)

Because of a lack of data on radioactive particle size distributions, local air turbulence effects, etc., there is considerable uncertainty on the estimation of deposition rates. A brief review of deposition processes and the available data are
The internal deposition term $D$ is defined as $D = \frac{\nu_d}{h}$ where $\nu_d$, the deposition velocity, is defined as the ratio of the deposition flux to the concentration within the structure, and $h$ is the height of the compartment (assumed here to be 3 m for both compartments).

The deposition velocity ($\nu_d$) is a strong function of the particle diameter in the size range of interest, 0.1 to 10 μm [7]. For assessing the consequences of core melt reactor accidents, Schwendiman, Droppo and Mahalingam [8] recommend that a mass median diameter of about 2 μm be assumed for the resultant aerosol plume. For particles in the 0.5 to 5.0 μm range Sehmel [7] indicates that in-shelter, that is, low air velocity, deposition is caused primarily by the combined effects of gravitational settling and Brownian diffusion. For a 2 μm diameter particle his calculations support a $\nu_d$ (on floors) of approximately $2.5 \times 10^{-2}$ cm/s. For a 1 μm diameter particle $\nu_d$ is approximately $6 \times 10^{-3}$ cm/s. Because of this sensitivity of $\nu_d$ to particle size, we are recommending a value of $1.5 \times 10^{-2}$ cm/s, with a possible range on $\nu_d$ of $1 \times 10^{-3}$ to $1 \times 10^{-1}$ cm/s. Deposition also occurs on walls, ceilings and furnishings. From the Sehmel data [7], in the size range of interest here, the wall deposition velocity was 20-40% of that for the floor while the ceiling deposition velocity is negligible. If we assume that in an average structure the surface area of walls and furnishings is 2.5 times the floor area and that $\nu_d$ (walls, furnishings) is 20% of $\nu_d$ (floor), then the effective deposition velocity should be increased by 50% (i.e., 20% x 2.5) over the $\nu_d$ (floor) to account for this added deposition. Using the previously recommended value for $\nu_d$, taking into account this added deposition and assuming $h = 3$ meters lead to a suggested value of $D = 0.3$ hr$^{-1}$ with a range of 0.02 to 2.0 hr$^{-1}$. 

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Since the noble gases are inert and have a low condensation temperature, no net surface deposition is expected \((D=0)\). Because the noble gases included in the Reactor Safety Study calculations (Kr and Xe) have been shown to have a small effect upon the calculated health effects when inhaled, they were arbitrarily assigned the same deposition rate as the other radioisotopes to simplify this analysis. The effect of this simplification, although not conservative, should be negligible. We have also assumed that deposition of the radiiodine occurs at the same rate as that for other radionuclides. For outside radiiodine deposition the Reactor Safety Study \([1]\) used a value of \(v_d = 0.5\) cm/s. Based upon Megaw's \([9]\) estimates that inside deposition velocity will be about 5% of the outside value, Anno and Dore \([3]\) assumed \(v_d = 0.025\) cm/s for radiiodine deposition on floors. This value is comparable to our adjusted velocity of .0225 cm/s.

C. Radioactive Decay Constant \((\lambda)\)

The radioactive decay constant, \(\lambda\), is a well established constant for each of the radionuclides present in the radioactive material release. Of the 54 radionuclides considered in the Reactor Safety Study consequence analysis, 14 have values of \(\lambda \geq 0.05\) per hour \((T_1 \leq 0.58\) days\). These are Kr-85m, Kr-87, Kr-88, Sr-91, Tc-99m, Ru-105, Te-127, Te-129, Te-129m, Sb-129, I-132, I-134, I-135 and Xe-135. For the time periods of interest here (0-10 hours), radioactive decay of these species might be expected to lead to significant reductions of in-shelter concentration and dosage. For most of the other radionuclides, \(\lambda \ll 0.05\) per hour, and the radioactive decay would not result in any appreciable reductions in in-shelter air concentrations. For each of the radionuclides, the contribution to calculated health effects (early, continuing, and late) from the inhalation of radionuclides are presented in Table VI 13-1 of
the Reactor Safety Study [1]. Ten of the 14 radionuclides with significant radioactive decay constants ($\lambda > 0.05$ per hour) result in negligible contributions to calculated health effects. These are Kr-85m, Kr-87, Kr-88, Te-99m, Ru-105, Te-127, Te-129, Sb-129, I-134 and Xe-135. The other four radionuclides (Sr-91, Te-129m, I-132 and I-135) are categorized as having small but important contributions to the total dose and therefore to health effects. With the possible exception of these 4 radionuclides, all of the 54 radionuclides have either very long half lives or contribute very little to health effects. Therefore, we have decided to neglect the radioactive decay term (i.e. assume $\lambda = 0$ for each radionuclide) when using the proposed ventilation models. This decision, which is conservative,* will not have a significant effect on the overall dose calculation. This is true for the release categories described in the Reactor Safety Study; but there may be releases from other accident sequences for which this is not true.

D. Ingress Fraction ($\xi$)[3]

Not all of the particulates in the external cloud will penetrate into the shelter. Some fraction will be removed during entry into the shelter by deposition or impaction in the cracks and fissures (around windows, doors, etc.) through which they pass, that is, by structural filtering. $\xi$ is defined as the fraction that does penetrate into the shelter. One would expect this parameter to depend on the chemical and physical properties of the aerosol (particularly on particle size), the infiltration rate, and structural features (tightness of cracks, etc.). For the rare gases one would expect no significant structural filtering.

*In this sense, conservative implies that our calculations indicates a larger dose due to inhaled radionuclides than actually expected. We are therefore underestimating the protection.
Data relevant to an estimation of $\xi$ are scarce. Yocom, Clink and Cote [5] reported measured indoor/outdoor air quality relationships for suspended particulates, soiling particulates, carbon monoxide and sulfur dioxide for six structures. Data for the soiling particulates are shown in Table 3. On the average, if no in-shelter sources are present, the ratio of indoor to outdoor pollutant concentration should approximate the ingress fraction $\xi$. Since soiling particulates are in the size range of interest in this paper, 1 to 2 microns, that data was taken as representative for this application.

Table 3.

Summary of Soiling Particulate Matter Indoor/Outdoor Concentration Ratios [6]

<table>
<thead>
<tr>
<th>Structure</th>
<th>Summer</th>
<th>Fall</th>
<th>Winter</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day</td>
<td>Day</td>
<td>Day</td>
<td></td>
</tr>
<tr>
<td>Public Building</td>
<td>0.81</td>
<td>0.92</td>
<td>0.50</td>
<td>0.75</td>
</tr>
<tr>
<td>Public Building</td>
<td>0.98</td>
<td>1.15</td>
<td>0.91</td>
<td>1.0</td>
</tr>
<tr>
<td>Office Building</td>
<td>0.87</td>
<td>0.69</td>
<td>0.85</td>
<td>0.82</td>
</tr>
<tr>
<td>Office Building</td>
<td>0.57</td>
<td>0.79</td>
<td>0.58</td>
<td>0.66</td>
</tr>
<tr>
<td>Private Home</td>
<td>0.89</td>
<td>0.88</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td>Private Home</td>
<td>1.19</td>
<td>0.80</td>
<td>0.93</td>
<td>0.92</td>
</tr>
<tr>
<td>Average</td>
<td>0.89</td>
<td>0.87</td>
<td>0.77</td>
<td>0.83</td>
</tr>
</tbody>
</table>

The above data suggest a value of 0.85 for the parameter $\xi$ with a range of 0.5 to 1.0. It should be noted that during the pollutant-level measurements for the data in Table 3 these buildings were in normal use, (that is, doors and windows open at times and ventilating systems operating) and that it is most likely that there were in-structure sources (indoor/outdoor ratios greater than 1.0). Therefore, the estimate of $\xi = 0.85$ is presumed to be conservative.
E. Duration of Cloud Passage ($t_o$)

The time it takes the radioactive cloud to pass a given point will depend on wind characteristics (persistence, speed and direction) and release duration. Estimates of wind characteristics could be based on either a statistical analysis of site-specific meteorology histories or real-time predicted wind behavior. Lacking such wind information, for accidents of interest, the range of $t_o$ should be fairly well typified by the release durations associated with the 14 release categories investigated in the Reactor Safety Study [1]. The duration of releases ranged between 0.5 to 10 hours, with most of the release durations falling in the 0.5 to 3.0 hour range.

F. Recirculation Loop Parameters ($k_{r_f}$)

A possible course of action to limit the amount of inhaled radioactive material is to seal off the structure and operate the air recirculating system (air conditioning or forced air) with the make-up inlet shut. In addition to providing some comfort to those in the shelter, the filters within the system will remove some portion of the airborne particulates [10]. Because the particle removal characteristics of most filters are size dependent (increased efficiency for larger particles), circulation through filters would tend to steepen the aerosol size distribution function. Lum and Graedel [10] found that the differential particle size spectrum went from a typically $r^{-4}$ dependence outdoors to a $r^{-7}$ dependence indoors, that the mass median diameter of containment particles was reduced, and that the dominant effect was simply a reduction in air concentration ($Ci/m^3$).
The efficiency of one type of a filter over another is a strong function of particle size [11]. For any specific filter the efficiency for removal tends to be fairly constant for particle diameters in the range of 0.1 to 1.0 μm. Filters in common use in home and commercial buildings are very inefficient for particles with radii less than 1 μm. Typical values for $\varepsilon_p$ might be 0.01 to 0.05 at 0.1 μm. Representative values for $k$, the recirculating air turnover rate, may range from 5 to 10 per hour or even higher.

Despite the additional protection that could be afforded by air recirculation systems when used as discussed above, their actual benefit in the general case is quite uncertain. This is due to a number of questions: How many structures have recirculating systems, would they be operated correctly, what are appropriate values for $k$, $\varepsilon_p$, etc? Therefore, as a conservative assumption this effect has been neglected in the current analyses ($k\varepsilon_p = 0$). Nevertheless, we do believe that this strategy offers considerable potential for significant additional protection in large institutional buildings such as hospitals, jails, schools and office buildings.

VI. RESULTS

The recommended input parameter values from the previous section were used to estimate the shelter effectiveness in reducing dose levels due to inhaled radionuclides and to explore the sensitivity of these estimates of dose reduction to variations in some of the model parameters. A program listing describing the code written to calculate indoor/outdoor dose ratios for inhaled radionuclides as a function of time using either the single- or two-compartment model is included as an appendix. Unless otherwise noted, the results presented in this section were obtained using the single-compartment model.
Figure 3 shows the indoor/outdoor dose ratio for inhaled radionuclides as a function of time and the ventilation rate, \( n \), given a release duration of 0.5 hours. The deposition term, \( D \), is assumed to equal \( 0.3 \, \text{hr}^{-1} \), the ingress fraction \( \xi = 0.85 \), while \( \eta \) is varied over approximately its entire range. The apparent slope discontinuities in these and similar curves are a result of the assumption of step functions on outside radioactive material concentrations. Note that within a few hours after cloud passage the dose ratios approach the asymptotic values \( \Psi(\infty)/\Psi_{0}(\infty) \) which are a function of the parameter values assumed. At short times varying \( \eta \) by a factor of 20 only alters the ratio by a factor of 6. At longer times (asymptotic region) there is even less dependence, the ratio varying by a factor of 2 to 2.5 for a 20 fold change in \( \eta \).

Figure 4 indicates the sensitivity of the calculated dose ratio to the assumed value of the deposition term, \( D \), given a release of duration 0.5 hr. Assumed parameter values are \( \eta = 1.0 \, \text{hr}^{-1} \) and \( \xi = 0.85 \). Results are insensitive to \( D \) since an order of magnitude change in \( D \) alters the ratio by at most a factor of 2.

Figure 5 shows the indoor/outdoor dose ratio for inhaled radionuclides as a function of time and the ventilation rate, \( n \), given a release duration of 10.0 hours. As in Figure 3, \( D = 0.3 \, \text{hr}^{-1} \) and the ingress fraction \( \xi = 0.85 \). Again, shortly after cloud passage the dose ratios approach the asymptotic values, \( \Psi(\infty)/\Psi_{0}(\infty) \). Note however that for a release of long duration the ratios are very nearly equal to the asymptotic values even before the completion of cloud passage.
Figure 3. Indoor/Outdoor Dose Ratio for Inhaled Radionuclides as a Function of Time and the Ventilation Rate, $\eta$, for a Release Duration of 0.5 hours. Assumed Parameter Values; $D = 0.3 \text{ hr}^{-1}$, $\xi = 0.85$. 
Figure 4. Indoor/Outdoor Dose Ratio for Inhaled Radionuclides as a Function of Time and the Deposition Term, D, for a Release Duration of 0.5 hours. Assumed parameter values: \( \eta = 1.0 \) hr\(^{-1} \), \( \xi = 0.85 \).
Figure 5. Indoor/Outdoor Dose Ratio for Inhaled Radionuclides as a Function of Time and the Ventilation Rate, $\eta$, for a Release Duration of 10.0 hours. Assumed parameter values: $D = 0.3 \text{ hr}^{-1}$, $\xi = 0.85$. 
For the single-compartment model an expression for the asymptotic dose ratio, \( \psi(\infty)/\psi_o(\infty) \), is obtained from equations (3) and (4) in section III.

\[
\psi(\infty)/\psi_o(\infty) = \frac{\xi}{\Sigma}
\]

(20)

where \( \Sigma = (\eta + D + \lambda + k\varepsilon_r) \), or

\[
\psi(\infty)/\psi_o(\infty) = \frac{\xi}{1 + \frac{D + \lambda + k\varepsilon_r}{\eta}}
\]

(21)

where \( D + \lambda + k\varepsilon_r \) is a ratio of terms which describes the material acting within the compartment to reduce its concentration to the turnover rate, \( \eta \). Clearly the asymptotic dose ratios will depend only on this ratio and not on the absolute magnitudes of the individual parameters. For \( \lambda \) and \( k\varepsilon_r = 0 \), the ratio simply reduces to \( D/\eta \). Figure 6 is a plot of the asymptotic dose ratio vs. the dimensionless ratio \( \frac{D + \lambda + k\varepsilon_r}{\eta} \), assuming \( \xi = 1.0 \). Other values of \( \xi \), such as \( \xi = 0.85 \), will reduce the ratio proportionally.

Based on the "best estimate" parameter values suggested earlier \( (\eta = 1.0 \text{ hr}^{-1}, D = 0.3 \text{ hr}^{-1} \text{ and } \xi = 0.85) \), the asymptotic ratio is 0.65. This corresponds to a reduction of 35 percent in dose due to inhaled radionuclides for sheltered individuals.

During the passage of the radioactive cloud, the external air concentrations of radionuclides as a function of time might look something like Curve A in Figure 7. Because of the restricted turnover or ventilation of outside air into a building, radioactive material concentrations within the building may remain significant for several hours after cloud passage and look something like Curve B. Therefore, an obvious strategy that would minimize the dose from inhaled radionuclides received by individuals in the
Figure 6. Asymptotic Dose Ratio, $\psi(\infty)/\psi_0(\infty)$ as a Function of the Dimensionless Parameter, $(D+\lambda+\kappa\epsilon_f)/\eta$, Assuming $\xi = 1.0$. 
structure would be to exit the building as soon as the outside air concentration dropped below the inside concentration (time t in Figure 7). However, individuals outside would then be subject to the external radiation from ground-deposited radionuclides without benefit of the shielding to this source provided by the structure. Therefore, a more prudent strategy might be to remain indoors but open windows, doors, turn on ventilating systems, etc. in an attempt to "air-out" the structure. One problem, of course, is that the individuals inside the structure may not know immediately, or even for several hours, that the outside air is less contaminated or that the cloud has passed. This time lag between cloud passage...
and when the building is "opened-up", which we have termed \( t_1 \), is quite significant. Tables 4, 5 and 6 present the indoor/outdoor dose ratios for inhaled radionuclides that would be applicable to sheltered individuals given different release durations, \( t_0 \), and different values of the time lag, \( t_1 \). \( \eta_1 \) is defined to be the ventilation rate of the structure when it is closed. \( \eta_2 \) is defined to be the effective ventilation rate of the structure after it has been "opened-up". The calculations for Table 4 assume that \( \eta_1 = 1.0 \, \text{hr}^{-1}, \eta_2 = 5.0 \, \text{hr}^{-1}, D = 0.3 \, \text{hr}^{-1} \) and \( \xi = 0.85 \). Note that for all values of duration \( t_0 \), \( t_1 = \infty \) corresponds to the situation where \( \eta \) remains at \( 1.0 \, \text{hr}^{-1} \) forever and the dose ratio equals the asymptotic value 0.65 as predicted earlier. The calculations for Table 5 assume a reduced value of \( \eta_1 = 0.5 \, \text{hr}^{-1} \) and the same values for \( \eta_2, D \) and \( \xi \) as used for Table 4. The results in Table 6 are based on the assumption that \( \eta_1 = 1.0 \, \text{hr}^{-1} \) but that the structure is more effectively "opened-up" with \( \eta_2 = 10.0 \, \text{hr}^{-1} \). For \( \eta_1 = 1.0 \, \text{hr}^{-1} \) and the assumed values for \( D \) and \( \xi \), Table 4 indicates that if any substantial benefit is to be obtained by this strategy, the time lag, \( t_1 \) must be less than an hour or so. Even then, the benefits are only obtainable for those releases of short duration, \( t_0 \leq 1 \) hour. For the reduced value of \( \eta_1 = 0.5 \, \text{hr}^{-1} \) assumed in Table 5, substantial benefits are afforded over somewhat larger ranges of \( t_1 \) and \( t_0 \). Comparison of Table 4 and Table 6 reveals that the benefits offered by this strategy are not increased significantly by raising \( \eta_2 \) above \( 5.0 \, \text{hr}^{-1} \). Because of the restriction of potential benefits to releases of short duration for \( \eta_1 = 1.0 \, \text{hr}^{-1} \) plus the difficulties that would be involved in reducing \( t_1 \) to very short times, this strategy would most likely not contribute significantly to reducing the dose from inhaled radionuclides. However, the calculations do suggest that the potential benefits and importance of the strategy would be increased if lower initial ventilation rates, \( \eta_1 \), were achieved.
Table 4
Indoor/Outdoor Dose Ratio for Inhaled Radionuclides for Different Release Durations, \( t_0 \), and Different Periods of Time Between Cloud Passage and When Windows and Doors are Opened, \( t_1 \). Assumed parameter values; \( \eta_1 = 1.0 \text{ hr}^{-1} \), \( \eta_2 = 5.0 \text{ hr}^{-1} \), \( D = 0.3 \text{ hr}^{-1} \), \( \xi = 0.85 \).

<table>
<thead>
<tr>
<th>( t_1 ) (hours)</th>
<th>1/2</th>
<th>1</th>
<th>3</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.29</td>
<td>0.38</td>
<td>0.53</td>
<td>0.62</td>
</tr>
<tr>
<td>1/2</td>
<td>0.46</td>
<td>0.51</td>
<td>0.59</td>
<td>0.63</td>
</tr>
<tr>
<td>1</td>
<td>0.56</td>
<td>0.58</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>0.63</td>
<td>0.63</td>
<td>0.64</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Table 5
Indoor/Outdoor Dose Ratio for Inhaled Radionuclides for Different Release Durations, \( t_0 \), and Different Periods of Time Between Cloud Passage and When Windows and Doors are Opened, \( t_1 \). Assumed parameter values; \( \eta_1 = 0.5 \text{ hr}^{-1} \), \( \eta_2 = 5.0 \text{ hr}^{-1} \), \( D = 0.3 \text{ hr}^{-1} \), \( \xi = 0.85 \).

<table>
<thead>
<tr>
<th>( t_1 ) (hours)</th>
<th>1/2</th>
<th>1</th>
<th>3</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.16</td>
<td>0.22</td>
<td>0.36</td>
<td>0.47</td>
</tr>
<tr>
<td>1/2</td>
<td>0.28</td>
<td>0.32</td>
<td>0.42</td>
<td>0.49</td>
</tr>
<tr>
<td>1</td>
<td>0.36</td>
<td>0.39</td>
<td>0.45</td>
<td>0.51</td>
</tr>
<tr>
<td>2</td>
<td>0.46</td>
<td>0.47</td>
<td>0.50</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Table 6

Indoor/Outdoor Dose Ratio for Inhaled Radionuclides for Different Release Durations, $t_0$, and Different Periods of Time Between Cloud Passage and When Windows and Doors are Opened, $t_1$. Assumed parameter values; $\eta_1 = 1.0 \text{ hr}^{-1}$, $\eta_2 = 10.0 \text{ hr}^{-1}$, $D = 0.3 \text{ hr}^{-1}$, $\xi = 0.85$.

<table>
<thead>
<tr>
<th>$t_0$ (hours)</th>
<th>1/2</th>
<th>1</th>
<th>3</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.23</td>
<td>0.33</td>
<td>0.51</td>
<td>0.61</td>
</tr>
<tr>
<td>1/2</td>
<td>0.43</td>
<td>0.49</td>
<td>0.58</td>
<td>0.63</td>
</tr>
<tr>
<td>1</td>
<td>0.54</td>
<td>0.57</td>
<td>0.62</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>0.62</td>
<td>0.63</td>
<td>0.64</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Additional protection against dose from inhalation of radionuclides may be provided by employing a variety of common household items as respiratory filters. The literature [22,23] discusses the use of both towels and handkerchiefs for example. We have not attempted to include considerations of respiratory filters in this discussion, although they should be considered further in the development of protective strategies.

Even though data were not available to readily specify or suggest values for the basement-related flow parameters in the two-compartment model, approximate values for the parameters were assumed and the resulting indoor/outdoor dose ratios for inhaled radionuclides for the two compartments are presented in Figure 8. The assumptions made were that the volumes of the two compartments were the same, that there was no net flow from either compartment.
Figure 8. Two-Compartment Model. Upper Compartment and Basement Dose Ratios for Inhaled Radionuclides as a Function of Time for a Release Duration of 0.5 hours. Assumed parameter values are indicated on plot.

to the other, that $\beta_i = \beta_{i0} = \beta_b = \beta_{bo} = 0.2 \text{ hr}^{-1}$, $\eta = \eta_0 = 1.0 \text{ hr}^{-1}$, $\gamma = \gamma_0 = 0.5 \text{ hr}^{-1}$, $D = 0.3 \text{ hr}^{-1}$ and $\xi = 0.85$. In effect we assumed that the ventilation rate to the basement was 1/2 that to the upper compartment, and that the exchange of air between the two compartments was quite small. Although the available data does not allow quantitative predictions of dose reduction, Figure 8 indicates qualitatively that significant reductions may be afforded by basements or other appropriately sealed-off rooms.
VII. CONCLUSIONS AND RECOMMENDATIONS

A multicompartment ventilation model has been presented for the calculation of airborne radioactive material concentrations internal to structures. The model was used to estimate the potential effectiveness of sheltering in reducing the dose due to inhaled radionuclides. The sensitivity of the model to parameter values and protection strategies was discussed. Using "best estimate" values for the model parameters, this analysis indicated that sheltered individuals received a reduction of 35 percent in the dose from inhaled radionuclides. Larger reductions would be possible if lower values of the ventilation rate $q$, could be achieved by either tighter building construction or emergency sealing of openings in the structure. Such emergency means could include taping windows, placing wet paper over cracks, etc. Further analysis indicated that the strategy of opening doors and windows, turning on ventilating systems, etc., in an attempt to "air-out" the structure after the cloud of radioactive material had passed will most likely not contribute significantly to reduction in dose due to inhaled radionuclides unless very low initial ventilation rates are achieved. Although the available data did not allow quantitative predictions of dose reductions afforded by basements or other appropriately sealed-off rooms, preliminary analysis indicated qualitatively that they could be significant.

Based upon the above preliminary results, further research into the air flow interactions of basements with both the outside and upper stories seems warranted. Other areas of research that would be fruitful are the acquisition of improved data concerning the ingress fraction.
and an evaluation of the effectiveness of strategies such as taping or papering cracks in the structure or other artificial means of reducing the ventilation rate, $\eta$. Although we have not considered the use of common household items as respiratory filters in this discussion, their use may provide significant additional protection against dose due to inhaled radionuclides and should be considered further in the development of protective strategies.
REFERENCES


21. Personal Communication with Dr. Gautam S. Dutt, Princeton University Center for Environmental Studies.


APPENDIX A

Dose Ratio Calculation Program

Attached is the program used to calculate indoor/outdoor dose ratios for inhaled radionuclides as a function of time and either single or two-compartment model parameter values assumed. Input parameters are A, B, C, D, E, F, TZERO, and TTAB(1) through TTAB(10), where (in terms of the two-compartment model parameters)

\[
A = -(n_0 + \beta_1 + \lambda + k\varepsilon_r + \varepsilon) \\
B = \beta_{10} \\
C = \beta_b \\
D = -(\lambda + \beta_{b0} + \lambda + D) \\
L = \eta \\
F = \lambda \\
\]

TZERO = t_o = release duration

TTAB(1) - TTAB(10) = 10 times at which dose ratio are calculated.

When using the single-compartment model use the same input parameters, but set \( n_0 = Y_o = \gamma = \eta = \) ventilation rate, and

\[
\beta_1 = \beta_{10} = \beta_b = \beta_{b0} = \text{any constant (e.g. 0.1).}
\]

Output from the program gives the upper compartment (UDOSE) and basement (BDOSE) dose ratios at the input times. In the single-compartment case UDOSE = BDOSE = shelter dose ratio.
PROGRAM DSOE (INPUT1, OUTPUT1)
DIMALUT2, MULT1, MULT2
CALL SCA$T
VT=10
READ E, A, S, O, E, F
READ E, TZERO (*TTAB(I), I=1, NT)
5 FORMAT (8FI.1, 1)
TEMP=SUM((A+C)*2-4*(A*D-B*C))
R1=(A+D+TTEMP)/2.
R2=(A+D)*TTEMP/2.
PRINT 10, TEMP, R1, R2
10 FORMAT (8E15.3)
ETA=4*E*(R2-A)*E+(R1*(R1-R2))
GAMMA=E*(R1-A)*E*(R1-R2))
MULT1=(R1-A)/8
MULT2=(R2-A)/8
GO TO 1
C IF(TTAB(I), 5. TZERO) GO TO 20
SUB I LESS THAN OR EQUAL TO SUB 0 - Y BRANCH
TEM1=1.+(1./R1)*TTAB(I)1)*1.-(EXP(R1*TTAB(I))
TEM2=1.+(1./R2)*TTAB(I)1)*1.-(EXP(R2*TTAB(I))
PRINT 10, ETA, GAMMA, MULT1, MULT2, TEMP, TEM2
UODSE(I)=ETA*TEM1*GAMMA*TEM2
UODSE(I)=MJ11*ETA*TEM1*GAMMA*TEM2
UODSE(I)=MJ11*ETA*TEM1*GAMMA*TEM2
GO TO 10
C Z SUB H=AM
DO 20, (*R1, 5. TZERO)
DO 20, (*R2, 5. TZERO)
TEM4=1.+(1./R2)*TTAB(I)-TZERO)*1.-(EXP(R2*TTAB(I))
TEM5=1.+(1./R2)*TTAB(I)-TZERO)*1.-(EXP(R2*TTAB(I))
UODSE(I)=ETA*TEM4*GAMMA*TEM2*ETA*TEM3*GAMMA*TEM4
UODSE(I)=MJ11*ETA*TEM3*GAMMA*TEM2
1 + MULT1*ETA*TEM3*GAMMA*TEM2
C CONTINUE
30 CONTINUE
30 CONTINUE
END
1233  J. M. Taylor
5000  A. Narath
      Attn:  J. K. Galt, 5100
             E. H. Beckner, 5200
             O. E. Jones, 5300
             J. H. Scott, 5700
             R. S. Claassen, 5800
5400  A. W. Snyder
      Attn:  J. V. Walker, 5420
             R. M. Jefferson, 5430
             R. W. Lynch, 5440
             J. A. Reuscher, 5450
5410  D. J. McCloskey
      Attn:  D. A. Dahlgren, 5411
             J. W. Hickman, 5412
5333  R. E. Akins
5412  D. M. Ericson (10)
5413  P. E. McGrath
5413  R. B. Jones
5413  D. C. Aldrich (20)
8266  E. A. Aas
3141  C. A. Pepmueller, Actg. (5)
3151  W. L. Garner (3)
      For DOE/TIC (Unlimited Release)
DOE/TIC (25)
      (R. P. Campbell, 3172-3)
Appendix C

Model of Public Evacuation

A MODEL OF PUBLIC EVACUATION FOR ATMOSPHERIC RADIOLOGICAL RELEASES

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ABSTRACT

A model of public evacuation is developed for use in evaluating the efficacy of evacuation as a protective measure in response to atmospheric releases of radioactive material. Differences between this model and the model of public evacuation previously developed for the Reactor Safety Study are described. Ranges for the temporal parameters in the new model are suggested based on an analysis of available EPA evacuation data. The relative importance of the model parameters is also discussed.
# TABLE OF CONTENTS

I. Introduction

II. Background

III. Description of Evacuation Model and Parameters

IV. Reinterpretation of EPA Evacuation Data

V. Relative Importance of Model Parameters

References

Appendix A - Graphical Description of Evacuation Model
I. INTRODUCTION

If an accident should occur at a nuclear power reactor, there exists the possibility of a release to the atmosphere of significant quantities of radioactive material requiring some form of emergency response for the protection of offsite individuals. Protection strategies to limit or mitigate the radiation exposure resulting from such a release, and therefore the consequences of exposure, are of prime concern to those responsible for radiological emergency planning and response. Potentially available protection strategies include sheltering, evacuation and medical prophylaxis.

Significant atmospheric releases of radioactive material would in general be preceded by one or more hours' warning [1], and depending on the wind speed following the release, several more hours might pass before the cloud of released radioactive material would reach a particular population group. Because of this available time period, evacuation* is given considerable attention as a public protective measure in most current radiological emergency preparedness programs in the United States. However, recent studies [2] support the view that it may be desirable to consider alternative or supplemental strategies to evacuation such as population sheltering followed by the selective and timely relocation of affected persons. To assist in the choice and design of appropriate response measures, a study, using

*Evacuation is the expeditious movement of people to avoid exposure to the passing cloud of radioactive material.
a revised version of the consequence model of the Reactor Safety Study (RSS) [1], was conducted to evaluate the relative merits of potential public protective measures, and to determine under what circumstances and over what areas they should be implemented. This report describes the model of evacuation developed for and used in the study of response measures. The effectiveness of evacuation and other protective measures, such as sheltering followed by relocation, is discussed in other papers [3,4,5].

II. BACKGROUND

Evacuation experience in the U.S. for the period from 1959 to 1973 is summarized in a report published by the U.S. Environmental Protection Agency (EPA) [6]. The report provides data on 64 evacuation events, most of which were in response to hazards from transportation accidents, floods or hurricanes. A simple evacuation model, based on a statistical analysis of this evacuation data, was included in the consequence model of the RSS for use in the calculation of public risks from reactor accidents. Specifics of the statistical analysis performed and the suitability of the EPA data for the modeling of evacuations in response to reactor accidents are discussed in Appendix VI of the RSS. The RSS evacuation model postulates that evacuated persons move radially away from the reactor at a constant "effective" speed immediately upon warning by nuclear facility
personnel* of the impending release. Representative effective evacuation speeds were determined from the EPA data by dividing the recorded evacuated distances by the corresponding total time periods required to complete the evacuations.** Evacuated persons are assumed to continue moving outward from the reactor site until overtaken by the cloud of radioactive material. At the distance they are overtaken by the cloud, they are exposed to the entire duration of the cloud and to ground contamination for an assumed period of 4 hours. Constant shielding factors for exposure to airborne radionuclides and ground contamination and a constant breathing rate are uniformly applied to the entire evacuating population.

The statistical analysis of the EPA data performed in the RSS showed that (1) a log-normal distribution can be suitably used to describe the distribution of effective evacuation speeds, (2) the likely effective speeds are small, (3) the range of likely effective speeds is large, and (4) the number of persons evacuated had no statistically significant effect on the effective speed of evacuation.

*No specific delay time is assumed for the notification of responsible authorities, the decision to evacuate, the time required by officials to notify people to evacuate, and the time required by people to mobilize and get underway.

**Because the recorded total evacuation times include all delays as well as the travel time required to leave the affected areas, the "effective" speeds determined are considerably lower than the speeds actually attained while evacuating.
Data for evacuations in response to transportation events, floods and hurricanes were analyzed both separately and together. However, the individual log-normal distributions of effective speed for the three evacuation categories were shown to be significantly different. Therefore, only data gathered for evacuations from the transportation accident category were used in developing the descriptive model for reactor accidents because (1) transportation accidents often involve airborne releases of noxious gases, and (2) the warning times and evacuation movements are comparable. A chart of the collected data for transportation accidents is presented as Table 1. Because there is a large variation in effective evacuation speed, the use of one "representative" speed was considered inappropriate. As explained in Appendix VI of the RSS, the distribution of evacuation speeds was therefore represented by three discrete effective speeds of 0, 1.2 and 7.0 mph with probabilities of 30 percent, 40 percent, and 30 percent, respectively.

While the evacuation model described above is most likely sufficient for the calculation of aggregate public risk from potential reactor accidents, it is inadequate for use in evaluating evacuation as a radiological emergency protective measure for several reasons. Effective evacuation speeds do not provide a realistic description of the space/time history of evacuating persons, and are difficult to interpret. The total time required to complete an actual evacuation will involve a delay time of some duration as well
Table 1. EPA Evacuation Data for Transportation Accidents (from Appendix VI of ref. 1)

<table>
<thead>
<tr>
<th>Event Number</th>
<th>Location and Date</th>
<th>Type of Area Evacuated</th>
<th>Area Evacuated (sq. miles)</th>
<th>Number of Persons Evacuated</th>
<th>Number of Miles Evacuated</th>
<th>Population Density (number per sq. mile)</th>
<th>Road and Conditions</th>
<th>Weather</th>
<th>Time of Day</th>
<th>Evacuation Plans</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Downington, PA; 2/3/72</td>
<td>Suburban</td>
<td>0.25</td>
<td>700 of 800</td>
<td>1.0</td>
<td>2.0</td>
<td>Dry S</td>
<td>Cloudy</td>
<td>Night</td>
<td>PU</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>16</td>
<td>Creve Coeur, MO; 8/1/61</td>
<td>Rural residential; suburban; urban</td>
<td>15</td>
<td>7.500</td>
<td>12</td>
<td>1.0</td>
<td>Dry S</td>
<td>Fog</td>
<td>Night</td>
<td>PU</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>18</td>
<td>Chadbourne, WI; 1/13/68</td>
<td>Suburban</td>
<td>0.5</td>
<td>350</td>
<td>1.0</td>
<td>5.0</td>
<td>Dry S</td>
<td>Cloudy</td>
<td>Night</td>
<td>NP</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>21</td>
<td>Wetanka, OK; 4/4/69</td>
<td>Rural residential</td>
<td>3</td>
<td>2,000</td>
<td>25</td>
<td>8</td>
<td>Dry S</td>
<td>Cloudy</td>
<td>Day</td>
<td>PU</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>34</td>
<td>Louisville, KY; 3/19/72</td>
<td>Urban</td>
<td>0.15</td>
<td>4,000</td>
<td>1</td>
<td>3</td>
<td>Wet U</td>
<td>Rain</td>
<td>Day</td>
<td>Pu</td>
<td>Private vehicles; chlorine barge; no chlorine release</td>
</tr>
<tr>
<td>35</td>
<td>Urbana, OH; 8/13/63</td>
<td>Suburban</td>
<td>3.1</td>
<td>4,000</td>
<td>0.75</td>
<td>3.5</td>
<td>Dry S</td>
<td>Clear</td>
<td>Evening</td>
<td>N.D.</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>36</td>
<td>Baton Rouge, LA; 8/6/65</td>
<td>Urban</td>
<td>8</td>
<td>150,000</td>
<td>30</td>
<td>2.0</td>
<td>Dry U, EU</td>
<td>Clear</td>
<td>Day</td>
<td>PU</td>
<td>Private vehicles; chlorine barge; no chlorine release</td>
</tr>
<tr>
<td>30</td>
<td>Morgan City, LA; 1/19/73</td>
<td>Urban</td>
<td>1.8</td>
<td>3,000 of 3,300</td>
<td>2</td>
<td>4</td>
<td>Ice u</td>
<td>Snow</td>
<td>Day</td>
<td>Pu</td>
<td>Private vehicles; chlorine barge; no chlorine release</td>
</tr>
<tr>
<td>39</td>
<td>Texarkana, TX; 8/27/67</td>
<td>Suburban</td>
<td>9.0</td>
<td>5,000</td>
<td>3</td>
<td>4</td>
<td>Dry U</td>
<td>Clear</td>
<td>Night</td>
<td>NP</td>
<td>Private vehicles</td>
</tr>
<tr>
<td>44</td>
<td>Glendora, MD; 9/11/69</td>
<td>Rural farming; rural residential suburban urban</td>
<td>1.200</td>
<td>15,000</td>
<td>20</td>
<td>4</td>
<td>Dry S</td>
<td>Cloudy</td>
<td>Night</td>
<td>P</td>
<td>Private vehicles</td>
</tr>
</tbody>
</table>

(a) Key: U = urban road; S = suburban road; R = rural road; EU = express way (unlimited access); EL = express way (limited access).
(b) Key: P = plan available (not used); PU = plan used; NP = no plan; N.D. = no data
as the actual travel time required to leave the affected area. The time required for notifying responsible authorities, interpreting data, deciding to evacuate, directing people to evacuate and for people to mobilize and get underway [7] may result is significant delays. Actual speeds attained while evacuating may be considerably higher than the calculated effective speeds. This could significantly affect the total time of exposure to ground deposited radioactive material. Responsible planning authorities will have some understanding of these delay components and the likely speeds attainable on routes leaving the evacuated area.

The assumption that evacuating persons overtaken by the radioactive cloud are exposed to the entire cloud duration and to ground contamination for a constant 4 hours is also an unrealistic description of the public's exposure to radiation during evacuation. In addition, rather than remaining constant during the total time of evacuation, shielding factors and breathing rates may be markedly different during the delay and transit periods. Therefore, a revised model of public evacuation has been developed for use in examining evacuation as a protective measure and is presented in the next section. Representative values for the temporal parameters in the revised treatment are determined based on a reinterpretation of the EPA data [6], as explained in Section IV of this report. It should be noted that the concepts enumerated in the proceeding discussions are applicable in general to emissions of airborne toxicants.
III. DESCRIPTION OF EVACUATION MODEL AND PARAMETERS

The revised model of public evacuation developed for use in examining evacuation as a protective measure for atmospheric releases of radioactive materials as a result of reactor accidents is described in this section. The new model is also designed for use in the RSS consequence model and is therefore similar in some respects to the RSS evacuation model described in the previous section. However, significant differences do exist between the two models and these differences are detailed here. In lieu of the effective evacuation speeds assumed in the RSS evacuation model, the revised treatment incorporates a delay time before public movement, followed by evacuation radially away from the reactor at a higher constant speed.* Both the assumed delay time and evacuation speed are required as input to the model. Different shielding factors and breathing rates are allowed while stationary and in transit. As assumed previously, all persons within the designated evacuation area move as a group with the same delay time and evacuation speed, and no consideration is given to the possibility of a nonparticipating segment of the population. This latter assumption results in upper bound estimates of evacuation effectiveness, given a specific delay time and speed.**

*The speed is higher than the previously assumed effective speed since the total evacuation times (delay plus travel time) must be the same.

**The evacuation effectiveness would decrease linearly with an increasing nonparticipating fraction of the population. In actual evacuations, Civil Defense personnel have observed a nonparticipating minority of approximately 5% [6].
Unlike the RSS model in which persons continue evacuating until either overtaken by the cloud or out of the spatial bounds of the model, all evacuating persons in the new model travel a designated distance from the evacuated area and then are removed from the problem. This option accounts for the fact that after traveling outward for some distance, people may learn their position relative to the cloud and be able to avoid it.

The new model also calculates more realistic exposure durations to airborne and ground deposited radionuclides than the RSS evacuation model. The RSS consequence model employs an exposure model for an instantaneous point source [8] and thus all releases have zero effective length. Because of this, evacuating persons overtaken by the cloud in the RSS evacuation model are exposed to the entire cloud at the point the cloud initially reaches them. In reality, however, a released cloud of radioactive material would have a finite release duration and a length that depends on the wind speed during and following the release of the radioactive material from the reactor containment building. A person overtaken by the front of the cloud might still escape before being passed by the entire cloud and thus receive only a fraction of the full cloud exposure as calculated in the consequence model.* The revised evacuation

*It is also possible that an evacuating person may travel under the cloud for a long time and thus receive more exposure than if he had remained stationary during the passage of the cloud.
model assigns the cloud a finite length which is determined using the assumed release duration and wind speed during the release. To simplify the treatment, the cloud is assumed to remain of constant length following the release (i.e., the front and back of the cloud travel at the same speed), and the concentration of radioactive material is assumed to be uniform over the length of the cloud. The radial position of evacuating persons, while stationary and in transit, is compared to both the front and the back of the cloud as a function of time to determine a more realistic period of exposure to airborne radionuclides.

The revised treatment calculates the time duration over which people are exposed to radionuclides on the ground while they are stationary and while they are evacuating. Because radionuclides would be deposited continually from the cloud as it passed a given location, a person while under the cloud would be exposed to ground contamination less concentrated than if the cloud had completely passed. To account for this, at least in a rudimentary way, the new model assumes that persons are exposed to the total calculated ground contamination concentration (the concentration calculated to exist after complete passage of the cloud) when completely passed by the cloud, one half the calculated concentration when anywhere under the cloud, and no concentration when in front of the cloud. A graphical description of the people/cloud interactions treated in this model is included in Appendix A.
IV. REINTERPRETATION OF EPA EVACUATION DATA

The EPA evacuation data [6] for transportation accidents presented in Table 1 was used to determine representative effective evacuation speeds* for use in the RSS evacuation model. The revised model of public evacuation described in this report requires as input estimates for both a delay time before public movement and an evacuation speed while in transit. While the data recorded for the evacuation events listed in Table 1 includes the total evacuation period or time, the delay and transit times are not given. However, sufficient information is available for the separation of delay and transit times if a specific actual evacuation speed is assumed. The transit time for each evacuation event can be estimated by dividing the recorded evacuated distance by the assumed evacuation speed. Subtracting the estimated transit time from the recorded evacuation period results in the appropriate delay time for that event. Performing this calculation for each of the ten evacuation events listed in Table 1 for selected assumed evacuation speeds leads to the following estimates of the mean and range of corresponding delay times.

<table>
<thead>
<tr>
<th>Assumed Evacuation Speed (MPH)</th>
<th>Mean Delay Time (hours)</th>
<th>Range of Delay Times (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.8</td>
<td>0 - 5.5</td>
</tr>
<tr>
<td>20</td>
<td>3.2</td>
<td>0.4 - 6.8</td>
</tr>
<tr>
<td>30</td>
<td>3.3</td>
<td>0.6 - 7.2</td>
</tr>
<tr>
<td>40</td>
<td>3.4</td>
<td>0.7 - 7.4</td>
</tr>
</tbody>
</table>

*Effective speeds were determined by dividing the recorded distance evacuated by the total evacuation period.
Statistical analysis of the data suggests that for each assumed evacuation speed, the distribution of delay times calculated may be satisfactorily represented by a normal distribution. Using a normal distribution for each of the assumed speeds suggests the following 15-85 percent range of delay times.

<table>
<thead>
<tr>
<th>Assumed Evacuation Speed (MPH)</th>
<th>15-85% Range of Delay Times (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.9 - 4.7</td>
</tr>
<tr>
<td>20</td>
<td>1.2 - 5.2</td>
</tr>
<tr>
<td>30</td>
<td>1.3 - 5.3</td>
</tr>
<tr>
<td>40</td>
<td>1.4 - 5.4</td>
</tr>
</tbody>
</table>

As indicated by the information above, the mean and likely range of delay times suggested by the EPA data are relatively insensitive to the evacuation speed assumed. Regardless of what speed is assumed the mean, 15 and 85 percent delay times are approximately 3, 1 and 5 hours, respectively.

V. RELATIVE IMPORTANCE OF MODEL PARAMETERS

To evaluate the relative importance of the evacuation model parameters, it is necessary to understand how the model interacts with the rest of the consequence model. Specifically, the evacuation model interfaces with the calculation of the early radiation dose to the population. Early dose is then used in the effects modelling to determine the total number of people that will be injured or killed. The early dose model is divided into three pathways of radiation.
exposure: (1) exposure to external penetrating radiation from the passing cloud of radioactive material; (2) exposure to external penetrating radiation from radionuclides deposited on the ground and other surfaces during cloud passage; and (3) internal exposure due to the quantity of radionuclides inhaled during passage of the cloud. Radiation doses to specific organs in the body are calculated, and effects are estimated on an organ by organ basis. The various radiation exposure pathways will have substantially different levels of impact on the different organs. The evacuation model determines the interaction between the people and the released radioactive material in terms of (1) the amounts of radioactive material involved, (2) the location(s) of the interaction(s), and (3) the time(s) of the interaction(s). Also included in the evacuation model are the shielding factors and breathing rates which correspond to the various locations and activities of the population during the exposure. It is the interrelations between the dose effects, the pathways of exposure, and the interaction of the people and the radioactive material that will determine the relative importance of the evacuation model parameters.

When considering these relationships, some important sensitivities are found. First, the delay time is most important because it determines when, where, and how long the population are exposed before they begin to move. The
exposure during the delay period generally result in the largest doses since the concentrations of radioactive material would generally be highest close to the reactor site and the people would have been caught unaware. Approximate delay times can range from 0 to almost 8 hours. As the exposure time increases, the dose due to exposure to external penetrating radiation from ground deposited radionuclides is the dominant contributor to the total dose, and bone marrow becomes the critical organ. Second, the assumed speed of the evacuation is relatively unimportant since the integrated dose after the people begin to move is very small when compared to the dose they could receive during the delay time.
REFERENCES


Appendix A

Graphical Description of Evacuation Model

The purpose of this appendix is to graphically illustrate the possible space/time interactions of evacuating persons and the cloud of radioactive material as treated by the revised evacuation model. Figure 1 shows the radial position of the radioactive cloud as a function of time following warning of the impending release. The warning is assumed to occur at time $t_0 = 0$, and $t_w$ is the time available after warning and before the start of the release. $t_r$ is the duration of release. The positions of both the front and back of the cloud are indicated, and for simplicity the speed of the cloud (windspeed) is assumed constant in this figure. In actual computations performed using the consequence model, the speed of the cloud can vary with spatial interval. Also, both in the model and figure, the speed of the front and back of the cloud are assumed to be identical (i.e., the cloud is of constant length).

Figure 2 shows the radial position of evacuating people initially located at $d_0$ as a function of time following warning. Again, the warning is assumed to occur at time $t_0 = 0$, and $t_w$ is the delay time before people begin to move away from the reactor. Evacuating persons are assumed to move radially away from the reactor with a constant $v_p$. The distance functions of the cloud and people are given by:
Figure 1. Radial Position of Cloud as a Function of Time

Figure 2. Radial Position of Evacuating People as a Function of Time
People:

\[ d_p(t) = \begin{cases} 
  d_0 & , \, t \leq t_0 \\
  v_p(t-t_0) & , \, t > t_0 
\end{cases} \]  

(A.1)

Front of Cloud:

\[ d_{cf}(t) = \begin{cases} 
  0 & , \, t \leq t_w \\
  v_c(t - t_w) & , \, t > t_w 
\end{cases} \]  

(A.2)

where \( v_c \) = average cloud velocity up to \( d_{cf}(t) \).

Back of Cloud:

\[ d_{cb}(t) = \begin{cases} 
  0 & , \, t \leq (t_w + t_r) \\
  v_c \left[ t - (t_w + t_r) \right] & , \, t > (t_w + t_r) 
\end{cases} \]  

(A.3)

Figure 3 combines Figures 1 and 2 as an example of the people/cloud interaction possibilities treated in the evacuation model. In the hypothetical situation indicated, the entire cloud passes by the population located at \( d_0 \) before they begin to move. However, once the population begins
Figure 3. One Example of the Interaction of Evacuating People and Cloud as a Function of Time
moving away from the reactor, they rapidly overtake and escape the cloud.

Exposure implications:* i) people are exposed to cloud twice: once while stationary, once in transit
ii) people are exposed to ground contamination for \((t_0 - t_1)\) while stationary and for \((t_2 - t_0)\) while in transit

The exposure history of downwind populations is calculated on a radial interval basis in the consequence model [1]. As people evacuate through each interval, there are nine possible people/cloud interaction possibilities treated in the evacuation model. The following figure schematically illustrates these situations.

*Shielding factors and breathing rates may be different while stationary and in transit.
1) (A, A'): People travel in front of cloud
2) (A, B'): Cloud overtakes people
3) (A, C'): Cloud overtakes and passes people
4) (B, A'): People escape from under cloud
5) (B, B'): People travel under cloud
6) (B, C'): Cloud passes people
7) (C, A'): People overtake and pass cloud
8) (C, B'): People overtake cloud
9) (C, C'): People travel behind cloud