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<u>Some Long-Term Consequences of</u>
<u>Hypothetical Major Releases of Radioactivity</u>
<u>to the Atmosphere from Three Mile Island</u>

Final Report to the
President's Council on Environmental Quality

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by
Jan Beyea*

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Program on Nuclear Policy Alternatives,
Princeton University

Frank von Hippel, Principal Investigator

Center for Energy and Environmental Studies
Engineering Quadrangle
Princeton University
Princeton, New Jersey 08544

*Present address: Environmental Policy Department, National Audubon Society
950 Third Avenue, New York, New York 10022

Foreword

The present report builds upon previous studies by the author concerning the potential consequences of major accidents at nuclear facilities. These studies include a major reactor study of potential reactor accident consequences for the Swedish Energy Commission in 1978 and a study in 1979 for the Government of Lower Saxony in West Germany on safety issues relating to the proposed Gorleben nuclear waste facility. A complete list can be found in Appendix F.

The draft version of this report (dated September 7, 1979) was reviewed and criticized at our request by a number of individuals and organizations. The comments received were directed primarily at the interpretation of the results, lack of detail, or particular phrasing used in the report rather than at technical details. These comments have been helpful in improving the language of the final version, but have not led to changes in the consequence results. Material has been added, however, on the economic cost of stockpiling potassium iodide. A discussion of the reviews can be found in Appendix G.

Discussion of the public response to the draft report can be found in Science, 206 (1979) p. 201.

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Introduction

This report provides, for those who are not experts in the field, a description of the nature and distribution of some of the major consequences of hypothetical releases of radioactivity following a major reactor accident. Because of public interest in the events which occurred at Three Mile Island (T.M.I.), the population distribution around the T.M.I. site has been used to provide a specific example. In addition, the report discusses emergency measures which can be taken to reduce the severity of the consequences of a major release of radioactivity.

This type of descriptive background information is needed for policy-making in four areas relating to nuclear safety:

i) To motivate and aid in the development of emergency plans for the protection of the population downwind should a large release of radioactivity occur from a reactor accident;

ii) To provide information helpful in determining the distance from a reactor site to which emergency planning should be required;

iii) To establish the value of making improvements in the safety-related design of nuclear power plants which will further reduce the probability of such releases; and

iv) To provide part of the information base required for the comparison of the risks of nuclear power to the risks from alternative sources of electrical power production.

The report focuses on some of the more important long-term consequences of a major release of radioactivity at the Three Mile Island site. These long-term consequences: cancer death, thyroid damage and contamination of land and property by radioactivity would mostly be associated with doses of radiation low enough so that they would not cause early health effects such as radiation illness.

They would, however, extend over a large area reaching far from the reactor and in most cases would affect much larger numbers of people at much larger distances from the reactor accident than the high dose effects. In particular, the distances to which significant numbers of health effects could appear in the population following large scale releases considerably exceed the distances for which emergency planning is required by current Federal guidelines.

This report focuses on the consequences of releases of radioactivity from a reactor accident. Their probability is a separate (although equally important) subject which is not addressed quantitatively here. No one knows for sure how close the Three Mile Island Accident came to a large release. The Rogovin study group suggests that the accident actually was heading toward severe core melting and that the uncontrolled loss of coolant through the stuck pressure operated relief valve was terminated with only an hour to spare.[1] However, since it is not clear whether or not such a "meltdown" would have also breached the T.M.I. containment, it is not possible to claim with any certainty that a disaster at T.M.I. was "narrowly" averted. Nevertheless, in light of the Three Mile Island Accident, and other earlier events,[*] it would appear to be a prudent course of action to carefully examine the potential consequences of hypothetical releases in order to determine the best way to protect the population should one occur. Preparations to reduce the consequences of a large release of radioactivity can be thought of as the equivalent of an insurance policy which it is hoped will never be needed. Emergency preparations for a major accident represent a logical extension of the "defense in depth" philosophy which has guided the regulation of nuclear reactor design.

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[*] Such as the Brown's Ferry accident in which a fire, ignited by a workman's candle, seriously disabled the reactor's safety systems.

The traditional position of the Nuclear Regulatory Commission and its predecessor, the Atomic Energy Commission, has been that regulations relating to safety design have reduced the probability of large releases of radioactivity to such a low level that they can be virtually ignored. This regulatory approach, in our view, has led to an imbalance between the enormous resources which have been devoted to accident prevention and the almost negligible resources which have been devoted to the development of consequence mitigation strategies.

It is time therefore to reconsider the low priority which has been assigned in the past to the development of emergency plans for population protection beyond a few miles from each power plant. Extending such plans to areas reaching 10 miles from reactors (one of the official responses to the Three Mile Island Accident) is a first step in this direction.[2,3] However, as this report will suggest, 10 miles is not an obvious distance beyond which all emergency planning should cease.[4]

Major Conclusions on Long-Term Consequences

Based on the analysis in this report of the public health consequences resulting from the releases studied, the following conclusions may be reached:

1) Long-term health impacts from major releases of radioactivity in reactor accidents, such as some of those considered in Table I, would affect much larger numbers of people at much larger distances than the short-term consequences which can be reduced by timely evacuation. Delayed effects - thyroid damage and radioactive land contamination in particular - can be a concern more than one hundred miles downwind from an accident and for many decades. The public, therefore, has a direct interest in the safety of distant reactors, as well as those nearby.

2) Consequently, emergency planning which focuses on areas close to nuclear power plants (even out to 50 miles) is not sufficient if the goal is to significantly reduce the consequences of major releases of radioactivity. Although evacuation may not be feasible beyond a distance of tens of miles from the reactor, the availability of thyroid protection medicine, sheltering in buildings, and air filters could all prove valuable in reducing radiation doses and the associated increased incidence of thryoid damage, cancer and other effects of low-level radiation at greater distances. Emergency planning at these distances from specific reactors may require cooperation between different states and, in some cases, with Canada or Mexico.

3) Delayed cancers and genetic defects due to radiation from ground and buildings contaminated with long-lived radioactive cesium could be one of the largest consequences from a major release. Research on decontamination should therefore be given high priority.

The consequences of a major release to the atmosphere from a reactor accident can be very large. To put these consequences in perspective, they should be compared with risks from other electricity generating technologies -- for example, the large number of deaths associated with respiratory illness caused by the burning of coal and residual fuel oil. (A nuclear reactor accident can be thought of as dumping the waste products from a huge industrial plant into the environment all at once; fossil fuel burning plants do so continuously.)

However, neither the magnitude of hypothetical reactor accident consequences nor the magnitude of fossil fuel air pollution effects can be used, by themselves, to make overall judgements about the comparative risks of these technologies. The consumption of energy in the U.S. has reached such a scale that all of the major energy technologies bring with them the potential for catastrophies of global scope such as nuclear war or climate change. Therefore, the major ~~purpose~~ usefulness of this report ~~is~~ to motivate improvements in emergency planning and safety related design, as well as to motivate expanded research into non-traditional sources of electricity and ways to use electricity more efficiently.

In this connection we would like to note that technical fixes, such as backfitting the containment buildings of existing nuclear power plants with the capability for rapid filtration of large volumes of radioactivity-contaminated gases, could strengthen the capability of these buildings to prevent the worst releases at relatively low cost. Such filter systems could substantially reduce off-site consequences should it be necessary to vent the containment building to prevent a hydrogen explosion or fire, should failure of the containment by over-pressurization be imminent, or should a major leakage path develop. (See Appendix C for additional information.)

Releases Considered

In order for a large release of radioactivity to occur during an accident, the containment building must fail to operate properly. Reactor containments can fail or be bypassed, theoretically, with or without a full core meltdown:

a) due to overpressurization following failure of the pressure-reducing spray systems (as in the PWR2 and PWR4 accidents described in the Reactor Safety Study),

b) due to failure of the containment to properly isolate from the atmosphere (as in a PWR5 accident in the RSS), or

c) conceivably due to a hydrogen explosion.*

It is also possible that the containment might be deliberately vented because of concern that a hydrogen explosion or fire might lead to a more catastrophic failure.

In the case of a full core meltdown, there is the additional theoretical possibility of a violent steam explosion breaching the containment (as in a PWR1 accident of the RSS) -- an event which might arise from a large fraction of the molten core falling "in a lump" into a pool of water at the bottom of the pressure vessel or containment building.

Large Scale Releases

Every major study of reactor safety including the Nuclear Regulatory Commission's 1975 Reactor Safety Study (WASH-1400),[7-9] has concluded that there is a significant probability of a major release of radioactivity into the atmosphere following a core meltdown. The containment buildings surrounding almost all the boiling water reactors which are in operation today have such small volumes, for example, that they would probably be ruptured by the buildup of the hydrogen and carbon dioxide generated during the course of such an accident.

*A hydrogen explosion apparently did occur during the T.M.I. accident. Although the energy released in the explosion was not sufficient to breach the large-volume containment in place at T.M.I., it should be noted that the same explosion could very well have breached containments in use at a number of other reactors.[5,6]

Larger volume containment buildings, such as those at Three Mile Island, have a lower, but still significant, probability of failing directly to the atmosphere. Failures of containment cooling systems subsequent to a meltdown could, for example, lead to breaching of the containment from the overpressure due to hot steam. The Reactor Safety Study estimated the probability of such a failure, given a core meltdown, at 20 percent.[10] Release to the atmosphere of a significant fraction of the enormous core inventories of volatile fission products -- including more than 20 percent of the radioiodines and radiocesiums -- was estimated to follow[11].

To illustrate the long-term consequences of releases which might occur following a meltdown and breach of containment, an example has been chosen from the Reactor Safety Study -- specifically the release associated with the most serious meltdown/overpressure sequence (a so-called "PWR2" release).

Intermediate-Scale Releases

Releases "intermediate" between those projected in a PWR2 accident and the release which actually occurred at T.M.I. have also been considered in this report. The character of the releases assigned to the intermediate, hypothetical accidents considered have been chosen keeping in mind the actual ratios of radioactive isotopes which were estimated to have escaped from the reactor fuel rods at Three Mile Island Reactor No. II[12]. The absolute magnitudes of these intermediate releases are, for the most part, arbitrary and have been chosen to illustrate the range of consequences which would be associated with different releases. We find that, even for most of the intermediate cases considered, mitigating measures could prove useful beyond 10 miles from the accident site.

The possibility of releases at pressurized water reactors (PWR's) intermediate between "design-base" accidents and maximal releases estimated for hypothetical meltdowns was also discussed in the Reactor Safety Study. Such intermediate releases, resulting from partially contained meltdowns, were considered relatively unlikely, however, and were assigned a significantly lower probability of occurrence than full scale releases. Thus, the pre-Three-Mile-Island Reactor Safety Study concluded in effect that nuclear power plants would tend to fail badly--or release hardly any radioactivity at all.

The complexity of the events which occurred in the Three Mile Island containment suggests, however, that there could be a whole spectrum of containment failures leading to a spectrum of releases. Emergency planning efforts should, therefore, take into account the possibility of releases of an intermediate scale.

In order to provide a physical mechanism for the intermediate releases considered, it is necessary to assume, for example, that a small but still substantial fraction of the radioactivity released from an overheated core is suspended in the containment building atmosphere when a failure of the containment building envelope occurs. A second possibility as considered in the Reactor Safety Study is that a large fraction of the radioactivity boiled off from a core meltdown is suspended in the containment atmosphere when a partial containment failure occurs.

None of the intermediate releases discussed in this report actually occurred at T.M.I. Apparently, very little radioactivity other than some small percentage of the inventory of noble gases was released from the containment--despite the fact that large quantities of volatile radioactive elements were boiled off from the core and entered the containment building. (The quantity of radioactive isotopes released from the fuel was similar to that which would be expected in a meltdown for the volatile elements such as radiocesium and radioiodine.)

This success at Three Mile Island in preventing a large release to the environment demonstrates the wisdom of fitting reactors with strong containment buildings and the wisdom of relying on a "defense in depth" philosophy of multiple barriers between reactor radioactivity and the public. However, it appears to be an open question whether or not there exist event sequences which could have led to a significant release to the atmosphere of the radioactivity which escaped from the fuel. Although a number of official alternate event sequence analyses have been made for T.M.I., concern has been directed at those sequences which could have led to full core melting, not sequences which could have led to escape to the atmosphere of some of the radioactivity which actually entered the coolant water. In the absence of such studies, a preliminary examination of some possibilities has been carried out in Appendix H. The analysis suggests that releases to the atmosphere of radioiodine and radiocesium would be smaller in magnitude than that which has been predicted in studies of full core meltdowns and would therefore be classified as "intermediate-scale" releases.

Specific Releases: (More details can be found in Appendix B)

Six hypothetical releases of radioactivity to the atmosphere at the T.M.I. site (labelled TMI 0-5) have been considered. (See Table I.) The smallest release (TMI 0) is slightly larger than, but similar to, the actual release that occurred; the largest release (TMI 5) is a meltdown scenario (PWR2) calculated by the Reactor Safety Study.

TMI 0,1 In these two hypothetical releases only the escape of radioactive noble gases is assumed. The radiation doses from the noble gases are only of concern immediately after a release since they do not stick to the ground, and are not absorbed by the body in significant quantities.

TMI 2 In this hypothetical release, in addition to noble gases, a 5% release of the reactor core's inventory of radioiodine is assumed (comparable to a PWR5 release in the RSS). Radioiodine is readily absorbed by the body after inhalation and delivers most of its radiation dose to the thyroid gland where it is selectively stored. Most of the thyroid dose from the stored radioiodine is accumulated within one month. (The possibility of preventing the body from storing radioiodine, by taking a "blocking dose" of non-radioactive potassium iodide before inhalation of radioiodine, is discussed later in the report.) Radioiodine also sticks to the ground downwind. Its presence could be of concern for periods of up to several months after the accident. The resident population would receive radiation doses from radioiodines deposited on buildings and ground. If the accident occurred during the grazing season, cattle would either have to be shifted to stored feed or their milk diverted from immediate human consumption in order to reduce exposure to radioiodines through the grass-cow-milk food chain.

TMI 3 In this last intermediate hypothetical release, the additional escape from the reactor of 10 percent of the long-lived radioactive cesium is assumed (an amount which is comparable to a PWR4 release in the Reactor Safety Study). Radioactive cesium-137 with its 30 year half life introduces a new dimension to accident consequences: long-term property and land contamination by radioactivity and the resultant increased level of radiation in the area downwind from the reactor accident for decades afterward.

TMI 4,5 In the final two hypothetical releases, fractional releases of radioisotopes are assumed such as might be expected after a complete meltdown and breach of containment. The fractional TMI 5 releases are identical to a Reactor Safety Study PWR2 release. The TMI 4 release assumes that only cesium escapes--in the same amount as in a PWR2 release. It is included for illustrative purposes to show that radioactive cesium dominates the long-term consequences from a TMI 5 release.

Quantitative Results

A summary of the quantitative calculations of long-term consequences for alternative hypothetical accidents at TMI is presented in Table I. (Technical details are given in Appendix E.) To demonstrate that a significant fraction of the long-term consequences of a reactor accident would affect populations so far downwind that they could not realistically be evacuated and that therefore other consequence mitigating measures must be considered at large distances, only health effects are included in the summary table that would occur in the population more than 50 miles downwind.

As indicated in Table 1, depending upon the magnitude of the release and the radiation dose-effects relationships assumed, the number of (delayed) cancer deaths resulting from the hypothetical releases at the TMI site range from zero to about 23,000 for "typical" meterological conditions.* These cancer deaths would occur over a 75 year period after the accident. Had the reactor core been operating for many years rather than a few months, the larger inventory of long-lived radioactive cesium would result in the high end of the range of estimated cancer deaths increasing to 60,000.

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*The range would be about zero to 6000 using the Reactor Safety Study's assumptions about shielding and cancer induction (see Appendix E).

Table I: Summary Table. Some Long-Term Consequences of Hypothetical Accidents at Three Mile Island[a)]

(Not including any early illness or deaths which might be associated with high doses to unevacuated populations a few tens of miles from the reactor.)

ACCIDENT DESIGNATION	HYPOTHETICAL RELEASES TO ATMOSPHERE	DELAYED CANCER DEATHS[b,c] (low/high[d])	THYROID NODULE CASES[c,e] (low/high)	TEMPORARY AGRICULTURAL RESTRICTIONS	AREAS REQUIRING DECONTAMINATION OR LONG-TERM RESTRICTIONS ON OCCUPATION[f]
TMI-0	10% of noble gases (similar to actual accident)	0/4		0	0
RELEASES GREATER THAN ACTUALLY OCCURRED					
TMI-1	60% of noble gases	1/25		0	0
TMI-2	5% Iodines plus 60% noble gases	3/350	200/27,000	$25,000mi^2$ g)	0
TMI-3a	TMI-2 plus 10% of Cesiums	15/2000	200/27,000	$25,000mi^2$ g)	$75mi^2$
TMI-4a	50% of Cesiums	100/12,000		$3700mi^2$ h)	$650mi^2$
TMI-5a	"PWR2" Release with complete core melt[i)]	200/23,000	3500/450,000	$175,000mi^2$ g)	$1400mi^2$
CONSEQUENCES ASSUMING THE REACTOR CORE HAD BEEN IN OPERATION FOR MUCH LONGER THAN 3 MONTHS (MATURE CORE)					
TMI-3b	TMI-2 plus 10% of Cesiums	65/8500	200/27,000	$25,000mi^2$ g)	$550mi^2$
TMI-4b	50% of Cesiums	440/48,000[j)]		$18,000mi^2$ h)	$4300mi^2$
TMI-5b	"PWR2" release[i)]	550/60,000[j)]	3500/450,000	$175,000mi^2$ g)	$5300mi^2$

Footnotes for Table I

a) All accidents are assumed to take place under "typical" meteorological conditions. Wind shifts and changes in weather neglected. Details can be found in the supporting tables in Appendix B and in the technical discussion in Appendix E. Health effects are totalled for people living beyond 50 miles.

b) Cumulative total over a 75 year period after the accident. The range of genetic defects would be equal, very roughly, to the range of delayed cancer deaths.

c) The low number is for the most favorable wind direction (Eastern Maryland), assuming the most optimistic coefficient relating dose to health effects, and evacuation out to 50 miles. (Without evacuation, the low number would be a factor of 2-5 higher depending on the accident.)

The high number is for the least favorable wind direction (N.Y.C./Boston) and assuming the most pessimistic coefficient relating dose to health effects. (Evacuation is also assumed out to 50 miles, but has a small impact on the high results.)

See Appendix E for a discussion of the dose/health-effect coefficient range used.

d) Reduce high value by a factor of about 4 to obtain the prediction which would result using the Reactor Safety Study Model under average weather conditions. Multiply by 4 to obtain the prediction which would result using health effects coefficients based on data of Mancuso, Stewart and Kneale. See Appendix E.

e) Cumulative total over a 25 year period after the accident. A blank entry implies a small number.

f) Areas in which the projected dose exceeds 10 rem in 30 years. See Table B-V in Appendix B for details.

g) Milk restrictions during the grazing season (see Table B-IV). Much of this area would be water for a wind from the west.

h) First year crop restrictions. (Harvested food not suitable for children.) See Table B-V. Much of this area could be water for a wind from the West.

i) A PWR2 accident as defined in the Reactor Safety Study

j) This number possibly could be reduced in half if massive decontamination or relocation efforts were undertaken in urban areas to avoid low-level radiation doses.

The number of thyroid nodule cases ranges from zero to 450,000 and land contamination ranges from zero up to many thousands of square miles.*

The number of health effects and the number of square miles of land contamination can range so high because a substantial fraction of the released radioactivity can be carried for hundreds of miles downwind before being removed from the atmosphere by deposition on the ground. Of course, the radioactivity would be much diluted at these distances, but many people over large areas would be exposed. (See Appendix A for details of dispersion calculations)

To obtain the figures in Table I, actual population data around the site have been used. Health effects and possible land use restrictions have been considered out to distances of 1000 miles and for periods of decades after the release.

Most of the hypothetical cancer deaths listed in Table I would result from fairly <u>low-level</u> radiation doses - on the order of tens of rem or less. Doses in excess of the 150 rem whole body dose threshold for early death due to radiation sickness could only occur within a few tens of miles of the reactor.

The probability of an exposed individual suffering adverse consequences from low-level radiation exposure beyond 50 miles is rather small -- less than a percent. Nevertheless, because a thousand or more people far from the reactor might be exposed to low-level doses for each person exposed to high doses, the numbers of people who would suffer adverse consequences from low-level radiation effects would ordinarily far exceed those affected by large doses -- even in reactor accidents in which massive amounts of radioactivity were released.

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*The number of expected genetic defects has not been shown in the table, but the range of numbers would correspond roughly to the range given for cancer deaths.

Numbers of early deaths are not estimated for the different releases considered in this report, principally because of their great sensitivity to assumptions which are quite uncertain. In particular the estimates are sensitive to assumptions about the movements of the radioactive gases and population shortly after the release. Our experience has been that it is difficult to achieve any technical consensus concerning quantitative estimates for these consequences.[13] Qualitatively, however, as discussed in Appendix D, it can be said that there exists a low, but not insignificant, probability that a large number of early fatalities (greater than 100) could have resulted from a full meltdown accident followed by a release directly to the atmosphere of the radioactive gases in the containment. (The release designated TMI 5 in Table I.) The probability is low because either: i) relatively improbable meteorological conditions would have to be present at the time of the accident to result in high doses ten miles away in a densely populated area such as Harrisburg, or ii) the evacuation strategy would have to fail so badly that the evacuation or such densely populated areas would not be completed for perhaps half-a-day after contamination of the area by radioactivity. Of course, all of these events are conceivable and should not be ignored - especially for emergency planning purposes - but the most likely result of a massive release of radioactivity at Three Mile Island, would be less than 100 early fatalities.* Therefore, the much larger numbers of persons potentially affected by the long-term consequences presented in Table I become very important for a realistic assessment of reactor risks and should be a principal concern in the design of population protection strategies. (Note that unusual weather conditions were not assumed in calculating those consequences.)

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* This opinion is based both on conclusions of the NRC's Reactor Safety Study and our own independent calculations of early effects for the Swedish Energy Commission[13] and the New Jersey Department of Environmental Protection.[14]

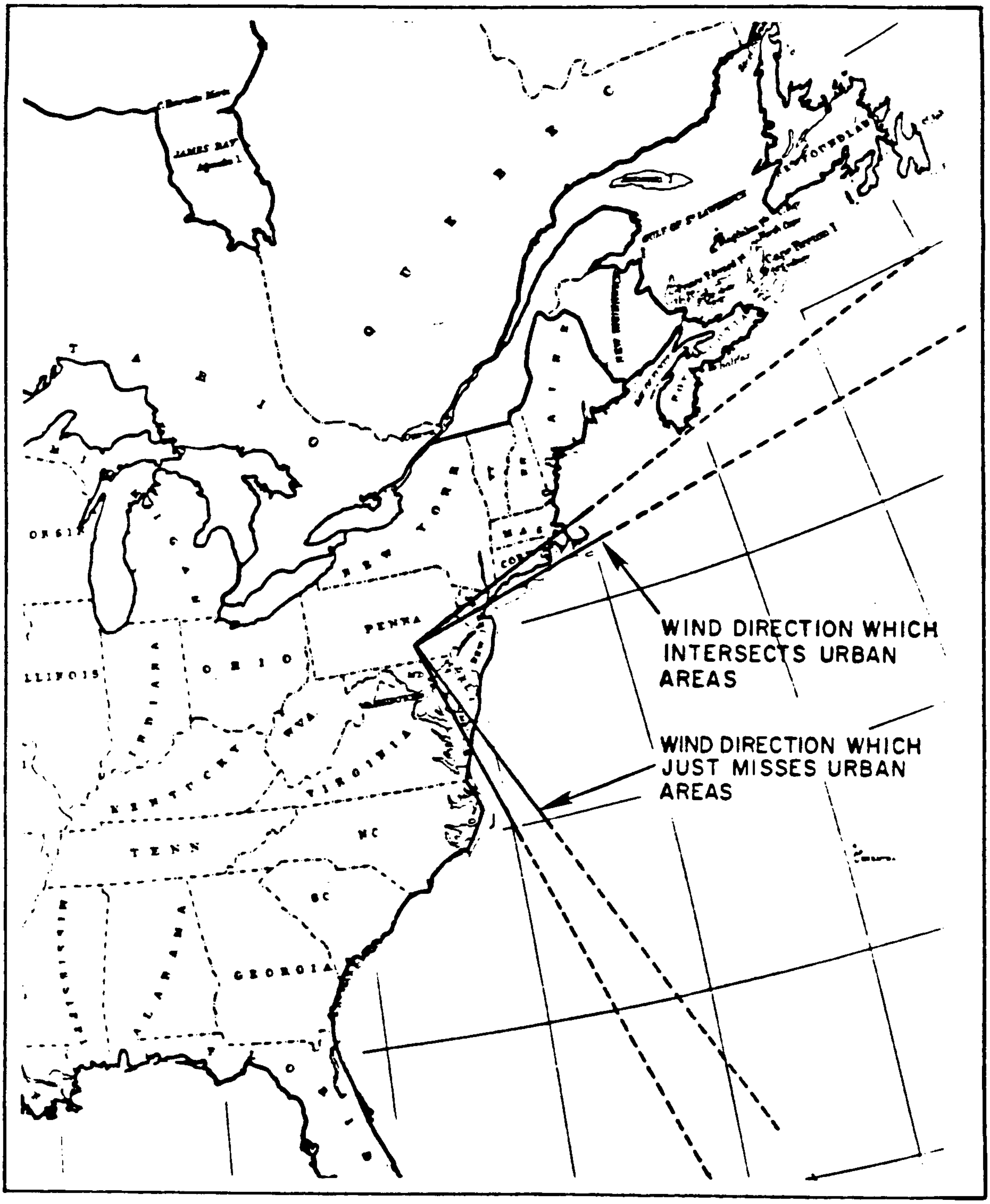

Figure I. Idealized areas of impact of a release of airborne radioactivity from the Three Mile Island site for two constant wind directions. The upper wedge indicates the direction which produces the greatest number of long-term health effects, while the lower wedge indicates the direction of minimum long-term health effects beyond 50 miles. The dotted lines indicate the area in which deposition of radioiodine would be high enough to require temporary restrictions on cattle grazing -- should the wind be blowing over land.

In preparing Table I, two specific wind directions have been used to define the extremes of the long-term consequences.* Figure I shows these two directions, indicating at the same time, the approximate wedge-shaped area in which residents would receive radiation doses (in the highly idealized case of no wind shift).** The populations lying in these two directions differ by a factor of thirty-five.***

At the maximum distance shown over land (about 400 miles) the whole body doses, while still of concern, are not extraordinary -- never exceeding, even for the worst accident considered, the lifetime dose a person would receive from natural background radiation. The thyroid doses can reach considerably higher values, however. The wedges shown on Figure I have been extended with dashed lines to the approximate distance to which (temporary) milk diversion might be required should the wind blow over grazing land after a worst-case release.

The results shown in Table I are not overly sensitive to weather variables other than wind direction or to dispersion parameters because the results do not depend upon the detailed distribution of doses to individuals - only upon their sum, the "population dose". Calculations have therefore been performed only for typical meteorological conditions.

In addition to uncertainty associated with the wind direction, the range in the high/low numbers given in Table I reflects uncertainties in the quantitative relationships between health effects and dose magnitudes - the

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*The maximum number of long-term health effects happens to occur for the New York City/Boston direction, but similar results were found for the wind blowing towards other urban areas. For 25% of all directions, the calculated health effects were more than half the maximum values. (See Table E-III.)

**A more realistic map would show curved wedges reflecting the effects of wind shift on the trajectory of the "puff" release of radioactivity.

***Because of the difference in the population distributions with distance, the expected numbers of health effects for the wind blowing in each of these directions do not differ by the same factor.

radiation "dose-effect relationships".* Information on the treatment of these uncertainties is given in the table footnotes and in Appendix E. We also indicate in Appendix E where in the uncertainty range the numbers would fall if the Nuclear Regulatory Commission's Reactor Safety Study (WASH-1400) assumptions were used, as well as the impact on our results of views on low-level radiation which lie outside the range we have used.

Numbers of People Affected At Different Distances

It is important for those who are developing population protection strategies to know the range of distances over which significant levels of low-level radiation effects would appear in the exposed population. We have therefore examined the numbers of affected individuals for the different hypothetical releases as a function of distance downwind. We show sample results for a particular "intermediate" release in Table II. (Other examples can be found in Appendix B.) In this case, if the wind blows towards the New York City area, the number of cancer deaths and thyroid nodule cases per 50 mile radial interval peaks at 100-200 miles. Thus evacuation, even out to 50 miles,** would not have much of an impact on the total long-term health consequences in this case -- or in other cases with large populations further downwind. (Successful evacuation out to

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* We have, however, assumed as is customary a direct proportionality between doses and the probability of each health effect. This "linear hypothesis", although almost standard in applications such as ours, is nevertheless the subject of considerable controversy as to its accuracy and as to its validity as an approximation to actual dose-effect relationships. We treat it simply as a mathematical convenience whose uncertainty can be adequately represented, for our purposes, by the uncertainty assigned to the proportionality constant.

** We are not necessarily recommending 50 miles as an appropriate evacuation distance. It has been used only for illustrative purposes.

Table II - Cancer Deaths at Different Distances Caused By The Hypothetical Accident Designated TMI-2 in Table I

(5% Iodines and 60% noble gases released)

Distance Range	Initial Population In Plume Path	Total Delayed Cancer Deaths Due to Accident[b)]	Percentage of Exposed People Who Eventually Die From the Accident[b)]
		Wind Towards N.Y. City Area	
0-50	95,000	(14-100[c)])	.01-.1[c)]
50-100	270,000	8-59	.003-.02
100-150	1,800,000	19-140	.001-.008
150-200	2,700,000	16-110[d)] ?	.0006-.004[d)] ?
200-250	850,000	3-21[d)] ?	.0003-.002[d)] ?
250-300	590,000	1-10[d)] ?	.0002-.002[d)] ?
300-400	1,300,000	1-6[d)] ?	.00005-.0004[d)] ?
400 -	0	0	
TOTAL	7,600,000	62-450[e)]	
		Wind Towards Eastern Maryland	
0-50	48,000	(24-180[c)]	.05-.4[c)]
50-100	66,000	2-18	.002-.03
100-150	72,000	1-7	.001-.01
150-200	26,000	0-1[d)] ?	.0006-.005[d)] ?
200-250	0		
250-300	0		
300-400	0		
400 -	0		
TOTAL	210,000	27-210[f)]	

Notes:

a) For typical meteorological conditions.

b) Variation in numbers is due to uncertainties in relating doses to cancer deaths.

c) The number of cancer deaths for the 0-50 mile range were calculated assuming no evacuation: The number would be zero if people were evacuated before arrival of the plume. These numbers can be up to 5 times higher for the wind blowing in other directions.

d) Doses beyond 150 miles for this accident are very small (see Tabel E-I), even to the child's thyroid, falling in dose regions where very little is known about health effects. These numbers must be considered highly speculative.

e) Would be 48-350, if people were evacuated out to 50 miles before arrival of the plume.

f) Would be 3-26, if people were evacuated out to 50 miles before arrival of the plume.

50 miles would make a major impact in the Eastern Maryland case, however, since the population at distances greater than 50 miles in that direction is relatively small.*)

Also shown at different distances in Table II, is the downwind risk of cancer death from the accident to the exposed individual. The individual risk is not large. Only a small fraction of exposed people would be affected. Even in the worst accident case we have considered (TMI5), the individual risk of death is less than one percent 50 miles downwind. (See Table B-III in Appendix B.) The total number of health effects can be high because the exposed population is large, not because the individual risk is high. It should be noted, however, that the fear of developing cancer as a result of a reactor accident might be the most serious consequence of all. Also, a large fraction of the exposed population would eventually develop cancer from other causes and might suspect that they were, in fact, radiation victims.

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* In order to investigate the sensitivity of the long-term health impacts to the rapidity of the evacuation, two extreme possibilities have been studied. Health effects have been calculated assuming that, out to 50 miles, either a) there is immediate evacuation before the cloud of radioactivity arrives, or b) evacuation is delayed for one week. Neither extreme has much impact on the results for the NYC/Boston direction since the totals are dominated by the large population beyond 50 miles. On the other hand, the rapid evacuation scenario has a relatively large impact on the results for the Eastern Maryland direction, since there is very little population beyond 50 miles.

Consequence Mitigation Strategies

In view of the distances at which the long-term consequences of major releases would occur, it is not sufficient to have emergency plans only for people living close to reactors if the goal is to significantly reduce long-term accident consequences. Dose reduction measures such as thyroid-blocking medication might be needed out to hundreds of miles. Long-term population removal and decontamination at such distances might also be needed in the years following the accident but the time over which decisions on these actions would be required would be great enough that elaborate prior planning would not be required. Decision criteria and decontamination techniques should be developed now however.

The fact that significant thyroid doses can be received out to hundreds of miles for a catastrophic release of, say, 50 percent of the radioiodine in the core is not a subject of debate (see e.g. Ref. 15). However, it is not immediately obvious to what distance protective actions would provide a net benefit. It seems reasonable to propose that protective actions should be taken out to distances where the risks of such actions become comparable to the health risks from projected doses. Making this principle quantitative is difficult but it appears that thyroid-blocking medication would certainly be justified out to a distance of a hundred miles for a TMI 5a or 5b release, and possibly much farther.[16-20] This distance extends considerably beyond the 10 mile guideline distance being promoted by the NRC for protective action planning.[2-4], (Ad hoc actions are assumed by the NRC to be sufficient beyond 10 miles.)

It would cost about 10 cents per person per year to maintain a fresh supply of thyroid-blocking medicine[21], and thus about 20 million dollars per year to maintain a fresh supply for the entire U.S. population. If a large release should not occur over the life of the nuclear program, then the money spent on potassium iodide would be wasted--just as the premiums are wasted on an individual's insurance policy if the policy is never needed. Thus, it is possible to argue, if one believes that the probability of a serious accident is very small, that the stockpiling of potassium iodide for the entire population would not be "cost effective"[22] --or else argue that the same amount of money could be spent more effectively to reduce other risks in our society which have a greater probability of occurring.

However, the validity of such arguments hinge upon the reliability of accident probability estimates which happen to be controversial and which are generally agreed upon to be uncertain.[23] The very strength of a potassium iodide stockpiling program lies in the fact that it bypasses the probability debate. It represents a backup protective measure which would be valuable to have should estimates of reactor accident probabilities prove to be inaccurate. The cost per individual would be small in absolute terms and the cost for the entire program would be small in comparison to the amount of money which is spent each year on regulating nuclear safety.

Additional discussion of accident mitigating measures is given in Appendix C.

Nuclear Reactor Accidents in Perspective

The accidents studied in this report can be thought of as dumping the waste products from a huge industrial operation into the environment all at one time instead of slowly over the years as occurs in many other industries. In the nuclear accident case the resulting health effects and land contamination would all be caused by one incident, but a comparison of cumulative totals might show other energy technologies taking a comparable or perhaps higher toll, per kilowatt-hour generated, averaged over a period of decades. Thus, it is necessary to put the numbers given in Table I, serious as they are, in perspective by comparing them with the casualties associated with other electric energy generating technologies. Estimates of the respiratory-related death toll taken by coal- and oil-fired electricity generating stations, for example, range, in the absence of modern control technology, from about 1 to 100 deaths per year per large plant.* [24,25] If all the kilowatt hours generated thus far by U.S. nuclear power plants had instead been generated by such coal- or oil-fired plants, hundreds to tens of thousands of additional air pollution deaths might have resulted.[26] This is comparable to the range of consequences which we have calculated for hypothetical releases at Three Mile Island. However, neither the magnitude of reactor accident consequences nor the magnitude of fossil fuel air pollution effects can be used, by themselves, to make overall judgements about the comparative risks of these technologies. The consumption of energy in the U.S. has reached such a scale that all of the major energy

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*Adverse health effects resulting from power plants fired by natural gas appear to be very much lower in number than those resulting from power plants fired by coal or residual fuel oil.

technologies bring with them the potential for catastrophies of global scope such as war or climate change. Therefore, we think that the principal usefulness of the results presented here will be to motivate improvements in emergency planning and safety related design, as well as to motivate expanded research into non-traditional sources of electricity and ways to use electricity more efficiently.

The risks from both coal/oil power plants and nuclear power plants can be reduced: coal/oil health effects can be reduced by installation and proper maintenance of modern control technology (scrubbers and precipitators); potential nuclear health effects can be reduced by relatively inexpensive methods such as improved containment buildings and more adequate emergency planning. (See Appendix C.)

Finally, and perhaps most importantly, improvement in the end use efficiency of electrical devices and elimination of waste reduces the risk from both sources by reducing consumption and the need for new power plants.

References and Notes for Main Report

1. The Special Inquiry Group on Three Mile Island set up by the Nuclear Regulatory Commission made an analysis of 15 alternative event sequences. It was concluded that several of these alternative sequences (including the one mentioned in the text) might have resulted in substantial fuel melting. [Nuclear Regulatory Commission Special Inquiry Group, M. Rogovin, G.T. Frampton, Jr., et. al., Three Mile Island, A Report to the Commissioners and to the Public (Washington, D.C., 1980 Volume I, Pages 20, 91, Volume II, Pages 553-570).]
2. U.S. Nuclear Regulatory Commission, NRC Action Plan Developed as a Result of the TMI-2 Accident (Washington, D.C., NUREG-0660, May 1980).
3. U.S. Nuclear Regulatory Commission and Environmental Protection Agency, Planning Basis for the Development of State and Local Government Radiological Emergency Response Plans in Support of Light Water Nuclear Power Plants, Washington, D.C., 1978, NUREG 0-396, EPA 520/1-78-016).
4. The Rogovin Inquiry Group has also suggested that 10 miles is not an appropriate cut off distance for emergency planning. [Reference 1, Volume I, Page 133.] For a discussion of the logic which went into the choice of a 10 mile cutoff distance, see T. Lombardo, T. Perry, "Mitigating the Effects of a Nuclear Accident", Spectrum, 17, July 1980, Page 30.
5. See "Alternative Accident Sequence 15" in Reference 1, Volume II, Pages 569-570. A detailed analysis can be found in Reference 1~~3~~6. Note that the susceptibility of smaller volume containments to hydrogen explosion can be reduced by filling the containments with nitrogen gas. As long as the nitrogen remains in the building there will not be oxygen available to burn with the hydrogen.

6. R.O. Wooton, R.S. Denning, P. Cybulskis, Analyses of the Three Mile Island Accident and Alternative Sequences (Nuclear Regulatory Commission, Washington, D.C., NUREG/CR-1219, 1980).

7. U.S. Nuclear Regulatory Commission, Reactor Safety Study, (Washington, D.C., WASH-1400, 1975.)

8. W.K. Ergen, et. al., Emergency Core Cooling - Report of Advisory Task Force on Power Reactor Emergency Cooling, TID-24226 (1966), N.T.I.S.

9. D.L. Morrison, et. al., An Evaluation of the Applicability of Existing Data to the Analytical Description of a Nuclear Reactor Accident -- Core Meltdown Evaluation, BMI 1910 (1971), N.T.I.S.

10. The sum of the yearly probabilities (1.3×10^{-6}) given in Ref. 7, Table VI 2-1, for PWR-1, 2 ~~or~~ and 3 core melt accidents divided by the sum of the probabilities (6×10^{-5}) of all core melt accidents (PWR1 through PWR7).

11. Reference 7, Table VI 2-1.

12. The Rogovin Inquiry Group /_Reference 1, Volume II, Page 527_/ has summarized estimates of the extent of fuel damage and the percentage releases of radioisotopes from the fuel rods during the Three Mile Island accident. It appears that "no significant quantity of fuel reached the melting point of U_2O (5200°f)" but that "about 50 percent of the reactor core was damaged enough to release the most volatile fission products." Even though complete melting of the fuel did not occur, the quantity of radioactive isotopes released from the fuel was similar to that which would be expected in a meltdown for the volatile elements (noble gases, iodines, bromines, cesiums and isotopes of rubidium). The Rogovin Group concluded, cautiously, that 40 percent to 60 percent of the core inventory of these volatile isotopes were released to the coolant. (Since bromine and rubidium isotopes

do not contribute significantly to accident consequences in comparison with the iodines and cesiums, they have been neglected ~~from~~ in this report.) In particular, average estimates suggest a 46 percent release for the noble gases, a 39 percent release for Iodine 131, a 63 percent release for cesium 137, and a 44 percent release for cesium 134 [Reference 1, Volume II, Table II-57, Page 527.]

As for the percentage of the core inventory of these isotopes which ended up in the containment (primarily through overflow of radioactive cooling water), the Rogovin Commission quotes 25 percent (Iodine 131), 51 percent (cesium 137), and 36 percent (cesium 134).

13. Jan Beyea, Some Consequences of Hypothetical Accidents at the Barsebäck Reactor, (Swedish Energy Commission, Stockholm, 1978, DsI 1978:5.)

14. Jan Beyea, "Program BADAC: Short-term Consequences of Hypothetical Reactor Accidents", New Jersey Department of Environmental Protection, Trenton, N.J., 1978.

15. D.C. Aldrich, P.E. McGrath, N.C. Rasmussen, Examination of Offsite Radiological Emergency Measures for Nuclear Reactor Accidents Involving Core Melts, (Sandia Laboratories, Albuquerque, New Mexico, 1978, Sand 78-0454), Figs. 5.12 and 5.13.

16. At a 10 rem dose to the child's thyroid -- which lies in the range where thyroid radiation effects have been seen (Ref. 17)-the risk of damage is in the range of 1300-13,000 per million exposed children. (See Table E-II.) The estimated risk from the thyroid-blocking medication at this dose level is much lower -- on the order of one-in-a-million or less (Ref. 18). On the basis of a balancing of these risks, therefore,

thyroid protection is clearly justified down to the 10 rem thryoid dose level and may be justified to prevent lower doses. Taking a projected 10 rem dose to the child's thyroid as the threshold for protective action (a number which is consistent with many recommendations including the dose used by the Food and Drug Administration in its guidelines for considering protective crop restrictions (Ref. 19), it is possible to estimate distances out to which protective medication should be given to children (should evacuation not be feasible): For a TMI 2 release, the distance would range between 15 and 150 miles depending upon whether the doses are calculated conservatively, as in this paper, or non-conservatively (Ref. 20). For a TMI 5a or b release, the distance range would be 100 to 500 miles. A similar calculation can be made for adults: for a 10 rem threshold, thyroid-blocking medication would be justifiable out to a distance between 15 and 75 miles for a TMI 2 release and between 100 and 300 miles for a TMI 5a or 5b release.

17. To our knowledge, the lowest thyroid dose for which a correlation has been established between thyroid damage and radiation is 6.5 rads. [B. Modan, H. Mart, D. Baidatz, R. Steinitz, S.G. Levin, Lancet, 1974, ii, 277.]

18. National Council on Radiation Protection and Measurements, Protection of the Thyroid Gland in the Event of a Release of Radioiodine,(Washington, D.C., 1977),Report 55, p. 24.

19. The F.D.A. has set a projected 15 rem dose from food as the threshold level for considering emergency action. [Department of Health, Education and Welfare, U.S. Food and Drug Administration, "Accidental Radioactive Contamination of Human and Animal Feeds and Potassium Iodide as a Thyroid-Blocking Agent in a Radiation Emergency", Federal Register, Friday, Dec. 15, 1978, Part VII, p. 58793.]

20. Uncertainty exists about 1) the ratio of child-to-adult dose, and 2) the effectiveness of the radiation from iodine 131 in causing biological damage relative to that from other iodine isotopes and X-rays.

21. Recent quotations from The Carter Wallace Company suggest a price, in quantity, of 40 cents per 14 tablet bottle. One bottle, attached for instance to the electricity meter for each residence, would supply even a family of seven with a two day dosage. (There would be sufficient time after the accident to distribute, from a central storehouse, tablets for the period beyond two days.)

The assumption of a three year shelf life and an average residence occupancy figure of three persons implies a yearly cost of 5 cents per person.

Potassium Iodide would also have to be stockpiled at workplace and schools--presumably in containers holding more than 14 tablets and therefore at less cost per person than in individual residences. As a result, the cost of supplying each individual would be higher than 5 cents per year, but certainly not more than 10 cents per year.

Should the shelf life prove to be longer than three years, the cost would drop proportionally.

22. It is the current position of the NRC Staff that wide distribution of Potassium Iodide prior to an accident is not cost-effective. [D.C. Aldrich, R.G. Blond, "Examination of the Use of Potassium Iodide (KI) as an Emergency Protective Measure for Nuclear Reactor Accidents," Nuclear Regulatory Commission, Washington, D.C. NUREG/CR-1433, March 1980.] Such a conclusion appears to depend primarily on the assumption that the probability of a serious accident is not more than a factor of 10 higher than estimated in Reference 7.

For a discussion of the history of the NRC's involvement with potassium iodide, see Frank von Hippel, "The NRC and Thyroid Protection - One Excuse After Another." Bulletin of the Atomic Scientists, October 1980, p. 44.

23. "Nuclear Regulatory Commission Statement on Risk Assessment and the Reactor Safety Study Report (WASH-1400) in the Light of the Risk Assessment Review Group Report," (January 18, 1979). See also, H.A. Lewis et al., Risk Assessment Review Group Report to the U.S. Nuclear Regulatory Commission, (Washington, D.C. NUREG/CR-0400, 1979).

24. As with radiation health effects, the number of air pollution deaths estimated to occur from fossil fuel plant emissions depends upon: 1) the amounts of pollutants emitted, and 2) the relationship assumed between health effects and "dose" magnitude (air pollution level). The high end of the air pollution consequence estimate (100 deaths per-year-per-plant) has been derived assuming high values for both factors: 1) a high sulfur fuel content (e.g. 3% sulfur coal), and 2) a high value for the "dose-effects" relationship.

Thus, the 100 deaths per-year-per-plant estimate has been calculated in a pessimistic manner -- an approach which is consistent with that taken in this report for calculating the upper range estimate of cancer deaths resulting from hypothetical reactor accidents.

A general survey of studies which have derived quantitative estimates of the relationship between fossil fuel power plant emissions and deaths can be found in, S.K. Keeny et al., Nuclear Power Issues and Choices, Ballinger, Cambridge, Mass., 1977, Ch. 5.

Ref. 25 is an example of work done at Brookhaven National Laboratories which provides the high end of the spectrum of estimates.

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25. L.D. Hamilton and A.S. Manne, "Health and Economic Costs of Alternative Energy Sources," International Atomic Energy Agency Bulletin 20, 1978.

26. Four hundred reactor years times 1-100 deaths per reactor year. [One reactor year equalling 60% of 1000 Mwe years or .5 x 10^{10} kwh(e).]