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Examination of Offsite Radiological Emergency Protective Measures for Nuclear Reactor Accidents Involving Core Melt

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

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PREFACE

This document was previously printed by Sandia Laboratories in June 1978 as SAND 78-0454, under NRC FIN No. A1039. NRC is re-issuing this document, at this time in the NUREG/CR series, in response to renewed interest generated by the accident at Three Mile Island.

ABSTRACT

Evacuation, sheltering followed by population reloca-
tion, 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 cate-
gory 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 avail-
able, 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 substan-
tially 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

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*Protective "measures" and "actions" are used interchange-
ably 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

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*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.

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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 versa-
tility, 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 unique and unfavorable weather conditions
exist at the time of the release. For these reasons, this
study has focused entirely on evaluting 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 protec-
tive measures can not be determined solely on the basis of
potential dose or consequence reductions. The specific res-
ponse planned should be a function of local population loca-
tions 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 pre-

sently 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) cur-
rent federal guidance for radiological emergency response
planning in the United States, and (3) previous studies that
evaluated the effectiveness of radiological emergency res-
ponse 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), dis-
cussed 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

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*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;

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*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. Radia-
tion 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 morta-
lities that are usually observed after large acute doses

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*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 radio-active material are released might also result in serious economic consequences. Deposition of radionuclides from the cloud of radioactive material may require the impound-ment 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 radio-
active 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 atmos-
phere. 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^{-1})	Time of Release (hr)	Duration of Release (hr)	Warning Time for Evacuation (hr)	Elevation of Release[g] (meters)	Energy Release (10^6 Btu/hr)	Fraction of Core Inventory Released[a]							
							Xe-Kr	Organic I[b]	I[b]	Cs-Rb	Te-Sb	Ba-Sr	Ru[c]	La[d]
PWR 1	9×10^{-7}[e]	2.5	0.5	1.0	25	20 and 520[e]	0.9	6×10^{-3}	0.7	0.4	0.4	0.05	0.4	3×10^{-3}
PWR 2	8×10^{-6}	2.5	0.5	1.0	0	170	0.9	7×10^{-3}	0.7	0.5	0.3	0.06	0.02	4×10^{-3}
PWR 3	4×10^{-6}	5.0	1.5	2.0	0	6	0.8	6×10^{-3}	0.2	0.2	0.3	0.02	0.03	3×10^{-3}
PWR 4	5×10^{-7}	2.0	3.0	2.0	0	1	0.6	2×10^{-3}	0.09	0.04	0.03	5×10^{-3}	3×10^{-3}	4×10^{-4}
PWR 5	7×10^{-7}	2.0	4.0	1.0	0	0.3	0.3	2×10^{-3}	0.03	9×10^{-3}	5×10^{-3}	1×10^{-3}	6×10^{-4}	7×10^{-5}
PWR 6	6×10^{-6}	12.0	10.0	1.0	0	N/A	0.3	2×10^{-3}	8×10^{-4}	8×10^{-4}	1×10^{-3}	9×10^{-5}	7×10^{-5}	1×10^{-5}
PWR 7	4×10^{-5}	10.0	10.0	1.0	0	N/A	6×10^{-3}	2×10^{-5}	2×10^{-5}	1×10^{-5}	2×10^{-5}	1×10^{-6}	1×10^{-6}	2×10^{-7}
PWR 8	4×10^{-5}	0.5	0.5	N/A[f]	0	N/A	2×10^{-3}	5×10^{-6}	1×10^{-4}	5×10^{-4}	1×10^{-6}	1×10^{-8}	0	0
PWR 9	4×10^{-4}	0.5	0.5	N/A	0	N/A	3×10^{-6}	7×10^{-9}	1×10^{-7}	6×10^{-7}	1×10^{-9}	1×10^{-11}	0	0
BWR 1	1×10^{-6}	2.0	0.5	1.5	25	130	1.0	7×10^{-3}	0.40	0.40	0.70	0.05	0.5	5×10^{-3}
BWR 2	6×10^{-6}	30.0	3.0	2.0	0	30	1.0	7×10^{-3}	0.90	0.50	0.30	0.10	0.03	4×10^{-3}
BWR 3	2×10^{-5}	30.0	3.0	2.0	25	20	1.0	7×10^{-3}	0.10	0.10	0.30	0.01	0.02	4×10^{-3}
BWR 4	2×10^{-6}	5.0	2.0	2.0	25	N/A	0.6	7×10^{-4}	8×10^{-4}	5×10^{-3}	4×10^{-3}	6×10^{-4}	6×10^{-4}	1×10^{-4}
BWR 5	1×10^{-4}	3.5	5.0	N/A	150	N/A	5×10^{-4}	2×10^{-9}	6×10^{-11}	4×10^{-9}	8×10^{-12}	8×10^{-14}	0	0

(a) 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, Zr, Nb, Ce, Pr, Nd, 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 4×10^{-7} per reactor-year and 20×10^6 Btu/hr and PWR 1B with a probability of 5×10^{-7} per reactor-year and 520×10^6 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

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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, particu-
larly for sensitive populations. However, if local con-
straints 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 emer-
gency 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.

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*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 clarfiy 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

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*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

*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 chracteristics 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 striclty 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

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*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].

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 conse-
quences is desirable.

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.**

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*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 signficantly different consequence predictions than when using time varying weather data, and was found to be inadequate for risk calculations [3].
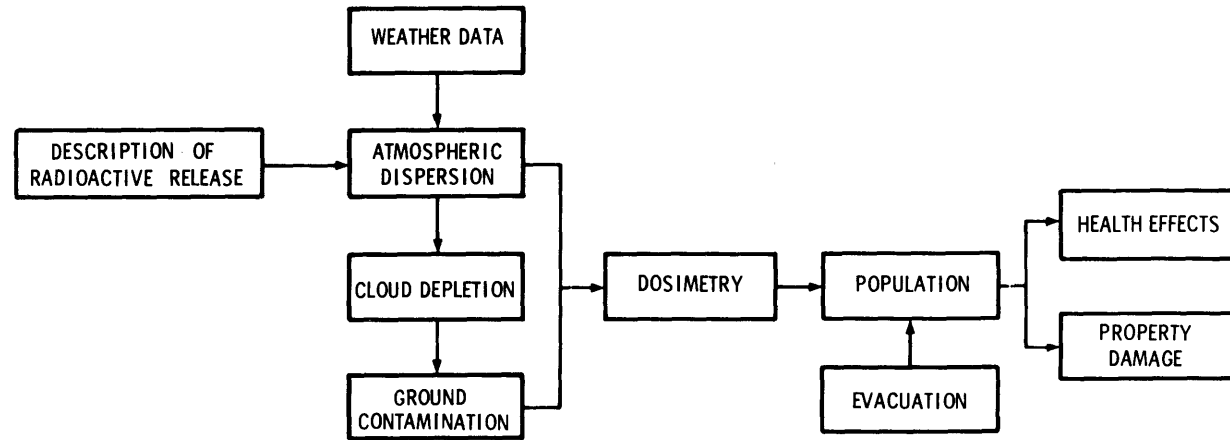
Figure 3.1 Schematic Outline of Reactor Safety Study Consequence Model (from Ref. 15).

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.

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*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

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*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 com-
puted 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 struc-
tures, 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 parti-
cular accident sequence, may result in a wide range of radio-
active 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 penetra-
tions, 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 pro-
babilities as listed in Table 2.1 suggests probabilities
of 4.6×10^{-5} per reactor-year for the PWR "Melt-through"
category and 1.4×10^{-5} per reactor-year for the PWR "Atmos-
pheric" 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)

	RELEASE CATEGORIES						
	1	2	3	4	5	6	7
LARGE LOCA A	$AB\text{-}\alpha$ 1×10^{-11} $AF\text{-}\alpha$ 1×10^{-10} $ACD\text{-}\alpha$ 5×10^{-11} $AG\text{-}\alpha$ 9×10^{-11}	$AB\text{-}\gamma$ 1×10^{-10} $AB\text{-}\delta$ 4×10^{-11} $AHF\text{-}\gamma$ 2×10^{-11}	$AD\text{-}\alpha$ 2×10^{-8} $AM\text{-}\alpha$ 1×10^{-8} $AF\text{-}\delta$ 1×10^{-8} $AG\text{-}\delta$ 9×10^{-9}	$ACD\text{-}\beta$ 1×10^{-11}	$AD\text{-}\beta$ 4×10^{-9} $AM\text{-}\beta$ 3×10^{-9}	$AB\text{-}\epsilon$ 1×10^{-9} $AHF\text{-}\epsilon$ 1×10^{-10} $ADF\text{-}\epsilon$ 2×10^{-10}	$AD\text{-}\epsilon$ 2×10^{-6} $AM\text{-}\epsilon$ 1×10^{-6}
A Probabilities	2×10^{-9}	1×10^{-8}	1×10^{-7}	1×10^{-8}	4×10^{-8}	3×10^{-7}	3×10^{-6}
SMALL LOCA S_1	$S_1 B\text{-}\alpha$ 3×10^{-11} $S_1 CD\text{-}\alpha$ 7×10^{-11} $S_1 F\text{-}\alpha$ 3×10^{-10} $S_1 G\text{-}\alpha$ 3×10^{-10}	$S_1 B\text{-}\gamma$ 4×10^{-10} $S_1 B\text{-}\delta$ 1×10^{-10} $S_1 HF\text{-}\gamma$ 6×10^{-11}	$S_1 D\text{-}\alpha$ 3×10^{-8} $S_1 M\text{-}\alpha$ 3×10^{-8} $S_1 P\text{-}\delta$ 3×10^{-8} $S_1 G\text{-}\delta$ 3×10^{-8}	$S_1 CD\text{-}\beta$ 1×10^{-11}	$S_1 H\text{-}\beta$ 5×10^{-10} $S_1 D\text{-}\beta$ 6×10^{-9}	$S_1 DF\text{-}\epsilon$ 3×10^{-10} $S_1 B\text{-}\epsilon$ 2×10^{-9} $S_1 HF\text{-}\epsilon$ 4×10^{-10}	$S_1 D\text{-}\epsilon$ 3×10^{-6} $S_1 M\text{-}\epsilon$ 3×10^{-6}
S_1 Probabilities	3×10^{-9}	2×10^{-8}	2×10^{-7}	3×10^{-8}	8×10^{-8}	6×10^{-7}	6×10^{-6}
SMALL LOCA S_2	$S_2 B\text{-}\alpha$ 1×10^{-10} $S_2 F\text{-}\alpha$ 1×10^{-9} $S_2 CD\text{-}\alpha$ 2×10^{-10} $S_2 G\text{-}\alpha$ 9×10^{-10} $S_2 C\text{-}\alpha$ 2×10^{-8}	$S_2 B\text{-}\gamma$ 1×10^{-9} $S_2 HF\text{-}\gamma$ 2×10^{-10} $S_2 B\text{-}\delta$ 4×10^{-10}	$S_2 D\text{-}\alpha$ 9×10^{-8} $S_2 M\text{-}\alpha$ 6×10^{-8} $S_2 F\text{-}\delta$ 1×10^{-7} $S_2 C\text{-}\delta$ 2×10^{-6} $S_2 G\text{-}\delta$ 9×10^{-8}	$S_2 DG\text{-}\beta$ 1×10^{-12}	$S_2 D\text{-}\beta$ 2×10^{-8} $S_2 H\text{-}\beta$ 1×10^{-8}	$S_2 B\text{-}\epsilon$ 8×10^{-9} $S_2 CD\text{-}\epsilon$ 2×10^{-8} $S_2 HF\text{-}\epsilon$ 1×10^{-9}	$S_2 D\text{-}\epsilon$ 9×10^{-6} $S_2 M\text{-}\epsilon$ 6×10^{-6}
S_2 Probabilities	1×10^{-7}	3×10^{-7}	3×10^{-6}	3×10^{-7}	3×10^{-7}	2×10^{-6}	2×10^{-5}
REACTOR VESSEL RUPTURE - R	$RC\text{-}\alpha$ 2×10^{-12}	$RC\text{-}\gamma$ 3×10^{-11} $RF\text{-}\delta$ 1×10^{-11} $RC\text{-}\delta$ 1×10^{-12}	$R\text{-}\alpha$ 1×10^{-9}				$R\text{-}\epsilon$ 1×10^{-7}
R Probabilities	2×10^{-11}	1×10^{-10}	1×10^{-9}	2×10^{-10}	1×10^{-9}	1×10^{-8}	1×10^{-7}
INTERFACING SYSTEMS LOCA (CHECK VALVE) - V		V 4×10^{-6}					
V Probabilities	4×10^{-7}	4×10^{-6}	4×10^{-7}	4×10^{-8}			
TRANSIENT EVENT - T	$TMLB'\text{-}\alpha$ 3×10^{-8}	$TMLB'\text{-}\gamma$ 7×10^{-7} $TMLB'\text{-}\delta$ 2×10^{-6}	$TML\text{-}\alpha$ 6×10^{-8} $TKQ\text{-}\alpha$ 3×10^{-8} $TKMQ\text{-}\alpha$ 1×10^{-8}		$TML\text{-}\beta$ 3×10^{-10} $TKQ\text{-}\beta$ 3×10^{-10}	$TMLB'\text{-}\epsilon$ 6×10^{-7}	$TML\text{-}\epsilon$ 3×10^{-6} $TKQ\text{-}\epsilon$ 3×10^{-6} $TKMQ\text{-}\epsilon$ 1×10^{-6}
T Probabilities	3×10^{-7}	3×10^{-6}	4×10^{-7}	7×10^{-8}	2×10^{-7}	2×10^{-6}	1×10^{-5}
(Σ) SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORY							
MEDIAN (50% VALUE)	9×10^{-7}	8×10^{-6}	4×10^{-6}	5×10^{-7}	7×10^{-7}	6×10^{-6}	4×10^{-5}
LOWER BOUND (5% VALUE)	9×10^{-8}	8×10^{-7}	6×10^{-7}	9×10^{-8}	2×10^{-7}	2×10^{-6}	1×10^{-5}
UPPER BOUND (95% VALUE)	9×10^{-6}	8×10^{-5}	4×10^{-5}	5×10^{-6}	4×10^{-6}	2×10^{-5}	2×10^{-4}

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)

	RELEASE CATEGORIES			
	1	2	3	4
LARGE LOCA DOMINANT ACCIDENT SEQUENCES (A)	$AE-\alpha$ $2x10^{-9}$ $AJ-\alpha$ $1x10^{-10}$ $AHI-\alpha$ $1x10^{-10}$ $AI-\alpha$ $1x10^{-10}$	$AE-\gamma'$ $3x10^{-8}$ $AE-\beta$ $1x10^{-8}$ $AJ-\gamma'$ $3x10^{-9}$ $AI-\gamma'$ $2x10^{-9}$ $AHI-\gamma'$ $2x10^{-9}$	$AE-\gamma$ $1x10^{-7}$ $AJ-\gamma$ $1x10^{-8}$ $AI-\gamma$ $1x10^{-8}$ $AHI-\gamma$ $1x10^{-8}$	$AGJ-\delta$ $6x10^{-11}$ $AEG-\delta$ $7x10^{-10}$ $AGHI-\delta$ $6x10^{-11}$
A Probabilities	$8x10^{-9}$	$6x10^{-8}$	$2x10^{-7}$	$2x10^{-8}$
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S_1)	$S_1E-\alpha$ $2x10^{-9}$ $S_1J-\alpha$ $3x10^{-10}$ $S_1I-\alpha$ $4x10^{-10}$ $S_1HI-\alpha$ $4x10^{-10}$	$S_1E-\gamma'$ $4x10^{-8}$ $S_1E-\beta$ $1x10^{-8}$ $S_1J-\gamma'$ $7x10^{-9}$ $S_1I-\gamma'$ $7x10^{-9}$ $S_1HI-\gamma'$ $6x10^{-9}$	$S_1E-\gamma$ $1x10^{-7}$ $S_1J-\gamma$ $3x10^{-8}$ $S_1I-\gamma$ $4x10^{-8}$ $S_1HI-\gamma$ $2x10^{-8}$ $S_1C-\gamma$ $3x10^{-9}$	$S_1GJ-\delta$ $2x10^{-10}$ $S_1GI-\delta$ $2x10^{-10}$ $S_1EI-\epsilon$ $1x10^{-10}$ $S_1GHI-\delta$ $2x10^{-10}$
S_1 Probabilities	$1x10^{-8}$	$9x10^{-8}$	$2x10^{-7}$	$2x10^{-8}$
SMALL LOCA DOMINANT ACCIDENT SEQUENCES (S_2)	$S_2J-\alpha$ $1x10^{-9}$ $S_2I-\alpha$ $1x10^{-9}$ $S_2HI-\alpha$ $1x10^{-9}$ $S_2E-\alpha$ $5x10^{-10}$	$S_2E-\gamma$ $1x10^{-8}$ $S_2E-\beta$ $4x10^{-9}$ $S_2J-\gamma'$ $2x10^{-8}$ $S_2I-\gamma'$ $2x10^{-8}$ $S_2HI-\gamma'$ $2x10^{-8}$	$S_2E-\gamma$ $4x10^{-8}$ $S_2J-\gamma$ $8x10^{-8}$ $S_2I-\gamma$ $9x10^{-8}$ $S_2HI-\gamma$ $9x10^{-8}$ $S_2C-\gamma$ $8x10^{-9}$	$S_2CG-\delta$ $6x10^{-11}$ $S_2GHI-\delta$ $6x10^{-10}$ $S_2EG-\delta$ $3x10^{-10}$ $S_2GJ-\delta$ $6x10^{-10}$ $S_2GI-\delta$ $2x10^{-10}$
S_2 Probabilities	$2x10^{-8}$	$1x10^{-7}$	$4x10^{-7}$	$4x10^{-8}$
TRANSIENT DOMINANT ACCIDENT SEQUENCES (T)	$TW-\alpha$ $2x10^{-7}$ $TC-\alpha$ $1x10^{-7}$ $TQUV-\alpha$ $5x10^{-9}$	$TW-\gamma'$ $3x10^{-6}$ $TQUV-\gamma'$ $8x10^{-8}$	$TW-\gamma$ $1x10^{-5}$ $TC-\gamma$ $1x10^{-5}$ $TQUV-\gamma$ $4x10^{-7}$	
T Probabilities	$1x10^{-6}$	$6x10^{-6}$	$2x10^{-5}$	$2x10^{-6}$
PRESSURE VESSEL RUPTURE ACCIDENTS (R)		P.V. RUPT. $1x10^{-8}$ Oxidizing Atmosphere	P.V. RUPT. $1x10^{-7}$ Non-oxidizing Atmosphere	
R Probabilities	$2x10^{-9}$	$2x10^{-8}$	$1x10^{-7}$	$1x10^{-8}$
SUMMATION OF ALL ACCIDENT SEQUENCES PER RELEASE CATEGORIES				
MEDIAN (50% VALUE)	$1x10^{-6}$	$6x10^{-6}$	$2x10^{-5}$	$2x10^{-6}$
LOWER BOUND (5% VALUE)	$1x10^{-7}$	$1x10^{-6}$	$5x10^{-6}$	$5x10^{-7}$
UPPER BOUND (95% VALUE)	$8x10^{-6}$	$3x10^{-5}$	$8x10^{-5}$	$1x10^{-5}$

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.

S_1- Small pipe break with an equivalent diameter of about 2-6 inches.

S_2- 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, are assigned 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 protecive 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 inven-
tories would be released to the atmosphere by accidents in
the "Melt-through" category, and the resulting doses down-
wind 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

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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.*

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*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. 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 radio-
active 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. Popu-
lation 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 path-
ways.

The potential of sheltering and relocation strategies
for limiting dose from exposure to radiation from airborne
and surface deposited radionuclides is discussed in reference
[17]. 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 struc-
tures, and (2) that basements of both homes and larger
buildings offer very effective shielding against external

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*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

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*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 pro-
 tection 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 reference [17]. 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 reference [17].

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 reference [17].

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 reference [18] 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

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*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

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*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 reference [17]) 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 2.66×10^{-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 reference [19]. 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 Reactor

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*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].

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Safety Study [2] for use in the calculation of public

risks from reactor accidents. However, for reasons which

are discussed in the reference [19], 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 incor-

porates 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 tran-

sit. 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 nonpar-

ticipating segment of the population. This latter assumption

results in upper bound estimates of evacuation effectiveness,

given a specific delay time and speed.* 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 reference [19], the evacuation data

gathered by the EPA contains sufficient information for

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*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].

the estimation 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. Therefore, the speed

of evacuation is assumed to be a constant 10 miles per

hour throughout this analysis. The EPA data is analyzed in

reference [19], assuming speeds of 10 mph and higher, to esti-

mate 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 appro-

priate 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

factors of 1.0 (cloud) and 0.5 (ground) are assumed. Persons

are evacuated within distances from the reactor of either 5,

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*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, per-
   sons begin evacuating 2 hours after the release begins at
   the reactor.

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 con-
tamintion 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 poten-
tially attractive as well, but require more detailed study
in living organisms before an acceptable prophylactic pro-
gram for the general public can be suggested [22].

Stable iodine has received more attention as a chemical
prophylactic agent than other elements because inhaled radio-
iodine 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
effects [6]. Inhaled radioiodine is quickly absorbed into
the blood stream and collects preferentially in the thyroid.

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*Persons are assumed in all cases to evacuate to a dis-
tance 5 miles beyond the evacuated area before they are
removed from the problem.

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 documented in reference [6].

If body fluids are saturated with stable iodine before exposure to radioiodine, the ultimate absorption of radioactive 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, essentially 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 attainable only during the first 3 or 4 hours [6]. For releases of long duration, and therefore prolonged exposure

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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.

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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]. Radio-
logical 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 (equi-
valent 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, reduc-
tion 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).*
Results for other reduction factors are easily constructed
from the results provided. The dose to the thyroid from

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*An average reduction factor of 0.05 (95% reduction) was
 assumed in most of this analysis to allow for the fact that
 some individuals may not receive or take the potassium
 iodide tablet.

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

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*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** pro-
jected 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 compo-
nents due to the inhalation of radioiodines and the inhala-
tion 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 calcula-
tional 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,

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*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 comparison 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

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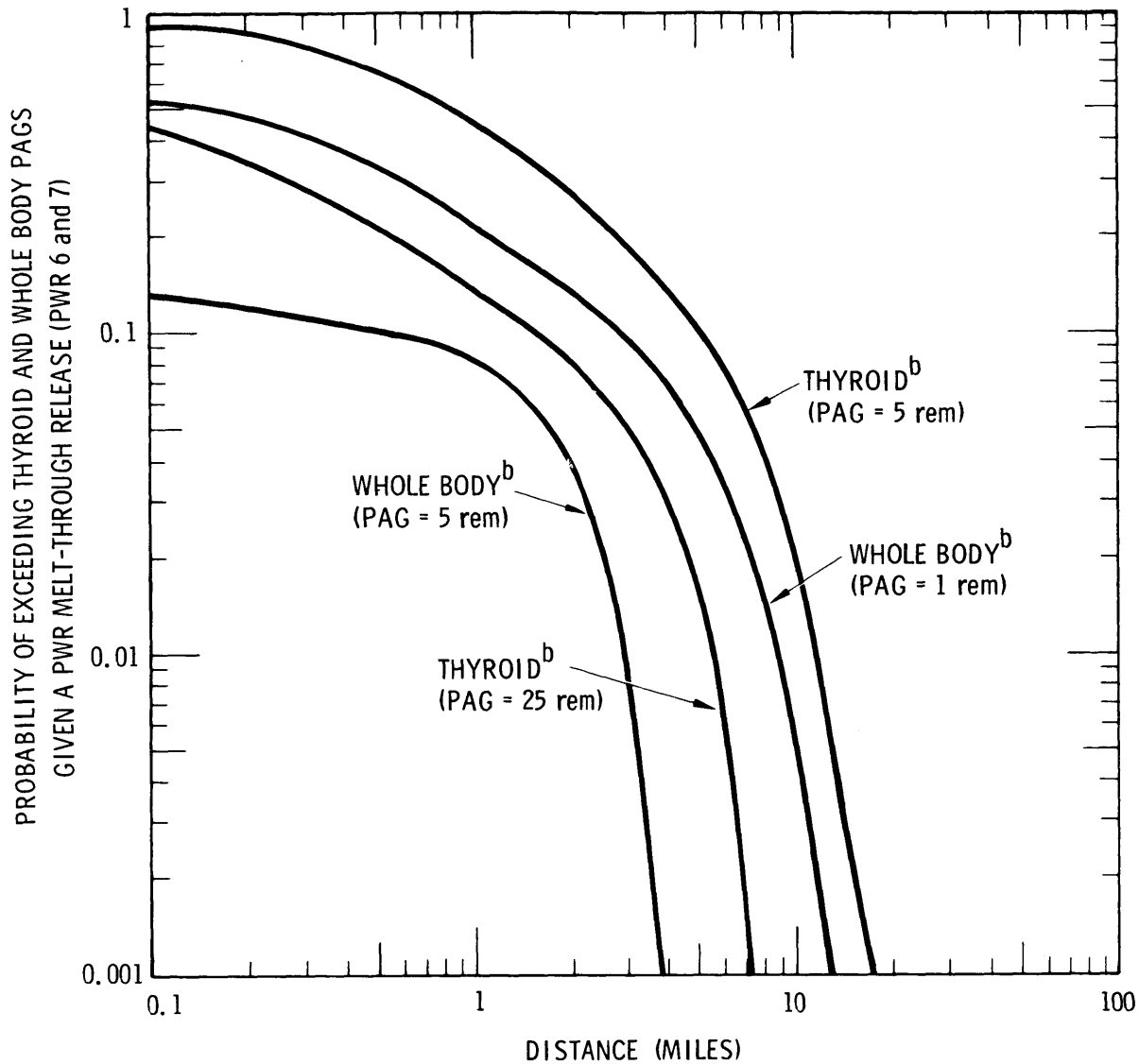*See subsection 4.2 for an explanation of effective exposure.

Figure 5.1 Conditional Probability of Exceeding Thyroid and Whole Body Protective Action Guides (PAGs) Versus Distance for an Individual Located Outdoors.[a] Probabilities are Conditional on a PWR "Melt-Through" Release (PWR 6 and 7).

[a]Shielding factor for airborne radionuclides = 1.0. Shielding factor for radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides on ground.

[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.
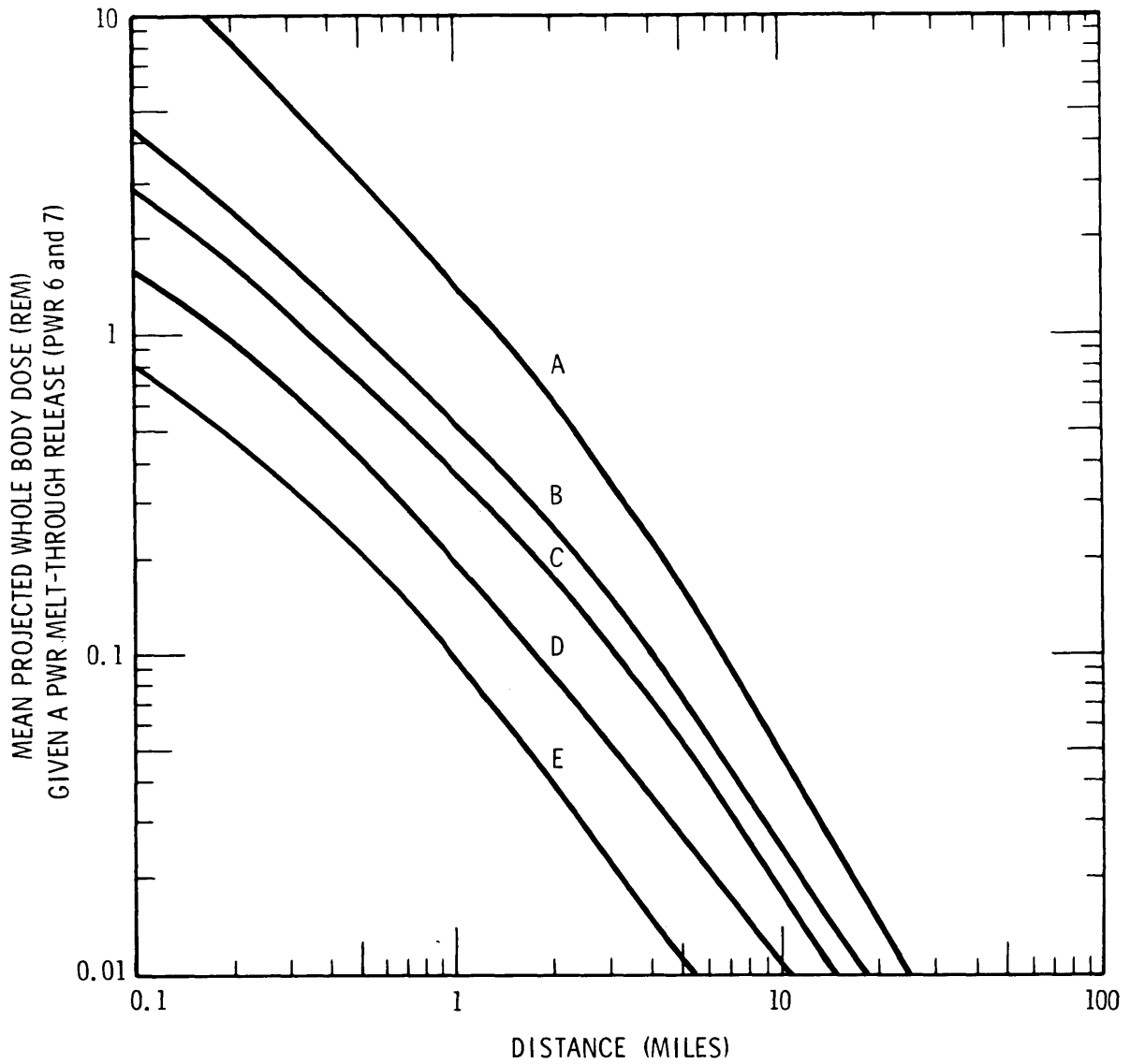
70

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.

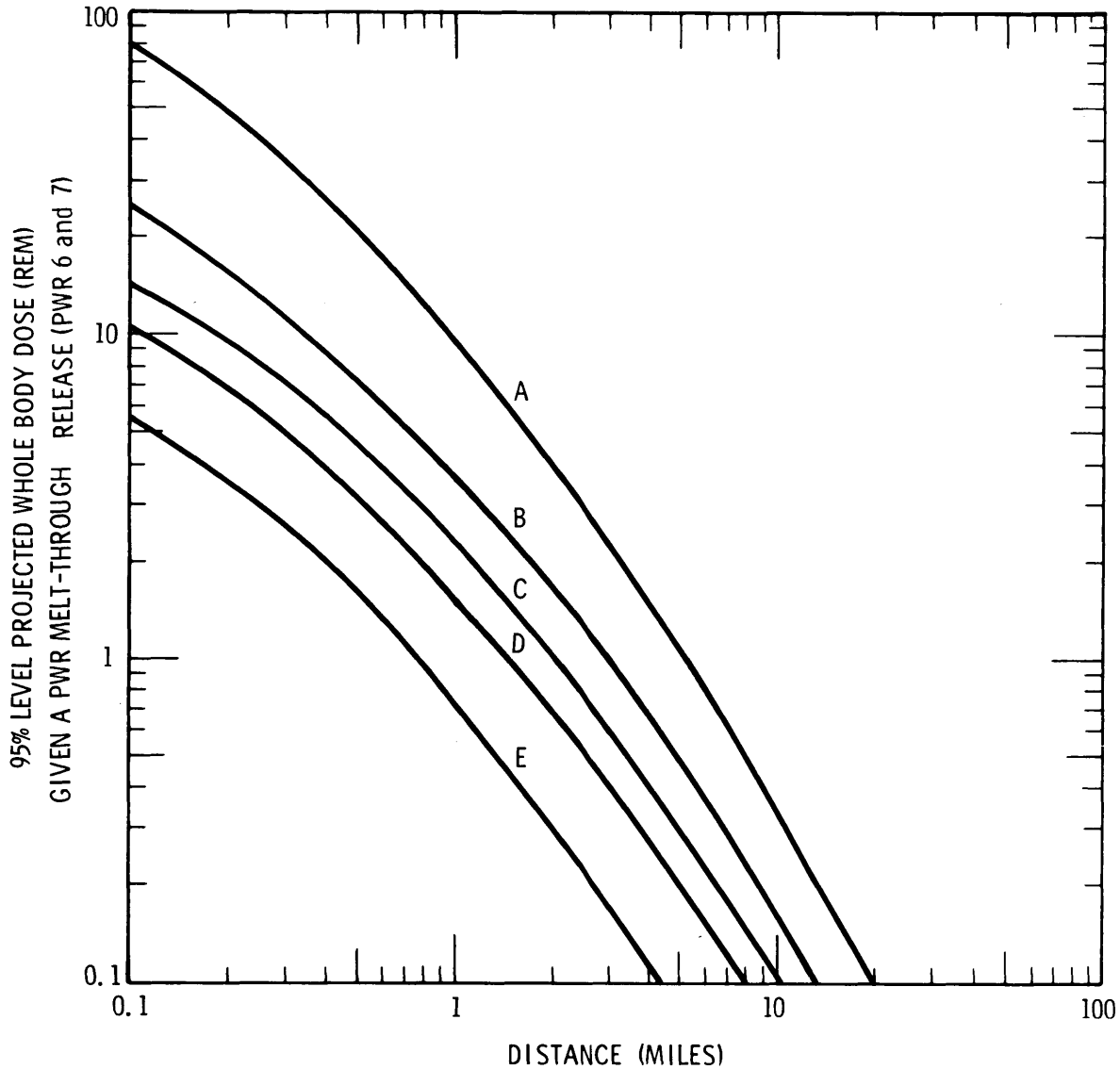Curve E Evacuation, 3 hour delay time, 10 MPH.

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 compo-
nents 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

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*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)
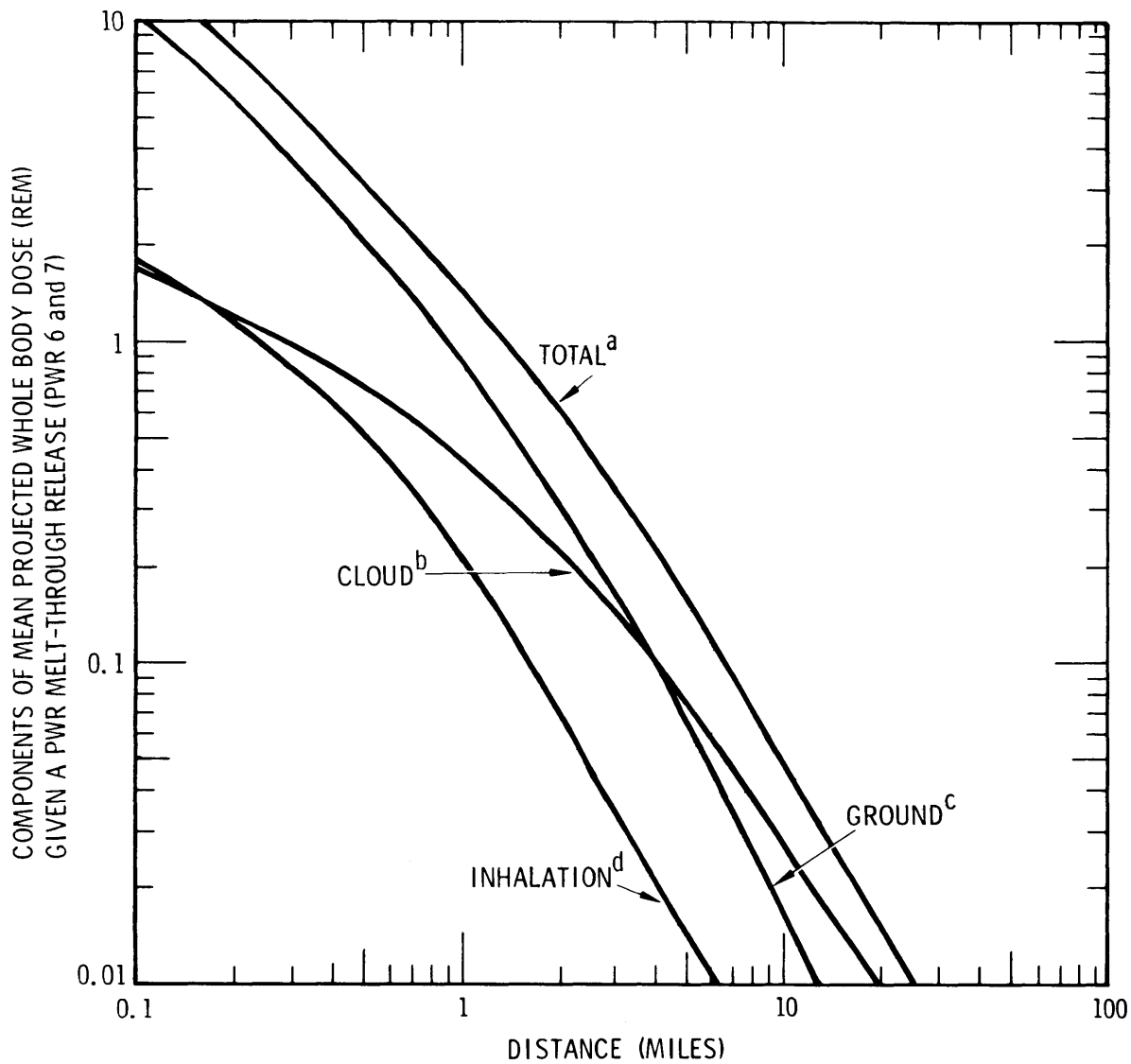increases with distance.

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).

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

[d]Whole 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.

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*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% reduc-
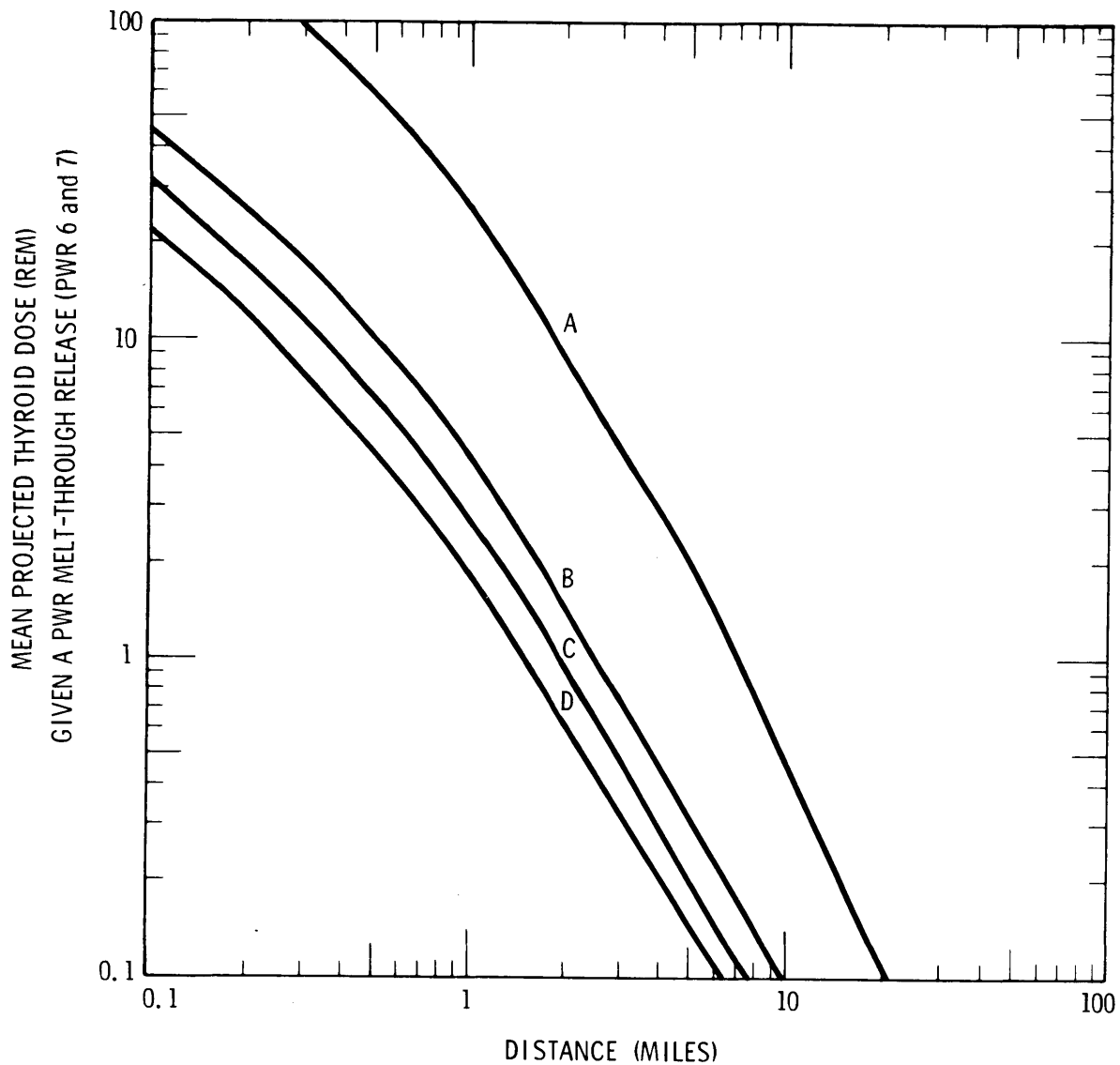 tion in dose to the thyroid from inhaled radioiodines.

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.

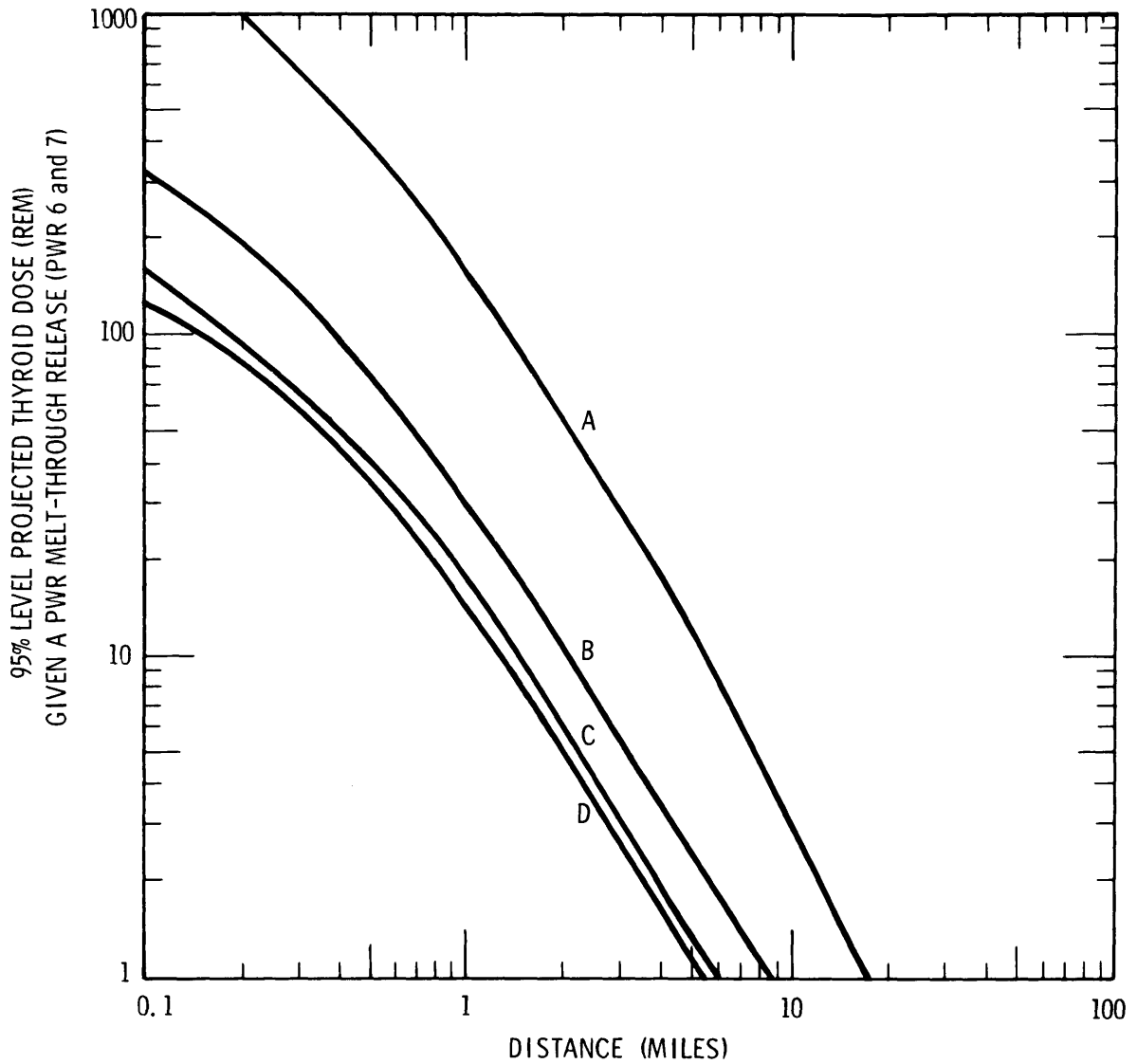Curve D   Evacuation, 3 hour delay time, 10 MPH.

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 radio-
iodines 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, evacua-
tion, even with delay times of 5 hours or longer, appears
to provide larger reductions in whole body dose than shel-
tering. This is due, in large part, to the fact that the
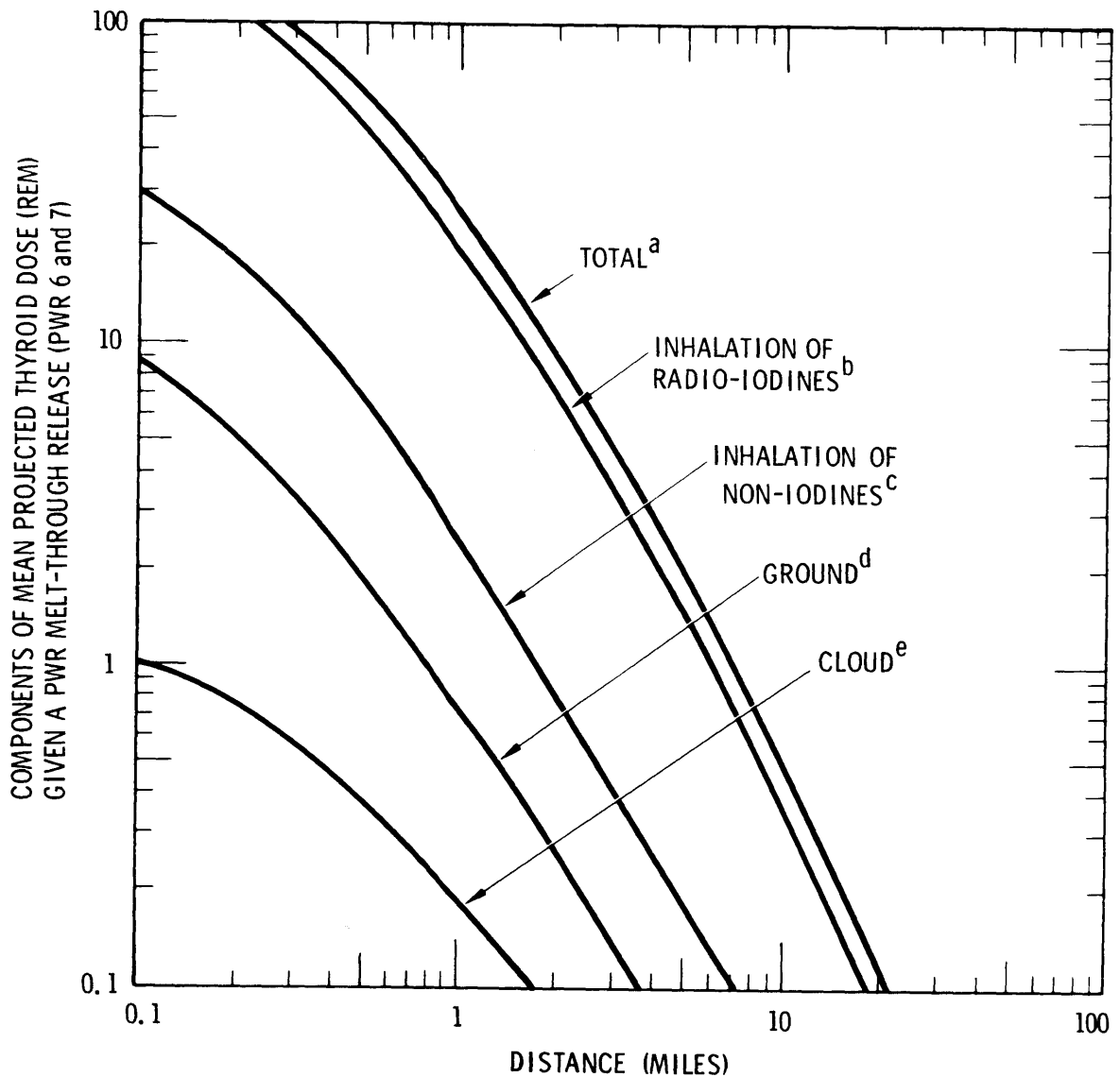release duration assumed is very long (10 hours), and that

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).

[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]Thyroid dose due to inhaled radioiodines within one year.

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

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

[e]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, particularily 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 administred in sufficient time, or evacuation

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*The assumed reduction factor for dose due to inhaled radionuclides 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

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*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.
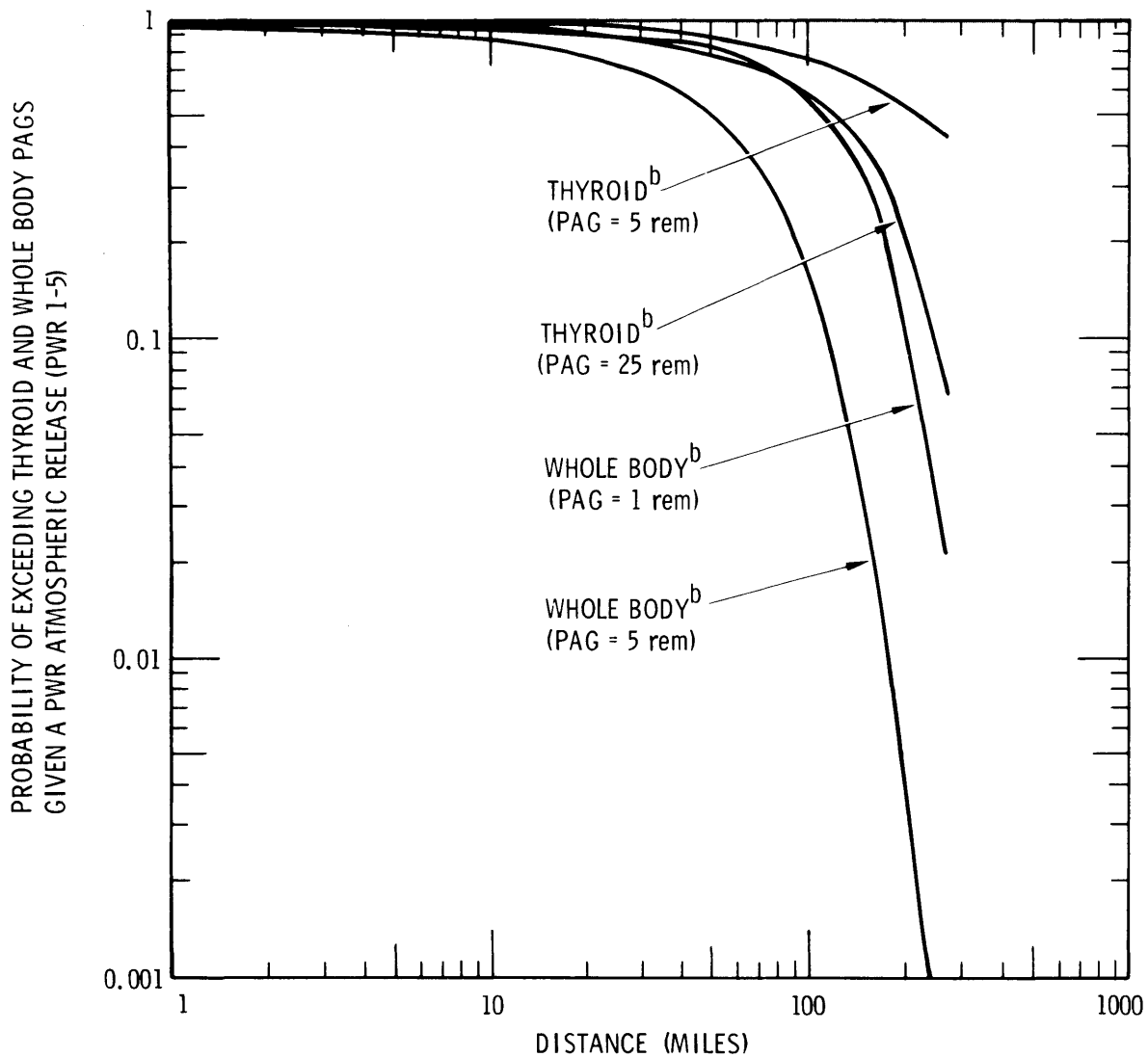
Figure 5.8 Conditional Probability of Exceeding Thyroid and Whole Body Protective Action
Guides (PAGs) Versus Distance for an Individual Located Outdoors.[a] Probabilities
are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

[a]Shielding factor for airborne radionuclides = 1.0. Shielding factor for
radionuclides deposited on ground = 0.7. 1-day exposure to radionuclides
on ground.

[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 indivi-
duals 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 "Atmos-
pheric" category of accidents are evaluated in this subsec-
tion 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, con-
ditional 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 out-
doors 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

MEAN PROJECTED WHOLE BODY DOSE (REM)
GIVEN A PWR ATMOSPHERIC RELEASE (PWR 1-5)

10^3

10^2

10

1

C

A

B

E

D

1   10   100   1000
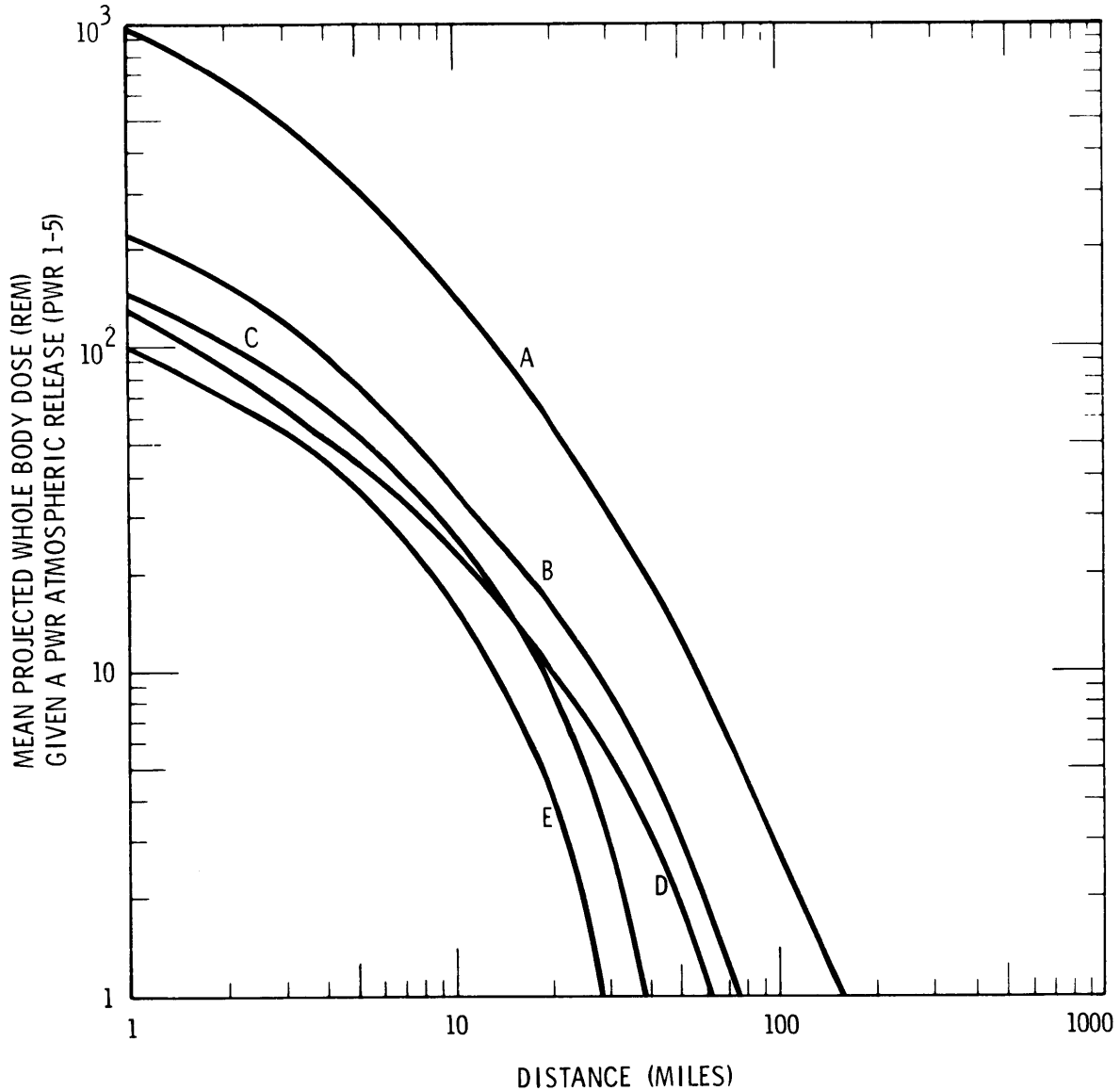
DISTANCE (MILES)

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.

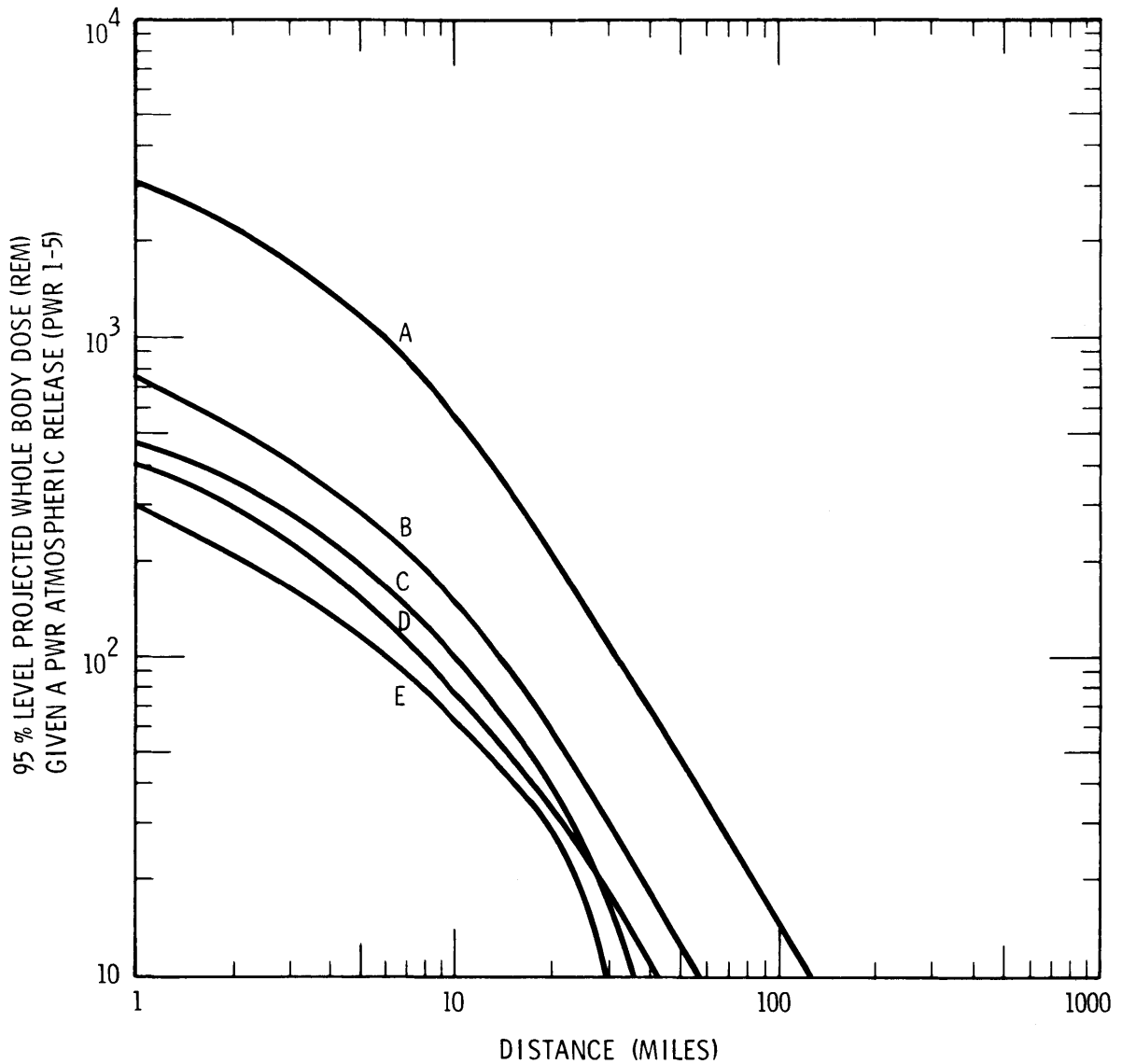Curve E   Evacuation, 3 hour delay time, 10 MPH.

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 compo-
nents 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 pro-
jected 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

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*Iodine prophylaxis is assumed here to result in a 95%
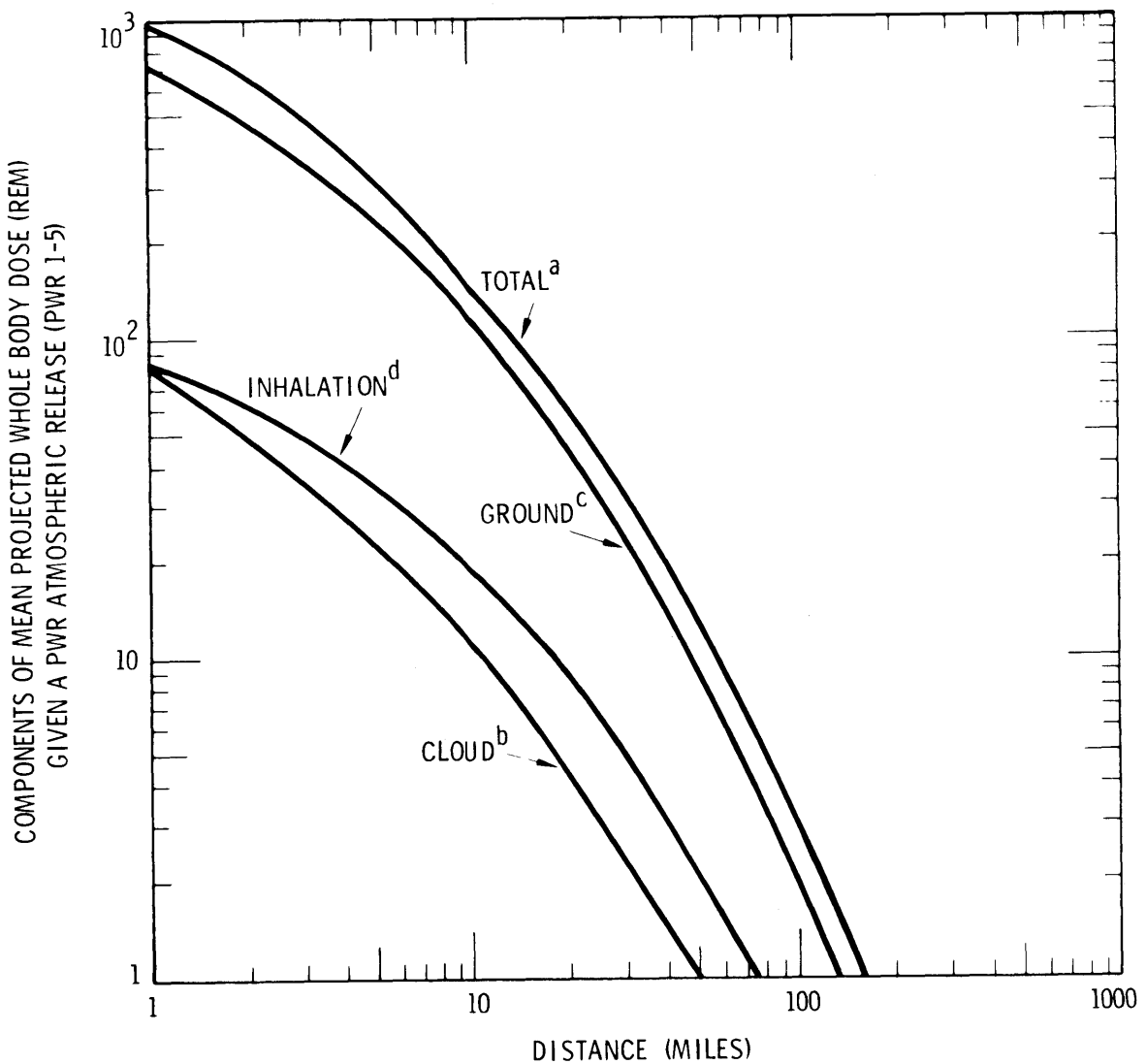 reduction in thyroid dose due to inhaled radioiodines.

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.

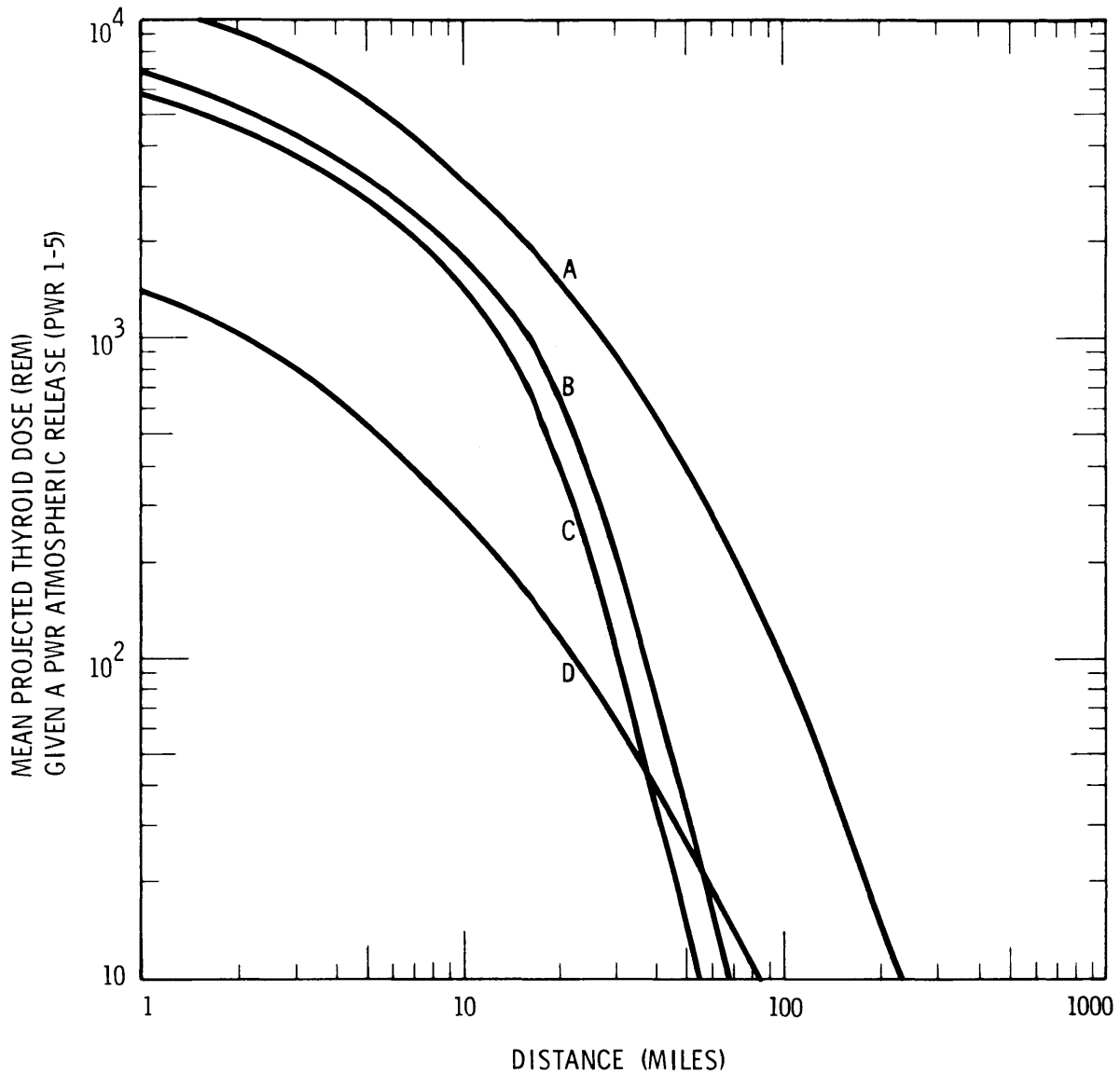[d]Whole body dose from inhaled radionuclides within one year.

Figure 5.12 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.
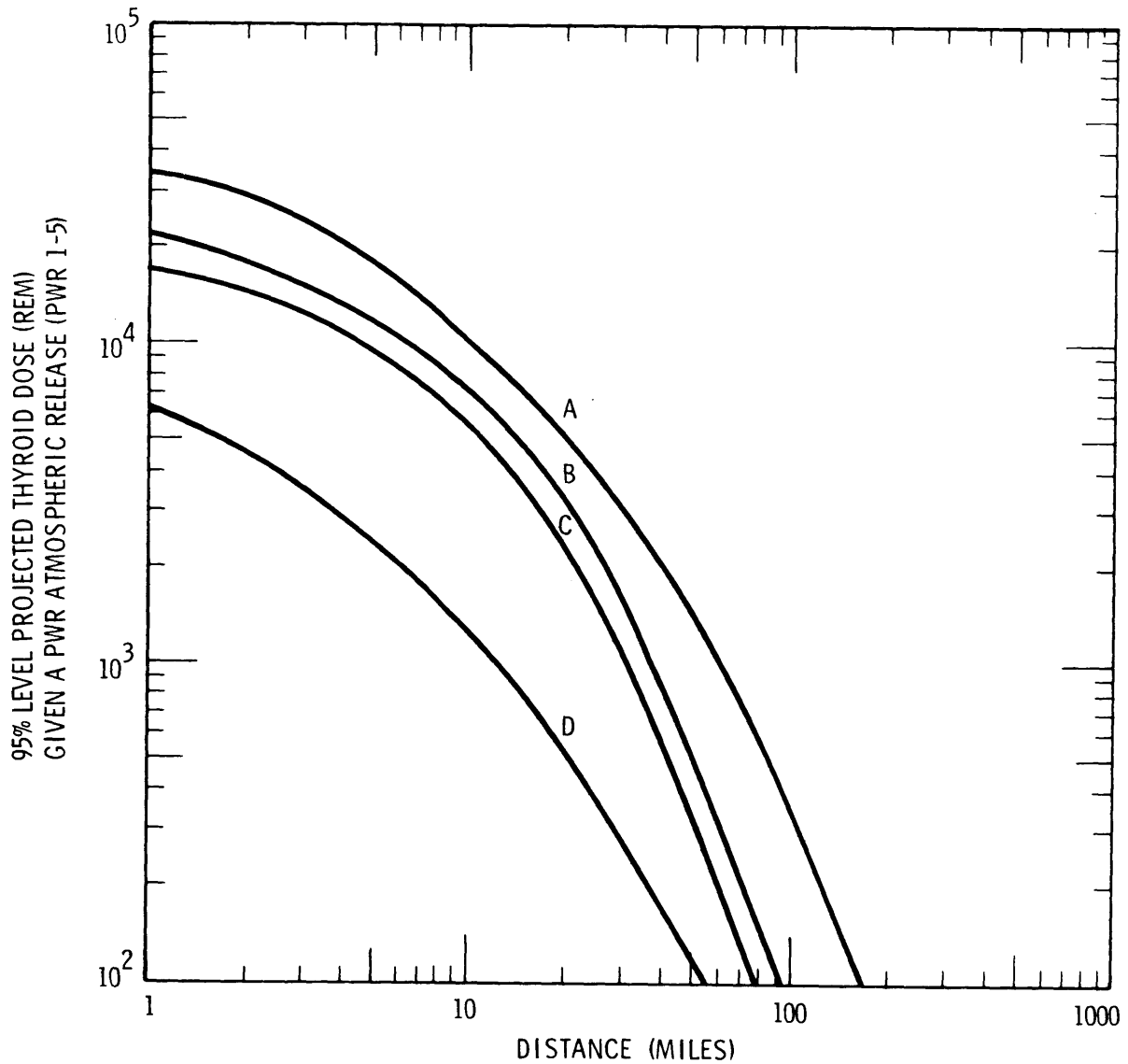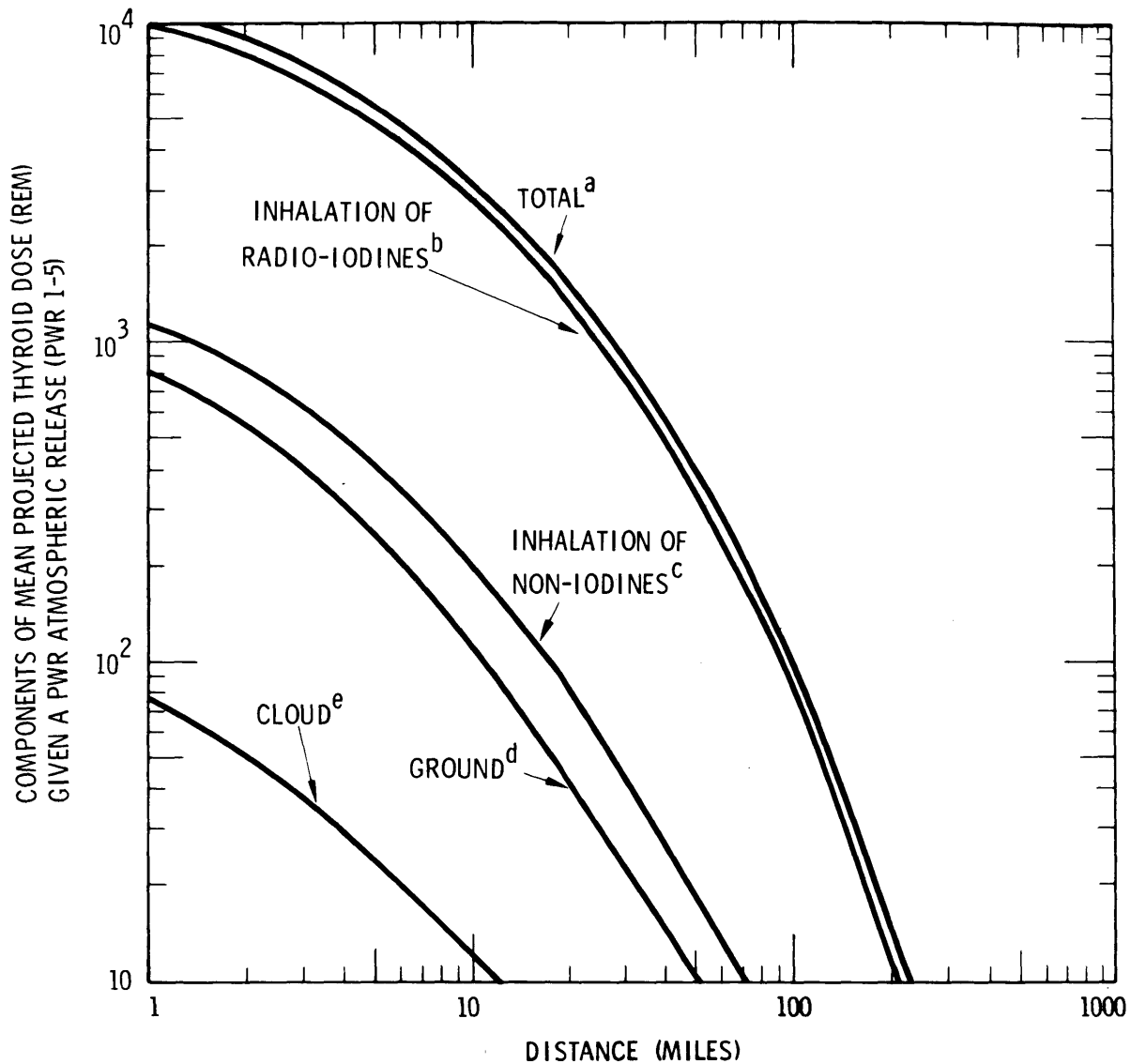
Figure 5.14 Components of Mean Projected Thyroid Dose Versus Distance for an
Individual Located Outdoors. Projected Doses are Conditional on a PWR
"Atmospheric" Release (PWR 1-5).

[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 radioiodines 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 dealy 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.

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*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, con-
ditional 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 imple-
mented in strategy 1, as listed in Table 5.1, and normal
activity shielding factors, (0.75, 0.33), and 1 day of expo-
sure 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

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*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 5.1 Projected Numbers of Early Health Effects for Sheltering/Relocation Strategies, Conditional on "Atmospheric" Release (PWR 1-5). A Uniform Population Density of 100 Persons per Square Mile is Assumed.

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

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

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

[c]Shielding factors (airborne radionuclides, ground contamination).

TABLE 5.1 (Continued)

Sheltering/Relocation Strategy[a]	Early Fatalities[b]		Early Injuries[b]	
	Mean	95% Level	Mean	95% Level
10. Sheltering of population within 10 miles, SF's[c] (0.75, 0.33), 6-hour exposure to radionuclides on ground.	23	120	150	630
11. Sheltering of population within 10 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.	11	24	120	570
12. Sheltering of population within 15 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.	20	100	130	540
13. Sheltering of population within 15 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.	8	17	96	530
14. Sheltering of population within 25 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.	15	87	31	280
15. Sheltering of population within 25 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.	3	16	42	150
16. Sheltering of population within 50 miles, SF's (0.75, 0.33), 6-hour exposure to radionuclides on ground.	15	87	64	250
17. Sheltering of population within 50 miles, SF's (0.5, 0.08), 6-hour exposure to radionuclides on ground.	3	16	25	100

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

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

[c] 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 pre-

sented in Table 5.2. Again, the mean and 95% level numbers

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*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.

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

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

depend strongly on the actual population distribution sur-
rounding 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

*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
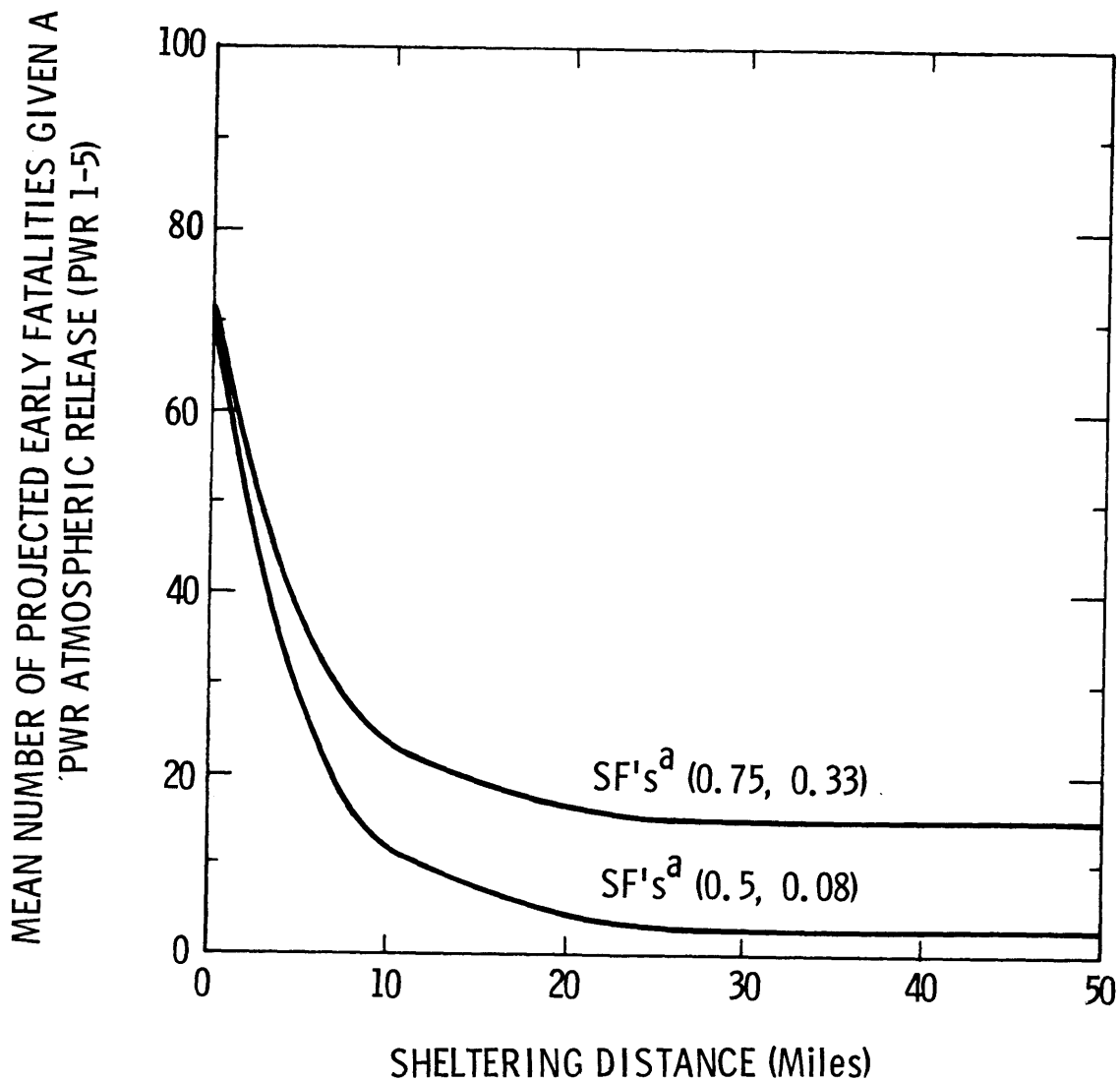 extended from 10 to 15 miles.

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.

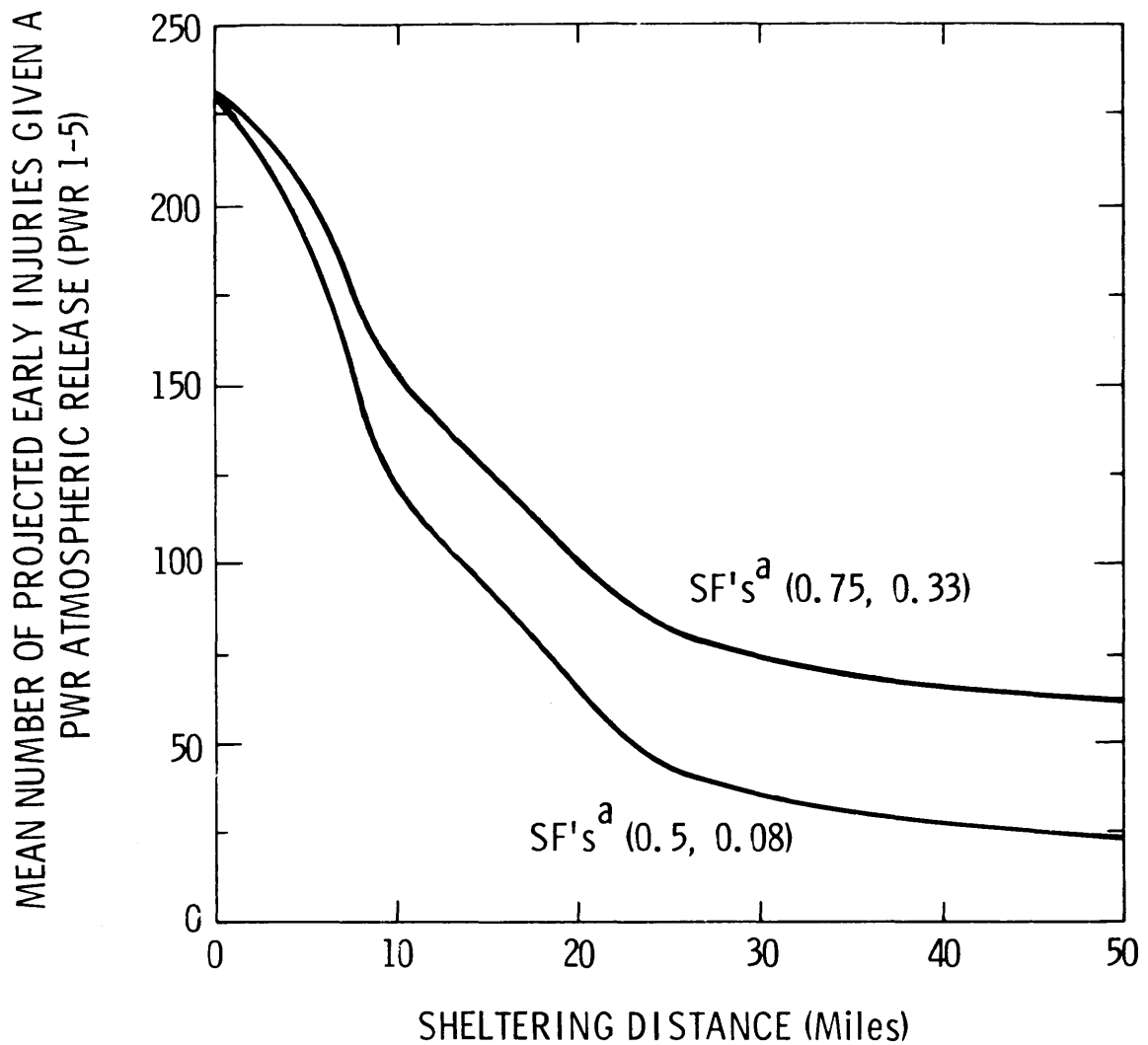[a]Shielding factors (airborne radionuclides, ground contamination).

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.

[a]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.

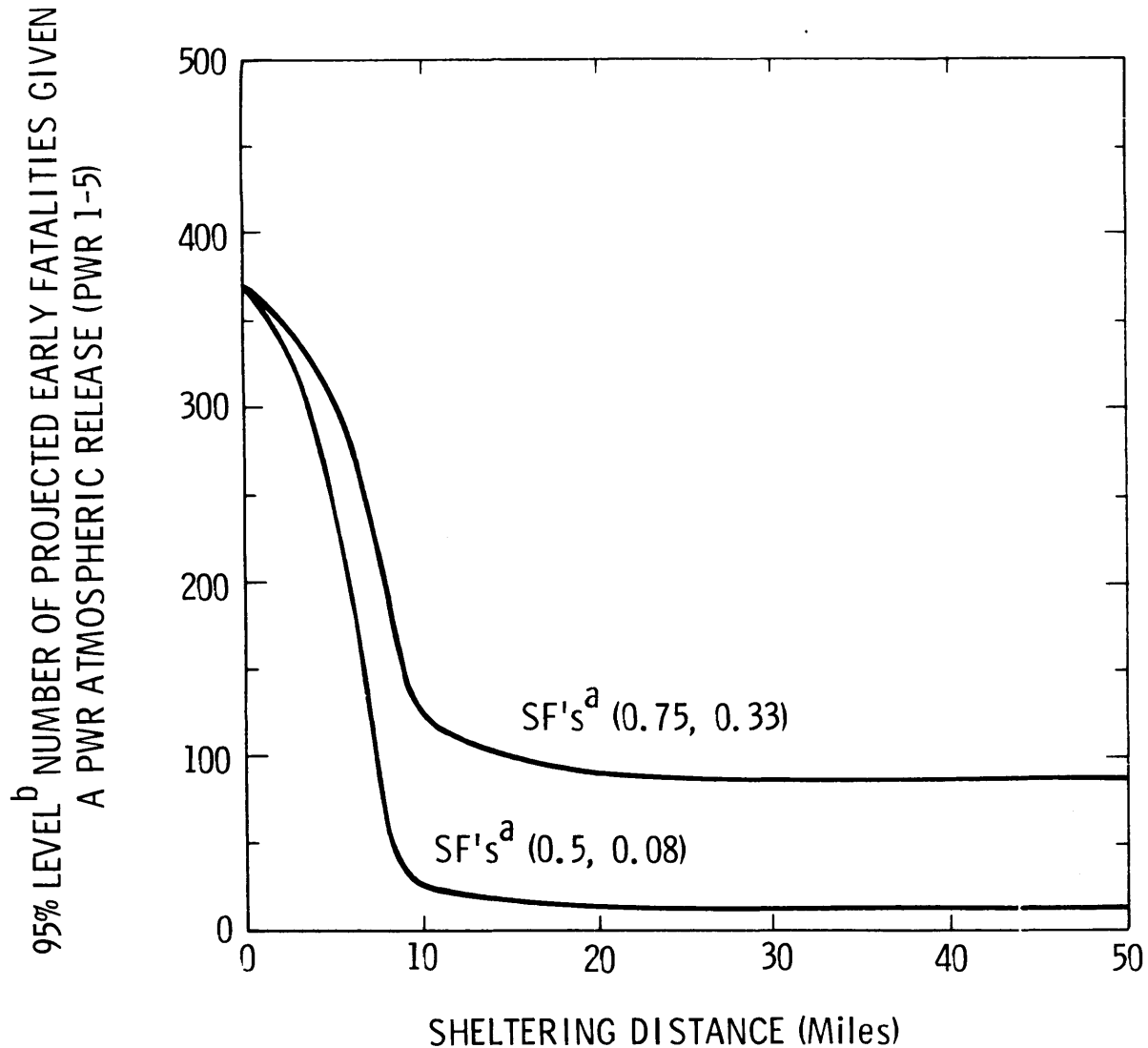[a]Shielding factors (airborne radionuclides, ground contamination).

[b]95% of the time a PWR "Atmospheric" accident occurs, the number of early fatalities will be less than the 95% level.

95% LEVEL[b] NUMBER OF PROJECTED EARLY INJURIES GIVEN A PWR ATMOSPHERIC RELEASE (PWR 1-5)

SF's[a] (0.75, 0.33)
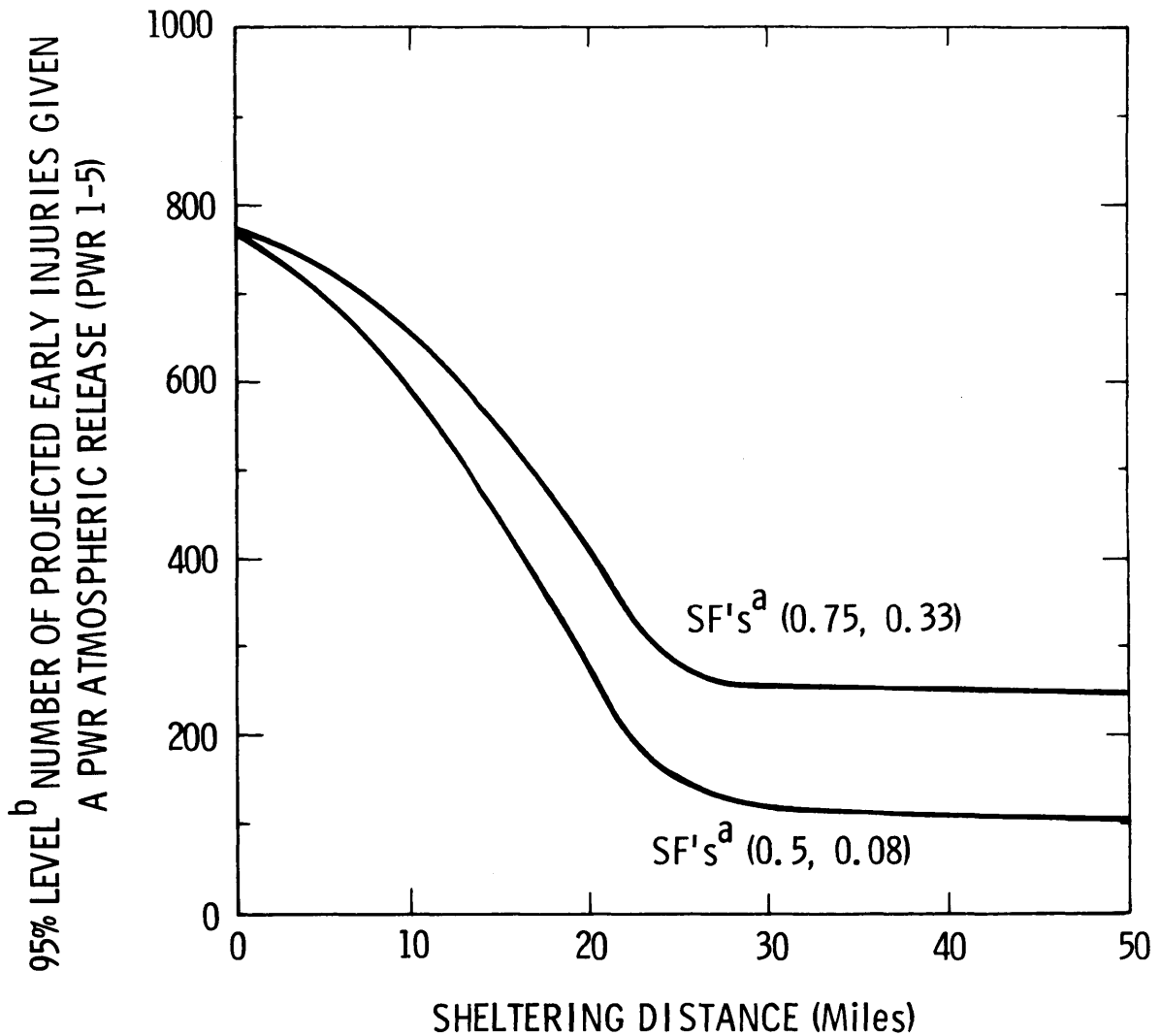
SF's[a] (0.5, 0.08)

SHELTERING DISTANCE (Miles)

Figure 5.18   95% Level[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.

[a]Shielding factors (airborne radionuclides, ground contamination).

[b]95% of the time a PWR "Atmospheric" accident occurs, the number of early injuries will be less than the 95% level.

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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

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*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.
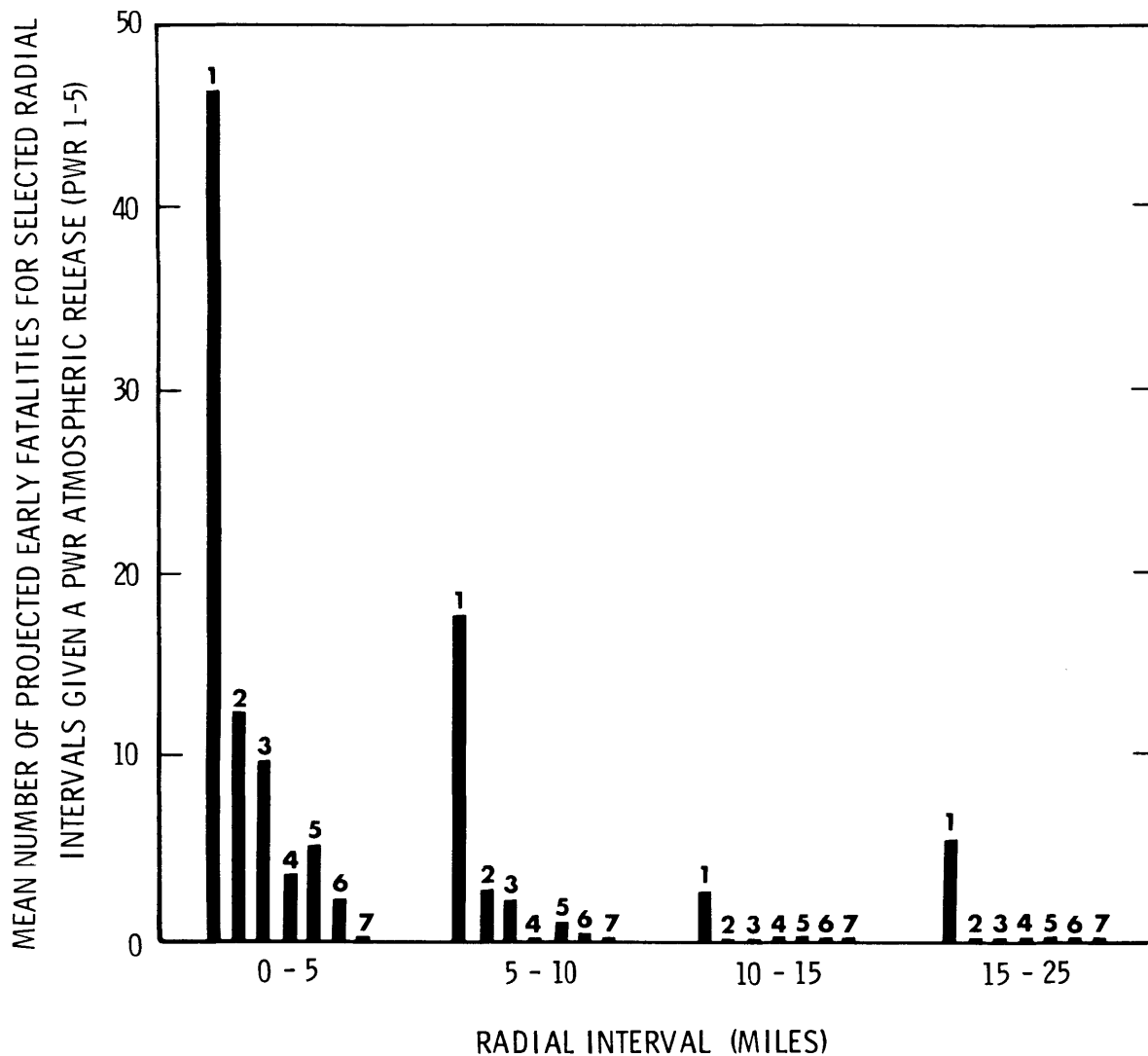
Figure 5.19 Mean Number of Projected Early Fatalities Within Selected Radial
Intervals for Evacuation and Sheltering Strategies, Given a PWR
"Atmospheric" Release (PWR 1-5). A Uniform Population Density
of 100 Persons per Square Mile is Assumed.

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.

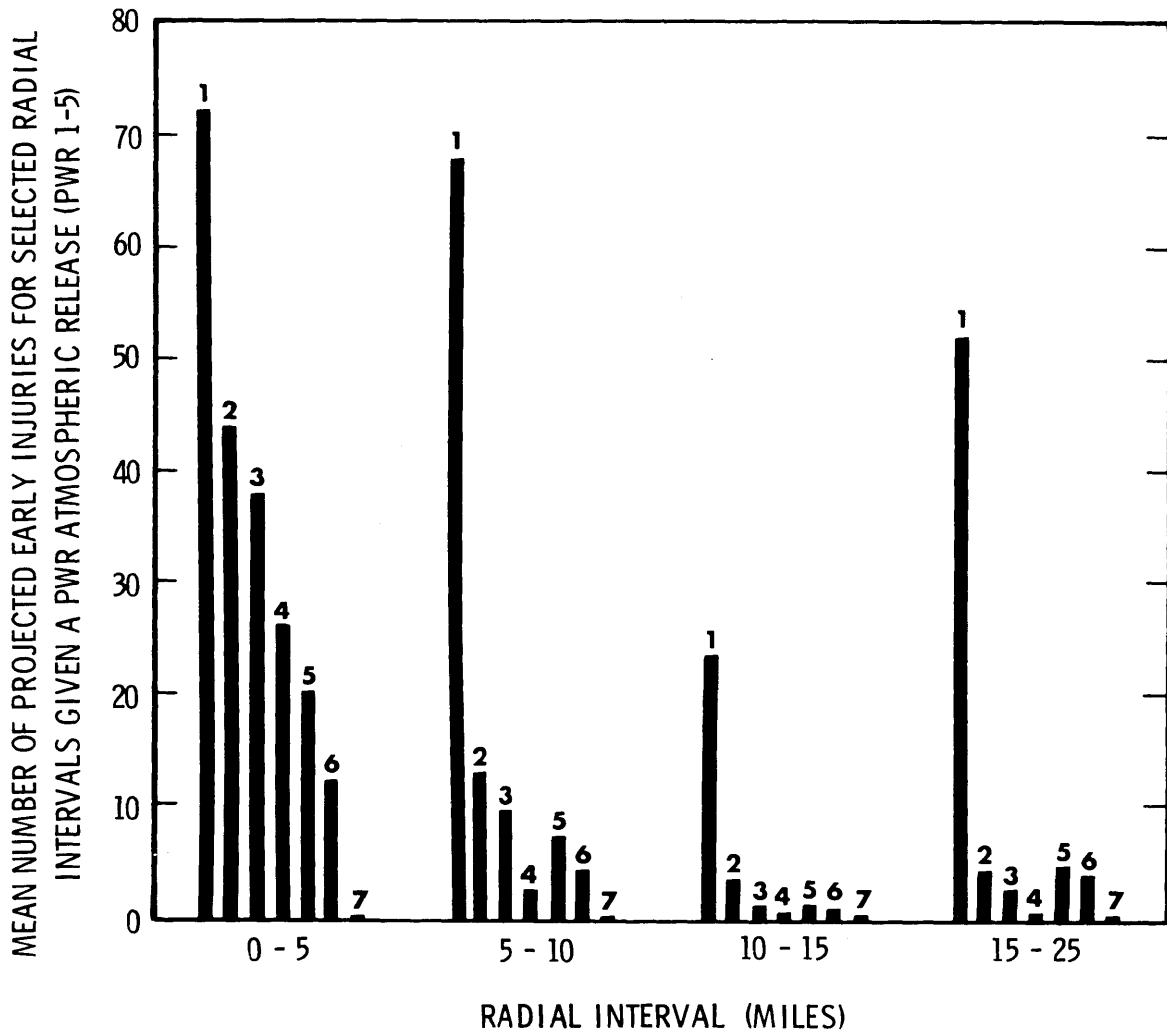[a]Shielding factors (airborne radionuclides, ground contamination).

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 SF'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

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*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

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*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 10^7 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 signi-

ficantly 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

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

**See subsection 3.2 of this report.

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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 appro-
priate, to briefly examine the manner in which the projected
dose varies as a function of easily observable weather condi-
tions 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 vari-
ables on the projected dose curves are examined in Figures
5.21 through 5.26. In each of these figures, whole body

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*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 pro-
 tective 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
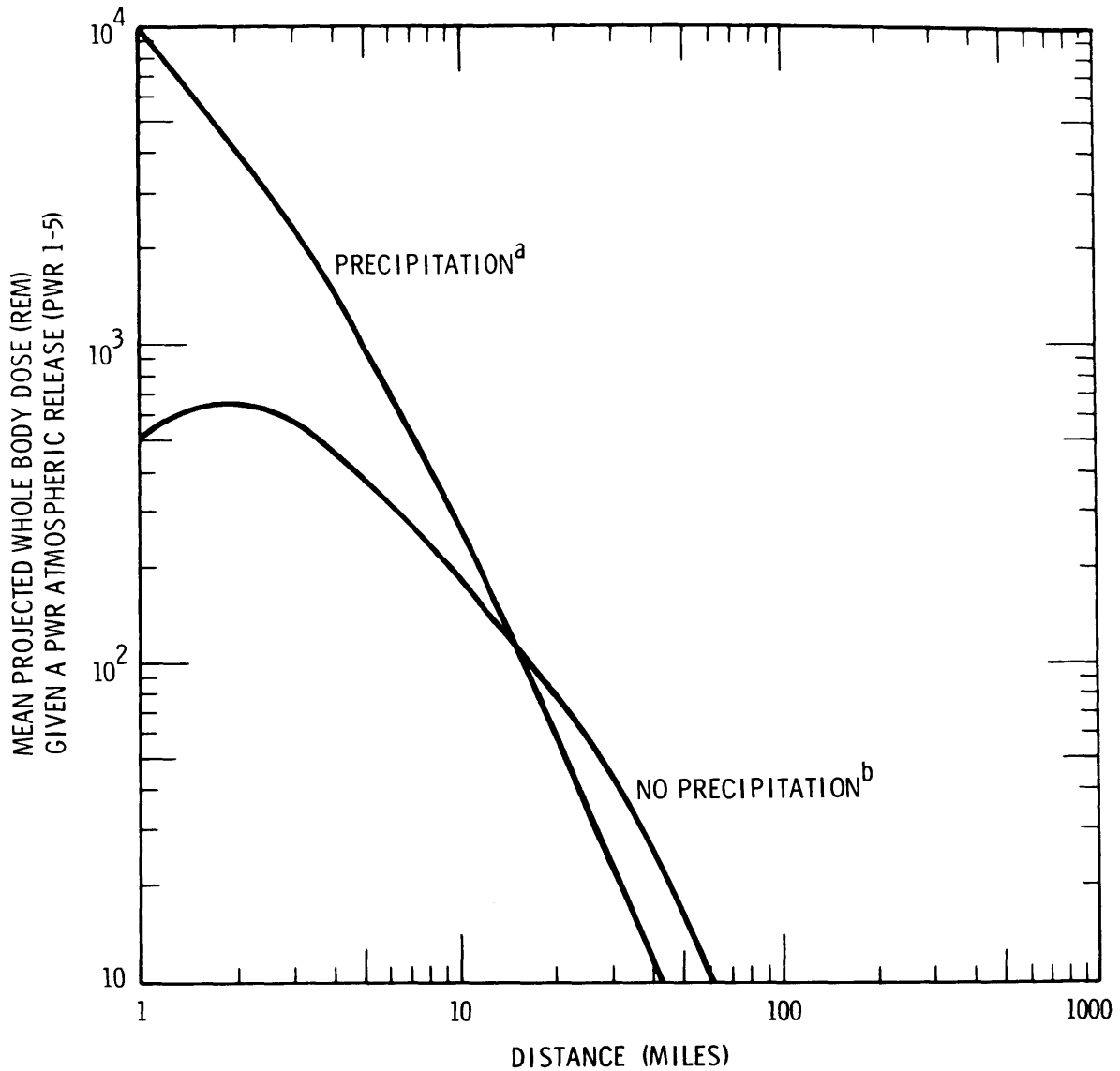 presented in reference [2].

Figure 5.21 Comparison of Mean Projected Whole Body Dose Versus Distance for Accidents in Which Precipitation[a] and No Precipitation[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 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.
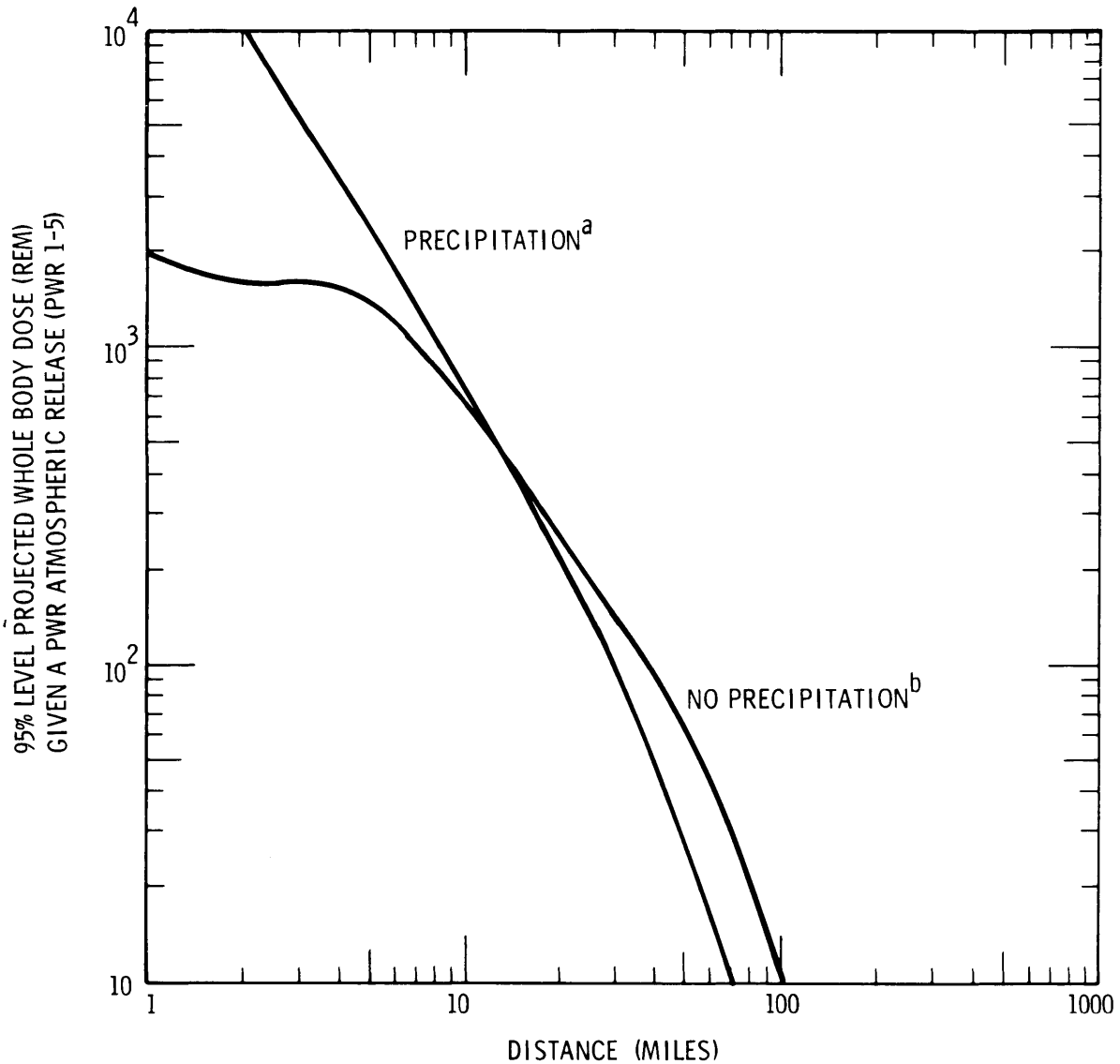
Figure 5.22 Comparison of 95% Level Projected Whole Body Dose Versus Distance for Accidents in Which Precipitation[a] and No Precipitation[b] Conditions Exist at the Start of Release. Projected Doses are for an Individual Located Outdoors,[c] and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

[a]Accidents in which 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.

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Figure 5.23 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.
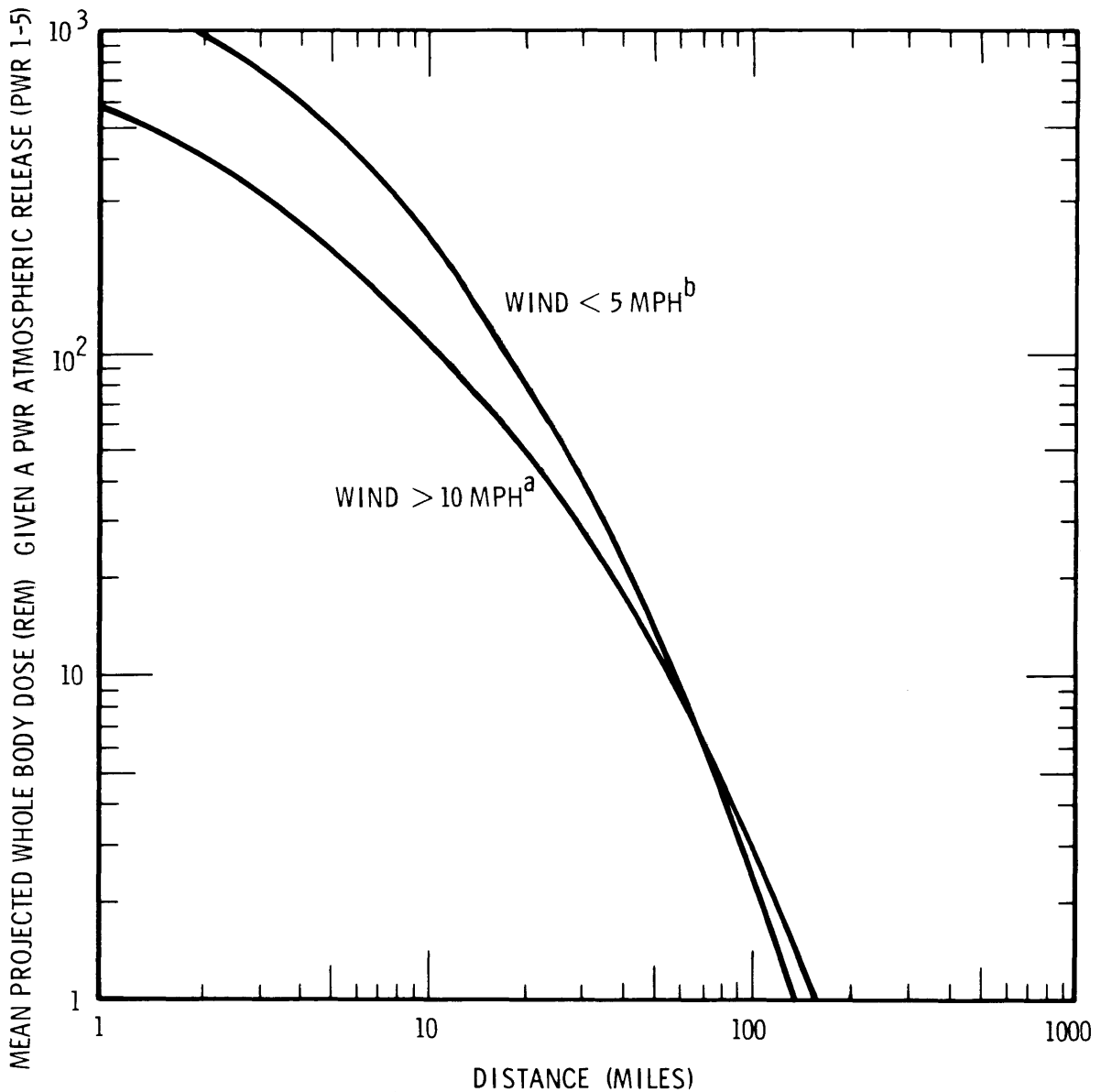
Figure 5.24 Comparison of 95% Level Projected Whole Body Dose Versus Distance for Accidents in Which High Wind[a] and Low Wind[b] Conditions Exist at the Start of Release. Projected Doses are for an Individual Located Outdoors,[c] and are Conditional on a PWR "Atmospheric" Release (PWR 1-5).

[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.
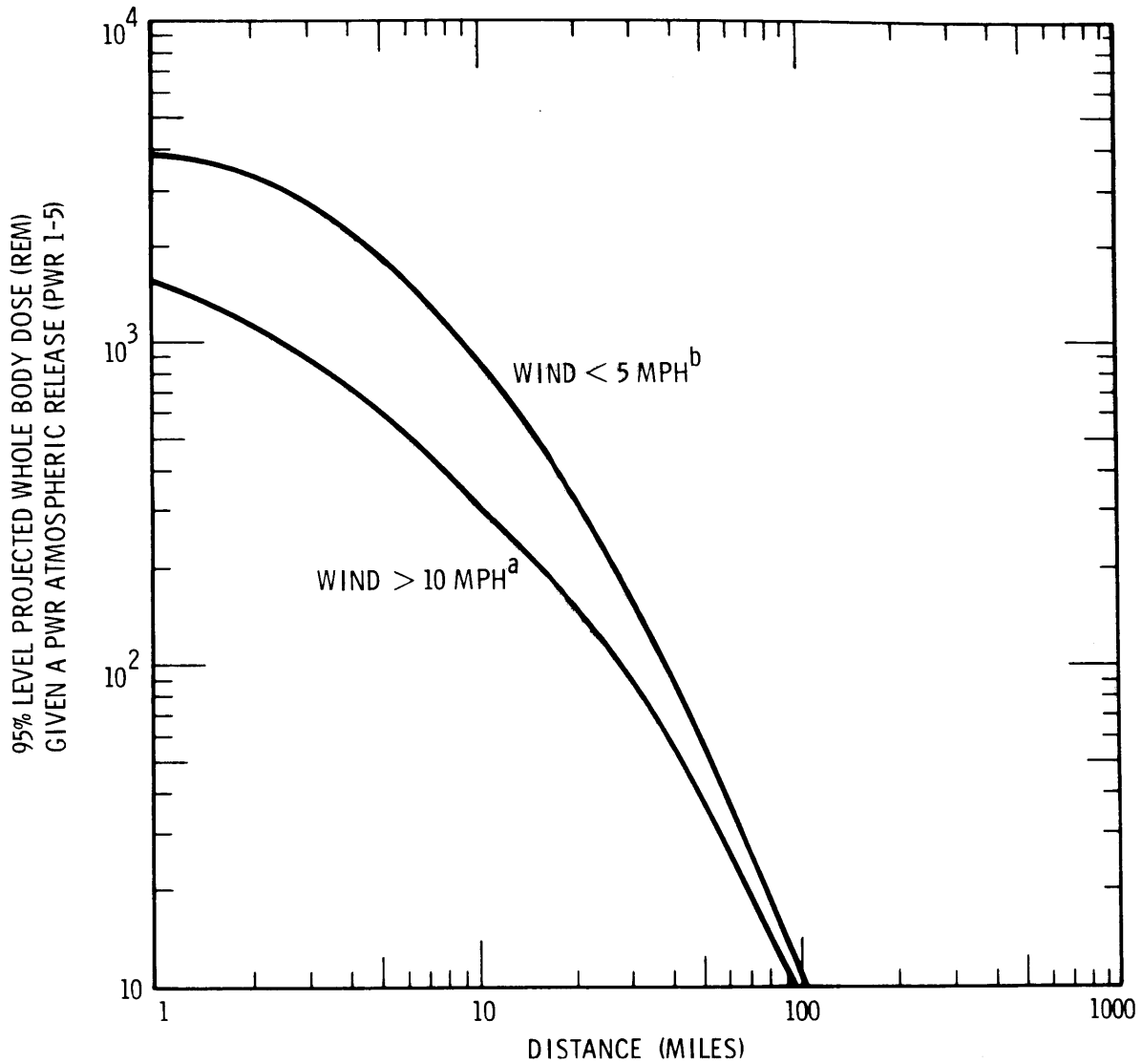
Figure 5.25 Comparison of Mean Projected Whole Body Dose Versus Distance for Accidents
that Begin During the Day[a] and Night.[b] Projected Doses are for an
Individual Located Outdoors,[c] and are Conditional on a PWR "Atmospheric"
Release (PWR 1-5).

[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
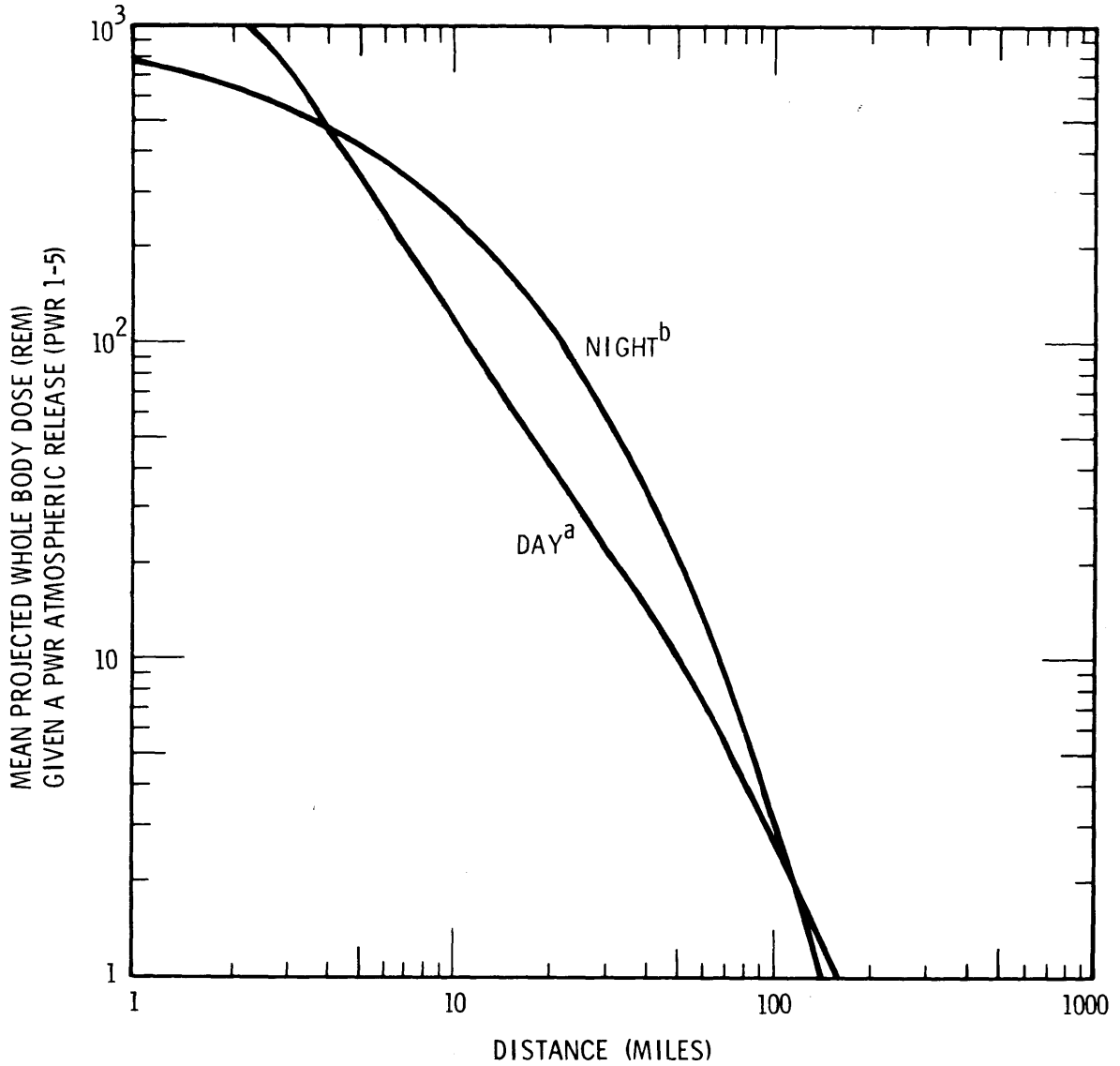on ground.

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Figure 5.26 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.
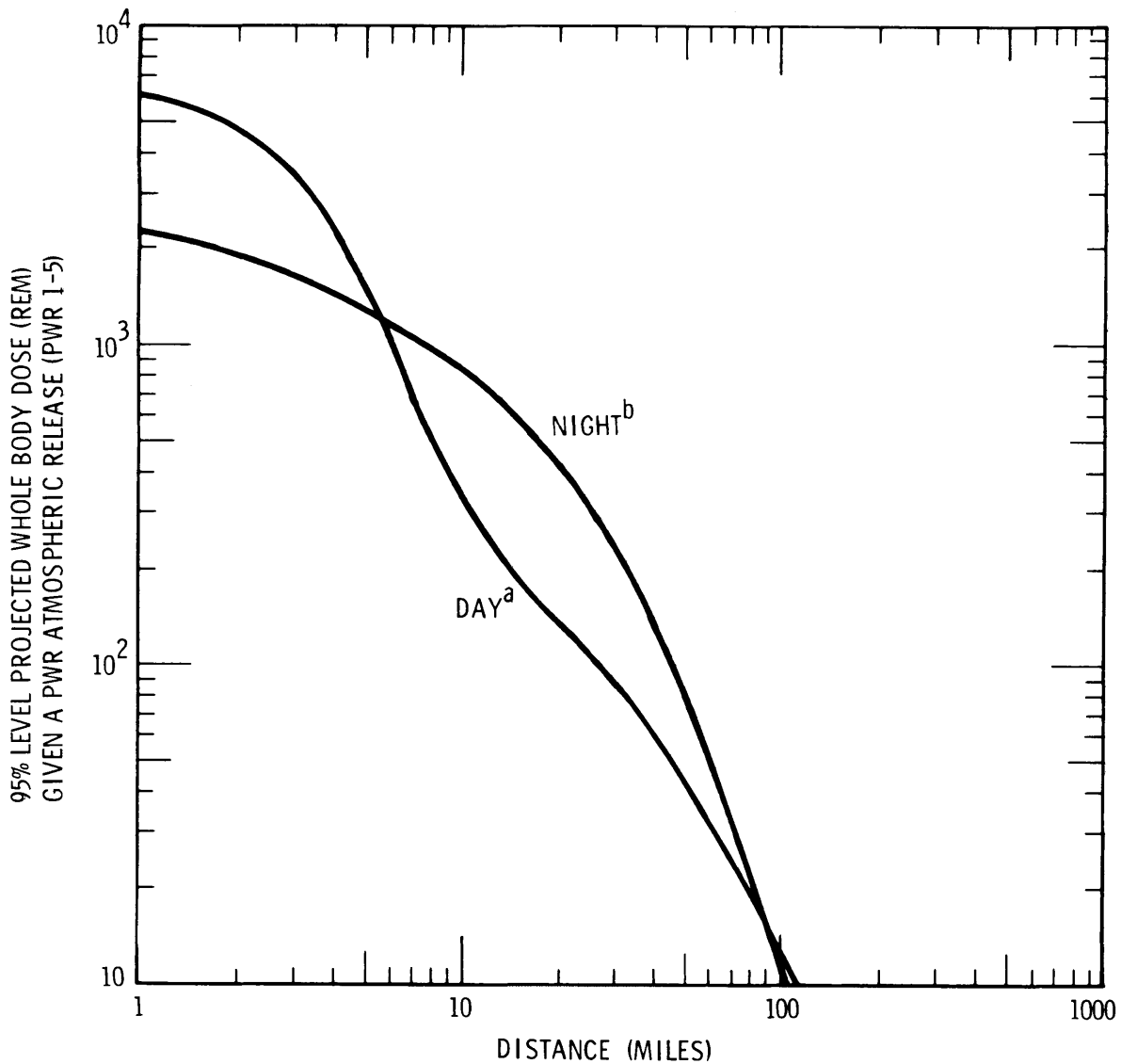
dose versus distance curves for an individual located out-
doors, and conditional on the occurrence of a PWR "Atmos-
pheric" release, are presented for observable weather con-
ditions at the start of release. For example, the curves
labeled PRECIPITATION in Figures 5.21 and 5.22 represent the
mean and 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 meteoro-
logical 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 preci-
pitation 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

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*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 condi-

tional 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 approx-

mately 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, pro-

jected 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

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*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.

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*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 qualita-
tively applicable for BWRs as well, given a similar contain-
ment failure mode.

Several important conclusions about the relative effec-
tiveness 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. Further-
more, 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. Be-
cause of the large thyroid doses projected for PWR "Atmos-
pheric" 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 admini-
stered 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.

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