ENGINEERING RESEARCH INSTITUTE
THE UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report

REPORT ON THE POSSIBLE EFFECTS ON THE SURROUNDING POPULATION OF AN ASSUMED RELEASE OF FISSION PRODUCTS INTO THE ATMOSPHERE FROM A 300 MEGAWATT NUCLEAR REACTOR LOCATED AT LAGOONA BEACH, MICHIGAN

Henry J. Gomberg
Project Supervisor

Thomas Bassett

Carlos Velez

Project 2506

ATOMIC POWER DEVELOPMENT ASSOCIATES, INC.
DETROIT, MICHIGAN

May 1957

PREFACE

This study, begun in October, 1955, is an attempt to evaluate the possible effects on the surrounding population of a release of fission products at the proposed nuclear reactor site at Lagoona Beach, Michigan. Prior to commencement of this study there had been compiled relatively little factual information on the basis of which such an evaluation could be made.

It was proposed that no account be taken of the degree of probability or even possibility of the release of fission products from the reactor containment vessel, but that an appraisal be made of the consequences of such an assumed release without in any way indicating that it would be a credible possibility. It was known that a cloud of emitted radioactivity might drift out over Lake Erie and dissipate itself in a relatively harmless manner, or that it might drift toward Monroe, Toledo, or Detroit and present a sizable problem. One purpose of the study was to evaluate these various possibilities. One thing the assumed cloud could not do, of course, would be to move in all directions at once and affect persons simultaneously in all directions.

To make this study ultraconservative it was decided to use those methods of analysis yielding the most pessimistic results to determine the maximum effect of such an assumed release of fission products. Factors taken into account include the quantity of radioactivity released to the atmosphere, the effect of weather conditions and terrain in dissipating the cloud of fission products, the distribution of the population around the plant site, and other variables which influence the behavior of a radioactive cloud and the number of persons exposed to it.

The particular design of the proposed reactor or even its general type has no significance here. The total potential amount of radioactivity which could be released is determined essentially by the power level and operating history of the reactor.

The methods and theories used are described in the report which follows. Basically three cases were considered in evaluating the effects of a release of fission products from the plant site:

a. the specific case for some preselected weather condition with no consideration given to its probability of occurrence;

b. the case for the fission product release occurring under the most probable weather conditions; and

c. the case for all factors of weather and wind direction with the number of persons affected calculated by an averaging process.

The last calculation, which is the longest and most detailed, gives the best appraisal of the consequences of a release of fission products.

a. SPECIFIC CASES

All possibilities, however remote, have been taken into account. In the report, there will be found specific cases in which all the worst factors are combined to calculate the largest conceivable number of persons who could be affected. Likewise, we have considered the case in which all the factors combine in a favorable manner and in which no one except plant personnel is affected. Both cases are essential to the study; yet the isolation and consideration of either case alone is totally unrealistic.

To be as pessimistic as possible, the case in which the maximum quantity of radioactive fission products is released was given major consideration. Realistically, only a fraction of the total activity would ever be released, even in case of the total destruction of the reactor. Commissioner Libby of the Atomic Energy Commission has reported on studies in which only 1% release of the fission products is considered to be realistic. The results of the study of specific cases are summarized in Tables I through VI in the report.

b. "MOST PROBABLE" CASE

In analyzing the cases in which specific weather conditions are considered, we looked also at the most probable consequences of a fission product release. In this case, a release of 100% of the maximum quantity of fission products present in the reactor would produce relatively minor consequences since the cloud of fission products would diffuse quickly while moving over the lake and over sparsely settled areas in Canada. In the most probable case, and assuming a 100% release of fission products <u>no</u> <u>one</u> on land, and off the plant site, would receive a mean lethal dose. (See Section 15-b of the report for a further discussion.) Since, however, the most probable conditions, of course, do not prevail all the time, account must be taken of the possibility that a release of fission products, if it occurs, might occur under less probable but more unfavorable weather conditions.

c. AVERAGE CASE

A satisfactory evaluation of the consequences of a release of fission products can only be obtained through use of the more realistic averaging process described in Appendix II. The results of this process for a 1% release of the fission-product activity are summarized below.

AVERAGE NUMBER OF PERSONS AFFECTED PER RELEASE OF FISSION PRODUCTS
ASSUMING A LARGE NUMBER OF RANDOMLY OCCURRING RELEASES

1% of the Fission Products Released*

Type of Radiation	Number of Persons Exposed to Specified Minimum Dose		
	450r	150r	25r
External Gamma	0	0	15
Beta Inhalation	20	30	50
Beta plus Gamma with Fall-out Considered	5	15	40

*Values in this table were obtained through use of the area-ratio method derived in Appendix I.

If the averaging method is retained, but the emission is increased to 100% of the maximum conceivable fission product activity, the results are as given below.

AVERAGE NUMBER OF PERSONS AFFECTED PER RELEASE OF FISSION PRODUCTS
ASSUMING A LARGE NUMBER OF RANDOMLY OCCURRING RELEASES

100% of the Fission Products Released

Type of Radiation	Number of Persons Exposed to Specified Minimum Dose		
	450r	150r	25r
External Gamma	35	140	2420
Beta Inhalation	3150	4620	8570
Beta plus Gamma with Fall-out Considered	500	2475	6300

These results can actually be refined by a more detailed study than has been made and presented in this report. However, it is our belief that the general range of the number of persons affected would, if anything, be lowered if the more precise analysis were made.

Thus, assuming that 1% of the fission products within the reactor is released, twenty persons on the average would receive a mean lethal (450r) dose or more due to the inhalation of beta-particle emitters. Under the same conditions, thirty persons would receive 150r or more; and fifty persons would receive 25r or more.

In the extreme case, involving the release of 100% of the fission product activity, one finds that 3,150 persons would receive a mean lethal dose or more, 4,620 persons would receive 150r or more, and 8,570 persons would receive 25r or more.

If fall-out, based on 10-micron particles, is taken into account, all these numbers are reduced. This is particularly true for the number of persons exposed to a 450r minimum dose. However, as is discussed in the report, fall-out does introduce clean-up problems.

Finally, these numbers of persons are again reduced if the protection afforded by houses, automobiles, etc., is considered. The numbers quoted above are based on the assumption that no protection whatever is provided. We have assumed that all persons are fully exposed to the fission product cloud.

More realistically, we know that more than half the population considered would be inside some sort of enclosure, be it auto, school, house, or factory. We have no quantitative method of evaluating the effect of this protection. We know, however, that the number of persons receiving a given dose would be significantly lowered.

SECOND PREFACE

While the Michigan report was in its final phases of preparation, the Atomic Energy Commission released a report prepared by the Brookhaven National Laboratory, entitled Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants. Since the Michigan and AEC studies were made by groups which were not only independent of each other, but between which there was effectively no communication, and since the Brookhaven study has been available to the recipients of the Michigan report, it was decided to add a section to this report which would compare the assumptions made, methods of calculations used, areas covered, and results obtained. This added section appears in Appendix V.

The comparisons were made to find those differences in assumptions and methods which led to differences in the results obtained. Finally, an evaluation of the Lagoona Beach site was made, using the methods, where applicable, of the AEC study.

It is to be expected that, with the lack of experience and data available in this field, differences would arise. However, as a result of the comparison of the two studies, it is concluded that the AEC analysis sheds no new light on the suitability of the Lagoona Beach site.

TABLE OF CONTENTS

	Page
LIST OF TABLES	vii
LIST OF FIGURES	viii
ABSTRACT	xi
1. INTRODUCTION	1
2. RELATION OF STUDY TO REACTOR TYPE	1
3. FACTORS ENTERING THE STUDY	1
4. RESULTS OBTAINABLE FOR A SPECIFIC SET OF WEATHER CONDITIONS	2
5. RESULTS EVALUATED ON BASIS OF WEATHER VARIABILITY	2
6. RADIATION LEVELS CONSIDERED	3
7. TYPES OF RADIATION DOSE CONSIDERED	4
8. CONDITIONS ASSUMED FOR MAXIMUM RELEASE OF RADIOACTIVE MATERIAL	5
9. WEATHER CONDITIONS CONSIDERED	6
10. THE LAGOONA BEACH SITE AND SURROUNDING TERRITORY	6
11. POPULATION ANALYSIS	11
12. WEATHER OBSERVATIONS	16
13. WEATHER CONDITIONS STUDIED IN DETAIL	16
14. ISODOSE CONTOURS CALCULATED	21
a. Total Airborne Activity	21
b. Correction for Fall-Out	37
15. EFFECT ON PERSONS IN THE SURROUNDING AREA	45
a. Specific Weather Condition	45
b. "Most Probable" Weather Conditions and "Most Probable" Number of Persons Affected	53
c. The Average Number of Persons Affected	54
16. PROBABILITY OF EFFECTS OF THE RANDOM RELEASE OF THE FISSION PRODUCTS	54
APPENDICES	
APPENDIX I. BETA-CONTOUR AREA AND LENGTH	59
APPENDIX II. AVERAGING PROCESS	63
A. Statement of Problem	63
B. Assumption 1—Classification of Temperature Gradients	63
C. Evaluation of $N_i(v,\theta,r)$ the Population Function	64
C. Probability Considerations	66
APPENDIX III. PROBABILITY CALCULATIONS	74
A. Introduction	74
B. Methods of Calculation	74
APPENDIX IV. EIGHTY-MILE RADIUS LIMIT	80
APPENDIX V. COMPARISON OF THE MICHIGAN WITH THE AEC STUDY	81
REFERENCES	93

LIST OF TABLES

No. Page

I. Number of Persons Affected by Release of 1% of Reactor Fission Products (Weather Condition—Strong Inversion, 4.5-mph Wind) 47

II. Number of Persons Affected by Release of 100% of Reactor Fission Products (Weather Condition—Strong Inversion, 4.5-mph Wind) 48

III. Number of Persons Affected by Release of 1% of Reactor Fission Products (Weather Condition—Weak-Lapse, 11.25-mph Wind) 49

IV. Number of Persons Affected by Release of 100% of Reactor Fission Products (Weather Condition—Weak-Lapse, 11.25-mph Wind) 50

V. Number of Persons Affected by Release of 1% of Reactor Fission Products (Weather Condition—Strong-Lapse, 13.5-mph Wind) 51

VI. Number of Persons Affected by Release of 100% of Reactor Fission Products (Weather Condition—Strong-Lapse, 13.5-mph Wind) 52

VII. Average Number of Persons Affected per Release of Fission Products Assuming a Large Number of Randomly Occurring Releases—1% of the Fission Products Released 55

VIII. Average Number of Persons Affected per Release of Fission Products Assuming a Large Number of Randomly Occurring Releases—100% of the Fission Products Released 55

LIST OF FIGURES

No.		Page
1.	Site area and immediate surroundings.	7
2.	Thirty-mile-radius map of area.	9
3.	Eighty-mile-radius map of area.	10
4.	Population distribution.	12
5.	Typical township map.	13
6.	Overlay for 30-mile-radius map.	14
7.	Overlay for 80-mile-radius map.	15
8.	Wind speed distribution under inversion conditions, Toledo, Ohio (all wind directions).	19
9.	Wind speed distribution under all lapse conditions, Toledo, Ohio (all wind directions).	20
10.	Radioactivity concentration at ground level along wind axis.	22
11.	Integrated external gamma radiation dose under three representative weather conditions as a function of downwind distance (100% release).	24
12.	Integrated external gamma-radiation dose under three representative weather conditions as a function of downwind distance (1% release).	25
13.	Integrated beta inhalation radiation dose under three representative weather conditions as a function of downwind distance (100% release).	26
14.	Integrated beta inhalation radiation dose under three representative weather conditions as a function of downwind distance (1% release).	27
15.	Total integrated beta plus gamma dose under three representative weather conditions as a function of downwind distance (100% release).	28

LIST OF FIGURES (Continued)

No. Page

16. Total integrated beta plus gamma dose under three representative weather conditions as a function of downwind distance (1% release). 29

17. Beta inhalation dose variation in the cross wind direction under inversion conditions. 30

18. Isodose contours for 450r beta inhalation, gamma external, and combined doses. 31

19. Effects of weather conditions on 450r beta inhalation isodose contour size and shape. 33

20. Effect of quantity of radioactive material released on 450r beta inhalation isodose contour size and shape. 34

21. Effect of fall-out on total integrated beta plus gamma dose due to airborne material under inversion conditions. 39

22. Effect of inclusion of fall-out correction on 450r combined beta plus gamma isodose contours. 40

23. Effect of fall-out on total integrated beta plus gamma dose due to airborne material under strong-lapse conditions. 41

24. Initial dose rate downwind due to fall-out. 42

25. Integrated dose due to fall-out (inversion weather conditions, 100% release). 43

26. Integrated dose due to fall-out (inversion weather conditions, 1% release). 44

27. Comparison of 450r isodose contours due to fall-out over periods of one day and one week with the 450r beta plus gamma isodose contour with the fall-out correction applied. 46

28. Probability that a minimum number of persons will be exposed to a minimum dose of γ radiation, expressed as an "all weather" average. 56

29. Probability that a minimum number of persons will be exposed to a minimum dose of β radiation, expressed as an "all weather" average. 57

LIST OF FIGURES (Concluded)

No. Page

30. Probability that a minimum number of persons will be exposed to a minimum dose of β plus γ radiation (With fall-out applied), expressed as an "all weather" average. 58

A-I-1. Effect of percent of fission products released on maximum extension of 450r beta dose contour. 62

A-II-1. Minimum number of persons exposed to a minimum dose of beta radiation during strong-lapse weather conditions, 13.5 mph wind. 66

A-II-2. Trend of contour area with wind speed, area normalized to 10 at 10. 69

A-II-3. Wind-direction distribution under inversion conditions (all wind speeds), Toledo, Ohio. 70

A-II-4. Wind-direction distribution under all lapse conditions (all wind speeds), Toledo, Ohio. 71

A-II-5. Probability that a minimum number of persons will be exposed to a minimum dose of β + γ radiation (with fall-out applied), expressed as an "all weather" average. 73

A-III-1. Probability that a minimum number of persons will be exposed to a minimum dose of γ radiation from airborne fission products under specific weather conditions. 75

A-III-2. Probability that a minimum number of persons will be exposed to a minimum dose of β radiation from airborne fission products under specific weather conditions. 76

A-III-3. Probability that a minimum number of persons will be exposed to a minimum dose of β + γ radiation from airborne fission products under specific weather conditions. 77

A-V-1. Comparison of AEC and Michigan study predicted doses due to airborne fission products as a function of downwind distance. 87

A-V-2. Comparison of AEC and Michigan study predicted doses due to airborne fission products as a function of crosswind distance. 88

ABSTRACT

The possibility of the release of fission products during the use of nuclear reactors for electric power generation makes the study of consequent conditions relating to persons in the area surrounding the plant one of timely importance. This report deals with one aspect of the results of such a possibility, pertaining to those persons in the vicinity of the Enrico Fermi Plant of the Power Reactor Development Company.

The problem can be analyzed in two parts, the probability of occurrence of a release of fission products, and the consequences of a release of fission products, should it occur. We have dealt exclusively with the latter.

For the initial studies, it was assumed that all (100%) the fission products are released into the atmosphere. Further data were obtained to determine the effects of a release of 1% of the fission products.

The fission products move downwind and spread out in a manner determined by the weather conditions. Three main classifications of weather conditions were established based on the variation of the atmospheric temperature with altitude. The classifications are:

a. inversion;
b. weak-lapse;
c. strong-lapse.

Further classifications were established for the following situations:

a. The consequences of a release of fission products under completely specified weather conditions, independent of the frequency of occurrence of the selected conditions;
b. The consequences of a release of fission products when the wind is blowing in the most probable direction;
c. The consequences of a release of fission products to an "average" number of persons per release.

Isodose contours were developed through use of the Sutton Diffusion Equation and the Holland Nomograms to determine the geographic area within which exposure could occur due to:

a. beta-emitter inhalation;
b. external gamma radiation;
c. combined beta plus gamma radiation.

The three isodose contours considered were: 25r, 150r, and 450r.

Knowing the area within which a given minimum dose is received, and knowing the distribution of the populace surrounding the plant, the number of persons exposed to the various dose levels was determined.

Several additional factors were studied to find their effect on the number of persons subjected to specific doses. These factors include:

a. fall-out of particulate matter from the cloud of fission products;
b. quantity of radioactive material released from the plant.

1. INTRODUCTION

A study has been made for Atomic Power Development Associates, Inc., of the possible effects on the surrounding population of a release of fission products at the Lagoona Beach site. Begun in the latter part of 1955, the study is intended to help reveal and evaluate the consequences of an event in which a reactor and its protective coverings are assumed to be totally or partially destroyed, with the subsequent release of all the radioactive gas and particles into the atmosphere. Additional data, based upon a release of 1% of the fission products, are included. The assumption of a 1% release is believed to be more realistic than a 100% release. Nevertheless the 100% release has been treated in detail since this is the obvious upper limit to the quantity released.

2. RELATION OF STUDY TO REACTOR TYPE

This study is unrelated to any particular type of reactor. The effects described here are those resulting from an assumed instantaneous, total or partial, release into the atmosphere of radioactive fission products. These effects will be substantially the same from any reactor operated at a given power level, whether thermal or fast, breeder or nonbreeder, and regardless of whether the fuel used is enriched or unenriched uranium or plutonium. This is because, in terms of their fission product activity or inventory of dangerous radioactive materials, all reactors that have operated at a given power level are essentially alike. Accordingly, the general type of reactor proposed for construction at the Lagoona Beach site is not a factor here. Whether an event permitting the assumed release of fission products is credible, is <u>not</u> within the scope of this study. We start with the assumption that such a release has in fact occurred, <u>without inquiring into the question of how or whether it could occur</u>.*

3. FACTORS ENTERING THE STUDY

Knowing the power level at which a reactor has operated, the amount of radioactivity present and its nature are easily found. This radioactive material represents the danger.

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

In the hypothetical case in which a release of fission products has occurred, the factors which determine the number of persons affected are:

a. Population distribution around the site to a depth of many miles.

b. The weather conditions at the time of the release and for many hours thereafter. The important factors here are:

(1) Wind direction;
(2) Wind velocity;
(3) Temperature change with altitude.

c. The nature of the terrain; whether it is flat or hilly, rough or smooth, whether any major valleys exist, etc.

d. The amount of material released as a gas cloud and the amount released as fine or coarse particles.

4. RESULTS OBTAINABLE FOR A SPECIFIC SET OF WEATHER CONDITIONS

Knowing factors a, c, and d above, and assuming a very specific set of weather conditions, we can calculate:

a. Over what area a radioactive cloud will extend.

b. What dose of radiation will be received due to gamma rays from the cloud as it passes over.

c. What dose will be received due to inhalation, particularly of the beta-particle emitters.

d. What fraction of the activity will fall out on the ground.

e. The dose rate due to fall-out.

f. The number of persons receiving given radiation doses.

5. RESULTS EVALUATED ON BASIS OF WEATHER VARIABILITY

To the best of our knowledge, there is no easily correlated connection between the weather and the probability of a release of fission products.

We assume, therefore, that the release can occur with equal likelihood at any time, day or night, and any day of the year.

We can evaluate its effects by assuming that the release occurs:

a. Under the worst possible weather conditions—regardless of its small probability.

b. Under the most probable set of weather conditions. This is the set which occurs most often and so has the greatest likelihood of prevailing should a release occur.

c. Under an average set of weather conditions. This average is arrived at, as will be shown later, by weighting both the frequency of occurrence of a given type of weather, and the significance, in terms of number of persons involved for a given set of conditions. Conditions which occur often, or conditions under which many persons would be affected, have the greatest effect on the results.

The results found by all three methods will be compared.

6. RADIATION LEVELS CONSIDERED*

Three principal radiation levels have been taken as significant for this study. These are:

a. 25 roentgen - This is taken as an emergency level which, while undesirable, may be justified under special conditions.**

b. 150 roentgen - At this level there will be some nausea and significant symptoms.

c. 450 roentgen - At this level half the exposed population can be expected to die.

Other levels can be selected and calculations made as desired. The methods used are completely general. However, in all cases, we study the number of persons receiving a given dose <u>or</u> <u>more</u>. In each case, the minimum dose will be clearly defined.

**The permissible "one-time" emergency dose of 25r has been reaffirmed by the National Committee on Radiation Protection, sponsored by the National Bureau of Standards (1956).

*For a discussion of this point as compared with the AEC study, see Appendix V.

7. TYPES OF RADIATION DOSE CONSIDERED

For the assumed release, there are three major types of radiation dose:

a. External whole-body radiation due primarily to the gamma rays emitted by the fission products in the air.

b. Internal dose due primarily to inhaled and ingested beta-ray emitters.

c. External dose rate due to gamma rays from fission products on the ground due to fall-out.

Knowing the amount of radioactive material per cubic foot in a cloud completely surrounding a person, the gamma dose due to external effects can be calculated. This has been done using the nomograms prepared by J. Z. Holland.[1]*

To obtain the effect of beta rays, the conversion factor 25 roentgen per 10 curie seconds per cubic meter was used. This states that a person breathing for one second in an environment containing 10 curies of activity per cubic meter of air receives a dose of 25-roentgen-equivalent whole-body radiation.* The conversion factor is at best a rough approximation which takes into account, by averaging, the effects of the different isotopes on the tissues in which they can be expected to concentrate. For specific cases, a detailed analysis would be needed, but to evaluate the general case, this approximation appears justified.

In assessing total radiation dose in a given case, the external gamma-ray exposure and the internal inhalation are added to give the total effective dose. The cases are treated individually and then combined.

The effect of fall-out is treated separately. Here, the major problem arises from material on the ground creating an external radiation field. Since the time spent in such a field can be controlled, the roentgen per hour due to fall-out on the ground is evaluated. The total exposure is the rate multiplied by the time spent, corrected for the natural decay of the activity.

We have calculated the dose rate and also the dose if (a) one uninterrupted day and (b) one uninterrupted week are spent in the fall-out field.

From an academic viewpoint, the question arises of how large a dose would be received if a person spent a very long or infinite time in such a fall-out field. The Way-Wigner formula[2] used to describe the decay of radioactive fission products is accurate for about the first 100 days. Thereafter

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

it is pessimistic, predicting too large a dose. For the case above, of very long exposure, it predicts a dose which would increase indefinitely toward infinity.

This is not true, but since the major error is introduced for periods after 100 days, it can be avoided by taking observations over realistic time periods.

In this report, we have confined our considerations of fall-out to its direct effect on persons in the area. The problem of property damage arising from the need to abandon contaminated areas for long or short periods has not been considered.* This can be done if desired since the size of areas affected can be found through use of the methods set forth in this study. However, for our present purposes, only the effect on persons was evaluated.

8. CONDITIONS ASSUMED FOR MAXIMUM RELEASE OF RADIOACTIVE MATERIAL

To determine the upper limits of possible radiation effects we have postulated the most pessimistic conditions without regard for their credibility. Accordingly, the release has been assumed to occur after the plant has been in operation for a long time at 300 megawatts and has built up its maximum inventory of fission products, 3 billion curies.* This is based on the empirical relationship:

$$\text{curies} \quad = \quad 10 \times \text{power (in watts)}.^1$$

The small additional amounts due to a power surge just before the accident and due to the radioactivity of the coolant have been neglected. If the coolant were sodium, for instance, the activity could amount to some 10 million curies as compared to the 3 billion curies of fission products.[3]

To determine the upper limits of possible damage, it has been assumed that all (100%) the fission products escape.* In the more realistic case in which 1% of the fission products escape, the radioactivity amounts to 30 million curies.

The presence of rain has not been taken into account.* The greatest problem occurs when the radioactive material is diffuse and airborne, so that it reaches the largest number of persons. Rain-out reduces this problem substantially and so has been neglected.

To calculate the concentration of material at any point in the general vicinity of a source discharging into the air, the weather factors and the amount of material discharged into the air in a single puff are all com-

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

bined in one equation called the Sutton Diffusion Equation.

Radioactive materials lose their activity with time. The best general statement of the behavior with time of fission products which have accumulated for a long period in an operating reactor is the integrated Way-Wigner Equation, which has been adopted for use in this study.* It is:

$$C = 10\,Pt^{-0.2} ,$$

where

C is the activity in curies,
P is the power in watts, and
t is the time in seconds.

9. WEATHER CONDITIONS CONSIDERED

The most important single weather parameter is the temperature gradient or change in temperature with altitude. Normally, the air is warmest near the ground and cools as altitude is increased. This is called a temperature lapse. Under lapse conditions, gases released at ground level will rise rapidly.

However, another possibility is that the air near the ground will be cooler than the air at higher altitude. This occurs particularly during a clear night when the ground cools by radiation and so cools the air in contact with it. This is a temperature inversion. Under these conditions, there is little tendency for gas to rise, but rather a tendency to spread over the ground. There are various strengths of lapse and inversion and, of course, the effect produced depends on their strength.

In addition to temperature gradient, two other parameters, wind velocity and wind direction, were studied.

10. THE LAGOONA BEACH SITE AND SURROUNDING TERRITORY

A map of the site area and its immediate surroundings is shown in Fig. 1. The site is bordered on one side by water; otherwise, it is surrounded by an isolated exclusion area about 3000 feet in radius. The terrain is flat and clear, with no marked prominences.

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

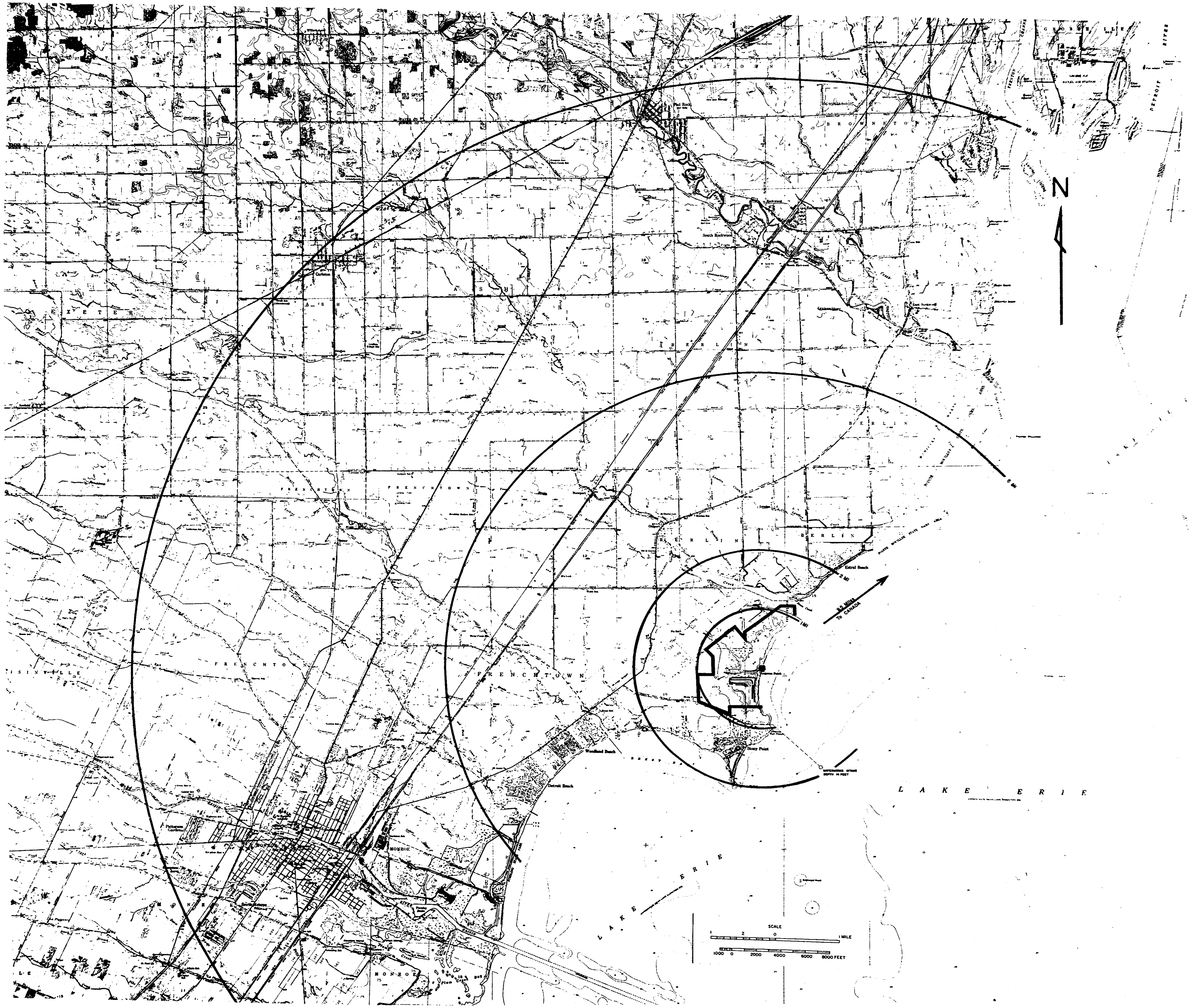


Fig. 1. Site area and immediate surroundings.

The nearest major population center is the city of Monroe lying 10 miles to the southwest on the Raisin River. Detroit City Hall is north-northeast about 30 miles, and the Toledo City Hall is about 25 miles to the south-southwest. All this country is essentially flat, with no deep valleys or ravines to cause marked channeling of air currents. This larger area is seen in Fig. 2.

In evaluating the drift of a fission product cloud toward and through these population centers, no account has been taken of the heat generated within the city. Heat causes lofting and turbulence which would help break up and dissipate the cloud. This is most important should the release occur on a day with low steady winds and a temperature inversion. The effect, while present, is not sufficiently predictable and reliable to count on. It has therefore been neglected in order to keep the study conservative.

Finally, in Fig. 3, a map taking in territory out to 80 miles is shown. In terms of immediate effects, we can find little justification for going out any greater distance, since the assumptions as to weather conditions on which these results are based would no longer be valid.* For an inversion with a 4-mph wind, 20 hours would elapse while the cloud traveled 80 miles. This is too long a period for continuous persistence of a strong inversion. Any change in weather conditions would be, in this case, for the better.

In addition, as shown in Section 14, the distance from the site to the farthest point receiving a given dose of radiation is reduced drastically as the weather improves. Fall-out also shortens the distance to the farthest point receiving a given dose. This is seen in Section 14b. These facts, along with the observed limited persistence of strong inversion conditions, formed the basis for the decision to cut off the study at 80 miles. For a further discussion of this topic, see Appendix IV.

It is most important to note how much of the area around the site is water—primarily Lake Erie. While a release in which radioactivity falls out into the lake could cause problems, time would be available to deal with them, as compared to the more immediate prospect of a gas cloud passing over a populated area. In this sense, the site is more favorable than one in which population centers would be reached by travel of short distances in any direction.

Since an electric plant should normally be located within economical transmission distance of its load, and close to a supply of water, a flat site at the edge of a large body of water appears to be a good choice.

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

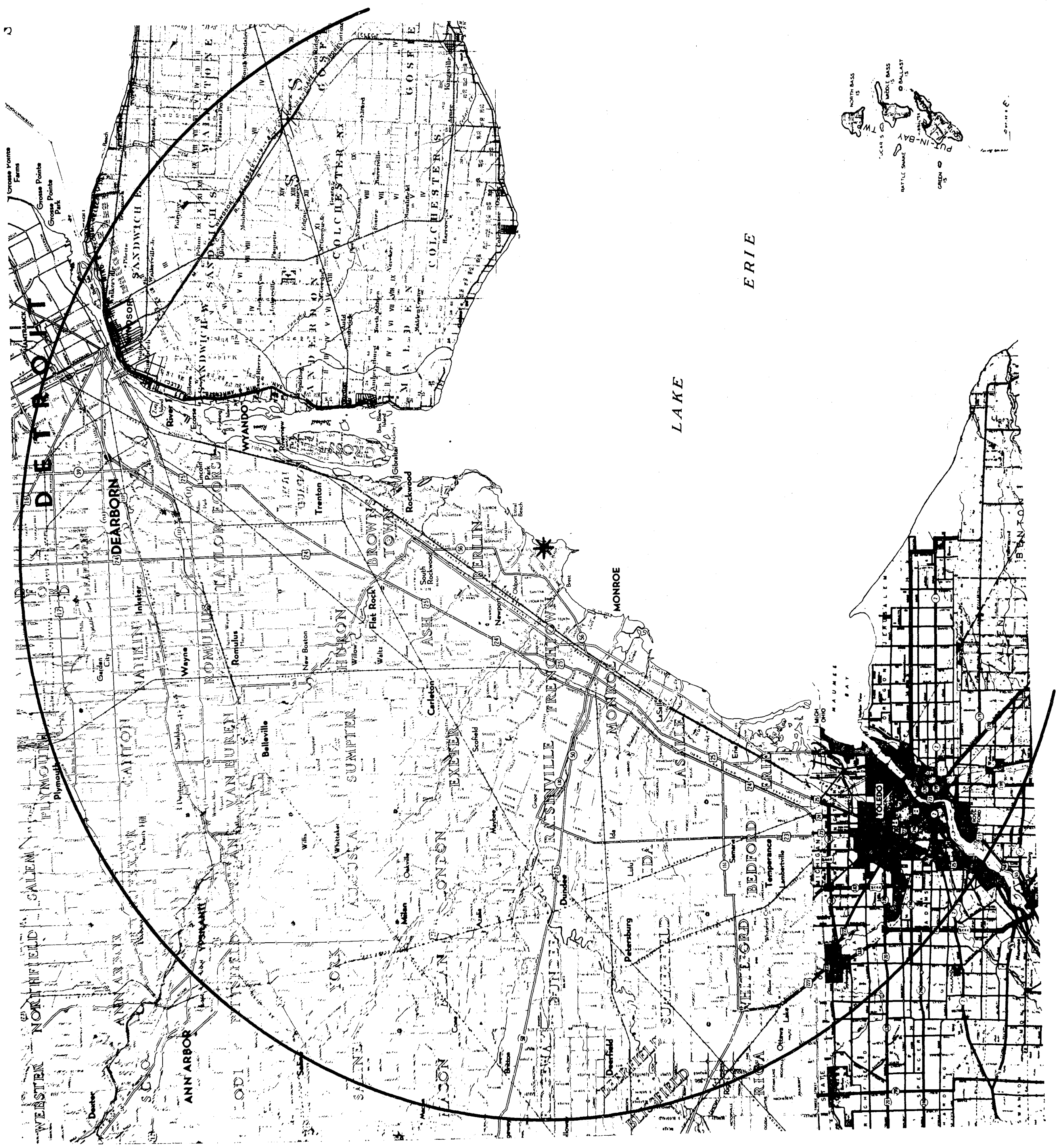


Fig. 2. Thirty-mile-radius map of area.

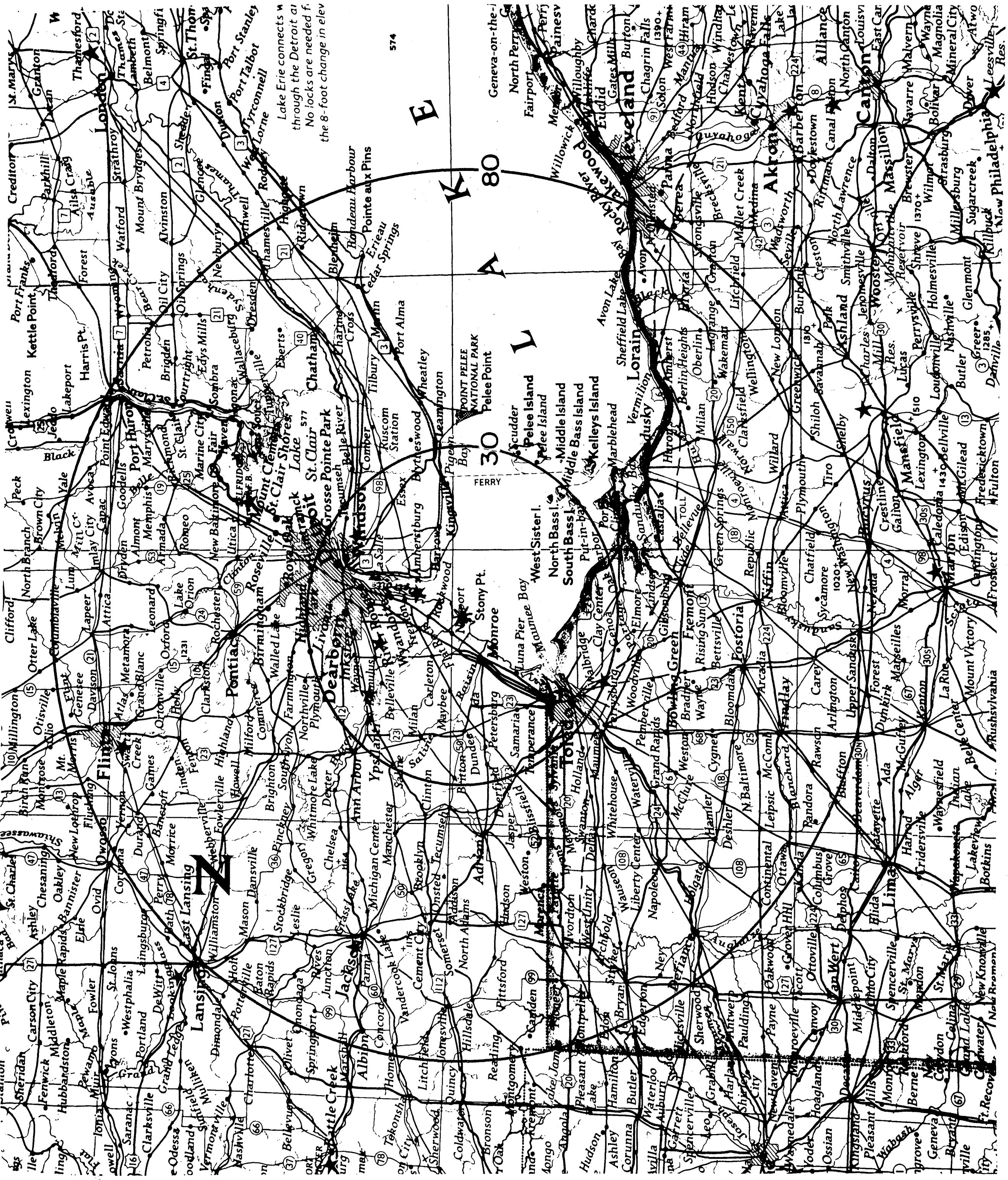


Fig. 3. Eighty-mile-radius map of area.

11. POPULATION ANALYSIS*

Figure 4 shows the population reached at different distances from the plant. However, since the wind will carry a cloud of fission gas in a specific direction, the detailed population distribution is more important. A fission product cloud passing over Monroe is a far more serious problem than a cloud passing over the lake.

For distances up to 10 miles from the plant, a detailed study of the population was made with the aid of the Detroit Edison Company's Meter Department. Residential meters were counted on every half-mile of rural road and on every block in urban areas. These counts were inscribed on township and municipal maps. It was found, checking against county census data, that there are 3.5 persons per residential meter. A typical marked township map is shown in Fig. 5.

For the 30-mile map (Fig. 2), township and municipality data and census tract data pertaining to Detroit and Toledo were used. For the 80-mile map (Fig. 3), county and municipality data were used.

In Fig. 6, an overlay for the 30-mile-radius map is shown. In each marked section the area in square miles and the number of persons per square mile are shown. A similar population study for the 80-mile map was prepared and is seen in Fig. 7.

These surveys show the population as distributed according to their permanent residences. Admittedly, redistribution will occur during working hours or special vacation periods. However, the population is least mobile and therefore most vulnerable when at home in bed at about 4:00 A.M. Therefore, for this study, an immobile population was assumed. In accordance with our objective, that is, to postulate the most pessimistic conditions to arrive at the outside limits of radiation effects, it was further assumed that the homes in which the persons are found have no roofs and so afford no protection from radioactivity. This assumption is of course not valid. Substantial major protection is provided in the case of beta airborne activity, and some protection in the case of the gamma activity. Actually the safest place to be in case a radioactive cloud is passing over is in a building with closed windows. Thus, a cold winter night would be safest. We have laid emphasis on the extreme case by assuming the equivalent of a hot summer night with everyone sleeping out of doors or in roofless houses. It would not be unreasonable to assume that 50% or more of the population within the radioactive cloud area would actually be protected from the cloud by shelter.

Finally, we will see that a cloud which would reach a population center some thirty miles away, like Detroit, would be very narrow. To reach

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

POPULATION WITHIN CIRCLE OF GIVEN RADIUS	RADIUS- MILES
175	1
600	2
1800	5
31,300	10
187,100	20
2,001,700	30

The population within 5 miles would be somewhat higher during the summer due to an influx of vacationing transients.

Fig. 4. Population distribution.

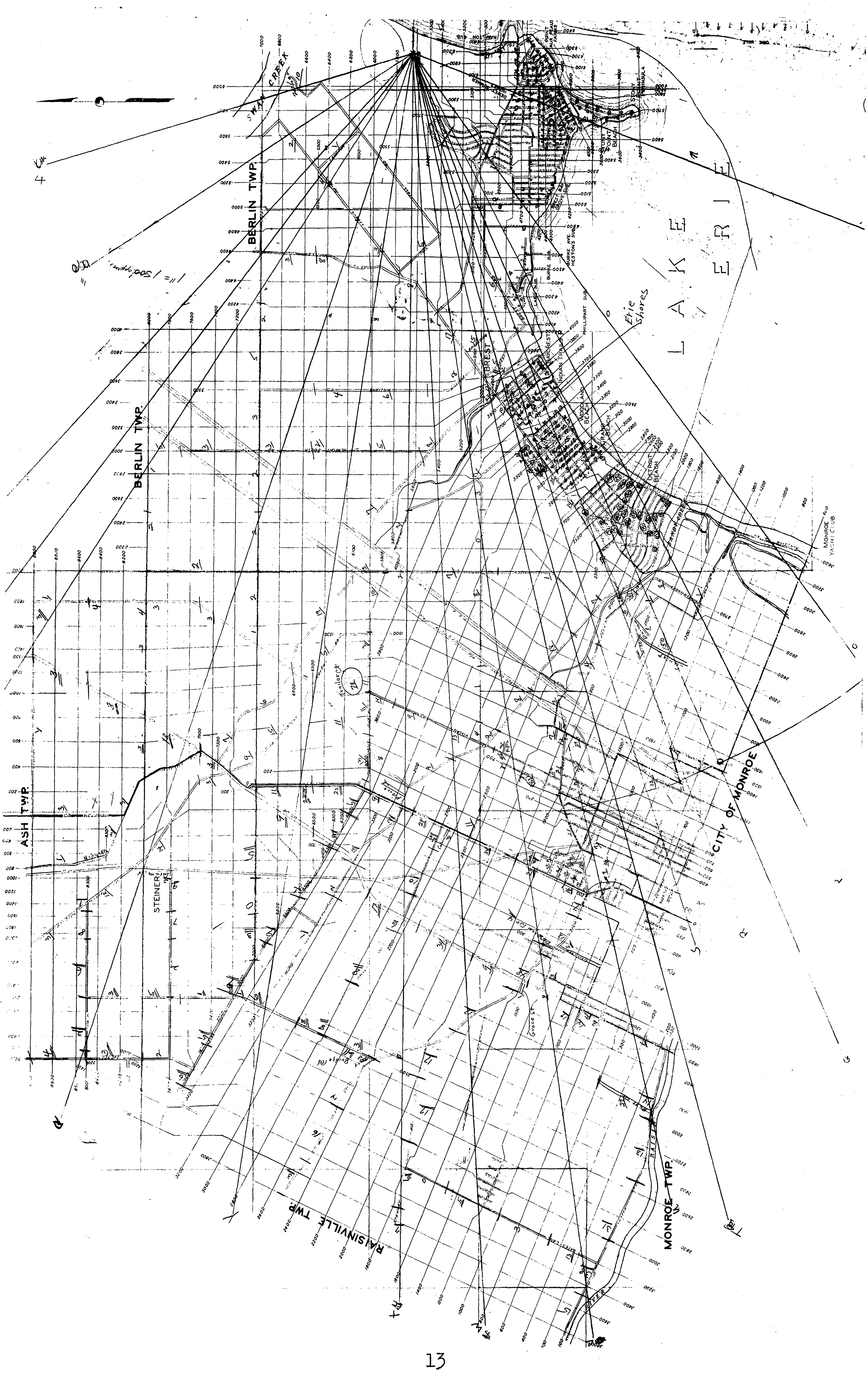


Fig. 5. Typical township map.

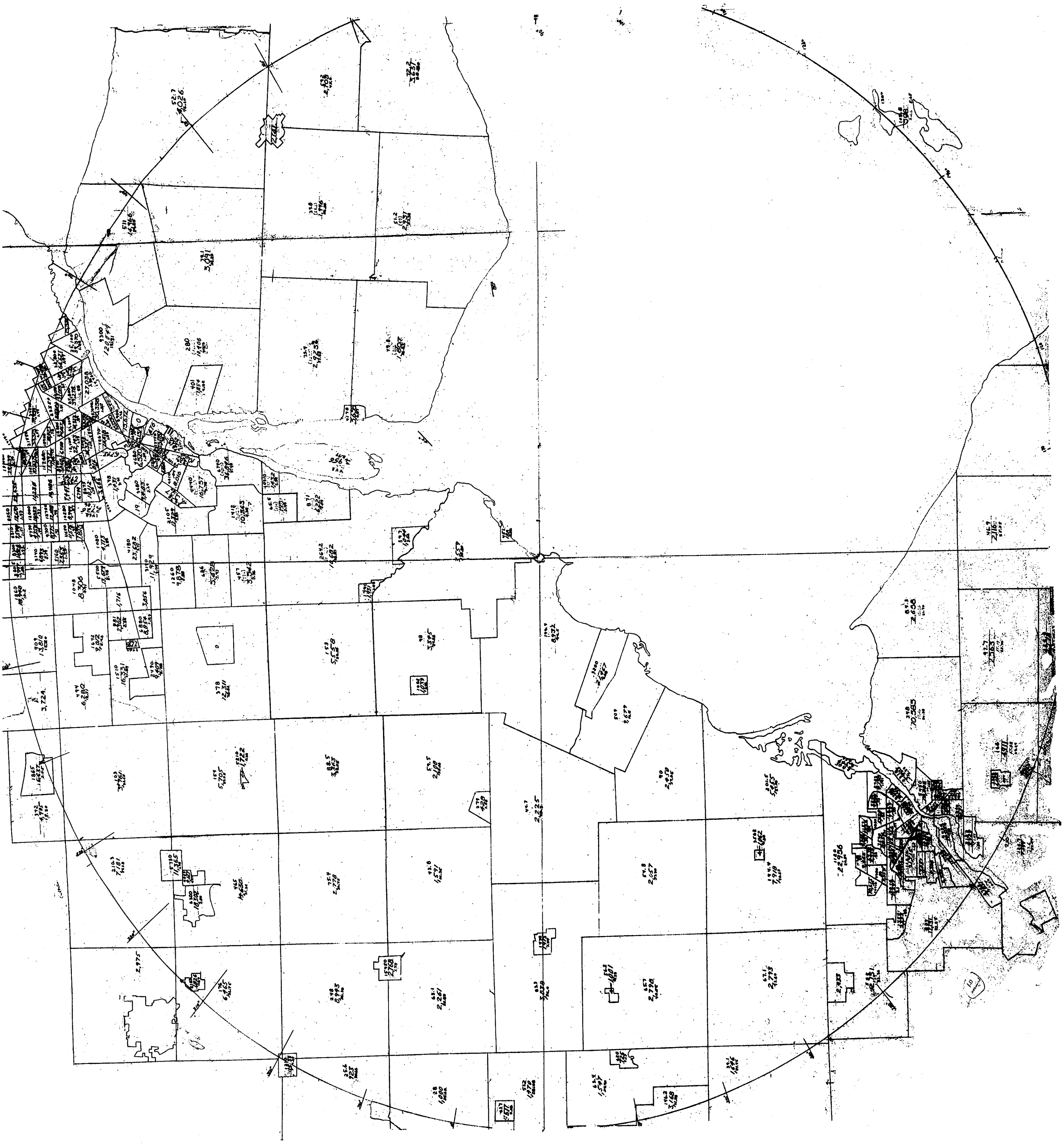


Fig. 6. Overlay for 30-mile-radius map.

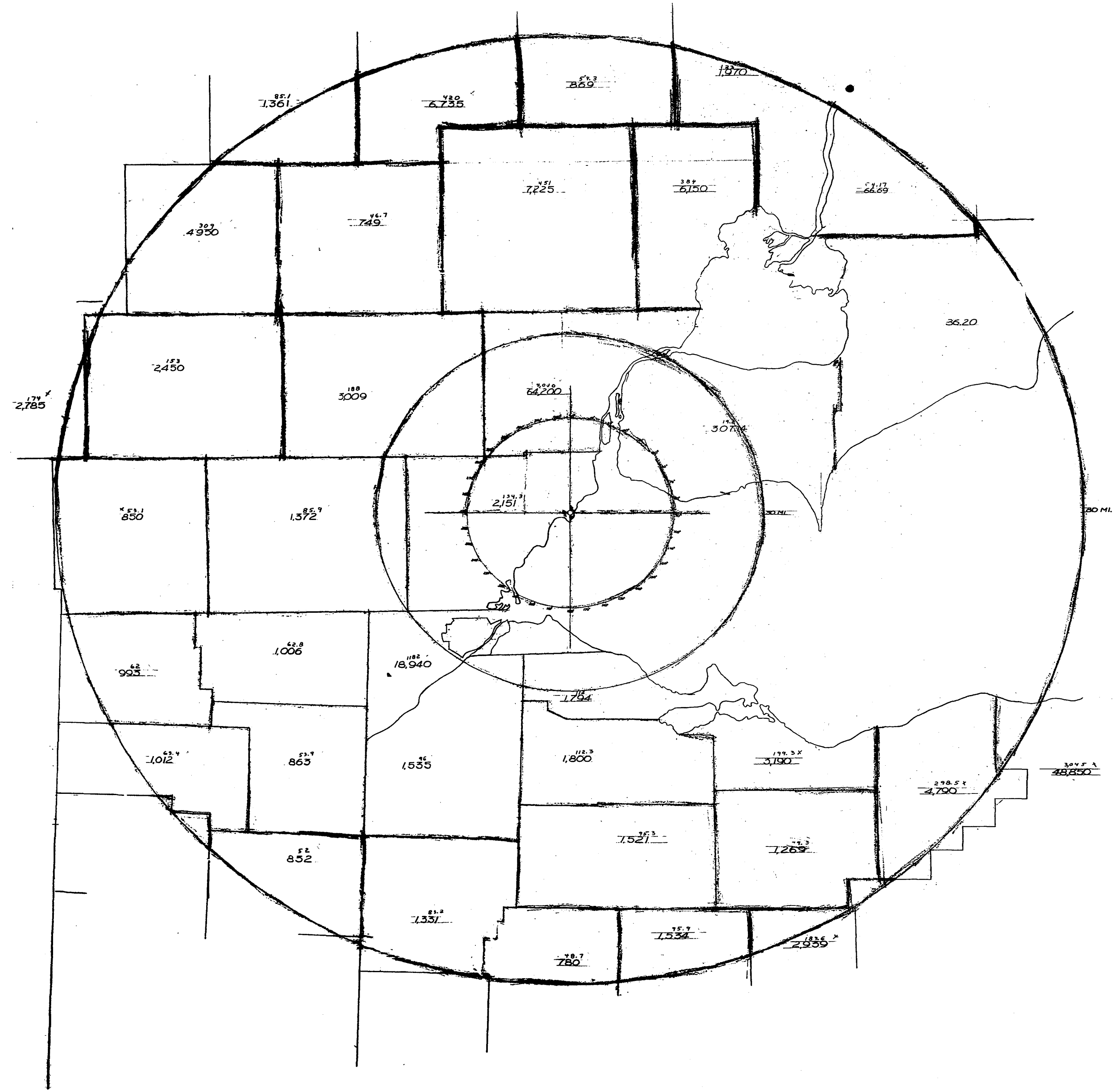


Fig. 7. Overlay for 80-mile-radius map.

Detroit in any strength, it would move slowly, thus allowing several hours for possible warning. No cognizance is taken of the possibility of shifting persons out of the cloud's path.

12. WEATHER OBSERVATIONS

As remarked earlier, once the fission product release is assumed to have occurred, the most important controlling condition is the weather. The best records of weather in the general area near the site are those taken at the Toledo Airport and at Selfridge Field. Weather data for the last eight years have been obtained from the United States Weather Bureau and analyzed.

A comparison made of records of the two stations indicates that, in general, the data taken are in agreement, provided allowance is made for the time of propagation from one station to the other over a distance of about 75 miles. On this basis, it is assumed that the available data are valid for the Lagoona Beach site, which is one-third the distance from Toledo to Selfridge Field.

Weather observations on the site itself have been started but data available in time for this study were insufficient.

The weather data used consist of annual and seasonal tabulations of observations of wind direction, velocity (in intervals 0-3, 4-7, 8-12, 13-18, 19-24, 25-31, 32-38, 39-46, and 47 plus miles per hour), presence and absence of cloud cover, observed occurrence of inversions, and occurrence of rainfall. These are the major factors which determine the behavior of any airborne material which might be released from the reactor. The survey was designed in cooperation with Professor E. Wendell Hewson of the Department of Civil Engineering of The University of Michigan.

13. WEATHER CONDITIONS STUDIED IN DETAIL

Weather conditions, as characterized by wind velocity and temperature gradient, vary widely over the year. To reduce the problem to one of manageable size for this study, it was decided, for this first analysis, to establish three major categories of weather conditions and to fit all observations within these categories.

As indicated earlier, it was assumed that the Sutton Diffusion

Equation provides an adequate description of the behavior of a cloud of radioactive fission products.

The Sutton Equation may be written:[4]

$$\chi = \frac{Q}{\pi^{3/2}\, C_x C_y C_z\, (ut)^{3(2-n)/2}} \exp\left[-(ut)^{n-2}\left(\frac{x^2}{C_x^2} + \frac{y^2}{C_y^2} + \frac{z^2}{C_z^2}\right)\right],$$

where

χ is the concentration of material in the air,
Q is the total amount of material released in one event from a small source,
C_x, C_y, C_z are diffusion coefficients in the x, y, and z directions,
u is the wind velocity in the x direction,
t is the elapsed time,
n is the atmospheric stability factor which reflects the effect of the temperature gradient above the ground,
x is the distance in the downwind direction,
y is the distance in the crosswind direction, and
z is the distance in the vertical direction.

From this equation, we can determine the concentration of material in the air after its release from a source.

The parameters C_x, C_y, and C_z were assumed to be equal and to vary only with the temperature gradient.* This reduces the general equation to that for the isotropic case, one in which diffusion takes place at the same rate in any direction. Sutton's Equation is now, for concentration of material anywhere,[5]

$$\chi = \frac{2Q}{\pi^{3/2}\, C^3\, (ut)^{3(2-n)/2}} \exp\left[-\frac{x^2 + y^2 + z^2}{C^2\, (ut)^{2-n}}\right].$$

The multiplier 2 in the numerator is introduced to account for reflection or bounce back of gas molecules which reach ground level.

In this equation, the parameters selected to cover the three chosen temperature-gradient conditions are:*

	n	C
a. Strong temperature inversion	0.60	0.22
b. Weak temperature lapse	0.30	0.28
c. Strong temperature lapse	0.22	0.30

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

All weather observations were fitted into one of these categories. The data reported by the Weather Bureau on temperature gradients were not sufficient, of themselves, to permit such a breakdown. Their report based on data obtained from radiosonde balloons flown from Toledo and from Selfridge Field, Mt. Clemens, Michigan, simply tells us when a temperature inversion exists. It does not provide information on the strength of the inversion.

Our parameters for the inversion case are characteristic of the strongest inversion which can be expected to persist and, since this is a pessimistic case, all inversions have been assumed to be of this strength.

Further, no report is available on the strength of the temperature lapse. Analysis of the mechanism of lapse formation, in consultation with Professor E. W. Hewson, provided the following breakdown in time of the three cases:

a.	Strong inversion	37%
b.	Weak lapse	36%
c.	Strong lapse	27%

For the chosen temperature gradient, the wind direction and wind velocities must be determined. The distribution curves for wind velocity under temperature inversion and under temperature lapse were derived from data and are shown in Figs. 8 and 9.

From these wind-velocity distribution curves, velocities which are characteristic of the temperature gradient and yet on the pessimistic side were selected. These are:

a.	Strong inversion	2 meters per second = 4.5 mph
b.	Weak lapse	5 meters per second = 11.25 mph
c.	Strong lapse	6 meters per second = 13.5 mph

Knowing the temperature gradient and the wind speed, the distribution of material released into the air can now be calculated, using the Sutton Theory.

We have reduced all weather to three groups. Further breakdown in detail would be more precise, but we believe that the more precise case would show a higher incidence of more favorable weather conditions. The necessary increase in labor for the complete analysis is formidable.

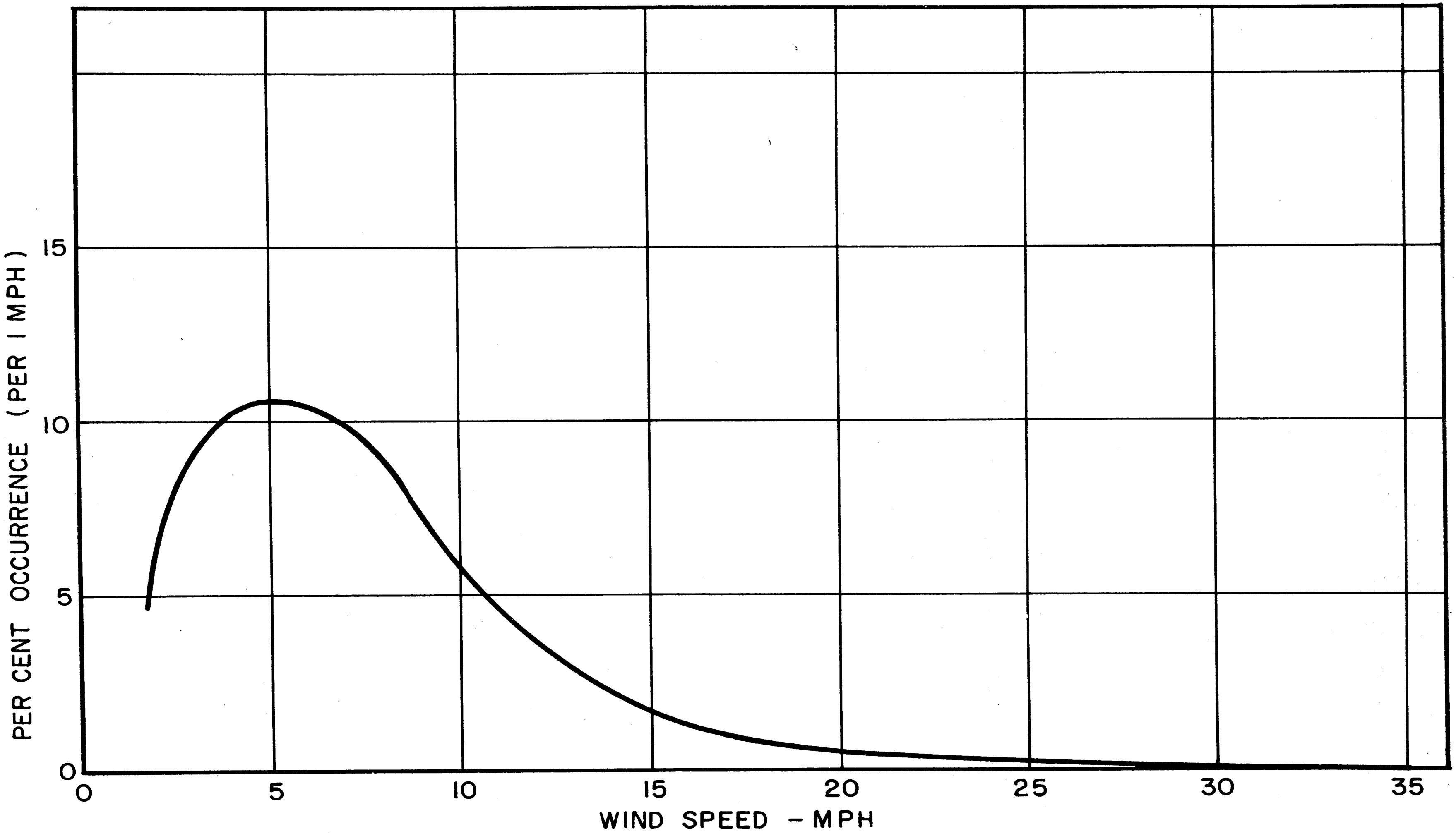


Fig. 8. Wind-speed distribution under inversion conditions, Toledo, Ohio (all wind directions).

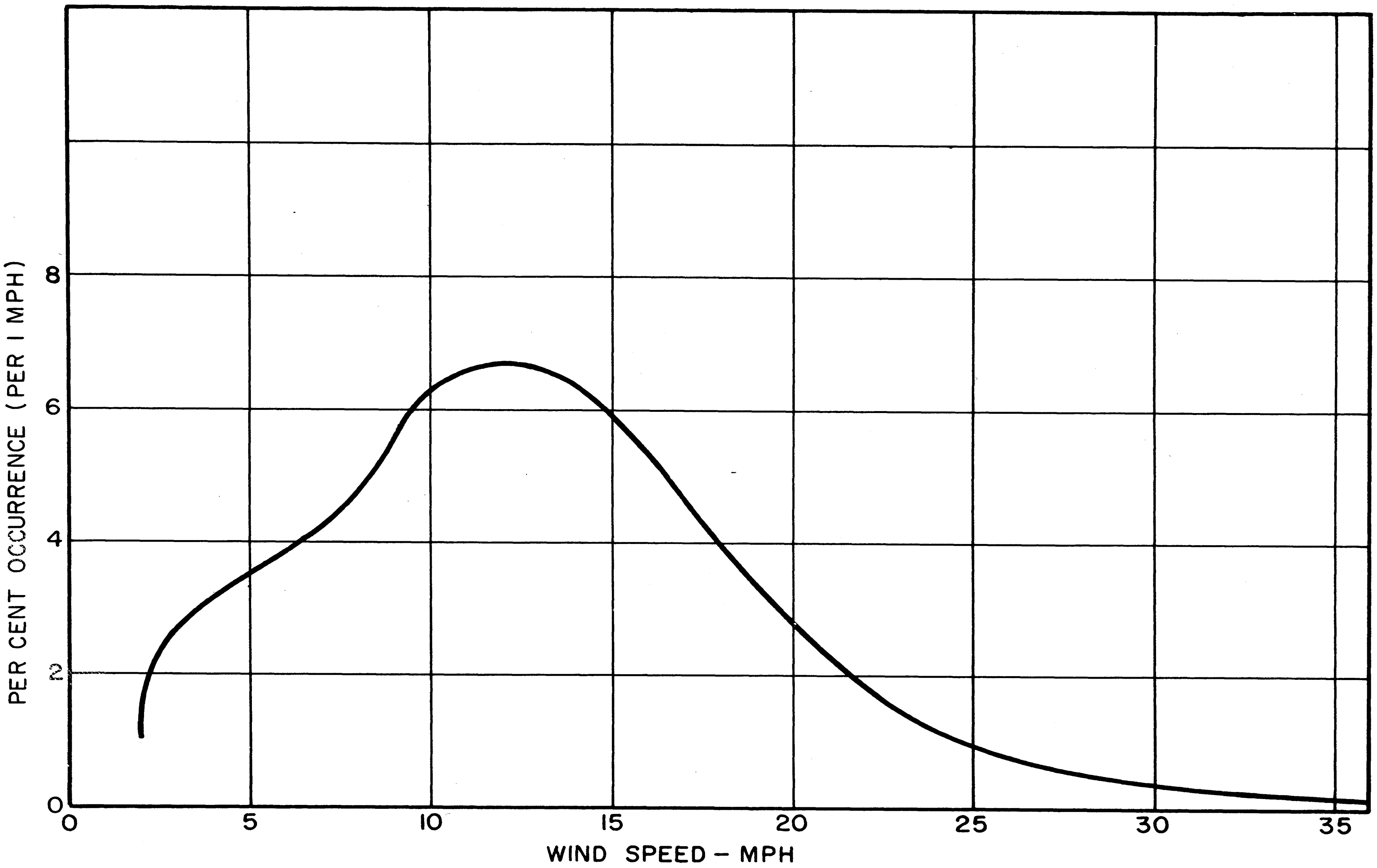


Fig. 9. Wind-speed distribution under all lapse conditions, Toledo, Ohio (all wind directions).

14. ISODOSE CONTOURS CALCULATED

a. TOTAL AIRBORNE ACTIVITY

For each specified weather condition and for a given amount of radioactive material released into the air, the radiation dose delivered to any point in the area can be calculated. This is done using the Sutton Theory for concentration of radioactive material in the air, correcting for the time decay of the material, and calculating the exposure due to a cloud of the nature described passing over a particular point or person.

The cloud itself has a bell-shaped variation in concentration known as a Gaussian distribution. The concentration of activity at ground level on the cloud axis as the cloud progresses downwind is shown in Fig. 10. The concentration above the ground is half Gaussian with the maximum at ground level.

The total dose to which a person is subjected is received as the cloud passes over and by. The time-decay factor for the whole cloud is taken as that for the center of the cloud when it arrives at the point occupied by the person.

The total dose consists of the sum of the gamma external radiation and the inhalation doses.

The external gamma dose is calculated from an equation which combines air concentration of radioactive material, time of exposure, the build-up effect due to Compton effect in air, and other pertinent factors.* As developed by Holland,[6] the equation for dose to a point or person on the ground from a source on the ground is:

$$D_g = \frac{\mu_a}{(4\pi)(6.8)(10^{10})} \int_0^{+\infty} \int_{-\infty}^{+\infty} \frac{Q_g \exp\left\{-\frac{x^2+y^2}{\sigma^2}\right\}}{\pi^{3/2}\, C^3 x^{3(2-n)/2}} \; \frac{B_r\, e^{-\mu r}}{r^2} \, dy\, dx \,,$$

where

Q_g is the gamma strength of the source,
μ_a is the air absorption coefficient,
B_r is the build-up factor,
μ is the total interaction coefficient,
σ is $C\, x^{(2-n)/2}$,
r is the distance from a point in the cloud where the gamma ray is emitted to the receiver,

and the other terms are the same as used in the Sutton Equation. The values of D_g have been calculated and published in nomogram form by J. Z. Holland.[1] This nomogram was used to obtain the values in the study of gamma ray dosage.

The inhalation dose is arrived at by direct calculation, using the equation[7]*

$$\text{T.I.D.} = \frac{(2Q)\,(2.5)}{\pi\, C^2 u\, x^{2-n}}\, t^{-0.2} \exp\left\{\frac{-y^2}{C^2\, x^{2-n}}\right\} \,,$$

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

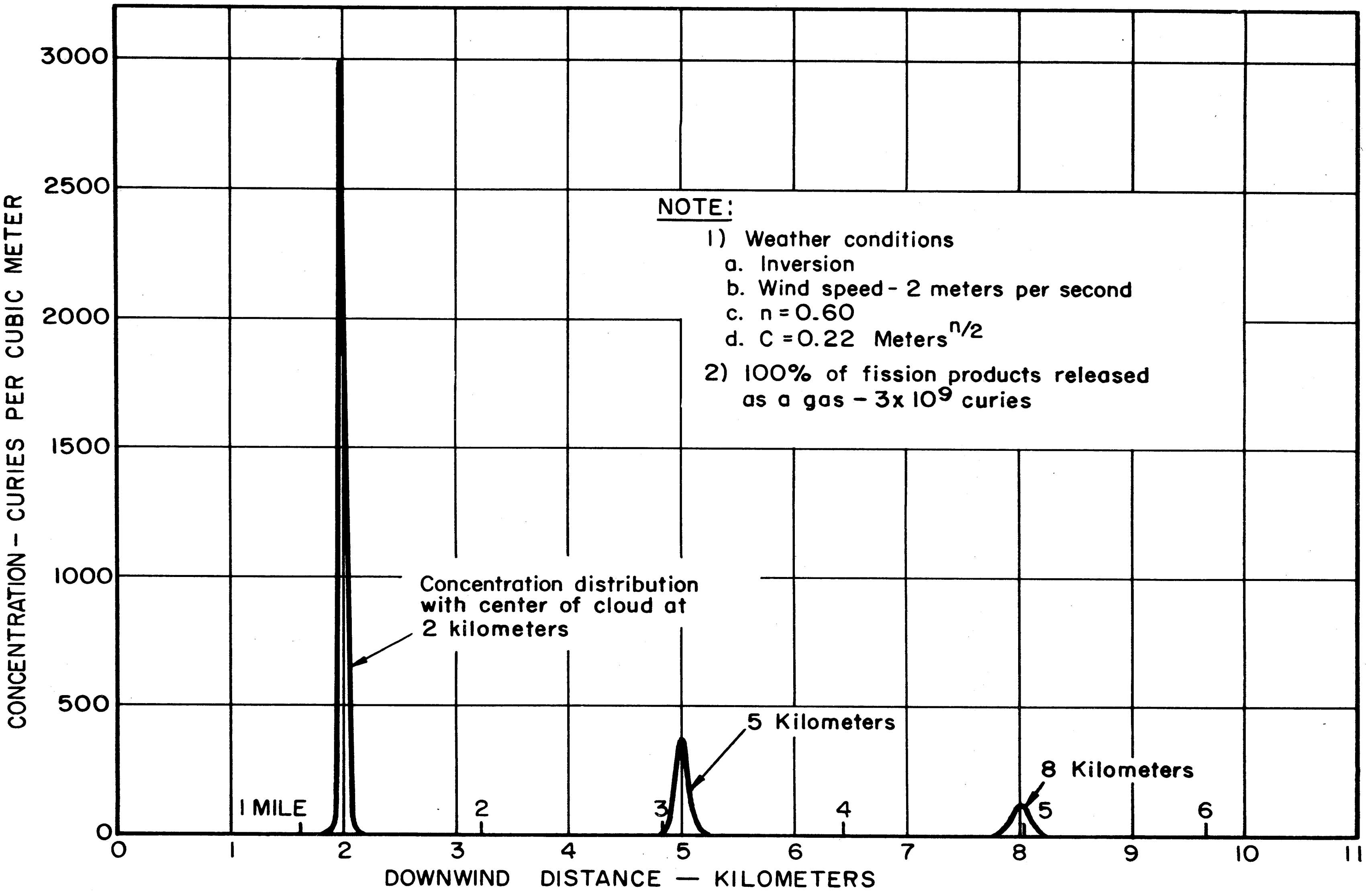


Fig. 10. Radioactivity concentration at ground level along wind axis.

where

T.I.D. is the total integrated dose received at the point under consideration,
Q is the amount of radioactive material in curies released at the time of the emission,
u is the wind velocity,
x is the distance downwind,
y is the distance crosswind,
C is the diffusion coefficient,
n is the stability parameter, and
t is the elapsed time to reach the point and equals x/u.

The factor $t^{-0.2}$ accounts for decay of the radioactivity with time.

The variation of the external gamma dose with distance in the downwind direction for the three selected weather conditions and for 100% and 1% release are shown in Figs.11 and 12, respectively. The corresponding plots for the beta-inhalation dose are given in Figs. 13 and 14, and the combined external and inhalation dose curves are shown in Figs. 15 and 16.

It will be noted upon examination of these curves that, at a constant downwind distance, for the same dose type and weather condition, the size of the dose is directly proportional to the quantity of fission products released from the site. Thus, for external gamma radiation under temperature inversion and 4.5-mph winds, the dose is 450r at 10 miles for an assumed 100% release. For a 1% release the dose is only 4.5r at the same distance.

To find the dose received by a person anywhere at ground level, values are calculated for points directly downwind and also off to the side. A traverse for inhalation dose taken in the crosswind direction, under temperature inversion with 4.5-mph winds and for an assumed 100% release of fission products, results in the plot shown in Fig. 17. The dose falls off more rapidly in the crosswind direction for the temperature-inversion case than for the lapse cases, emphasizing the narrowness of the cloud under inversion conditions.

By connecting all the points on the ground which receive the same dose under a given set of conditions, an isodose contour is produced. The 450r isodose contours for inhalation and for external gamma under temperature inversion and 4.5-mph winds are shown in Fig. 18.

It will be seen that the inhalation contour would enclose a far larger area than would the external gamma contour. However, down close to the source, the gamma contour is wider than the beta contour.

This arises from the fact that gamma rays are effective over a long

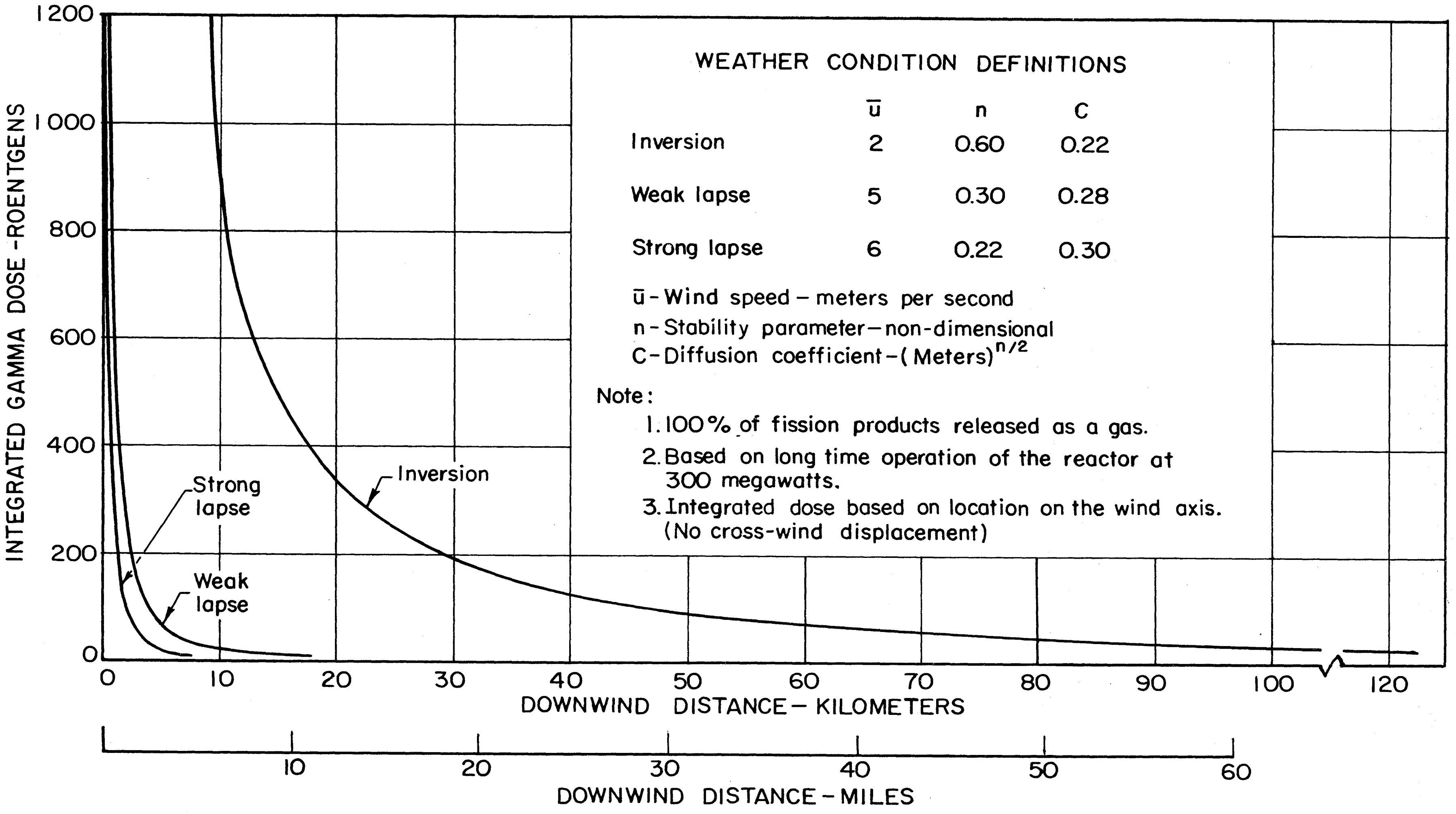


Fig. 11. Integrated external gamma-radiation dose under three representative weather conditions as a function of downwind distance (100% release).

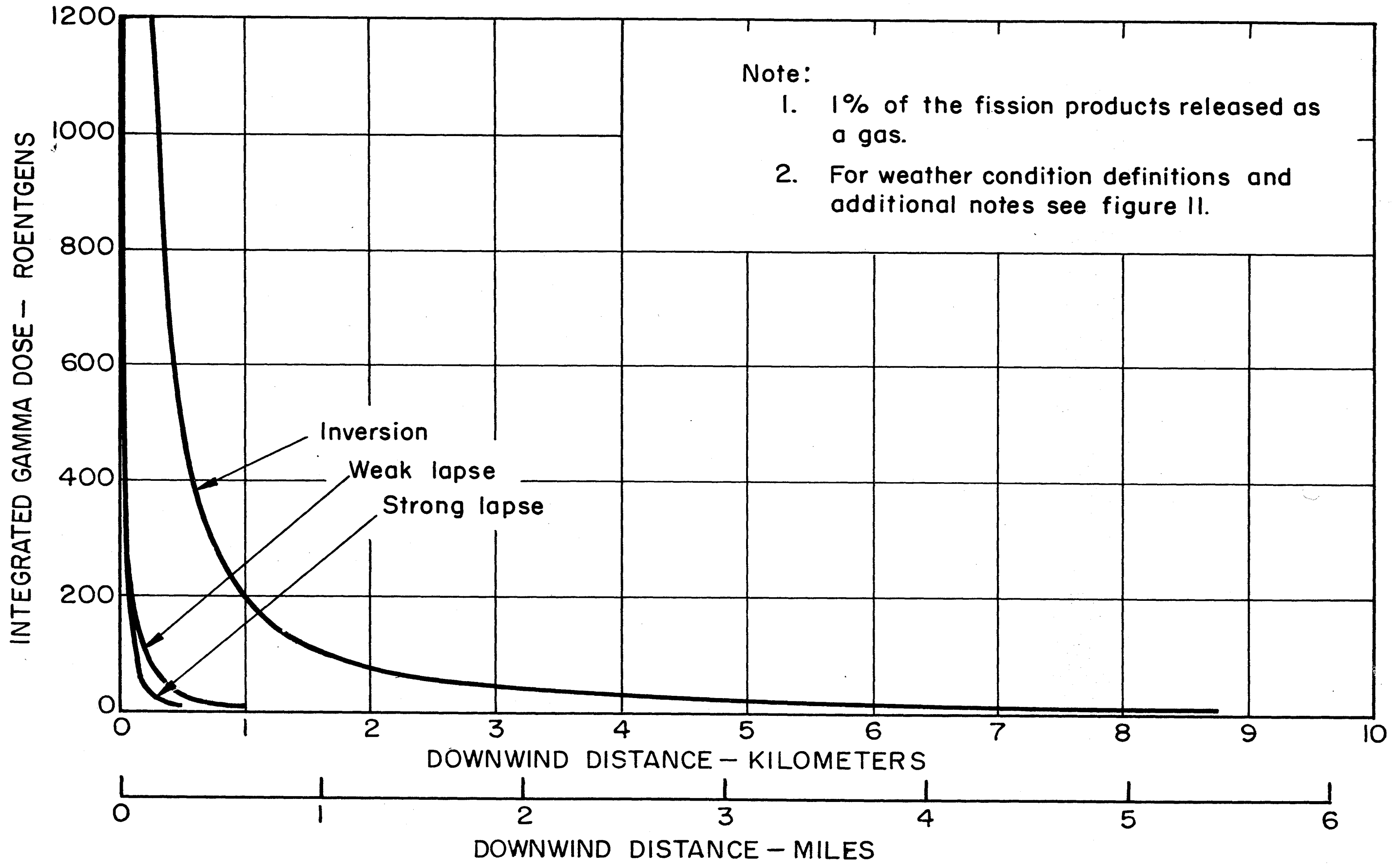


Fig. 12. Integrated external gamma-radiation dose under three representative weather conditions as a function of downwind distance (1% release).

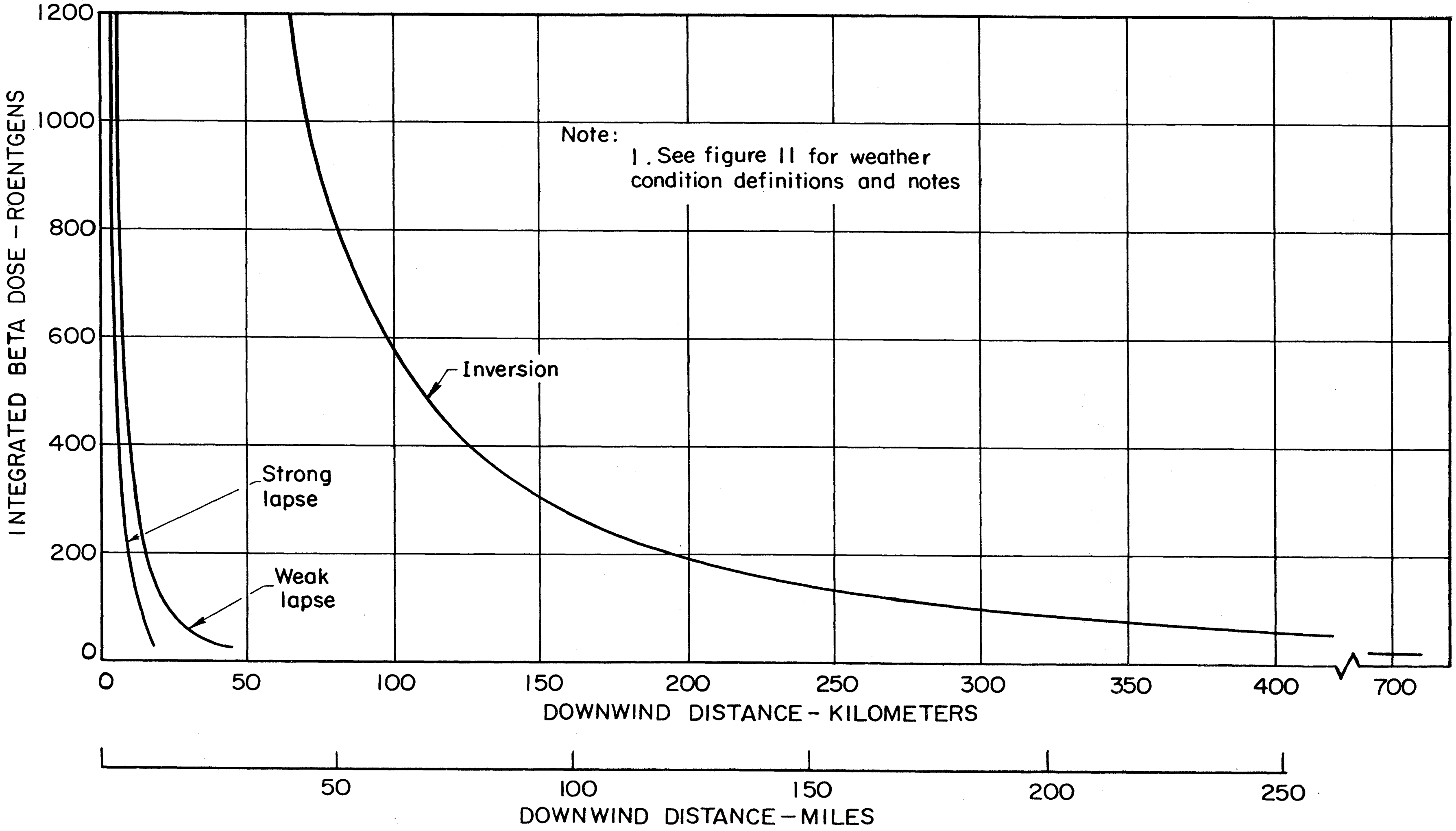
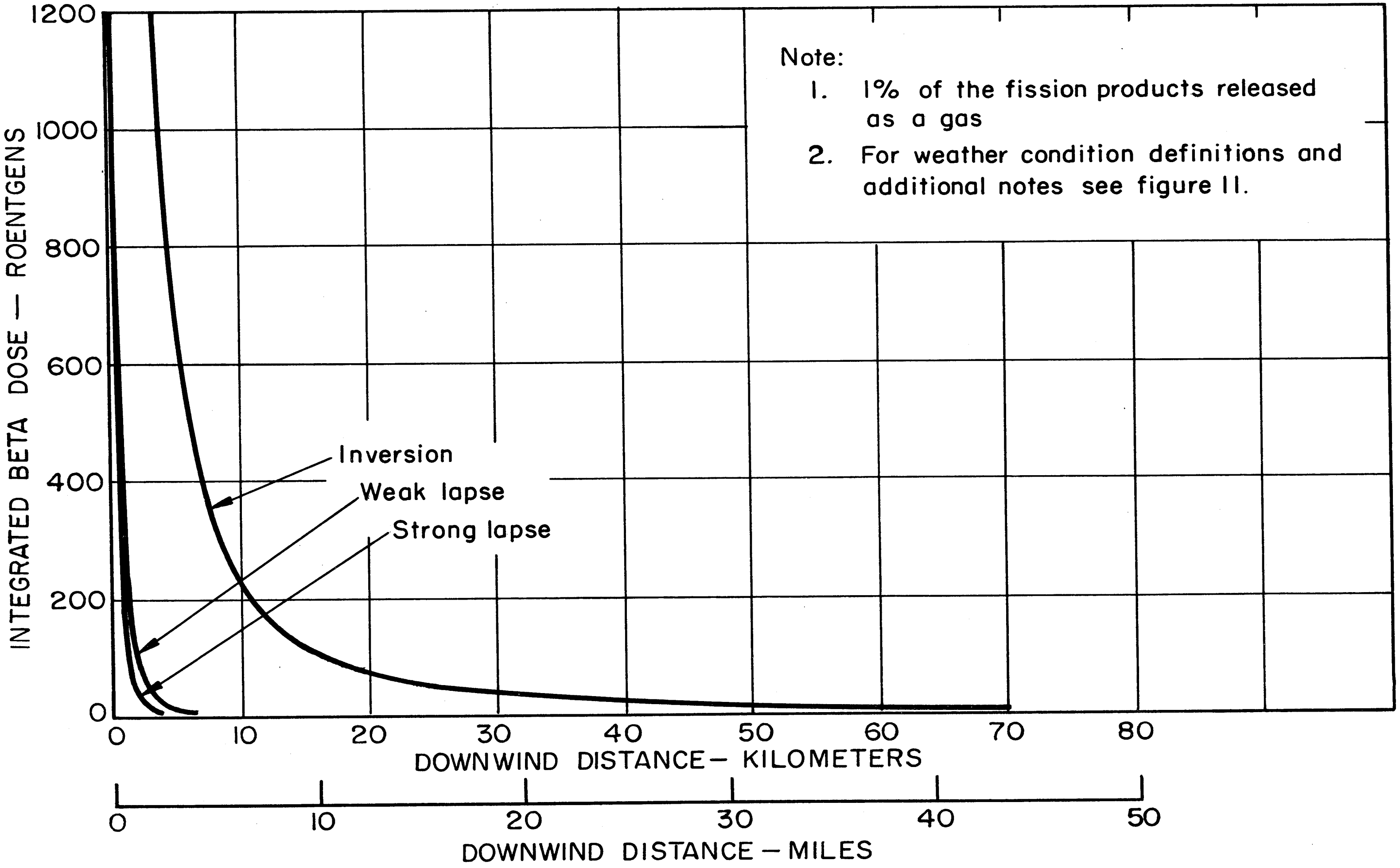


Fig. 13. Integrated beta inhalation radiation dose under three representative weather conditions as a function of downwind distance (100% release).



Note:
1. 1% of the fission products released as a gas
2. For weather condition definitions and additional notes see figure 11.

Fig. 14. Integrated beta inhalation radiation dose under three representative weather conditions as a function of downwind distance (1% release).

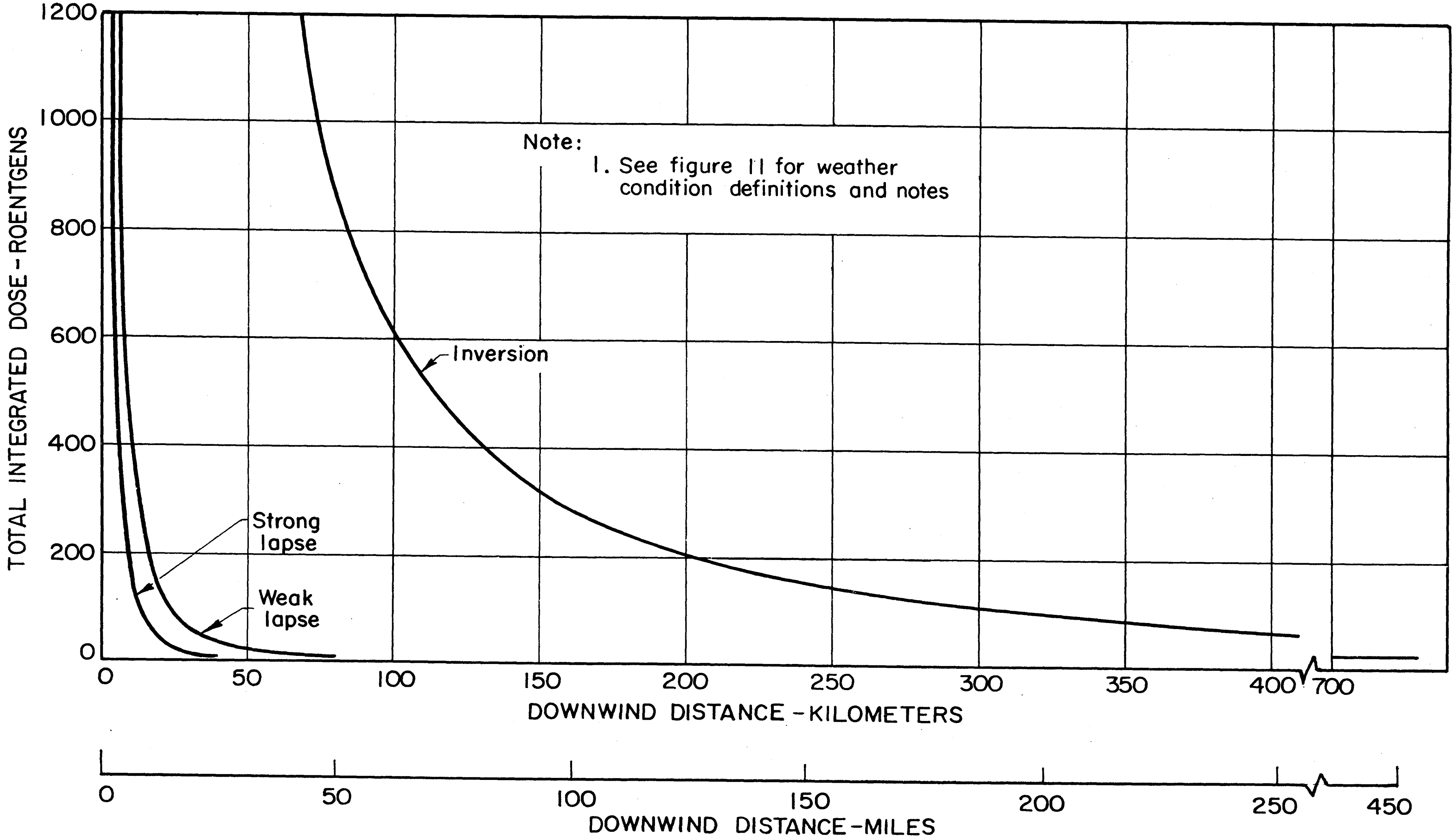


Fig. 15. Total integrated beta plus gamma dose under three representative weather conditions as a function of downwind distance (100% release).

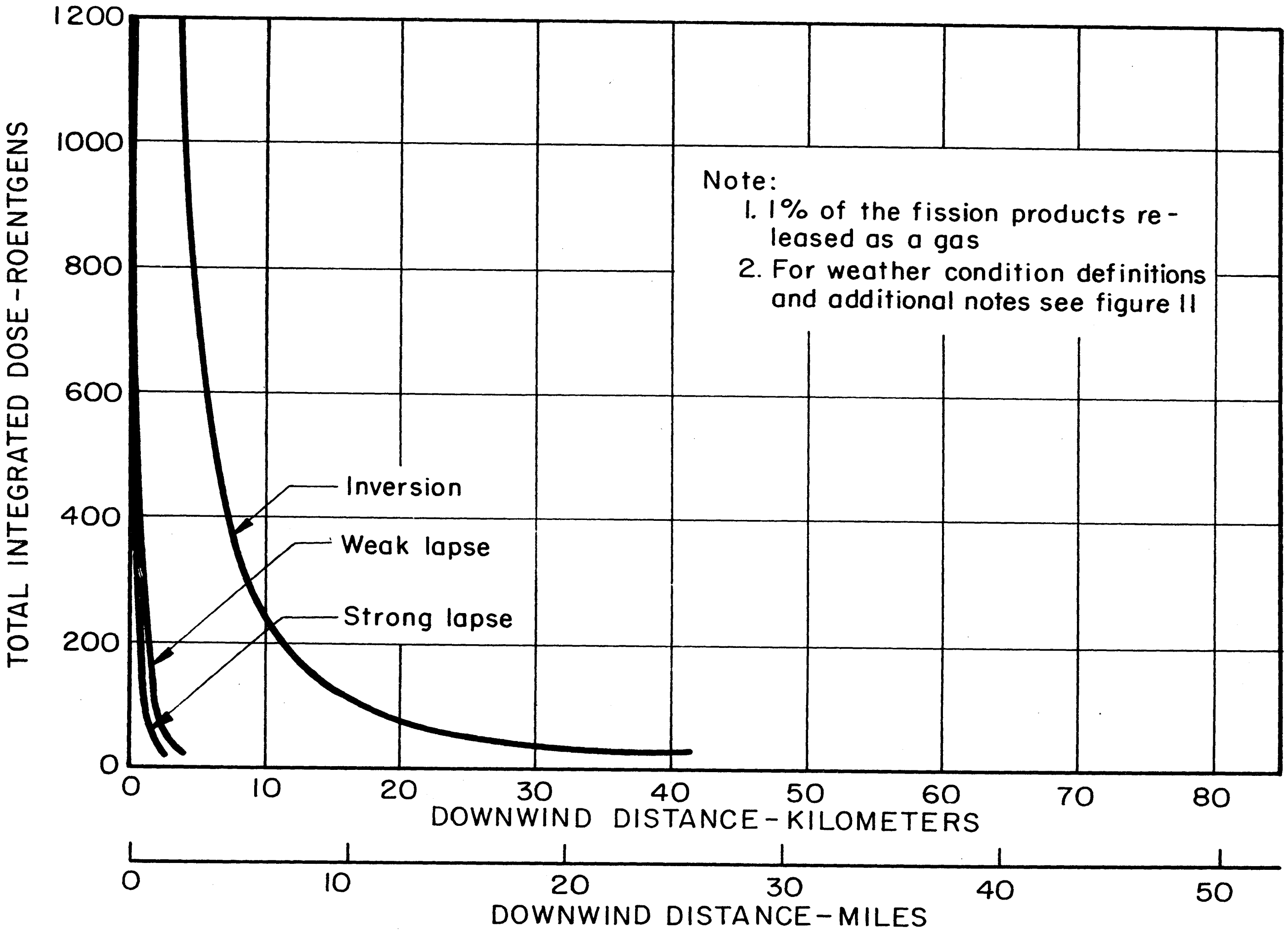


Fig. 16. Total integrated beta plus gamma dose under three representative weather conditions as a function of downwind distance (1% release).

Note:

1. 100% of fission products released as a gas.
2. Long time operation of the reactor at 300 megawatts.
3. Sutton equation parameters:
   - $\bar{u} = 2$ meters per second
   - $n = 0.60$ (non-dimensional)
   - $C = 0.22$ (meters)$^{n/2}$

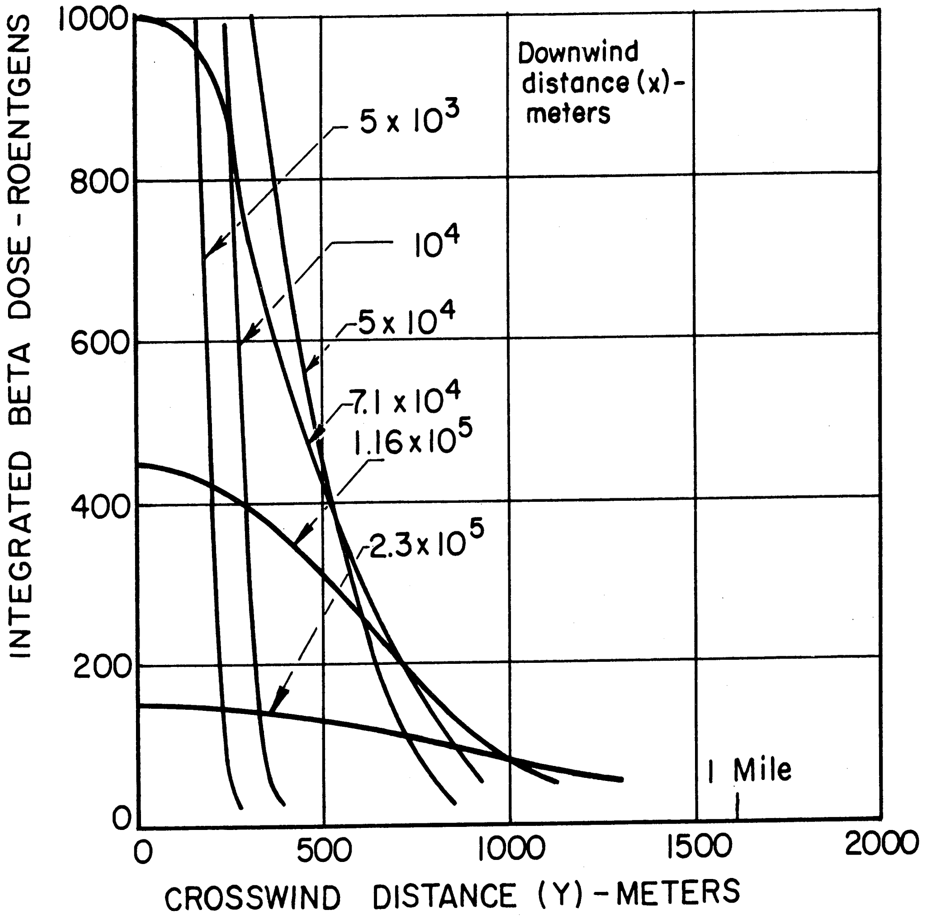


Fig. 17. Beta inhalation dose variation in the crosswind direction under inversion conditions.

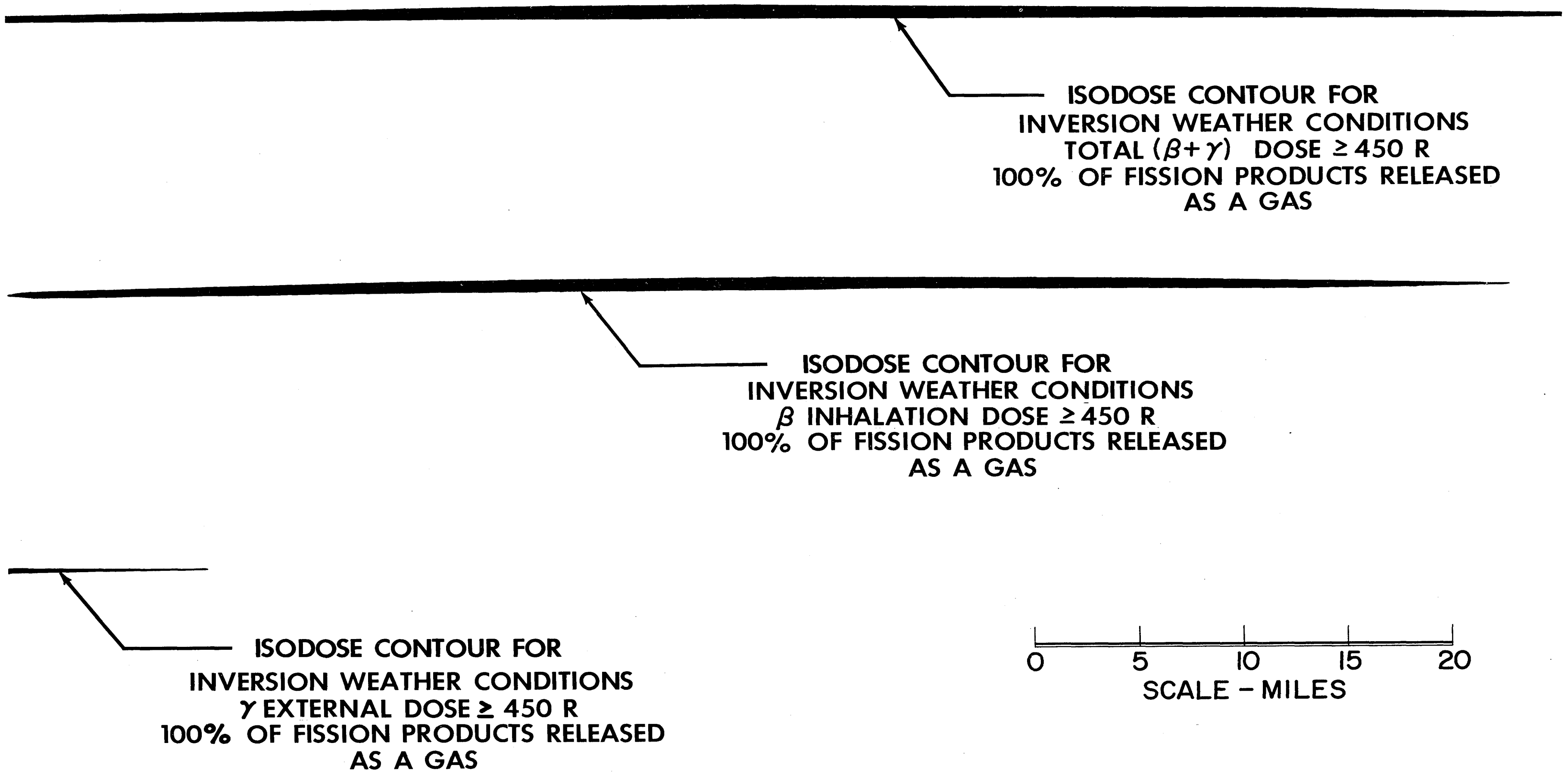


Fig. 18. Isodose contours for 450r beta inhalation, gamma external, and combined doses.

distance, so a point or narrow source produces substantial effect outside the limits of the cloud itself. However, the inhalation dose is received only inside the cloud proper. As the cloud moves out, it spreads and dilutes. The amount of material necessary to produce a given dose by external exposure is greater than the amount necessary to produce a given inhalation dose. Therefore, the spreading and thinning of the cloud causes the external-gamma dose level to fall more rapidly than the inhalation dose.

Adding the doses due to inhalation and external gamma received at points on the ground, and then connecting points receiving the same dose, isodose contours for the combined effect may be drawn. The third contour in Fig. 18 is for 450r combined effect under temperature inversion and 4.5-mph winds for a 100% release of fission products. The dominant effect of the inhalation dose is clear.

It should be pointed out that these contours do not compensate in any way for possible protection afforded by buildings, automobiles, or other enclosures. The inhalation dose received assumes that the person is completely exposed and unprotected.

Under suitable conditions of protection, the inhalation dose contour could be one-half or less of its indicated size, but to keep the study pessimistic, no credit is taken for this possible reduction.

The 450r inhalation dose contours for the temperature-inversion, 4.5-mph-wind case and the strong-lapse, 13.5-mph-wind case, both for a 100% release of fission products, are compared in Fig. 19. The importance of the weather condition in influencing the effects of a fission product release is very great.

To show the relative importance of the temperature gradient and the wind velocity, 450r inhalation contours are compared in Fig. 19 for 4.5-mph and 13.5-mph winds, both under temperature inversion and both for an assumed 100% release of fission products. It is apparent that the temperature gradient is far more important than wind velocity in diluting and dissipating a cloud of fission products.

Finally, to show how greatly the amount of radioactivity released affects the size of a contour, 450r inhalation dose contours under temperature inversion and 4.5-mph winds have been drawn for 100% release, 10% release, and 1% release. These are compared in Fig. 20. The area varies roughly as the factor:

$$\frac{\text{Area}_1}{\text{Area}_2} = \left[\frac{Q_1}{Q_2}\right]^{1.25} .$$

This relationship is derived in Appendix I.

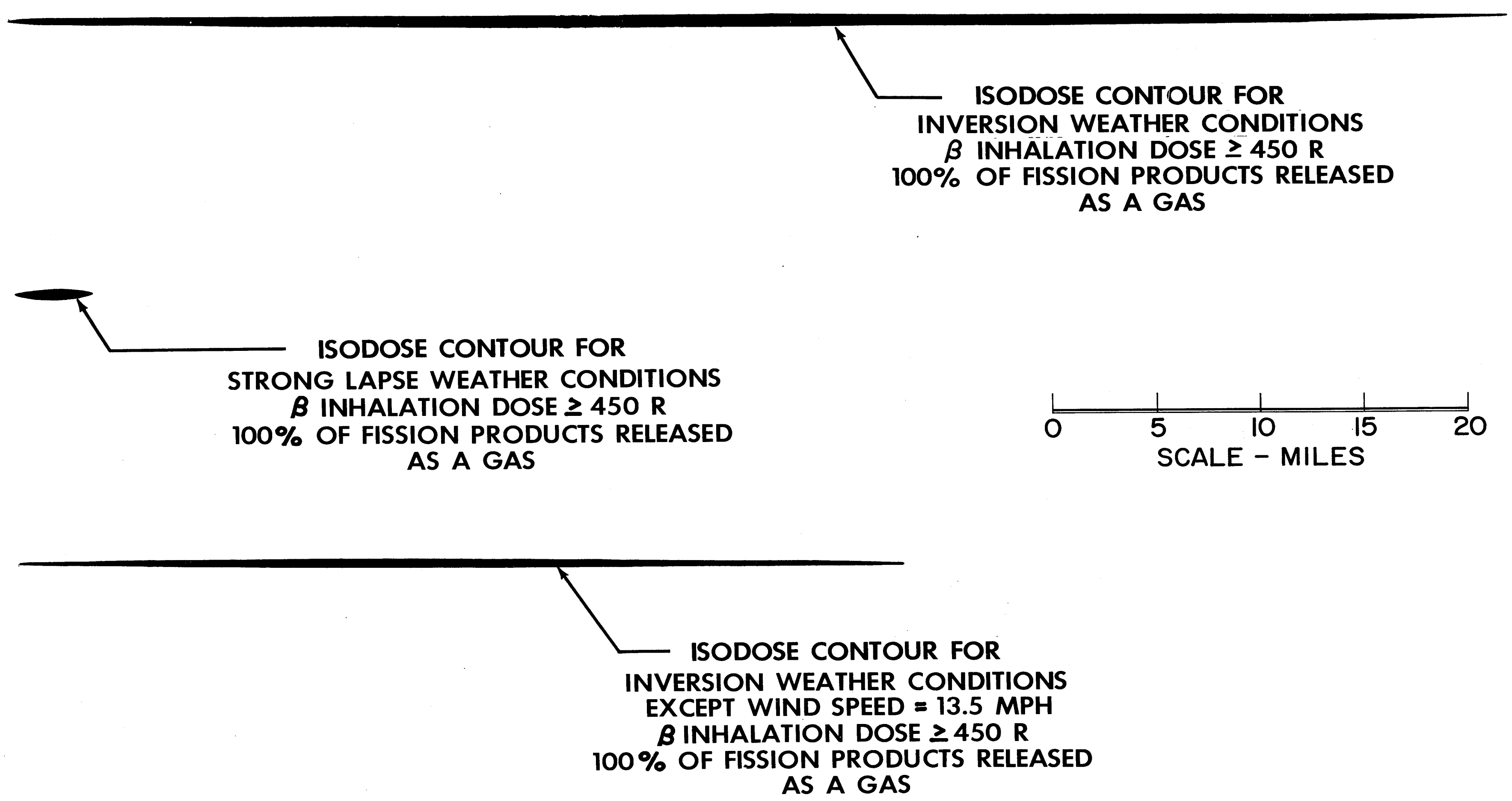


Fig. 19. Effect of weather conditions on 450r beta inhalation isodose contour size and shape.

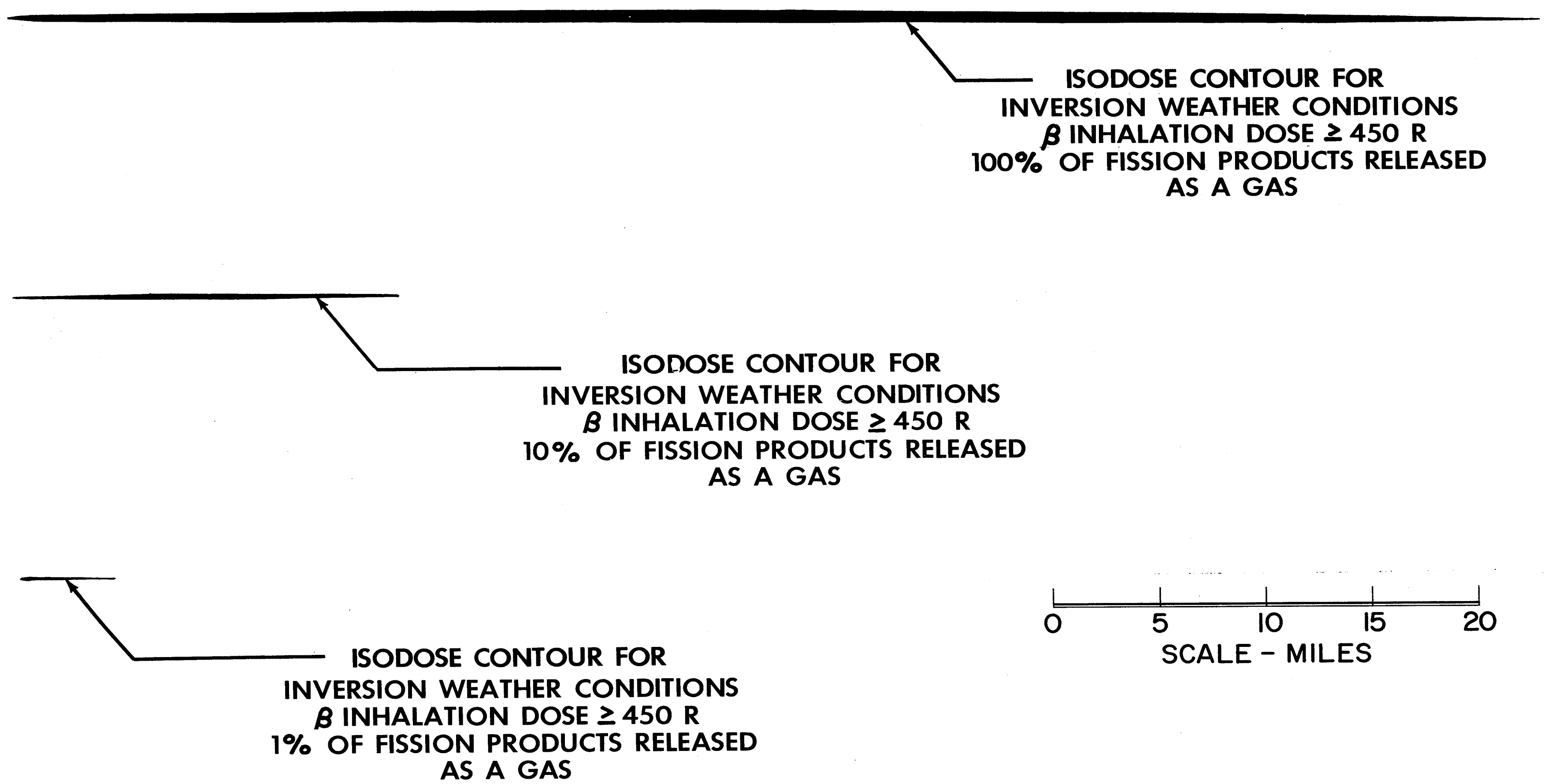


Fig. 20. Effect of quantity of radioactive material released on 450r beta inhalation isodose contour size and shape.

If we assume for this case that the population distribution is roughly uniform, the number of persons affected at a given dose level will vary with the dose as does the area, somewhat more rapidly than a linear proportion. A reduction in the Q ratio to 1/10 of its original value reduces the area of the 450r contour to about 1/18 of its former value. A reduction in the Q ratio to 1/100 of its original value reduces the area to about 1/300 of its former value.

Sets of contours have been developed for the following conditions and maps:

Scale: 1 inch = 1500 feet

- Gamma-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r
  - Strong-Lapse Weather Conditions
    - 25r
    - 50r
    - (higher doses fall within the plant property)

Scale: 1 inch = 1200 feet

- Gamma-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r

Scale: 1 inch = 1000 feet

- Gamma-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r

30-Mile Map

- Gamma-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r
    - 150r
- Beta-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r
  - Weak-Lapse Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r
  - Strong-Lapse Weather Conditions
    - 25r
    - 50r
    - 150r
    - 450r
    - 1000r
- Beta- plus Gamma-Radiation Dose with Fall-out Correction
  - Weak-Lapse Weather Conditions
    - 25r
    - 150r
    - 450r
  - Strong-Lapse Weather Conditions
    - 25r
    - 150r
    - 450r

80-Mile Map

- Gamma-Radiation Dose
  - Inversion Weather Conditions
    - 25r
    - 50r

Beta-Radiation Dose
Inversion Weather Conditions
25r
50r
150r
450r
1000r

Beta- plus Gamma-Radiation Dose with Fall-out Correction
Inversion Weather Conditions
25r
150r
450r

b. CORRECTION FOR FALL-OUT

It was stated in Section 4 that fall-out would be taken into account. This is done by modifying the Sutton Equation through introduction of a factor accounting for loss of material by settling out on the ground.

We have assumed up until now that all the fission products came out as a gas. This is difficult to support or justify. In debris measurements in bomb tests, a very wide distribution of particle size is observed. In the Japanese observations on the fall-out on their fishing boat <u>Fukuryu Maru</u>, the average particle size was 250 microns in diameter.[8]

Because of the lack of information on fission product releases from a reactor, an estimate was made which we believe to be quite conservative. It was assumed that the emitted particles are 10 microns in diameter. Actually, there will be a spread in size from straight gas molecules to large chunks of matter. The available theory is designed to deal with only one particle size at a time.

The correction factor to account for loss of particles from the cloud due to fall-out under a given set of weather conditions is:[9]

$$Q = Q_o \exp\left\{\frac{-4\, V_g x^{n/2}}{n u \pi^{1/2}\, C_z}\right\},$$

where

x is the distance downwind,
Q is now the effective amount of material available for spreading,
Q_o is the original amount released from the reactor,
V_g is the settling velocity for the particles due to gravity,
u is the wind velocity,

n' is the stability factor, and
C_z is the vertical diffusion coefficient.

The total dose due to airborne material along the wind axis for an assumed 100% release of fission products, corrected for fall-out, and plotted against distance for the temperature-inversion condition, is shown in Fig. 21, along with the uncorrected curve. Where inversion conditions exist, fall-out drastically reduces the maximum distance at which a given dose is received.

For 100% of the fission products released as 10-micron particles and under inversion conditions with 4.5-mph winds, the extension of the 450r total dose contour is reduced from 75.2 miles to 26.4 miles. The area enclosed by the contour is reduced to about 1/8 its original size when the fall-out factor is applied. These contours are shown and compared in Fig. 22.

However, under lapse conditions, the 10-micron particle is not heavy enough to affect cloud concentration to any important degree. Total doses due to airborne fission products along the wind axis under temperature lapse, both with and without the fall-out correction, are shown in Fig. 23. The reduction in dose is not significant. In terms of the airborne cloud effect, fall-out under strong inversion makes the problem of exposure due to airborne activity less severe by a substantial margin.

However, a new, longer range problem of clean-up is introduced since what is lost from the cloud is now on the ground. The dose due to the fall-out is taken as external only and due to gamma rays. These doses have been calculated in terms of roentgens per hour for reasons discussed previously on page 4.

The dose rates in roentgens per hour on the ground along the wind axis due to fall-out and under temperature inversion and temperature lapse are given in Fig. 24. The dose rates under inversion run as high as 450r per hour at 4.4 miles and drop to 25r per hour at 19 miles for an assumed 100% release of fission products. These dose rates would be reduced to 4.5r per hour and 0.25r per hour at the same distances if it is assumed that 1% of the fission products is released from the site.

The dose received in one day and in one week due to fall-out alone by a person in the downwind direction under inversion conditions is shown in Figs. 25 and 26. Figure 25 denotes the integrated dose due to fall-out for an assumed 100% release of fission products and Fig. 26 denotes the corresponding dose for an assumed 1% release. A rescue worker entering the area of fall-out very soon after deposition occurs would be subject to the dose due to fall-out and yet might have received a negligible dose due to the cloud itself.

The contours for 450r per day and per week due to fall-out with an

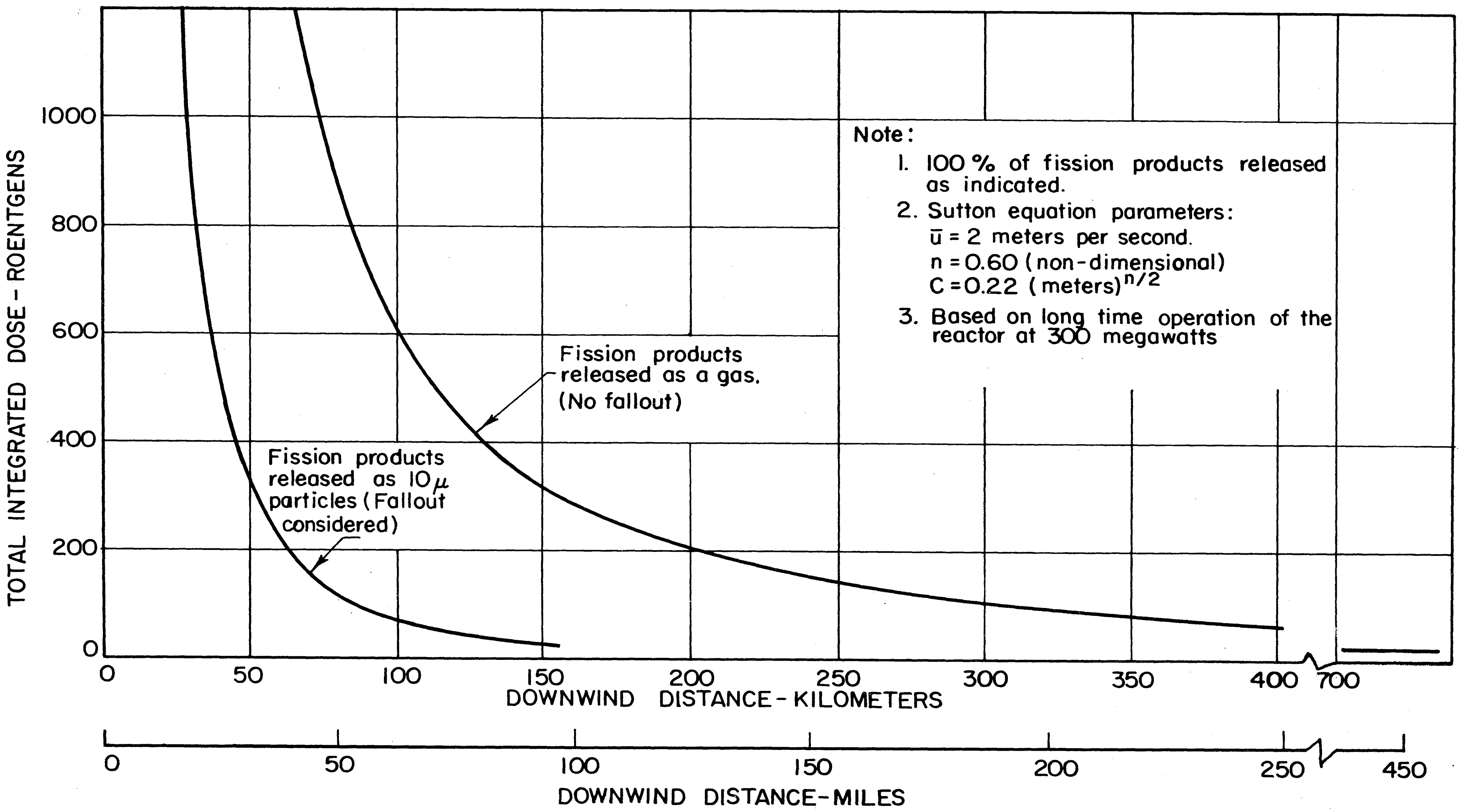


Fig. 21. Effect of fall-out on total integrated beta plus gamma dose due to airborne material under inversion conditions.

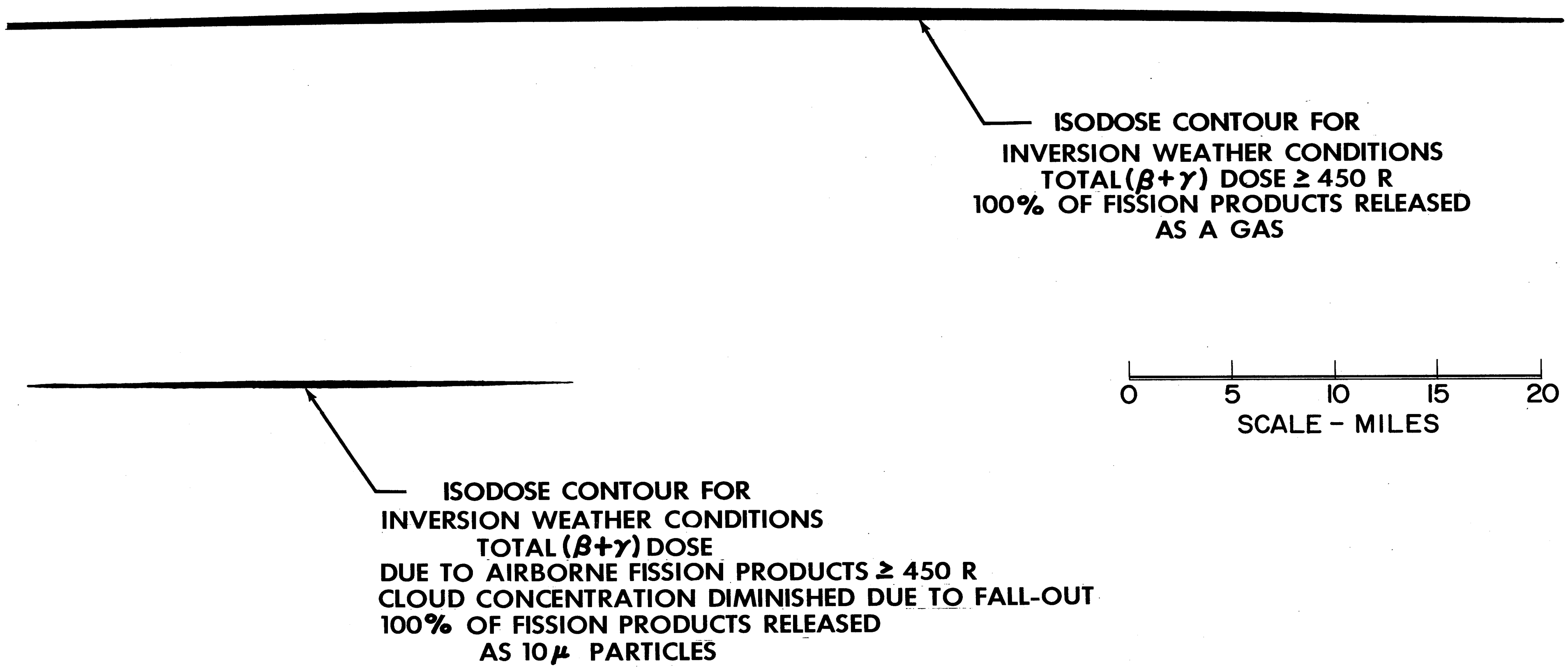


Fig. 22. Effect of inclusion of fall-out correction on 450r combined beta plus gamma isodose contours.

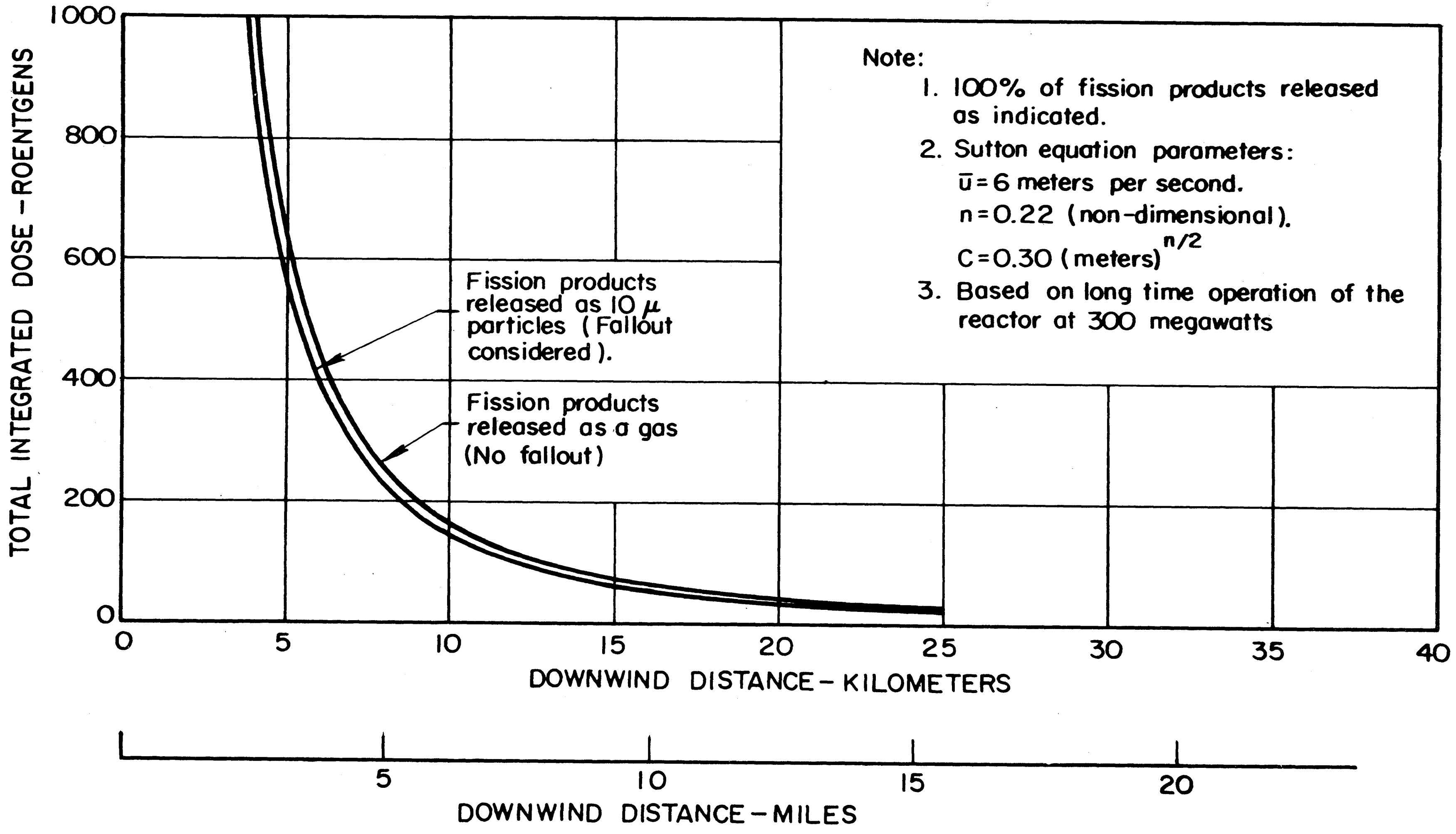
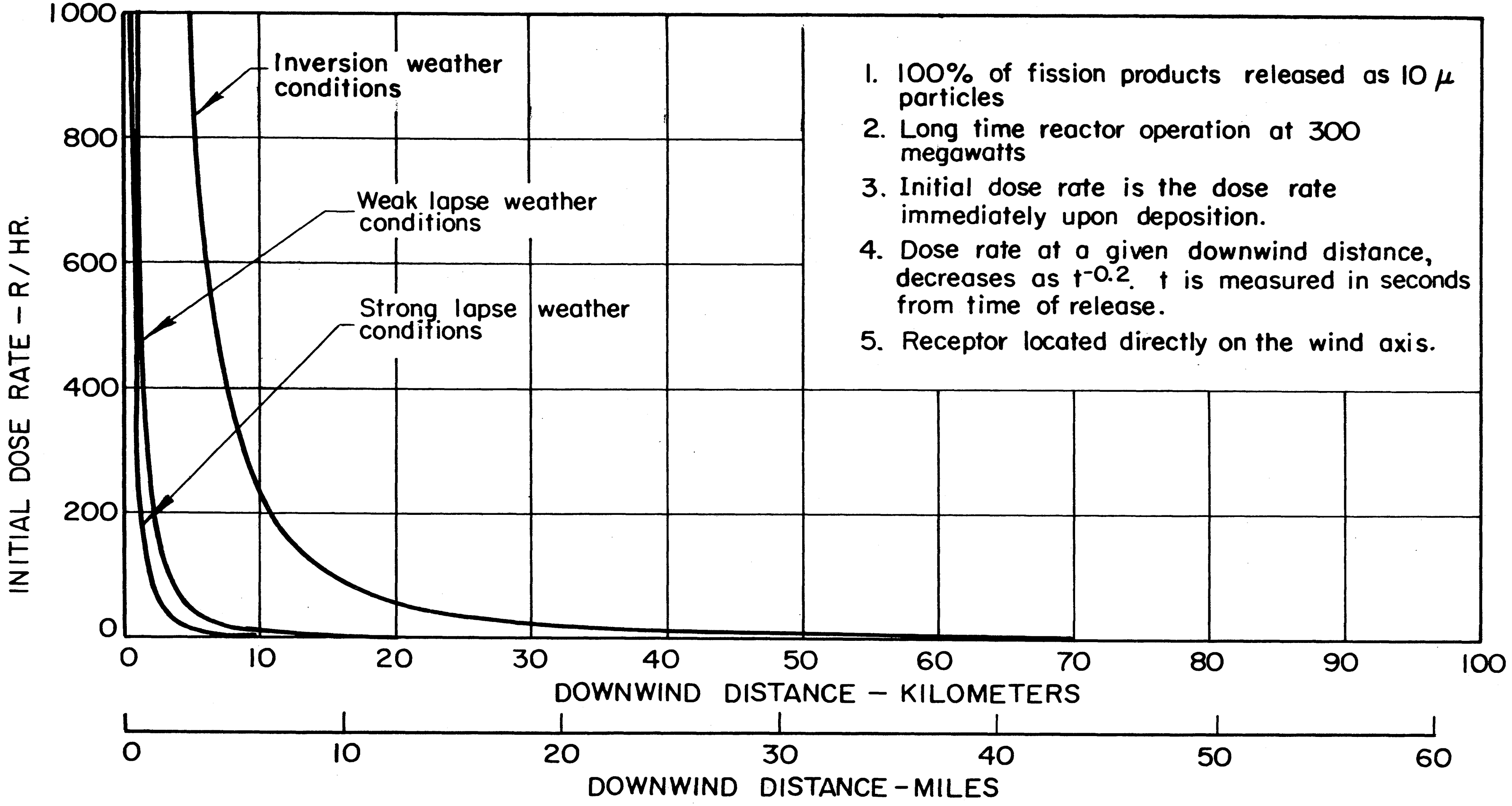


Fig. 23. Effect of fall-out on total integrated beta plus gamma dose due to airborne material under strong-lapse conditions.



1. 100% of fission products released as 10 μ particles
2. Long time reactor operation at 300 megawatts
3. Initial dose rate is the dose rate immediately upon deposition.
4. Dose rate at a given downwind distance, decreases as $t^{-0.2}$. t is measured in seconds from time of release.
5. Receptor located directly on the wind axis.

Fig. 24. Initial dose rate downwind due to fall-out.

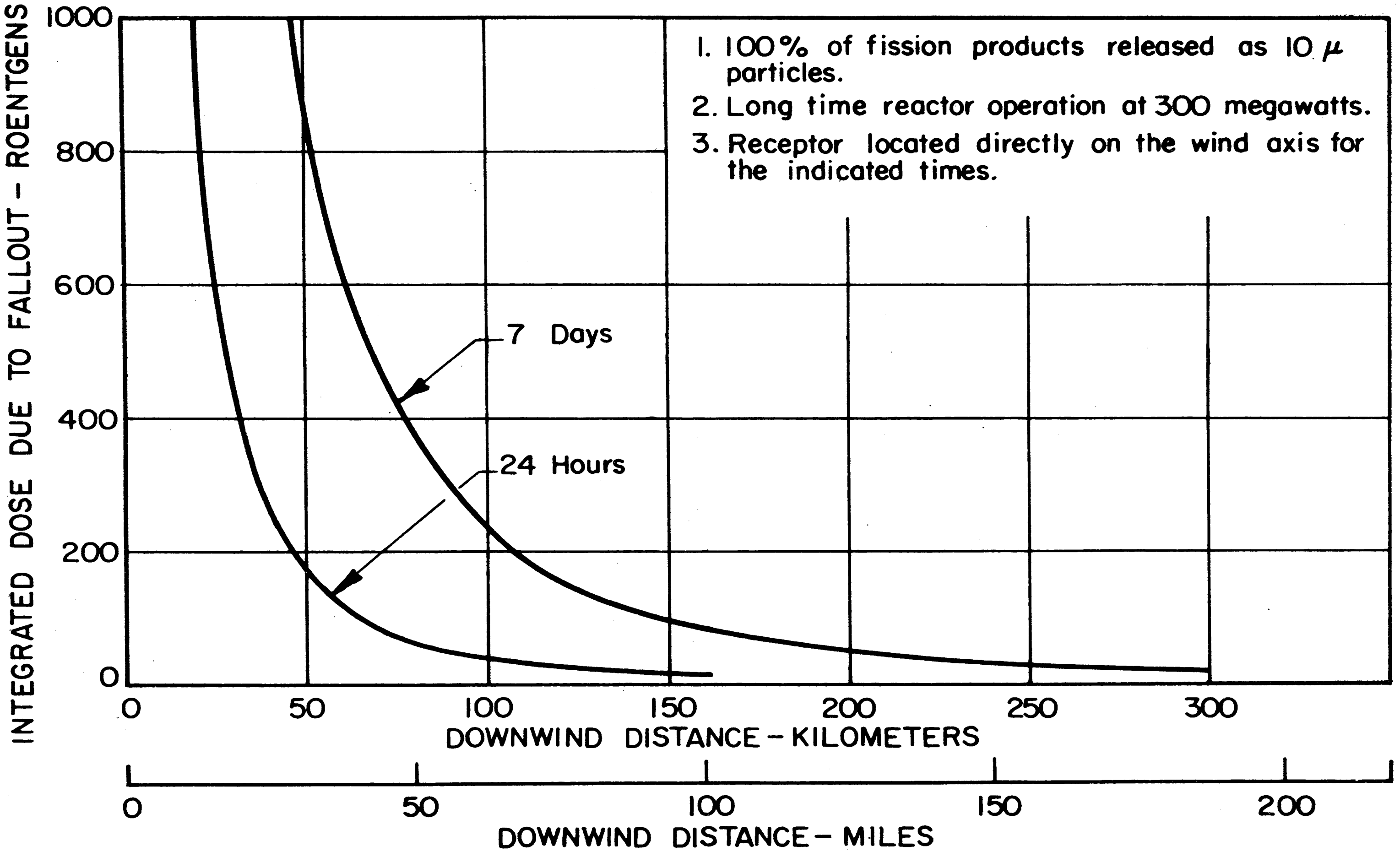


Fig. 25. Integrated dose due to fall-out under inversion weather conditions (100% release).

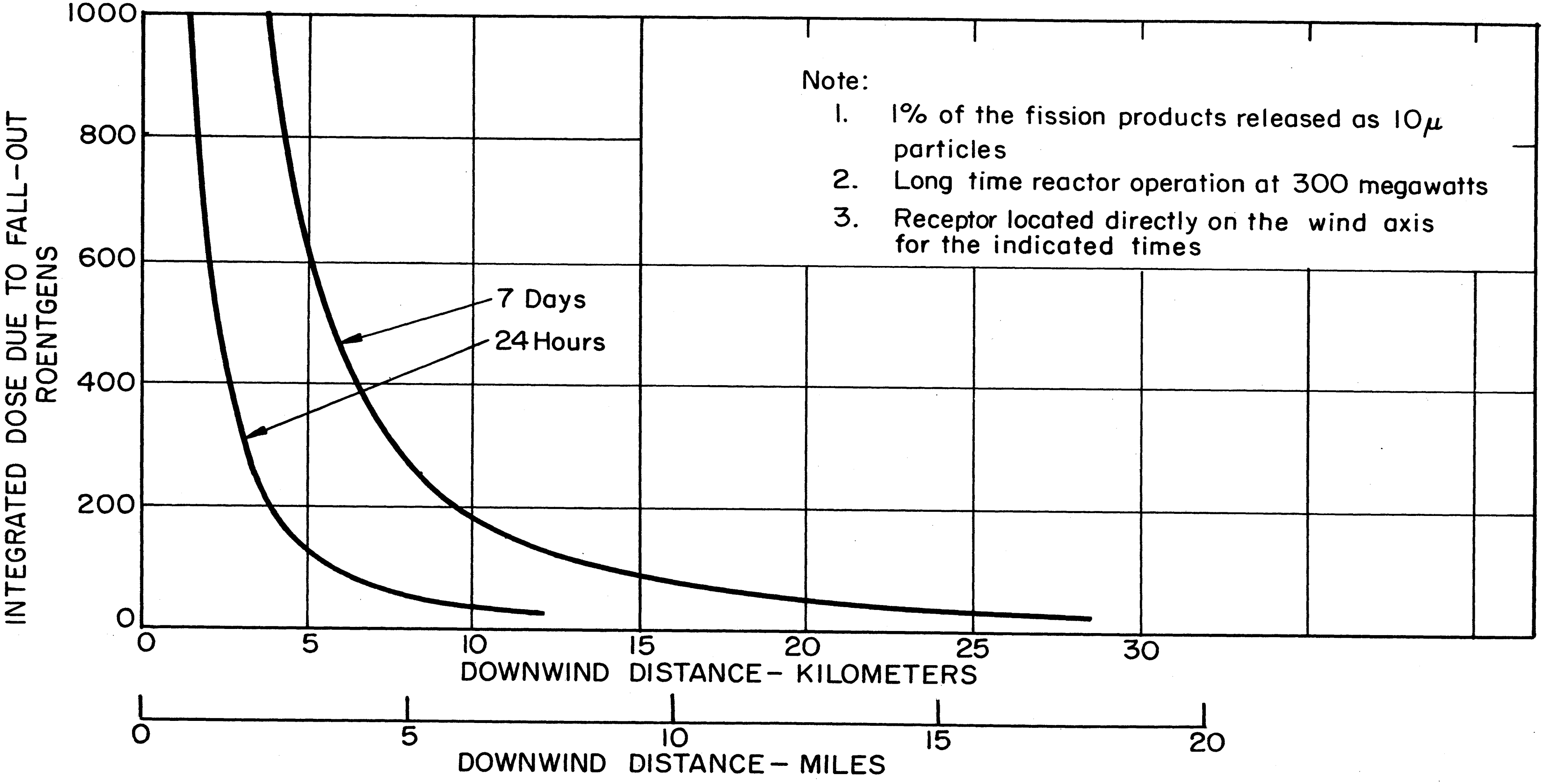


Fig. 26. Integrated dose due to fall-out under inversion weather conditions (1% release).

assumed 100% release of fission products and under temperature inversion and 4.5-mph winds are shown in Fig. 27, where they are compared with total airborne dose contours for 450r corrected for 10-micron-particle fall-out under the same conditions.

Several contours were developed incorporating the correction for 10-micron-particle fall-out. The contours which were obtained were used to determine the number of persons exposed to specific doses when the fall-out correction was applicable. The calculated contours include 25r, 150r, and 450r for inversion, weak-lapse, and strong-lapse weather conditions.

15. EFFECT ON PERSONS IN THE SURROUNDING AREA

a. SPECIFIED WEATHER CONDITIONS

All the foregoing factors enable us to estimate the number of persons involved due to a fission product release under a specific set of weather conditions. This is done by placing the appropriate contour on the corresponding population-distribution map and counting the number of persons enclosed by the contour. For example, let us select our worst weather conditions, temperature inversion with 4.5-mph winds.

Taking the properly scaled 450r contour for total airborne activity and placing it over the 80-mile-radius map, we can find the number of persons enclosed when the wind is blowing in any preselected direction. It must be recognized that the persons inside the 450r contour line will receive 450r or more, and those outside will receive less than 450r. This operation can be repeated for different dose contours and weather conditions as well as for different wind directions.

The results of specific case studies using these techniques are shown in Tables I through VI. In addition to tabulating the number of persons affected under specific conditions, such as the weather, presence or absence of fall-out, and wind direction, the incidence of the necessary weather conditions in days per year is also given.

It will be seen in examining Table I that for the pessimistic weather conditions with the wind blowing toward the Detroit area, between 190 and 420 persons could receive 450r or more if it is assumed that 1% of the fission products are released as a gas. The necessary weather conditions prevail 5.4 days per year and a release of the specified severity must occur during that time, with no benefit of fall-out or shelter of any kind to those persons downwind from the site. On the other hand, a release occurring under identical conditions but with the wind blowing over the lake could deliver 450r off the

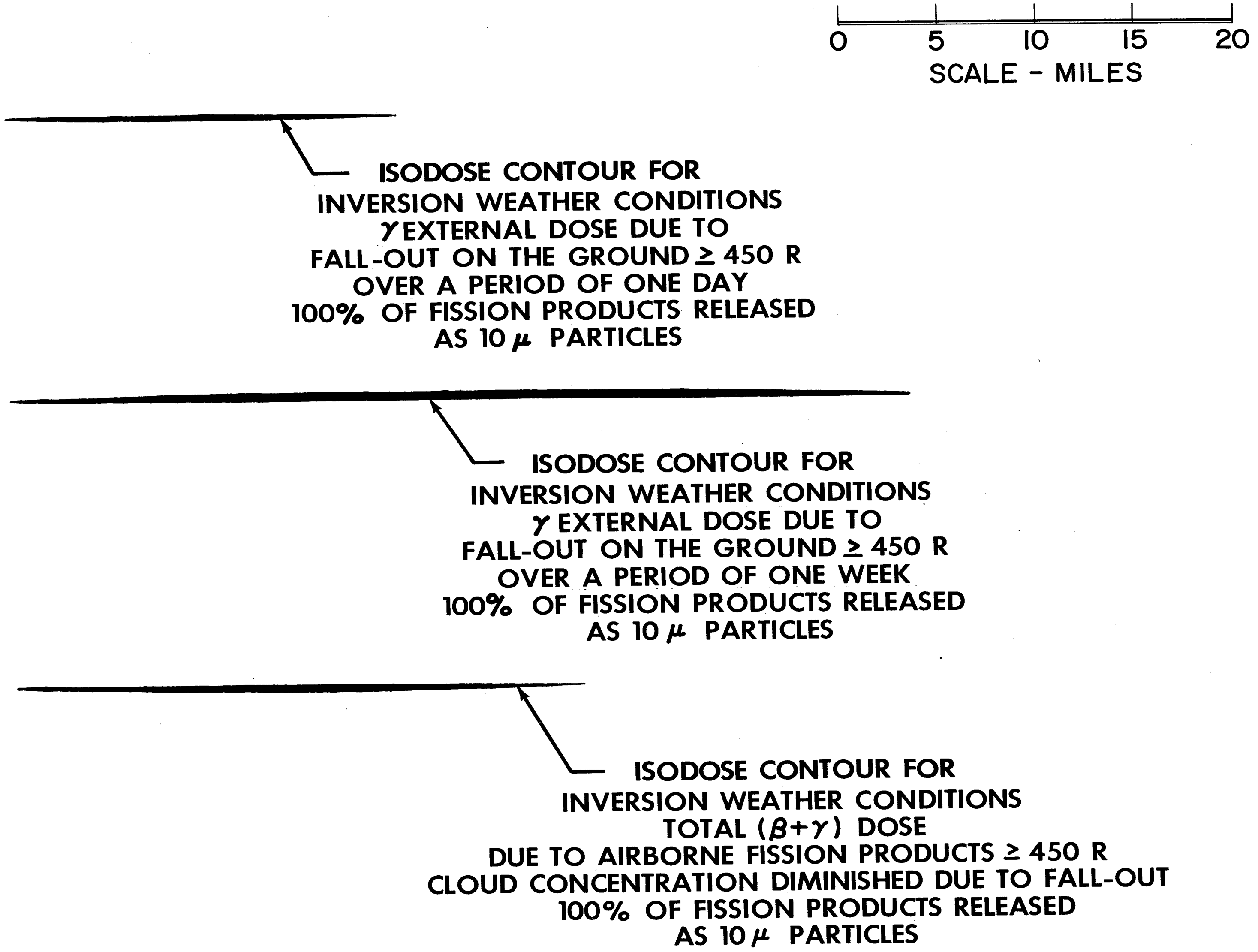


Fig. 27. Comparison of 450r isodose contours due to fall-out over periods of one day and one week with the 450r beta plus gamma isodose contour with the fall-out correction applied.

TABLE I

NUMBER OF PERSONS AFFECTED BY RELEASE OF 1% OF REACTOR FISSION PRODUCTS
Weather Condition—Strong Inversion, 4.5-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne)			Days per Year for This Weather Condition
				450r or More	150r or More	25r or More	
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	185	265	365	5.4
		Down River Communities-	16°	420	575	780	
		Downtown Detroit-	23°	285	375	535	
	MONROE	Southern Limit-	227°	50	75	120	2.4
		Downtown Monroe-	245°	20	30	40	
		Northern Limit-	265°	15	20	25	
	TOLEDO	Maumee River-	211°	110	125	180	1.2
		Downtown Toledo-	215°	135	205	320	
		NW Limit-	226°	55	85	130	
	OVER LAKE	Northern Limit-	62°	0	0	0	8.0
		Zero People (Inv.)-	95°-112°	0	0	0	
		Southern Limit-	170°	0	5	10	
Corrected for 10-μ-Particle Fall-out	DETROIT	Dearborn and NW Detroit-		30	155	245	5.4
		Down River Communities-		80	365	390	
		Downtown Detroit		10	185	325	
	MONROE	Southern Limit		10	30	70	2.4
		Downtown Monroe		10	15	25	
		Northern Limit		5	10	15	
	TOLEDO	Maumee River		25	75	115	1.2
		Downtown Toledo		40	140	190	
		NW Limit		10	35	80	
	OVER LAKE	Northern Limit		0	0	0	8.0
		Zero People (Inv.)		0	0	0	
		Southern Limit		0	5	5	

NOTE: These data were obtained through use of the area ratio method described in Appendix I.

TABLE II

NUMBER OF PERSONS AFFECTED BY RELEASE OF 100% OF REACTOR FISSION PRODUCTS
Weather Condition—Strong Inversion, 4.5-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne)			Days per Year for This Weather Condition
				450r or More	150r or More	25r or More	
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	59,000	83,000	112,000*	5.4
		Down River Communities-	16°	133,000	181,000	245,000*	
		Downtown Detroit-	23°	90,000	118,000	168,000*	
	MONROE	Southern Limit-	227°	16,000	24,000	38,000*	2.4
		Downtown Monroe-	245°	6,000	9,000	12,000*	
		Northern Limit-	265°	4,000	6,000	8,000*	
	TOLEDO	Maumee River-	211°	34,000	40,000	57,000*	1.2
		Downtown Toledo-	215°	42,000	65,000	101,000*	
		NW Limit-	226°	17,000	27,000	41,000*	
	OVER LAKE	Northern Limit-	62°	300	400	500*	8.0
		Zero People (Inv.)-	95°-112°	0	0	0*	
		Southern Limit-	170°	0	1,400	3,600*	
Corrected for 10-μ-Particle Fall-out	DETROIT	Dearborn and NW Detroit		9,800	49,300	76,400*	5.4
		Down River Communities		24,500	114,200	122,700*	
		Downtown Detroit		3,900	58,200	103,200*	
	MONROE	Southern Limit		3,000	9,900	22,400*	2.4
		Downtown Monroe		2,800	5,100	8,200*	
		Northern Limit		1,100	2,800	5,500*	
	TOLEDO	Maumee River		7,600	24,200	35,900*	1.2
		Downtown Toledo		13,000	44,600	59,700*	
		NW Limit		3,000	10,700	24,900*	
	OVER LAKE	Northern Limit		200	200	300*	8.0
		Zero People (Inv.)		0	0	0*	
		Southern Limit		0	800	2,200*	

*These contours extend beyond the distance considered by the study (80 miles radius) - See page 8.

ADDENDUM

Added After Release of AEC Report of March, 1957

REVISION OF TABLE II, USING CALCULATION TECHNIQUES EMPLOYED IN AEC REPORT AS APPLIED TO THE LAGOONA BEACH SITE

This Procedure Is Fully Explained in Appendix V

Fall-out	Wind Blowing Toward			Dose - 450r or More	
				Using Michigan Study Only	Using AEC Techniques
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	59,000	17,200
		Down River Communities-	16°	133,000	39,700
		Downtown Detroit-	23°	90,000	20,200
	MONROE	Southern Limit-	227°	16,000	3,500
		Downtown Monroe-	245°	6,000	1,800
		Northern Limit-	265°	4,000	1,100
	TOLEDO	Maumee River-	211°	34,000	8,700
		Downtown Toledo-	215°	42,000	15,500
		NW Limit-	226°	17,000	3,700
	OVER LAKE	Northern Limit-	62°	300	100
		Zero People (Inv.)	95°-112°	0	0
		Southern Limit-	170°	0	0
Corrected for 10-µ- Particle Fall-out	DETROIT	Dearborn and NW Detroit		9,800	2,900
		Down River Communities		24,500	7,300
		Downtown Detroit		3,900	900
	MONROE	Southern Limit		3,000	600
		Downtown Monroe		2,800	800
		Northern Limit		1,100	300
	TOLEDO	Maumee River		7,600	1,800
		Downtown Toledo		13,000	4,800
		NW Limit		3,000	700
	OVERLAKE	Northern Limit		200	100
		Zero People (Inv.)		0	0
		Southern Limit		0	0

TABLE III

NUMBER OF PERSONS AFFECTED BY RELEASE OF 1% OF REACTOR FISSION PRODUCTS

Weather Condition—Weak Lapse, 11.25-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne)			Days per Year for This Weather Condition
				450r or More	150r or More	25r or More	
Not Considered	DETROIT	Dearborn and NW-	8°	5	10	450	2.3
		Down River Communities-	16°	5	10	1,115	
		Downtown Detroit-	23°	5	10	175	
	MONROE	Southern Limit-	227°	5	50	135	4.3
		Downtown Monroe-	245°	5	50	130	
		Northern Limit	265°	5	10	50	
	TOLEDO	Maumee River-	211°	0	0	345	1.5
		Downtown Toledo-	215°	0	5	595	
		NW Limit-	226°	5	45	135	
	OVER LAKE	Northern Limit-	62°	0	0	10	16.3
		Zero People (Inv.)-	95°-112°	0	0	0	
		Southern Limit-	170°	0	0	0	
Corrected for 10-μ-Particle Fall-out	DETROIT	Dearborn and NW		5	10	410	2.3
		Down River Communities		5	10	1,025	
		Downtown Detroit		5	10	160	
	MONROE	Southern Limit		5	45	125	4.3
		Downtown Monroe		5	45	115	
		Northern Limit		5	10	45	
	TOLEDO	Maumee River		0	0	315	1.5
		Downtown Toledo		0	5	545	
		NW Limit		5	40	125	
	OVER LAKE	Northern Limit		0	0	10	16.3
		Zero People (Inv.)		0	0	0	
		Southern Limit		0	0	0	

NOTE: These data were obtained through use of the area ratio method described in Appendix I.

TABLE IV

NUMBER OF PERSONS AFFECTED BY RELEASE OF 100% REACTOR FISSION PRODUCTS
Weather Condition—Weak Lapse 11.25-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne) 450r or More	150r or More	25r or More	Days per Year for This Weather Condition
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	300	1,300	57,100	2.3
		Down River Communities-	16°	300	1,300	142,400	
		Downtown Detroit-	23°	300	1,200	22,500	
	MONROE	Southern Limit-	227°	600	6,200	17,300	4.3
		Downtown Monroe-	245°	400	6,600	16,300	
		Northern Limit-	265°	500	1,400	6,500	
	TOLEDO	Maumee River-	211°	0	100	44,000	1.5
		Downtown Toledo-	215°	100	400	75,800	
		NW Limit-	226°	600	6,000	17,500	
	OVER LAKE	Northern Limit-	62°	0	0	1,000	16.3
		Zero People (Inv.)-	95°-112°	0	0	0	
		Southern Limit-	170°	0	0	200	
Corrected for 10-μ-Particle Fall-out	DETROIT	Dearborn and NW Detroit		300	1,200	52,300	2.3
		Down River Communities		300	1,200	130,300	
		Downtown Detroit		300	1,100	20,600	
	MONROE	Southern Limit		500	5,500	15,800	4.3
		Downtown Monroe		300	5,900	14,900	
		Northern Limit		400	1,200	6,000	
	TOLEDO	Maumee River		0	100	40,300	1.5
		Downtown Toledo		100	400	69,400	
		NW Limit		500	5,300	16,000	
	OVER LAKE	Northern Limit		0	0	900	16.3
		Zero People (Inv.)		0	0	0	
		Southern Limit		0	0	200	

TABLE V

NUMBER OF PERSONS AFFECTED BY RELEASE OF 1% OF REACTOR FISSION PRODUCTS
Weather Condition—Strong Lapse, 13.5-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne)			Days per Year for This Weather Condition
				450r or More	150r or More	25r or More	
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	0	5	50	1.9
		Down River Communities-	16°	0	5	60	
		Downtown Detroit-	23°	0	5	40	
	MONROE	Southern Limit-	227°	0	20	125	3.6
		Downtown Monroe-	245°	5	5	150	
		Northern Limit-	265°	5	10	35	
	TOLEDO	Maumee River-	211°	0	0	5	1.3
		Downtown Toledo-	215°	0	0	10	
		NW Limit-	226°	0	10	120	
	OVER LAKE	Northern Limit-	62°	0	0	5	13.9
		Zero People (Inv.)-	95°-112°	0	0	0	
		Southern Limit-	170°	0	0	0	
Corrected for 10-µ-Particle Fall-out	DETROIT	Dearborn and NW Detroit		0	5	45	1.9
		Down River Communities		0	5	60	
		Downtown Detroit		0	5	40	
	MONROE	Southern Limit		0	15	120	3.6
		Downtown Monroe		5	5	145	
		Northern Limit		5	10	35	
	TOLEDO	Maumee River		0	0	5	1.3
		Downtown Toledo		0	0	10	
		NW Limit		0	10	115	
	OVER LAKE	Northern Limit		0	0	5	13.9
		Zero People (Inv.)		0	0	0	
		Southern Limit		0	0	0	

NOTE: These data were obtained through use of the area ratio method described in Appendix I.

TABLE VI

NUMBER OF PERSONS AFFECTED BY RELEASE OF 100% OF REACTOR FISSION PRODUCTS

Weather Condition—Strong Lapse 13.5-mph Wind

Fall-out	Wind Blowing Toward			Radiation Dose Due to Beta and Gamma Radiation (All Fission Products Airborne)			Days per Year for This Weather Condition
				450r or More	150r or More	25r or More	
Not Considered	DETROIT	Dearborn and NW Detroit-	8°	100	400	5,200	1.9
		Down River Communities-	16°	100	400	6,500	
		Downtown Detroit-	23°	100	500	4,400	
	MONROE	Southern Limit-	227°	100	2,000	13,300	3.6
		Downtown Monroe-	245°	200	600	15,800	
		Northern Limit-	265°	300	900	3,900	
	TOLEDO	Maumee River-	211°	0	100	200	1.3
		Downtown Toledo-	215°	0	100	1,100	
		NW Limit-	226°	100	1,200	12,600	
	OVER LAKE	Northern Limit-	62°	0	0	200	13.9
		Zero People (Inv.)-	95°-112°	0	0	0	
		Southern Limit-	170°	0	0	100	
Corrected for 10-μ-Particle Fall-out	DETROIT	Dearborn and NW Detroit		100	400	4,900	1.9
		Down River Communities		100	400	6,200	
		Downtown Detroit		100	400	4,100	
	MONROE	Southern Limit		100	1,800	12,600	3.6
		Downtown Monroe		200	600	15,000	
		Northern Limit		300	800	3,700	
	TOLEDO	Maumee River		0	100	200	1.3
		Downtown Toledo		0	100	1,000	
		NW Limit		100	1,100	11,900	
	OVER LAKE	Northern Limit		0	0	200	13.9
		Zero People (Inv.)		0	0	0	
		Southern Limit		0	0	100	

site to anywhere from 0 to 10 permanent residents. The necessary weather conditions for this case prevail 8.0 days per year.

Under favorable weather conditions, 13.5 mph and strong-lapse, as shown in Table V, about 100 persons will receive 450r or more if it is assumed that 100% of the fission products are released in a gaseous state and if the wind blows toward Detroit. It does this for the above conditions about 1.9 days per year. Under these same weather conditions, the wind blows over the lake 13.9 days per year and if fission-product release occurred during this time, no one in a permanent off-site residence would receive 450r.

Taking fall-out into account, based on the assumption of 10-micron particles, and assuming that 1% of the fission products are released, it is seen in Table I that the number of persons in the direction of Detroit receiving 450r or more due to a fission-product release under adverse weather conditions with the wind in the proper direction is now somewhere between 80 and 10 as compared with a range of 420 to 190 without fall-out. The ratio is not fixed because the population distributions in the directions considered are not uniform.

Consideration of fall-out makes a very significant difference when an inversion exists. Under lapse conditions, however, the 10-micron particle does not settle as readily and the effect of fall-out is relatively small. This may be seen by examining the data in Table III.

b. "MOST PROBABLE" WEATHER CONDITIONS AND "MOST PROBABLE" NUMBER OF PERSONS AFFECTED

With such a wide variation in the number of persons affected from one condition to the next, some more powerful method of analysis is needed to evaluate the over-all effects of a fission-product release at the site.

One approach to an evaluation is to determine the most probable wind direction for the most probable temperature gradient. The effect of the release is then rated according to the number of persons affected in this most probable case.

For 63% of the time, the condition of temperature lapse exists. Also, the most probable wind blows approximately toward the east-northeast at the most probable velocity of 12 mph. Under these most probable conditions and assuming a 100% release of fission products, no permanent residents would receive a mean-lethal dose since these weather conditions cause the cloud to drift over the lake and to break up quickly. The most probable effects are of comparatively low severity with no one on land and off the plant site receiving a dose of more than 100r.

c. THE AVERAGE NUMBER OF PERSONS AFFECTED*

We have already seen that, for a given dose level, the number of persons involved due to a release of fission products is very strongly dependent on the weather condition existing at the time of the release. Also, if we arbitrarily take the most probable condition as representative, the number of persons involved would be small because the prevailing winds blow over the lake. Use of values based on the most probable conditions is too optimistic since it tends to minimize the effects of a release of fission products. It is therefore proposed that the average number of persons affected is more representative than any of the earlier proposals.

The details of calculating this average are given in Appendix II. In general, the approach taken is the following. Each combination of weather conditions is weighted according to the probability of its occurrence. In addition, a weighting factor gives greater importance to those fission-product releases in which many persons are involved as opposed to those in which few are affected. The average arrived at may be interpreted as the number affected per fission-product release in a large series of randomly-occurring releases. The results of this calculation are shown in Tables VII and VIII. In every case the number lies between the extremes shown in Tables I through VI. Table VII shows the average number of persons affected due to a 1% release of fission products and Table VIII gives corresponding data for a 100% release.

16. PROBABILITY OF EFFECTS OF THE RANDOM RELEASE OF THE FISSION PRODUCTS*

The "average" provides a single number whereby the potential effects of the assumed occurrence can be judged. A more detailed analysis, described in Appendix III, yields the probability curves shown in Figs. 28, 29, and 30. In these, the probability is given for a random release of fission products affecting some minimum number of persons with a selected minimum dose of gamma, beta, and beta plus gamma corrected for fall-out. In these cases it was assumed that 100% of the fission products is released. However, these same curves apply for a 1% release if the indicated dose values are divided by 100.

It may be seen that the probabilities decrease very rapidly as the number of persons involved increases. When the fall-out correction is applied to the case of beta plus gamma for a minimum dose of 450r, the probability that 100 or more persons will be involved is 45%; for 1000 persons, it is 8%; and for 10,000 persons it is essentially zero.

It should be noted that, if the 1% release factor is used, the 450r dose lines of Figs. 28, 29, and 30 become 4.5r dose lines. Similar reasoning is appropriate in the case of the 150r and the 25r dose lines since the quantity of dose is directly proportional to the amount of radioactivity released from the site.

---

*For a discussion of this point as compared with the AEC study, see Appendix V.

TABLE VII

AVERAGE NUMBER OF PERSONS AFFECTED PER RELEASE OF FISSION PRODUCTS ASSUMING A LARGE NUMBER OF RANDOMLY-OCCURRING RELEASES

1% of the Fission Products Released*

Type of Radiation	Number of Persons Exposed to Specified Dose		
	450r	150r	25r
External Gamma	0	0	15
Beta Inhalation	20	30	50
Beta plus Gamma with Fall-out Considered	5	15	40

*Values in this table were obtained through use of the area-ratio method derived in Appendix I.

TABLE VIII

AVERAGE NUMBER OF PERSONS AFFECTED PER RELEASE OF FISSION PRODUCTS ASSUMING A LARGE NUMBER OF RANDOMLY-OCCURRING RELEASES

100% of the Fission Products Released

Type of Radiation	Number of Persons Exposed to Specified Dose		
	450r	150r	25r
External Gamma	35	140	2,420
Beta Inhalation	3,150	4,620*	8,570*
Beta plus Gamma with Fall-out Considered	500	2,475	6,380*

*These contours extend beyond the distance considered by the study (80-mile-radius)—See page 8.

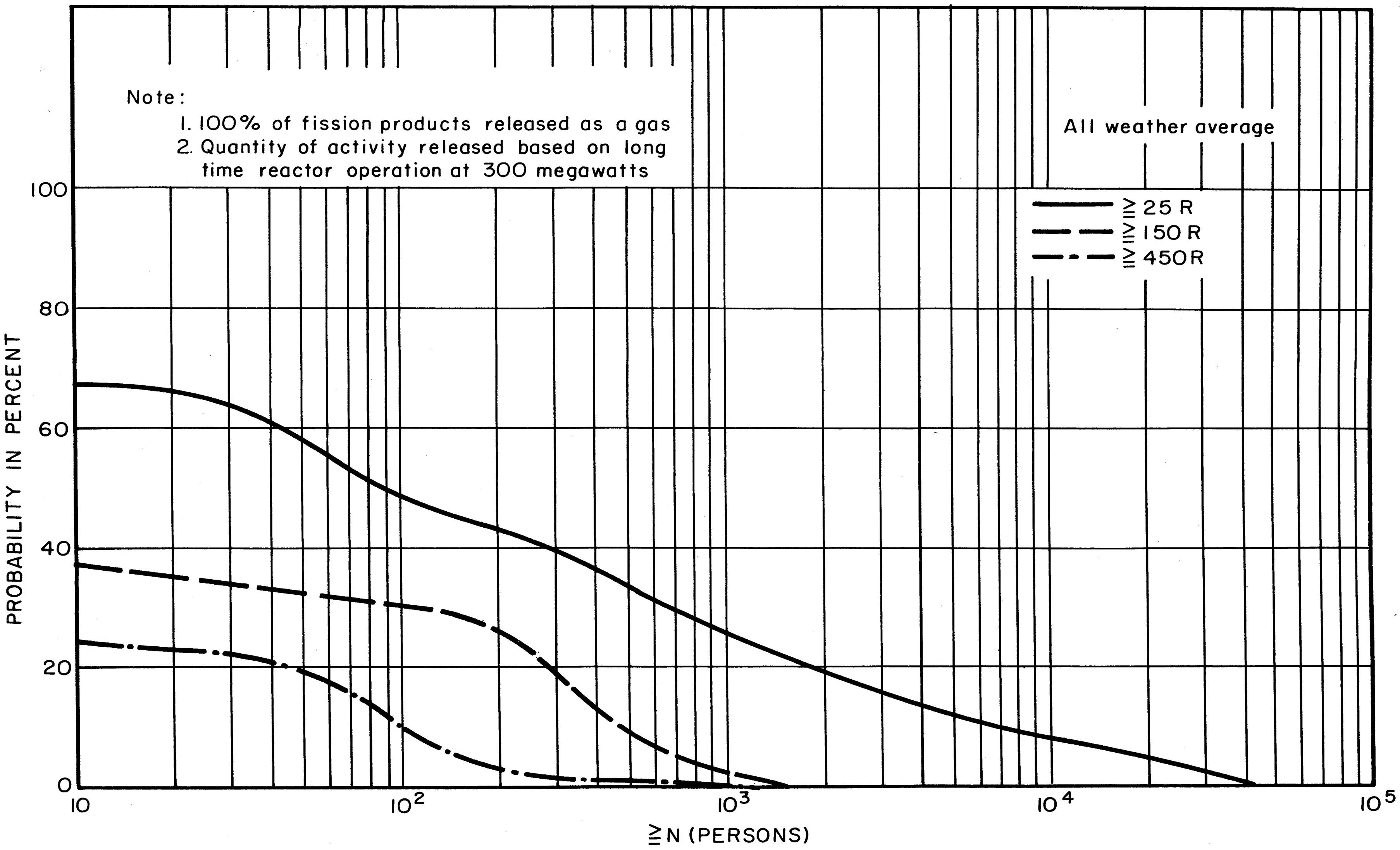


Fig. 28. Probability that a minimum number of persons will be exposed to a minimum dose of γ radiation, expressed as an "all weather" average.

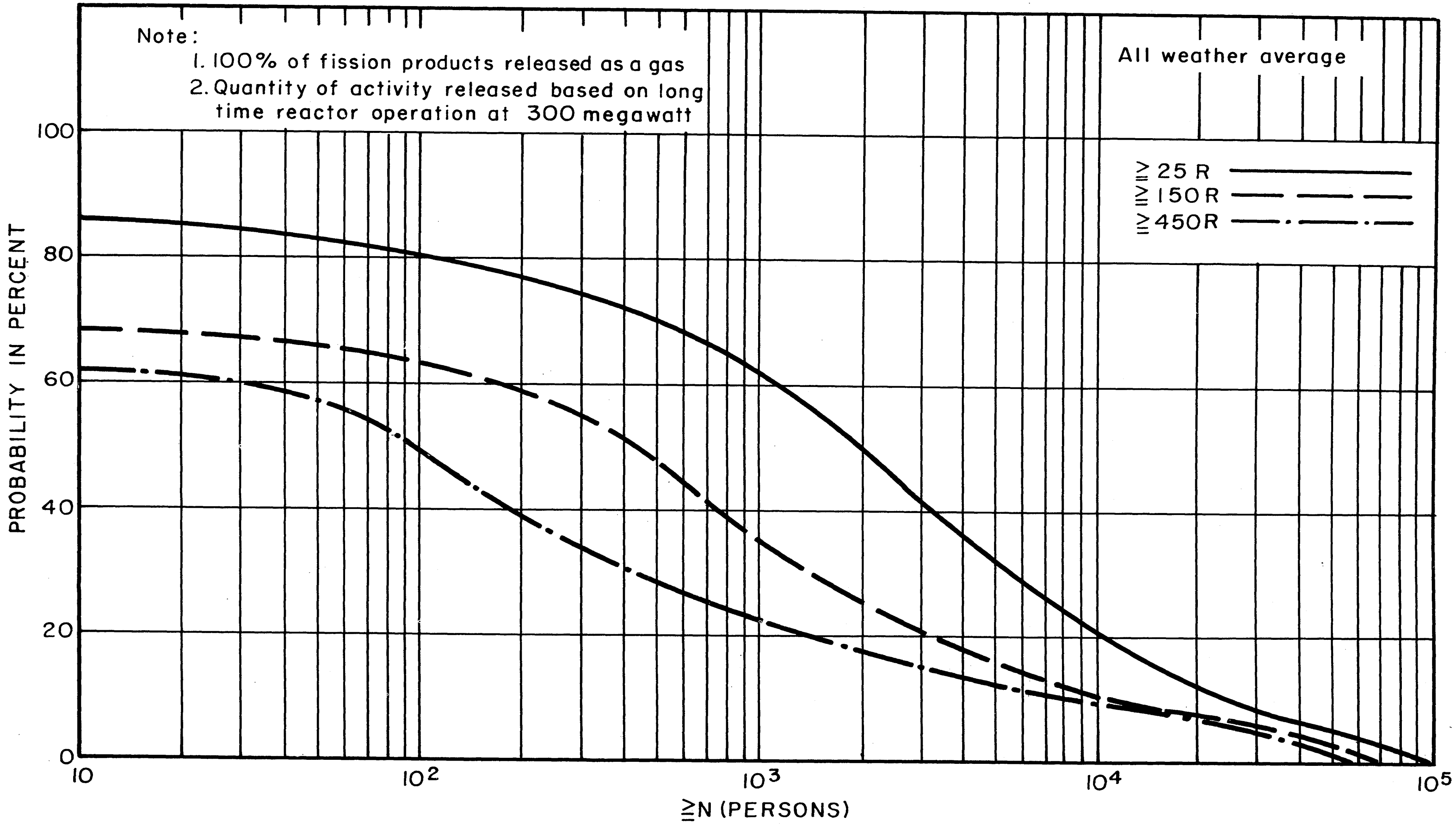


Fig. 29. Probability that a minimum number of persons will be exposed to a minimum dose of β radiation, expressed as an "all weather" average.

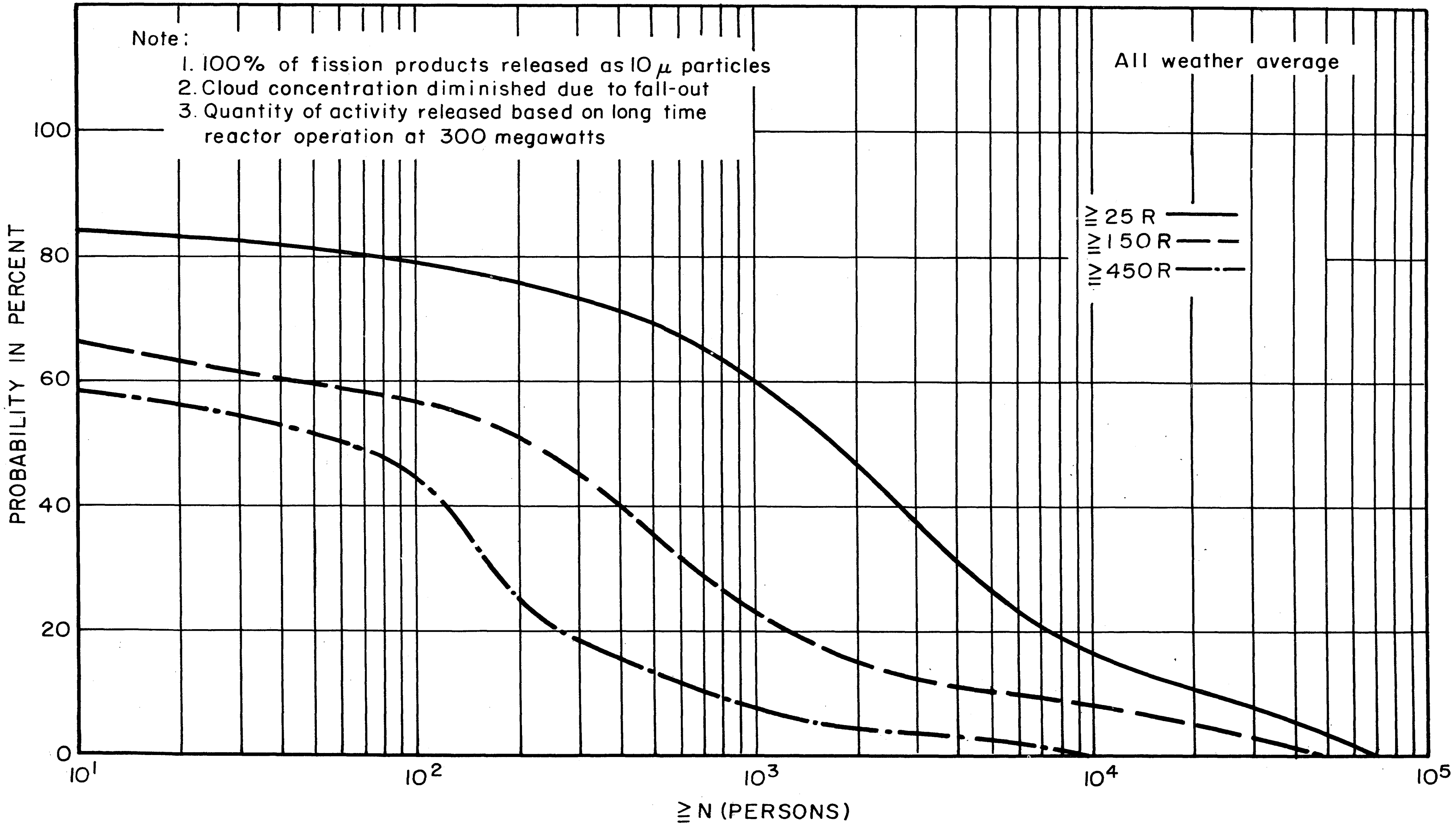


Fig. 30. Probability that a minimum number of persons will be exposed to a minimum dose of $\beta + \gamma$ radiation (with fall-out correction applied), expressed as an "all weather" average.

APPENDIX I

BETA-CONTOUR AREA AND LENGTH

It is evident that the area of a beta-inhalation dose contour is a function of the quantity of the radioactive material released from the source. The derived relationship, based on the inversion weather condition, was found to yield a fair degree of accuracy when compared with graphical integrations of the calculated contours.

The primary assumption involved is that

$$\text{Contour Area} \propto (\text{contour length})^2 \quad .$$

The rest of the derivation is rigorous.

The Sutton Diffusion Equation for beta-inhalation dose computation may be expressed in the following condensed form when $y = 0$:

$$\text{TID} = \frac{kQ}{x^{2.2-n}} \qquad (1)$$

where

- k is a constant for a given weather condition,
- Q is the quantity of radioactivity released,
- x is the downwind distance,
- y is the crosswind distance,
- n is the non-dimensional stability parameter, and
- TID is the total integrated beta-inhalation dose.

Now, since this relationship is primarily designed for use on inversion weather contour areas,

$$\text{TID} = \frac{kQ}{x^{1.6}} \quad , \qquad (2)$$

since $n = 0.60$ under inversion conditions.

If we are to consider two beta-inhalation dose contours which enclose areas of equal minimum doses,

$$\text{TID} = \frac{kQ_1}{x_1^{1.6}} \qquad (3)$$

$$\text{TID} = \frac{kQ_2}{x_2^{1.6}} , \tag{4}$$

or

$$\frac{kQ_1}{x_1^{1.6}} = \frac{kQ_2}{x_2^{1.6}} , \tag{5}$$

and

$$\left(\frac{x_2}{x_1}\right)^{1.6} = \frac{Q_2}{Q_1} , \tag{6}$$

which may be rearranged to

$$\left(\frac{x_2}{x_1}\right)^{2} = \left(\frac{Q_2}{Q_1}\right)^{1.25} . \tag{7}$$

This again may be written as

$$\frac{\text{Area}_2}{\text{Area}_1} = \left[\frac{Q_2}{Q_1}\right]^{1.25} . \tag{8}$$

The effect of the quantity of radioactivity released upon the maximum extension of a beta-inhalation dose contour may be derived through use of Equation (1):

$$\text{TID} = \frac{kQ}{x^{2.2-n}} .$$

For example, given a particular weather condition, more specifically, a value of n, one may determine the effect of quantity released upon maximum extension of a contour for a specific dose. If two quantities are released, one may write:

$$x_1 = \left[\frac{k_1Q_1}{\text{TID}}\right]^{\frac{1}{2.2-n}} , \tag{9}$$

and

$$x_2 = \left[\frac{k_2Q_2}{\text{TID}}\right]^{\frac{1}{2.2-n}} . \tag{10}$$

Now

$$k_1 = k_2 \tag{11}$$

if the weather condition is the same in both cases, and

$$\frac{x_1}{x_2} = \left[\frac{Q_1}{Q_2}\right]^{\frac{1}{2.2-n}} \qquad (12)$$

since we are dealing with the same dose, TID.

This treatment is rigorous and entirely consistent with the Sutton Diffusion Equation noted in the body of the text.

A plot of the maximum extension of the 450r beta-inhalation dose contour when $n = 0.60$ is shown in Fig. A-I-1. Equation (12) was utilized in developing this plot.

Inversion Weather Conditions

Note:

1. Fission products released as a gas
2. Activity of 100% of fission products based on long time operation at 300 megawatts = 3 x 10^9 curies
3. Receptor located directly on wind axis (No crosswind component).

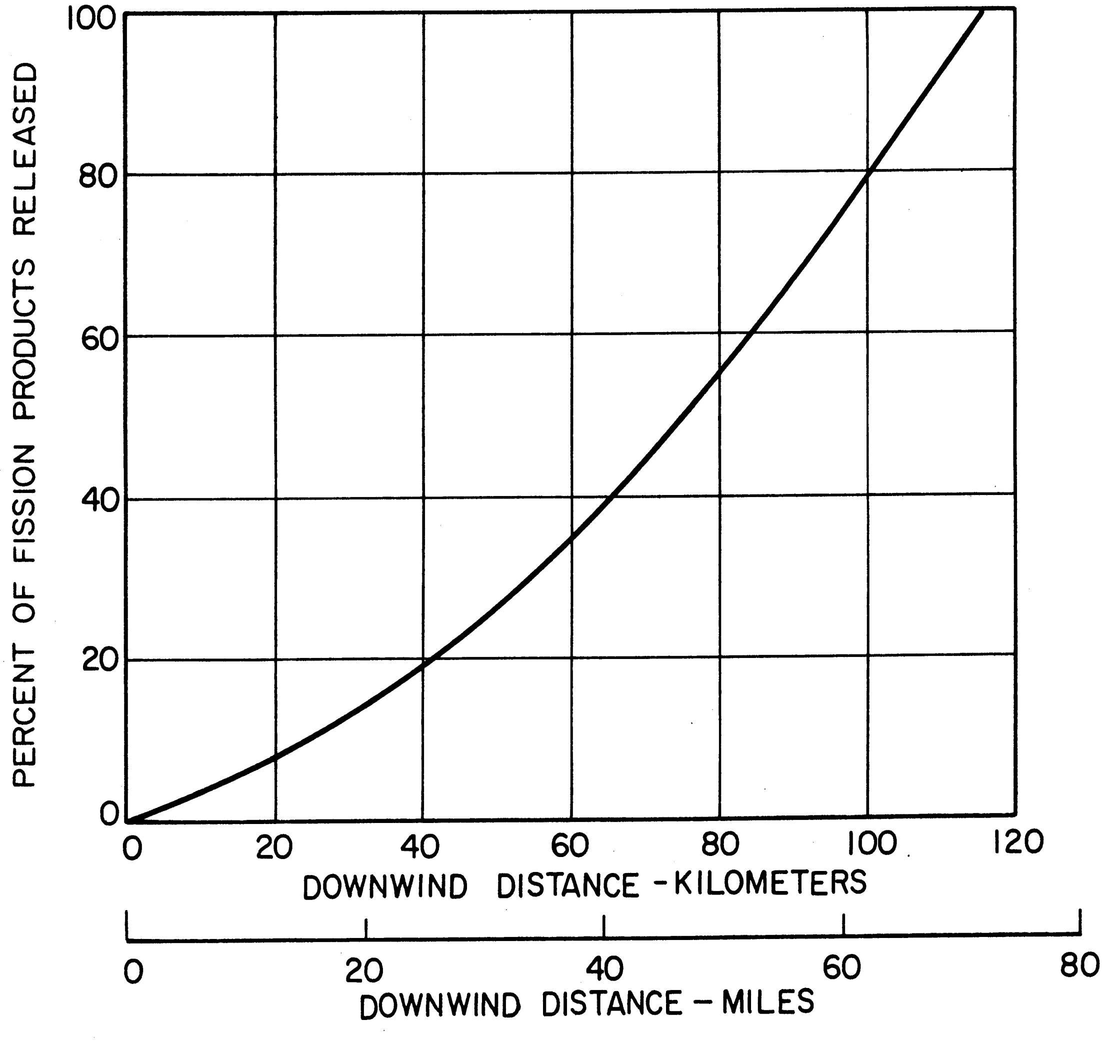


Fig. A-I-1. Effect of percent of fission products released on maximum extension of 450r beta dose contour.

APPENDIX II

AVERAGING PROCEDURE

A. STATEMENT OF THE PROBLEM

In Tables VII and VIII, the average number of persons receiving a minimum dose or more due to a release of 1% and 100% of the fission products, respectively, is presented. The method of arriving at these numbers is important in that it determines the validity and significance of the results.

These methods along with the underlying assumptions are detailed in this section.

The most desirable method of determining the average number of persons receiving a dose of r or more may be expressed mathematically as:

$$\overline{N}(r) = \frac{\iiint N(v,\Theta,t_g,r)\, P(v,\Theta,t_g)\, dv\, d\Theta\, dt_g}{\iiint P(v,\Theta,t_g)\, dv\, d\Theta\, dt_g} \qquad (1)$$

where

$\overline{N}(r)$ is the average number of persons receiving r or more roentgens;

$N(v,\Theta,t_g,r)$ is the number of persons receiving r or more roentgens when the wind velocity is between v and $v + dv$, the wind direction angle lies between Θ and $\Theta + d\Theta$, and the temperature gradient lies between t_g and $t_g + dt_g$; and

$P(v,\Theta,t_g)$ is the probability of the weather condition corresponding to those outlined above.

This approach is based on the validity of the Sutton Diffusion Theory in which we assume that, knowing the wind velocity, wind direction, and the temperature gradient, we can predict the diffusion of material released into the air.

B. ASSUMPTION 1—CLASSIFICATION OF TEMPERATURE GRADIENTS

Evaluation of the average as defined in Equation (1) is not possible in detail because the required functions, N and P, are not known.

The first simplifying assumption reduces the number of temperature gradients to three major categories:

1.	Inversion	All positive gradients
2.	Weak lapse	Temperature gradients ranging from 0 to -10°C per kilometer
3.	Strong lapse	All gradients more negative than -10°C per kilometer.

Within these categories, we can now find the average number of persons affected per release for a given temperature gradient. Mathematically, this may be expressed as:

$$\overline{N}_i(r) = \frac{\iint N_i(v,\theta,r)\, P_i(v,\theta)\, dv\, d\theta}{\iint P_i(v,\theta)\, dv\, d\theta} \; ; \qquad (2)$$

$$i = 1,2,3;$$

where i is the appropriate index for the temperature gradient condition under consideration. The values $\overline{N}_i(r)$ would then be averaged, applying to each $\overline{N}_i(r)$ a weighting factor proportional to the incidence of the selected temperature gradient.

From an analysis of the records of the U. S. Weather Bureau from the Toledo, Ohio, observation station, the breakdown into three categories given on page 18 was obtained.

C. EVALUATION OF $N_i(v,\theta,r)$, THE POPULATION FUNCTION

We require information on the number of persons who, for a selected temperature gradient, could receive a given minimum dose as a function of the selected dose, wind velocity, and wind direction.

1. Radiation Source.—In specifying the selected dose, we must establish the source of the radiation: whether it is due to airborne material or due to fall-out on the ground, and whether it is due to gamma rays, beta rays, or both. As discussed in the body of the report, the doses due to airborne material can be treated individually or combined. The effects due to fall-out must be treated separately unless definite time limits are established.

We have limited the calculated averages to those cases involving airborne radiation sources.

2. Isodose Contours.—We have been unable to find an analytical method for the direct calculation of the number of persons receiving a selected minimum dose as a function of wind velocity, direction, etc. We have had to resort to graphical and other techniques to find the ground area which receives the selected minimum dose. Knowing this area, we then find the number of persons within it by the direct counting techniques. The area considered is outlined by the isodose contour.

With the type of radiation specified we can, with the help of Sutton Diffusion Theory and other considerations, determine the isodose contour within which a person receives r or more roentgens and outside which he receives less than r roentgens. These contours are functions of the temperature gradient, wind velocity, and radiation source. Typical contours were shown and compared in Figs. 18, 19, and 22. For a given value of θ, v, and r, $N_i(v,\theta,r)$ is found by placing the isodose contour over a properly scaled population map and determining the number of persons within the contour.

To carry out the operation as required in Equation (2), a large series of contours for fixed r and variable v would be required. Since preparation of these contours is a lengthy operation, the following simplification was made.

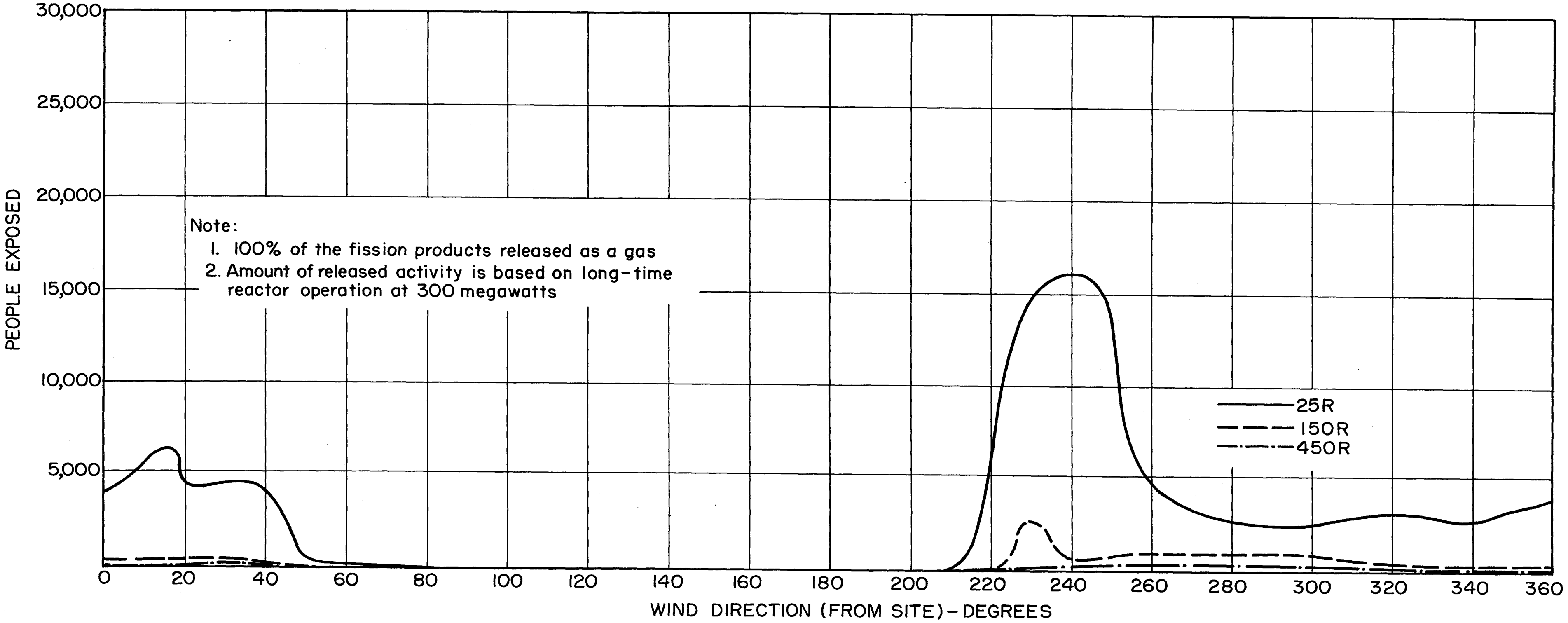
The velocity v which was most probable or typical for a given temperature gradient was selected. This, or a lower velocity which would make the results more conservative, was used to determine isodose contours. Population-distribution curves as a function of θ were prepared, and an example is shown in Fig. A-II-1.

The typical velocities used were:

Temperature Gradient	Typical Velocity
1. Inversion	4.5 mph
2. Weak lapse	11.25 mph
3. Strong lapse	13.5 mph

It was now assumed that the shape of the curve did not change as v changed. This is the equivalent of assuming that, for a given direction θ, the population is proportional to the area of the isodose contour. As the contour shrinks, with increase in v, it will not cease to affect any population centers, nor will it affect any other population centers as v decreases and the contour grows.

It must be emphasized that this is quite different from the more drastic assumption of uniform population distribution. The major variations of population with angle, found for the case of the typical velocity, are



Note:
1. 100% of the fission products released as a gas
2. Amount of released activity is based on long-time reactor operation at 300 megawatts

Fig. A-II-1. Minimum number of persons exposed to a minimum dose of beta radiation during strong-lapse weather conditions, 13.5 mph wind.

preserved for all velocities.

This may be stated quantitatively:

$$N_i(v,\Theta,r) = k_i(\Theta,r)\, A_i(v,r) \quad , \tag{3}$$

where

k_i is a proportionality factor which varies with wind direction and dose, and

A_i is the area of the isodose contour which varies with wind speed and dose.

Thus Equation (2) becomes:

$$\overline{N}_i(r) = \frac{\iint k_i(\Theta,r)\, A_i(v,r)\, P_i(v,\Theta)\, dv\, d\Theta}{\iint P_i(v,\Theta)\, dv\, d\Theta} \quad . \tag{4}$$

D. PROBABILITY CONSIDERATIONS

We have no valid reason to believe that the wind direction and wind velocity are interdependent. We will therefore assume that the probabilities of wind velocity and wind direction are distinct and independent, or that

$$P_i(v,\Theta) = P_i(v) \cdot P_i(\Theta) \quad . \tag{5}$$

Equation (4) now may be written

$$\overline{N}_i(r) = \frac{\int k_i(\Theta,r)\, P_i(\Theta)\, d\Theta}{\int P_i(\Theta)\, d\Theta} \cdot \frac{\int A_i(v,r)\, P_i(v)\, dv}{\int P_i(v)\, dv} \quad . \tag{6}$$

We have already selected typical wind speeds v_1, v_2, and v_3, to characterize each of the selected temperature gradients. For any one speed, v_o:

$$\overline{N}_{i_o}(r) = A_{i_o} \frac{\int k_i(\Theta,r)\, P_i(\Theta)\, d\Theta}{\int P_i(\Theta)\, d\Theta} \quad . \tag{7}$$

We may rewrite (6) as

$$\overline{N}_i(r) = \overline{N}_{i_o}(r) \frac{\int A_i(v,r)\, P_i(v)\, dv}{A_{i_o}} \quad , \tag{8}$$

assuming that
$$\int P_i(v)\, dv = 1 .$$

Evaluation of Equation (8) now depends on

$$\int A_i(v,r)\, P_i(v)\, dv$$

which can be determined graphically. For a given r, the value of the isodose contour area, as a function of the velocity, follows a trend as shown in Fig. A-II-2.

The wind-speed-probability curves for given temperature gradients were shown in Figs. 8 and 9. These are readily combined with the area of the actual contour based on the typical wind speed to evaluate the factor ρ_i where:

$$\rho_i = \frac{\int A_i(v,r)\, P_i(v)\, dv}{A_{i_o}} . \tag{9}$$

Throughout the calculation process ρ_i was checked periodically and was found to be essentially independent of r.

There now remains the evaluation of $\overline{N}_{i_o}(r)$, the average number of persons affected by a release of fission products with selected temperature gradient and typical wind velocity but with variable wind direction:

$$\overline{N}_{i_o}(r) = \frac{\int N_{i_o}(\theta,r)\, P_i(\theta)\, d\theta}{\int P_i(\theta)\, d\theta} . \tag{10}$$

The distribution curves for wind direction are shown in Figs. A-II-3 and A-II-4. In our calculation, both were based on one-degree intervals. The required population distribution curve is as given in Fig. A-II-1.

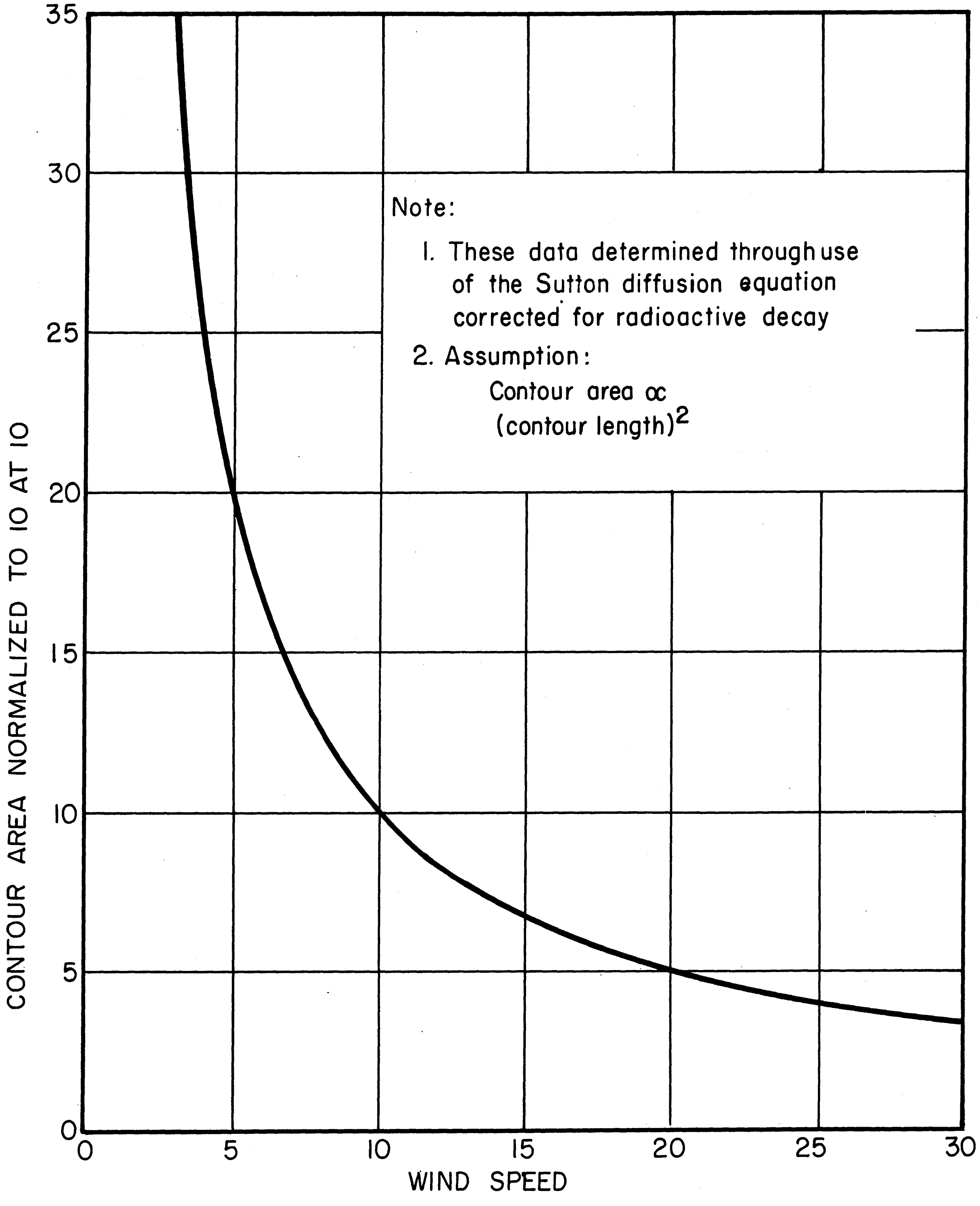
We now have the factors for determining $\overline{N}_i(r)$ since

$$\overline{N}_i(r) = \rho_i\, \overline{N}_{i_o}(r) . \tag{11}$$

Using the correct weighting factors, we find $\overline{N}(r)$ since

$$\overline{N}(r) = \sum_{i=1}^{3} \tau_i\, \overline{N}_i(r) , \tag{12}$$

where τ_i, the percentage of time a given temperature gradient exists, is:



A-II-2. Trend of contour area with wind speed, area normalized to 10 at 10.

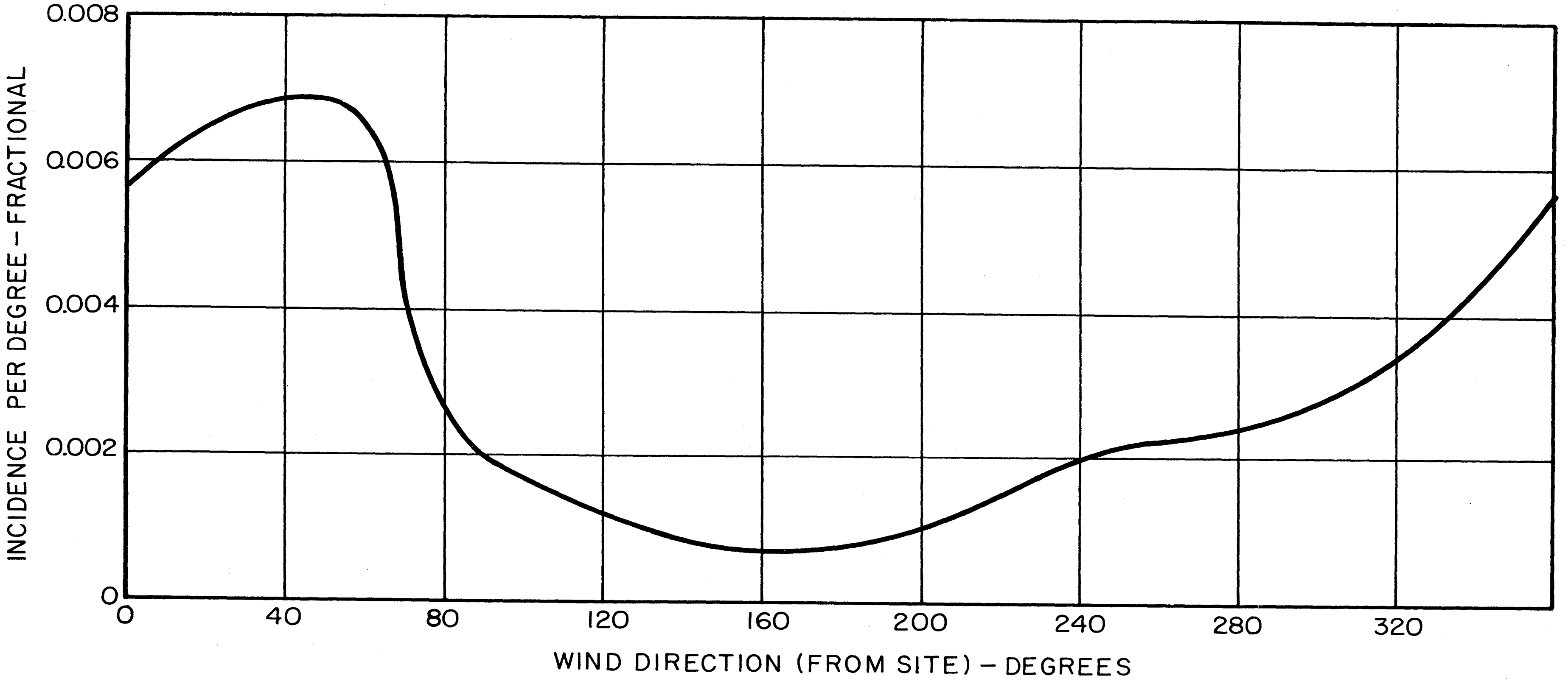


Fig. A-II-3. Wind-direction distribution under inversion conditions (all wind speeds), Toledo, Ohio.

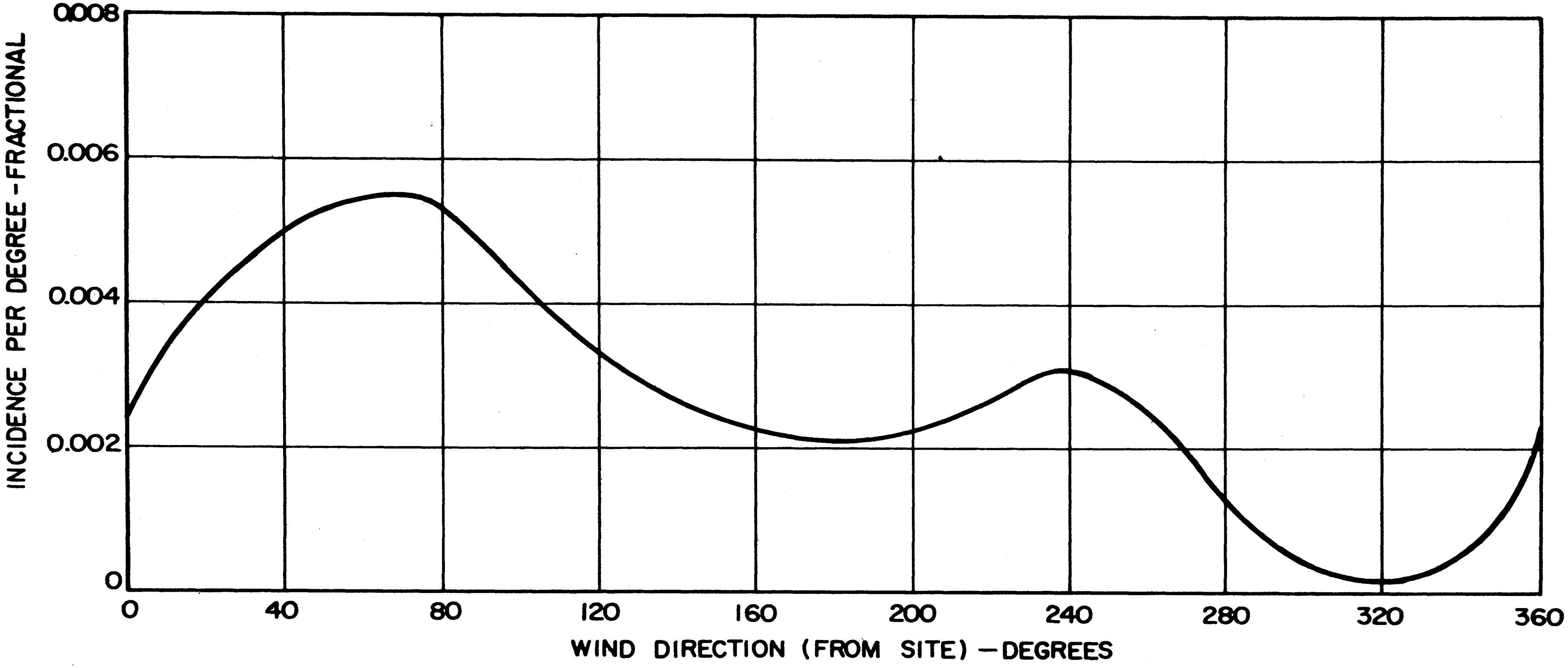


Fig. A-II-4. Wind-direction distribution under all lapse conditions (all wind speeds), Toledo, Ohio.

τ_1	—	Inversion	37%
τ_2	—	Weak lapse	36%
τ_3	—	Strong lapse	27%

A duplicate of Fig. 30, plotted on arithmetic paper, is shown in Fig. A-II-5.

Note:

1. 100 % of fission products released as 10 μ particles
2. Cloud concentration diminished due to fallout.
3. Probabilities determined through an all weather weighted average
4. Long-time operation of the reactor at 300 megawatts

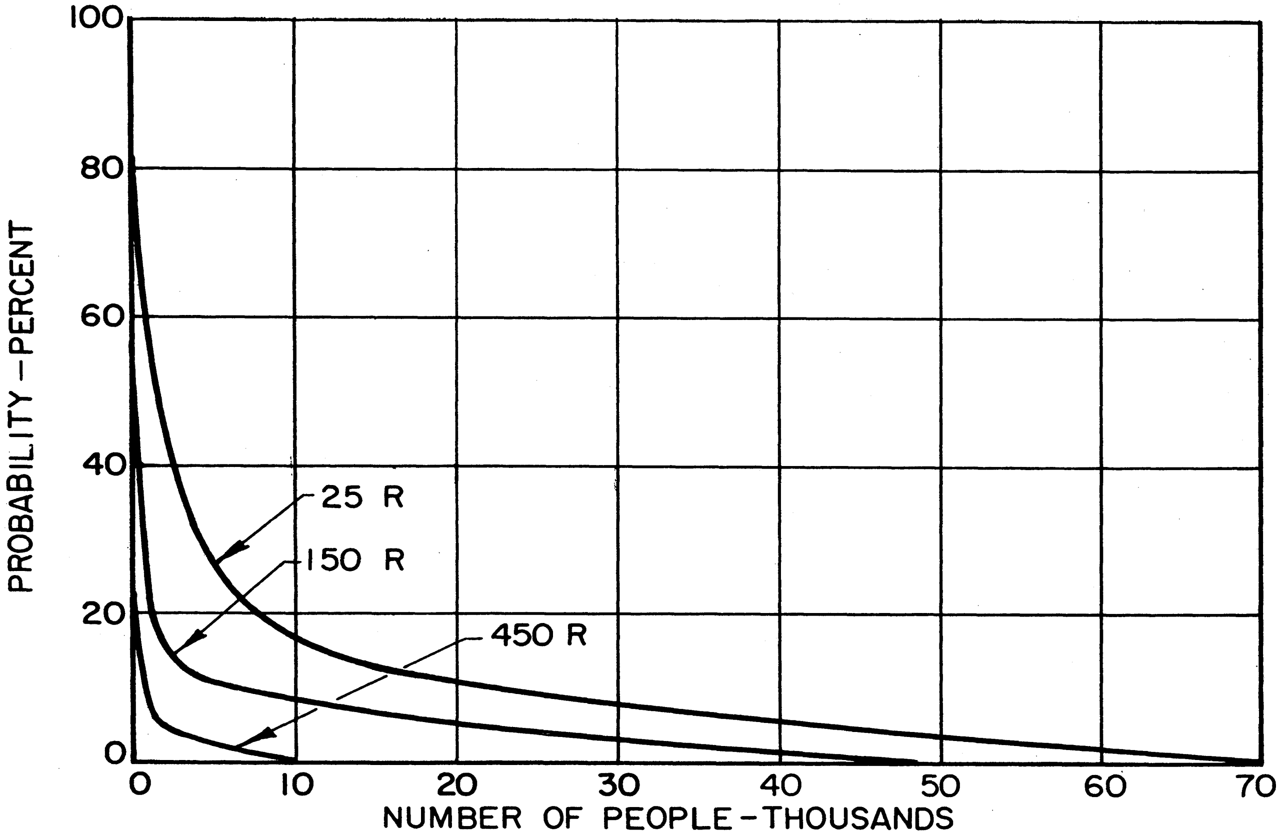


Fig. A-II-5. Probability that a minimum number of persons will be exposed to a minimum dose of $\beta + \gamma$ radiation (with fall-out correction applied), expressed as an "all weather" average.

APPENDIX III

PROBABILITY CALCULATIONS

A. INTRODUCTION

We have calculated, employing the Sutton Diffusion Theory, the probability of a minimum number of persons receiving a selected minimum dose of beta radiation, gamma radiation, and beta plus gamma radiation with the fall-out correction applied. The results were given in Figs. 28, 29, and 30.

This curve set was arrived at by processes and assumptions similar to those used in the calculation of the average number of persons affected by a release of fission products as described in Appendix II.

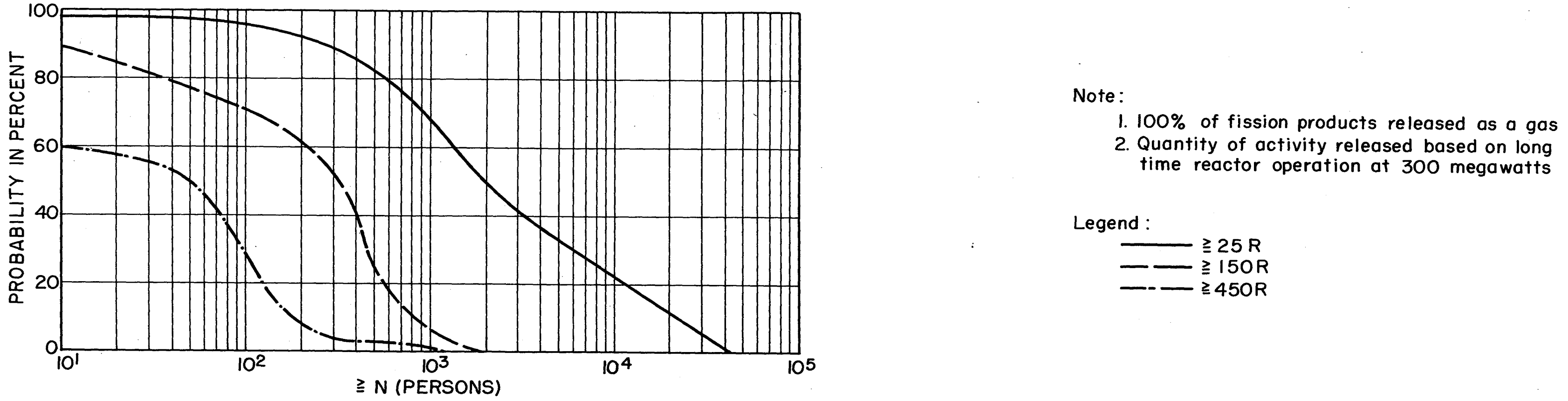
B. METHODS OF CALCULATION

1. The All-Weather Curve Set.—Each of the all-weather curve sets (Figs. 28, 29, and 30) was developed from the sets of data represented in Figs. A-III-1, A-III-2, and A-III-3, respectively. These curves demonstrate the probability that for the average release of fission products, a minimum number of persons will be exposed to a given type and quantity of radiation dose under specified weather conditions. The ordinates of each such curve of probability versus the number of people are weighted by the weather-incidence probability factor, and then the results are added. The result is the all-weather curve. The weather-incidence factors are:

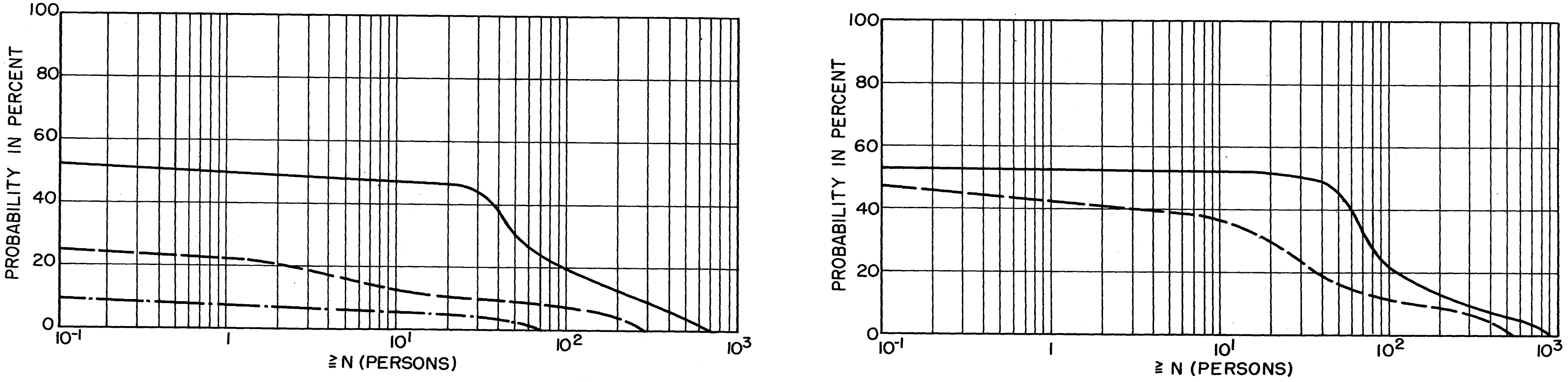
a.	Inversion	37%
b.	Weak lapse	36%
c.	Strong lapse	27%

2. The Curve Sets for Specified Weather Conditions.—The method of obtaining these curves can be explained by outlining the procedure step by step. As an example, let us calculate the curve for the 25r beta-inhalation dose under strong-lapse conditions.

First, we select the typical wind velocity, in this case 13.5 mph (6 meters per second). As shown in Appendix II, this value is close to the most probable value for strong-lapse conditions. The isodose contour is now



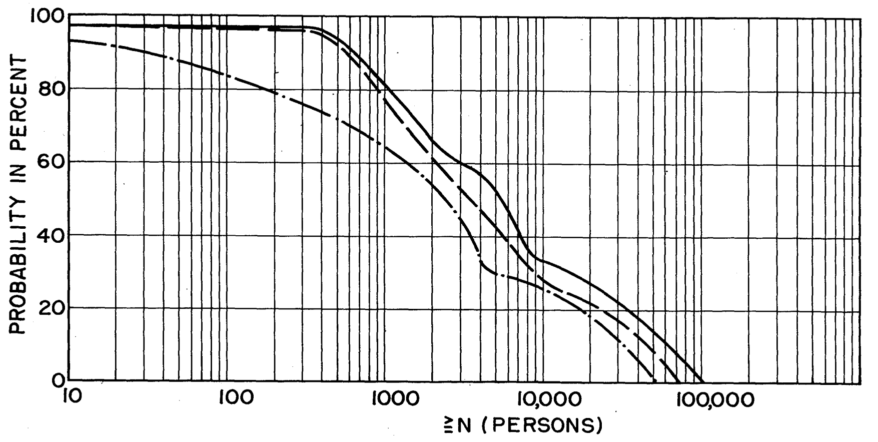
Inversion weather conditions



Weak lapse weather conditions

Strong lapse weather conditions

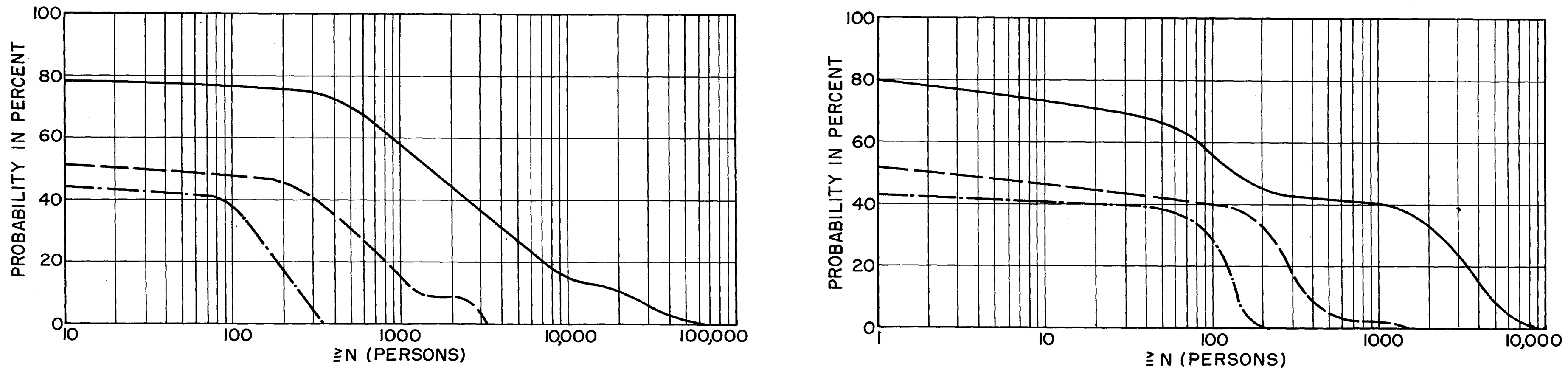
Fig. A-III-1. Probability that a minimum number of persons will be exposed to a minimum dose of γ radiation from airborne fission products under specific weather conditions.



Inversion weather conditions

Note:
1. 100% of fission products released as a gas
2. Quantity of activity released based on long time reactor operation at 300 megawatt

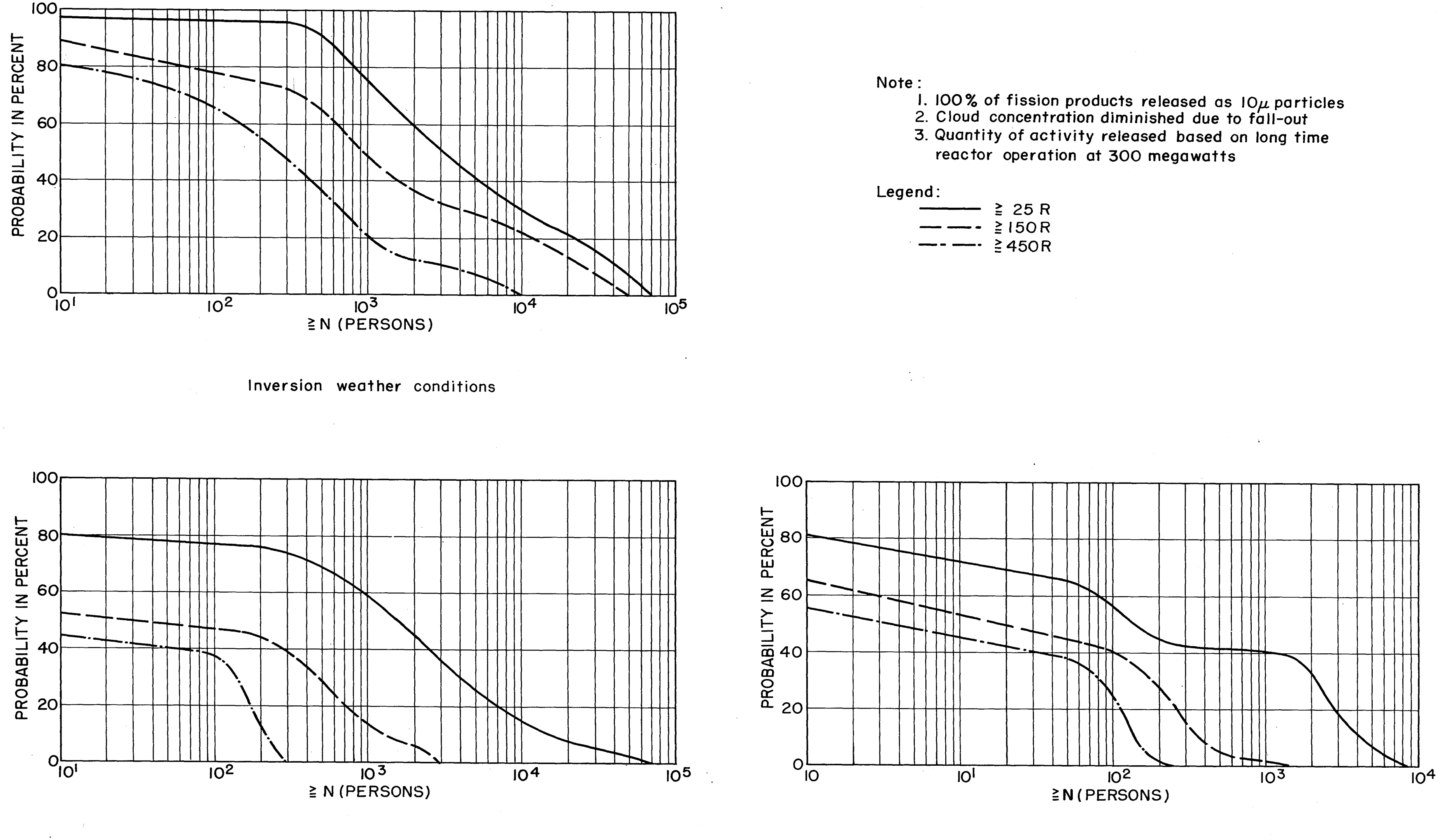
Legend:
———— ≥ 25R
— — — ≥ 150R
—·—·— ≥ 450R



Weak lapse weather conditions

Strong lapse weather conditions

Fig. A-III.2. Probability that a minimum number of persons will be exposed to a minimum dose of β radiation from airborne fission products under specific weather conditions.



Note:
1. 100% of fission products released as 10μ particles
2. Cloud concentration diminished due to fall-out
3. Quantity of activity released based on long time reactor operation at 300 megawatts

Fig. A-III-3. Probability that a minimum number of persons will be exposed to a minimum dose of $\beta + \gamma$ radiation from airborne fission products under specific weather conditions.

calculated, using the equation on page 17 of this report.

A map of the area, showing population distribution (see Fig. 6) and drawn to a suitable scale, is prepared and the isodose contour, drawn to the same scale, is placed over it. The number of persons within the contour can be determined for as many different wind directions as one may desire.

Utilizing this procedure, a population-distribution curve, as a function of direction from the site, is constructed. This curve is shown in Fig. A-II-1. It indicates the number of persons who are affected by a minimum 25r beta-inhalation dose, for strong-lapse, 13.5 mph winds, and for any wind direction.

If we multiply the ordinates of the curve by the averaging factor, ρ_i, as derived in Appendix II, we obtain the population-distribution curve. This modified curve gives the average number of persons who would receive a dose of 25r or more as a function of wind direction, if the release occurred during strong-lapse weather.

It may be seen from the original unmodified curve (Fig. A-II-1) that the ordinate for 10,000 persons intersects the 25r curve at 223° and at 252°. If we multiply the ordinate by the strong-lapse averaging factor, 0.58, we obtain 5800 persons. Thus, when the cloud of fission products moves away from the plant site in a direction lying between 223° and 252°, 5800 or more persons, on the average, will receive a dose of 25r or more of beta radiation.

The maximum number of persons who will receive a dose of 25r or more is 9280 on the average, with the wind blowing toward 240°. With the typical wind velocity of 13.5 mph, 16,000 persons will receive a dose of 25r of beta radiation or more.

The next step is the determination of the probability that during a strong-lapse the wind will blow in the direction under consideration, in this case between 223° and 252°. This is determined by graphical integration between these limits under the appropriate wind-direction distribution curve. The curve is shown in Fig. A-II-4 and the result is 5.2%.

We have thus found that if one considers the average case, the probability that 5800 or more persons will receive 25r or more due to beta inhalation, during strong-lapse weather conditions, is 5.2%. This gives us one point on the curve of probability of 25r versus number of persons for strong-lapse weather, shown in Fig. A-III-2. In a similar manner, other points for the same curve can be obtained and other curves drawn for each quantity of dose, type of radiation, and weather condition considered.

In Fig. A-III-2, there are curves of probability versus the number of persons for 25r, 150r, and 450r minimum doses due to beta radiation during inversion, weak-lapse, and strong-lapse weather conditions.

Figure A-III-1 shows a similar set for radiation from external gamma sources.

Figure A-III-3 shows another set of data which gives beta plus gamma total-dose curves. In this case the correction for fall-out, based on 10-micron particles, has been made.

As stated earlier, individual curves in each set are combined to obtain the all-weather curves of Figs. 28, 29, and 30.

APPENDIX IV

EIGHTY-MILE RADIUS LIMIT

As noted in the body of the text, population counts to determine the number of persons affected due to the release of fission products from the reactor were conducted to a maximum distance of 80 miles. For our typical inversion-weather condition we have assumed a wind speed of 4.5 mph. This means that a cloud would have to travel for a period of about 17.5 hours to reach the 80-mile radius circle.

Recently, an inversion which lasted in the neighborhood of 60 hours was observed in the vicinity of the plant site. This event has been investigated for its bearing on our assumptions. This type of situation is known to occur occasionally in coastal areas. In this case, it appears that rather than being caused by long-wave radiation as one might suspect, the inversion was due primarily to the movement of a warm air-mass into the area at high levels.

This inversion was observed during a period when the wind speed averaged approximately 15 mph, 100 feet above ground level. This speed is roughly three times that assumed for the typical inversion case. Therefore, the diffusion of a cloud emitted from the plant site would have been much more rapid than in our typical case.

In addition, data taken at the WJBK-TV tower in the Detroit area during the same period indicate that the phenomenon was not continuous over the city. The inversion actually broke up for an hour or two each day in the early afternoon.

Since it is quite uncommon for an atmospheric inversion to exist as long as 24 hours over the land, we feel that an inversion time of 17.5 hours is not unreasonably short. In actuality it is longer than the time during which the average inversion exists. Since the 60-hour inversion which was observed in the vicinity of the plant site appeared to exist only in the area over the lake and in a narrow band of land surrounding it, this tends to justify our choice of an 80-mile limit.

A further discussion of the observed 60-hour inversion may be found in Engineering Research Institute Report No. 2515-1-P, First Progress Report on Meteorological Installation and Analysis, by E. Wendell Hewson and Gerald C. Gill, for the Power Reactor Development Company of Detroit, Michigan.

APPENDIX V

COMPARISON OF THE MICHIGAN WITH THE AEC STUDY

A. INTRODUCTION

While the Michigan report was in its final phases of preparation, the Atomic Energy Commission released the report prepared by Brookhaven National Laboratory for the AEC, entitled Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants. Since the Michigan and Brookhaven studies were made by groups which were not only independent of each other, but between which there was effectively no communication, and since the Brookhaven study has been available to the recipients of the Michigan report, it was decided to add a section to this report which would compare the assumptions made, methods of calculations used, areas covered, and results obtained.

The comparison was not compiled to show which group was right or wrong in those areas where disagreement exists. Rather, it was made to find those differences in assumptions and methods which led to the differences in results. It is not possible, from direct experience, to say at this time which of the methods is most accurate in predicting the consequences of a fission-product release. It may be possible to decide, however, which set of assumptions seems more acceptable as starting conditions and which calculation techniques may be more exact.

B. MAJOR ITEMS CONSIDERED IN ONE REPORT AND NOT FOUND IN THE OTHER

1. In the AEC study, a section (Appendix A) is devoted to consideration of the possible causes of a fission-product release. No such section appears in the Michigan report. Rather, the assumption is made that the release has occurred and that we are concerned only with its consequences. On the basis of our assumption, we consider only the power level and operating history of the reactor, as these determine its fission-product burden. The amount of radioactive fission products present is independent of the reactor type or design.

2. In the AEC study, fall-out of radioactivity on the ground is treated in detail, concluding with an evaluation of its consequences in terms of dollar value. The Michigan report does not attempt to translate the predicted ground contamination and its duration into equivalent economic loss.

We have considered in detail the radiation effect only on the people in the area in which fall-out occurs. In addition, control of the total radiation exposure through evacuation after twenty-four hours or after one week was evaluated.

3. In considering the danger to persons due to a fission-product release, the AEC study considers only specific cases: the number of persons affected by a release occurring under a selected set of weather conditions. In the Michigan report, these data are also given, but in addition, a complete set of probability studies for these conditions has been made. This has been done by combining an analysis of weather data compiled over the past eight years and its break-down into definable groups with the effect on population of a release occurring under any one of the defined weather conditions. In this way, the probability that a given number of persons will be affected by a release occurring at random can be calculated, and also, the average number of persons affected per release occurring at random can be predicted.

These calculations are particularly important for determining the general risk taken in the surrounding area by the establishment of a nuclear power plant which <u>might</u> release fission products. When combined with data on probability of fission-product release, as it becomes available, true risk evaluation can be made, for insurance purposes and for final and definitive site evaluation.

4. In analyzing the fission-product release under specific conditions, rain at the time of the release and release of the fission products at high temperature were considered in the AEC report. Both of these assumptions were omitted from the Michigan analysis.

Rain during the release washes down a large part of the fission-product burden of the cloud, thereby reducing drastically the number of persons affected in the area downwind from the site.

Release of the gas at high temperature reduced the effect of the release to the point where, it was predicted in the AEC report, no personal injuries would result from a release under these conditions.

It was decided by the Michigan group that determination of the probability of rain or other mitigating circumstances at the time of the release could not be carried out with sufficient accuracy and therefore should not be used to reduce the apparent risk due to the airborne fission-product cloud.

C. IMPORTANT DIFFERENCES IN BASIC ASSUMPTIONS

1. <u>Fraction of Radioactivity Released at the Time of the Accident</u>.— The AEC study is based on an assumed limit on the release of 50% of the contained fission products, with anything more than this considered beyond the range of credibility. In the Michigan study, the more pessimistic assumption of

100% release was used. We can find no reason for favoring one over the other, and since this is a study of the consequences of a hypothetical release, the assumption of 100% removes one possible area of controversy. No supporting data exist for either. Dr. Willard Libby has made an "educated guess" that a 1% release would be realistic. We do find reason to accept this number, particularly for an accident not followed by fire and continued vaporization of the core. We have therefore included some calculations of the effect of an accident based on 1% release.

2. Amount of Contained Radioactivity.—The AEC study uses a detailed analysis of the build-up of the different fission products to arrive at an estimate of the contained radioactivity at the time of the release. The reactor was assumed to have operated at 500,000 kw (heat) for 180 days before the accident. The base time for all calculations of activity is 24 hours after the release has occurred. Activity at any other time is calculated from this point. The number quoted in the AEC report as contained activity under the above conditions is 4.1×10^8 curies. Correcting back to the time of the accident, the contained burden at that time was about 4×10^9 curies.

In the Michigan study, we have accepted the Way-Wigner equation for radioactive decay of mixed fission products, and have further assumed that the reactor had been operating long enough to reach its maximum possible burden of fission products. Under these assumptions, the contained burden is 5×10^9 curies for a 500,000-kw reactor or 3×10^9 curies for the 300,000-kw rating assumed in the Michigan study.

3. Time Decay of Fission Products.—All fission products are assumed, in the AEC study of radioactive cloud formation, to be two hours old and to remain at that level of activity for all time.

Using the Way-Wigner equation, the Michigan study assumes that radioactivity in a fission-product cloud decays with time as $t^{-0.2}$.

The two-hour assumption used in the AEC study results in a smaller estimate of the radiation doses received at short distances where they are high, often lethal. On the other hand, it predicts higher doses than does the Michigan method at distances reached only after a few hours of travel.

In this case, we believe our own method to be more realistic and significant.

4. Relationship Between Radioactivity in the Cloud and Dose Received by Person on the Ground.—The most significant difference between the two studies occurs at this point. Evaluation of the effect of airborne radioactivity is still uncertain and controversial. Many of the available data have been extrapolated from animal experiments or from experience with those few cases where people were subjected to large doses of radiation.

In both studies, it is recognized that radiation doses may be received in two ways:

(a) external dose, assumed uniform over the whole body from gamma rays emitted by the fission products, and

(b) internal dose, often to localized parts of the body, due primarily to inhaled or ingested beta-particle emitters.

For the external gamma-ray dose, there is little difference in the results obtained, although the methods are quite different.

In the AEC study, it is assumed that the dose is proportional to the time integral of the activity per unit volume. For the general fission product activity at two hours, this is

$$1 \frac{\text{curie-second}}{(\text{meter})^3} = 0.28 \text{ rad.}$$

The Michigan study is based on the actual integration of all dose increments received at the point under study, as a function of time, distance, and absorption or scatter in the medium. This method has been best developed by J. Z. Holland; he reduces all considerations including cloud formation to a nomogram. This nomogram method, discussed in the body of the report, is believed somewhat more accurate although, as indicated above, the different methods used yielded minor differences in results.

For the effect of inhaled and ingested beta emitters, there is much wider disparity. In the AEC study, it is assumed that fission-product concentration, at two hours after release, may be equated to whole body dose through

$$1 \frac{\text{curie-second}}{(\text{meter})^3} = 1.29 \text{ rad or } 1.29 \text{ roentgen.}$$

This value is based on a detailed consideration of each fission product, the organ in which it localizes, the local radiation dose, and its whole-body equivalent.

The equivalence is based on estimated values of tolerance for each individual organ and it is here that some questions may be raised. As an example, it is assumed that the estimated roentgen dose to the lungs may be divided by a factor of 5 to establish a whole-body equivalent. This same factor has been used to set the radiation tolerance of body extremities, particularly the hands, as compared to whole-body tolerance. Inquiry at The University of Michigan Department of Roentgenology revealed some skepticism about the factor of 5 and the equivalence of radiation resistance of the hands and lungs.

The Michigan study does not take individual organ tolerance into account, largely because we do not have satisfactory expert information. If all parts of the body are assumed to have equal sensitivity, then using a dose-conversion scheme similar to that used above, we find:

$$1 \frac{\text{curie-second}}{(\text{meter})^3} = 2.5 \text{ roentgen.}$$

This is the value used in the Michigan study.

5. Classification of Dose Received.—In determining the significance of the dose in terms of damage to the person irradiated, slightly different criteria were used in each study. A table, based on broad groups of effects and comparing the two studies has been prepared.

Effect on Persons Exposed (Categories taken from AEC report)	Time Integrated Activity - $\frac{\text{curie-seconds}}{(\text{meter})^3}$		Corresponding Whole-Body Dose-roentgens	
	Values Taken from AEC Report (activity at 24 hours)	Values Calculated for Michigan Study (activity at time of exposure)	Based on $1 \frac{\text{curie-sec}}{(\text{meter})^3} =$ 1.29r	Based on $1 \frac{\text{curie-sec}}{(\text{meter})^3} =$ 2.5r
Lethal Exposure	> 400	> 180	> 450	> 450
Illness Likely	400-90	180-40.5	450-100	450-100
Injury Unlikely	90-10	40.5-4.5	100-25	100-25
No Injury	<10	<4.5	<25	<25

To produce a given inhalation dose as determined in the Michigan study, slightly more than one-half the amount of time-integrated radioactivity concentration necessary in the AEC study is sufficient.

6. Differences in Meteorology.—In both studies, the Sutton Diffusion Equation was assumed to apply. However, there is some difference in the parameters selected. As an example, in representing the inversion conditions, which is the most dangerous since the fission products dissipate slowly, some differences in the parameters appear. However, the end result is not very sensitive to these differences.

The following table is a summary of the values used for the inversion condition:

	Wind Speed (u)-meters per second	Stability Parameter-n	Diffusion Coefficients-(meters)$^{n/2}$	
			C_y	C_z
AEC Study	3	0.55	0.40	0.05
Mich. Study	2	0.60	0.22	0.22
Range of acceptable values as noted in AEC report	1-5	0.40-0.75	0.08-0.05	0.02-0.07

The only significant difference occurs in the case of C_Z. This parameter has some effect on the concentration of radioactivity in the cloud, both in the downwind and crosswind directions.

Rather than single out this one parameter, the variation in concentration downwind and crosswind are given in Figs. A-V-1 and A-V-2.

In general, the cloud behavior in the Michigan study leads to higher concentration in the downwind direction than is found using the AEC assumptions.

7. Use of a Hypothetical vs a Real Site.—The AEC study, designed to be of general value, is made by postulating a site with assumed terrain including a river valley, assumed weather conditions, and assumed population distribution. Its fits no known existing site with any precision.

The Michigan study applies specifically to the Lagoona Beach site and all detailed data are as accurate as could be obtained at the time of the study.

At this point, we must simply analyze the two studies so that results can be compared as related to the actual site in question at Lagoona Beach.

The AEC report assumes that the population around the plant site out to a distance of 30 miles is uniformly distributed in all directions and varies with distance as

$$P = 200 R^{2.83}$$

where

P is the number of persons within a circle of radius R, and

R is radial distance in miles.

Using the approach of counting all persons within a circle of radius R, regardless of direction, the data for the Lagoona Beach site are better represented by

$$P = 175 R^{2.32} .$$

The true population density, measured on a purely radial basis, is much lower for the Lagoona Beach site within a 5-mile circle. The two equations yield results which differ by a factor of about 10, and at 20 miles they differ by about 5.

The following is a table of persons within circles of specified radii for the two sites:

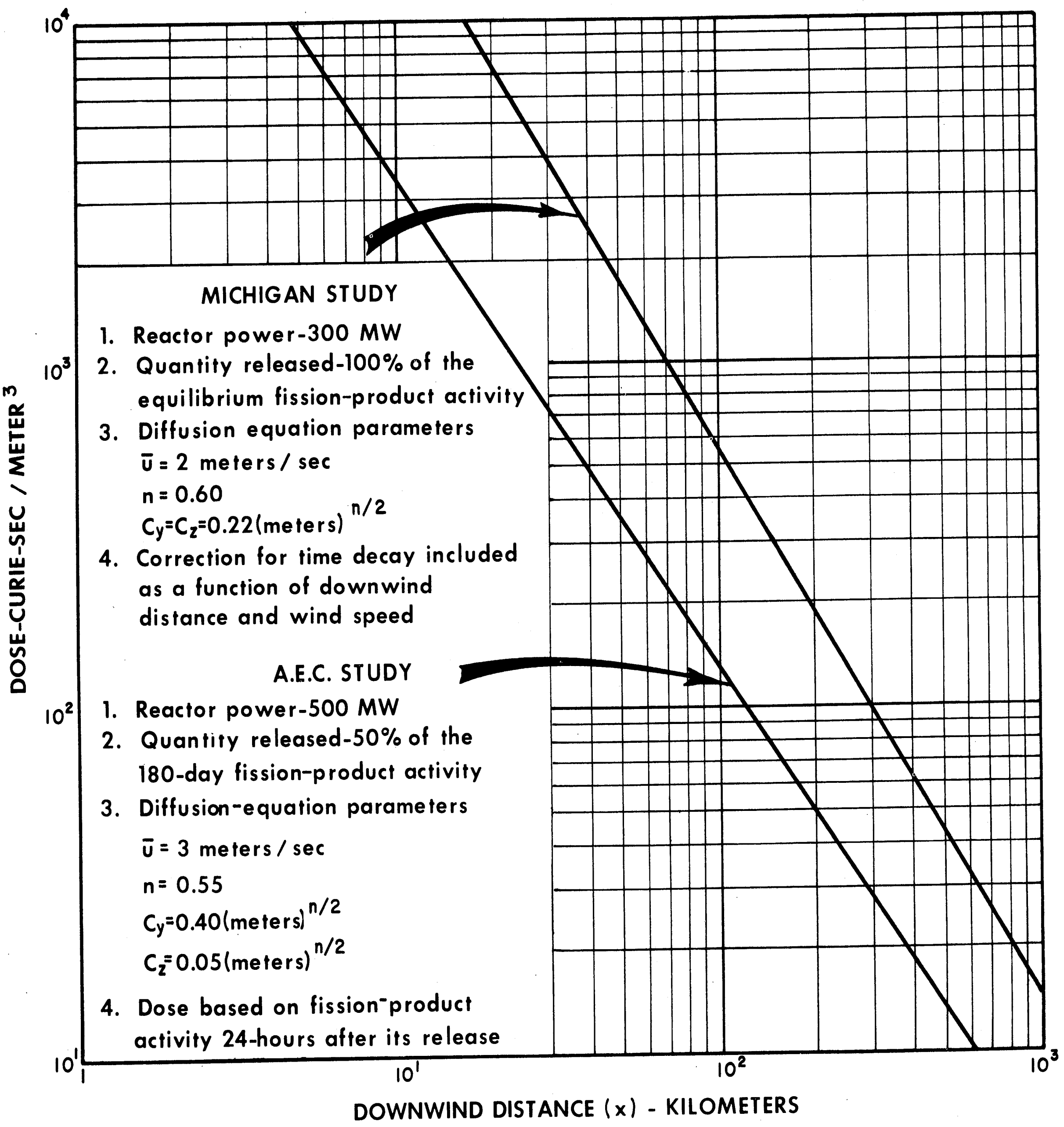


Fig. A-V-1. Comparison of AEC and Michigan study predicted doses due to airborne fission products as a function of downwind distance.

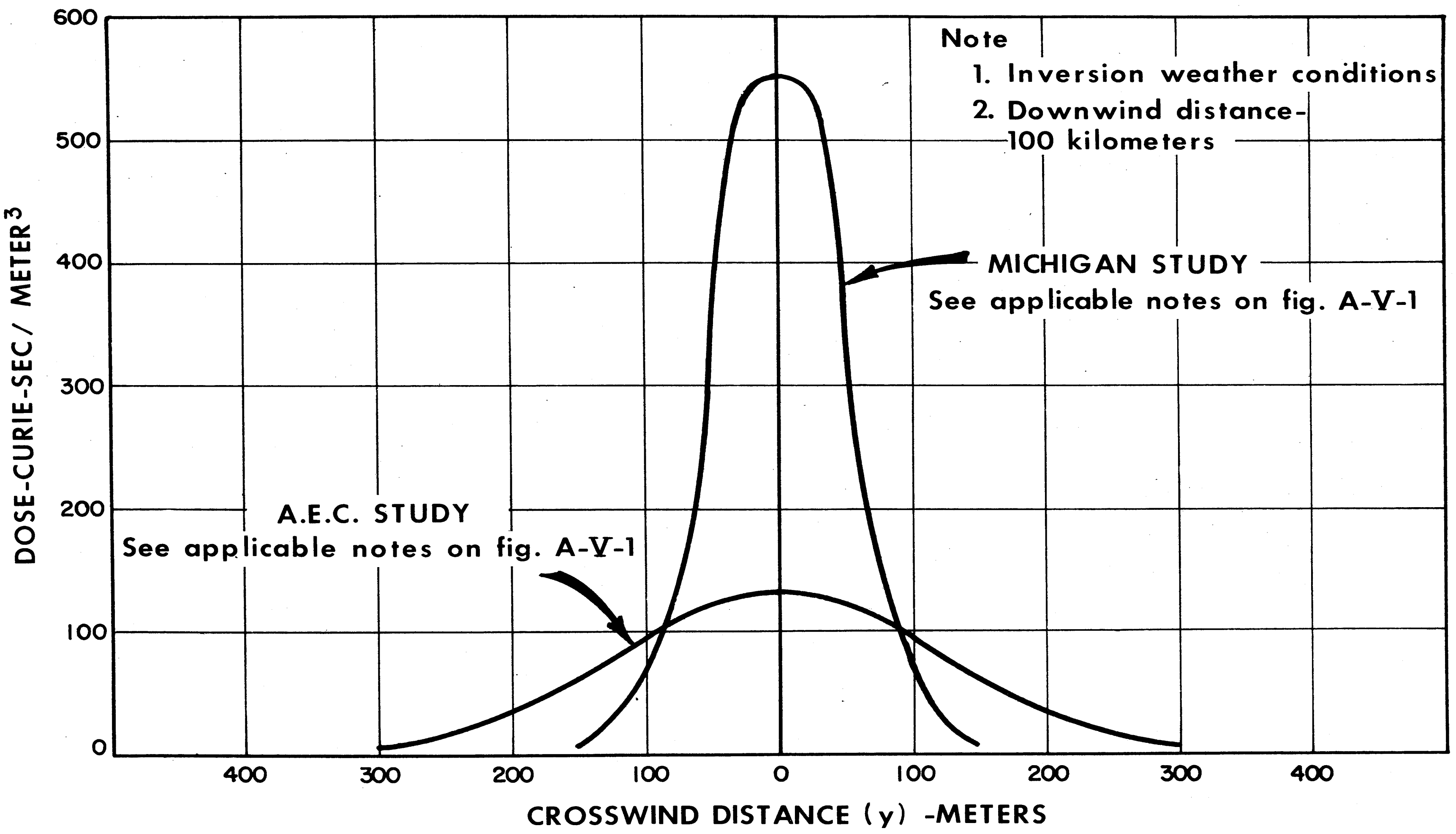


Fig. A-V-2. Comparison of AEC and Michigan study predicted doses due to airborne fission products as a function of crosswind distance.

Circle Radius - Miles	AEC Study (hypothetical site)	Lagoona Beach (actual site)
1	200	175
2	1,420	600
5	19,000	1,800
10	135,500	31,300
20	965,000	187,100
30	3,030,000	2,001,700

In addition to the difference in radial population distribution, there is the very important difference in angular distribution.

The AEC site calculation is based on uniform population distribution in all directions, except for a city 30 miles down the river valley.

The Lagoona Beach site is on the western shore of Lake Erie, so that within a sector of almost 110°, there is no significant permanent population. This is very important since the most probable wind direction is out over the lake as discussed in the body of the report.

The assumption in the AEC study of a major city at 30 miles from the site does coincide with the Lagoona Beach case fairly well. Detroit City Hall is 28.5 miles from the reactor site. The assumed population of the city was 1 million, whereas the Detroit population is about 2 million. This accounts for the great reduction in difference between population figures at 30 miles as seen in the preceding table.

In general, population distribution will be a function of direction as well as distance, particularly over short distances from a reactor site. Depending on the weather conditions, this can have a profound effect on the probability that a random accident will do some amount of damage to persons and property. The Michigan study, since it deals with a real site, includes in its analysis the effect of the population distribution as found.

8. <u>Establishment of Realistic Limits on Distance Traveled by a Radioactive Cloud in Contact with the Ground.</u>—The Sutton Diffusion Equation as used for the major part of both studies predicts that the highest concentration of fission products at any distance from the site is at ground level. This is most significant for the inversion condition.

The weather conditions necessary for the cloud to remain stable as it moves out are necessarily limited in duration. In the AEC study, at one point, it was assumed that the cloud has traveled 3100 miles in the rain in about 19 days under continued inversion conditions. The persistence of either condition alone for the distance and time involved is outside the realm of any data or experience known to us.

Their simultaneous persistence is far more difficult to visualize. From consultation with experts on meteorology and study of the eight-year weather data, a limiting assumption of 100 miles or 22 hours checks far better with known data, and an assumption of 8 hours as the persistence time of a strong inversion is realistic. This must not be confused with radioactivity in low concentration carried at high altitude by persistent jet-stream winds.

In the Michigan study, we have established a limit of 80 miles for the distance a cloud could be expected to travel under strong-inversion conditions. The distance would be traveled in about 18 hours, a long period for persistence of a strong inversion. This problem is discussed more fully in Appendix IV of this report.

C. AN EVALUATION OF THE LAGOONA BEACH SITE USING THE SAME ASSUMPTIONS AS APPEAR IN THE AEC STUDY

In making the original analysis of the Lagoona Beach site, we attempted to make only those assumptions which we felt were defensible from data or because they represented the upper limit of hazard which could exist. The first is typified by our treatment of weather data and the second by our use of 100% fission-product release.

It is felt that it would be useful for comparison purposes to re-evaluate some specific Michigan-study cases, using the same assumptions, where possible, as were used in the AEC study.

These assumptions are as follows:

1. The 400-curie-second/(meter)^3 exposure to airborne activity is equivalent to a radiation dose of 450r. This replaces the 180-curie-second/(meter)^3 factor used previously.
2. Only 50% of the fission products are released, as opposed to 100%.
3. The time decay factor $t^{-0.2}$ as used in the Michigan study is still valid.
4. The parameters for the Sutton Equation used in the Michigan study need not be changed.

In the following table, the original results from Table II in the body of the report for a mean-lethal radiation dose, and the new results using the above assumptions, are compared.

Wind Blowing in the Direction of		Table II of Mich. Study	New Assumptions
Detroit	8°	59,000	17,200
	16°	133,000	39,700
	23°	90,000	20,200
Monroe	227°	16,000	3,500
	245°	6,000	1,800
	265°	4,000	1,100
Toledo	211°	34,000	8,700
	215°	42,000	15,500
	226°	17,000	3,700
Over lake	62°	300	100
	95°-112°	0	0
	170°	0	0

If now we add the assumption that there is fall-out because the particles are 10 microns in diameter, we find:

Wind Blowing in the Direction of		Table II of Mich. Study	New Assumptions
Detroit	8°	9,800	2,900
	16°	24,500	7,300
	23°	3,900	900
Monroe	227°	3,000	600
	245°	2,800	800
	265°	1,100	300
Toledo	211°	7,600	1,800
	215°	13,000	4,800
	226°	3,000	700
Over lake	62°	200	100
	95°-112°	0	0
	170°	0	0

It is seen that using the new assumptions, which are compatible with those made in the AEC report, the predicted effect of a fission-product release is substantially reduced.

D. CONCLUSION

Further detailed analysis and comparisons do not appear worthwhile. We observe, for example, that the AEC analysis leads to the conclusion (as stated in the Tables in their Appendix I) that no one in a city 30 miles from the reactor site would receive a dose of 450r due to the airborne cloud in the case of an accident which would release 50% of the contained fission products regardless of weather conditions. The maximum range for 450r is 15.5 miles as stated in Table I, page I-3. However, Eq. (11), page F-2, predicts that the 450r contour extends 27.1 miles under inversion weather conditions, approximately the same value one obtains from Fig. 2 in the AEC's Appendix E. We feel that further detailed analysis should await clarification of these discrepancies.

It is important to note however, that almost invariably the AEC assumptions, where applicable, do predict a less severe result than does our study.

The conclusion cannot be drawn that the Lagoona Beach site is less desirable than the hypothetical AEC site because the AEC prediction of accident severity is less severe than ours. Actually, the strict application of their techniques to our data leads to the conclusion that Lagoona Beach may be more desirable than we have pictured it. We have not gone all the way with this, because, as indicated above, we cannot accept some of the premises used to obtain their results.

Our major conclusion is that the AEC analysis sheds no new light on the suitability of the Lagoona Beach site. If anything, the AEC report indicates that the site is more acceptable than our study shows.

REFERENCES

1. Meteorology and Atomic Energy. Washington, D. C.:AECU 3066, p. 108 (July, 1955).

2. Way, K., and Wigner, E. P., "The Rate of Decay of Fission Products," Physical Review, 73, pp. 1318-1330 (June 1, 1948).

3. Description of Developmental Fast Breeder Power Reactor Plant. Detroit: APDA-108 (Sept. 1, 1955).

4. Meteorology and Atomic Energy, p. 45.

5. Ibid., p. 45.

6. Ibid., p. 102

7. Ibid., p. 150.

8. "Radioactive Dust from the Nuclear Detonation," Bull. Inst. Chem. Res. Kyoto: Kyoto Univ. (Nov., 1954).

9. Chamberlain, A. C. Aspects of Travel and Deposition of Aerosol and Vapour Clouds. Harwell, Berks.:A.E.R.E. HP/R 1261 (1955).