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DEVELOPMENT OF A WINDSPEED RISK MODEL FOR THE SAVANNAH RIVER PLANT SITE

Prepared for

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by

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FOREWORD

The development of tornado and extreme wind risk models for the Savannah River Plant site was conducted under E. I. Du Pont De Nemours Purchase Order No. AXC 672-W. Mr. Fred Morris of the Du Pont De Nemours Company served as the technical representative for monitoring the project. Dr. James R. McDonald of Texas Tech University served as project manager and principal investigator. He was assisted by Dr. Kishor C. Mehta, Dr. Joseph E. Minor, Dr. Richard Peterson, and Mr. Lynn Beason also of Texas Tech University. The research was coordinated through the Department of Civil Engineering and the Institute for Disaster Research, Texas Tech University.

This document provides a basis for determining design windspeeds and appropriate tornado and extreme wind parameters for any specified level of risk. These parameters may then be used to determine appropriate design loads on structures. The determination of the design loads, however, is beyond the scope of this project.

SUMMARY

A windspeed risk model, which, by definition, is the point probability of windspeeds exceeding some threshold value in one year, has been developed for the Savannah River Plant site. The risk models account for the possibility of tornadoes and extreme winds at the site. The windspeed risk models recommended for determining design wind loads are given in Table IX and are plotted in Figure 8. For any selected level of risk, the maximum horizontal windspeed resulting from tornadoes or extreme (straight) winds can be determined from the windspeed risk models. Other windspeed related parameters such as wind velocity components, atmospheric pressure change relationships and windborn missile characteristics may then be derived. The relationships between these various parameters are summarized in Table X. Parameter values for various maximum horizontal windspeeds are also given in Table X.

The windspeed risk model was developed from records of tornado and extreme wind occurrences that have taken place near the Savannah River Plant site. The tornado records cover a 15 year period from 1959-1973, whereas the windspeed records are based on a 21 year period, 1945-1965.

In the report the meteorological conditions expected and observed are reviewed. The methodology for calculating the tornado risk model is developed, and details of the computations for the Savannah River Plant region are summarized. The uncertainties associated with the tornado risk model methodology are evaluated and discussed.

Next the extreme (straight) wind risk model is determined. In the last section appropriate tornado and extreme wind parameters relating to wind, pressure change and missiles are provided for various levels of risk.

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I. INTRODUCTION

A windspeed risk model gives the probability that any point within a defined geographical region will experience windspeeds greater than or equal to some threshold value in one year. Tornado and extreme wind risk models are presented in this report for the geographical region surrounding the Savannah River Plant Site near Aiken, South Carolina. The tornado risk model was developed from records of tornadoes during the period 1959-1973. The extreme wind records cover a period of 21 years (1945-1965).

Once the risk models are established, the maximum design windspeed is determined for any specified level of risk. It is not the purpose of this study to advance probability values that represent acceptable levels of risk. These decisions must be made by appropriate plant authorities. The level of risk selected depends on the criticality of the structure with respect to personnel and environmental safety. Other wind parameters such as atmospheric pressure change and windborne missile characteristics are dependent on the maximum design windspeed. These parameters are deduced from straight wind and an appropriate tornado wind field model.

The first tornado risk model is attributed to Wen and Chu [1]. They used a limited amount of data accumulated by Fujita [2] to construct a joint probability distribution for average tornado damage path area and peak windspeed. The damage path area of a tornado is defined as the area bounded by damage from winds greater than or equal to 75 mph. Although peak intensity winds occur only over a small portion of this area, the original Wen and Chu Model assumed that the peak windspeed extended over the whole area. McDonald [3] and Garson [4] suggested that a windspeed decay from peak out to gale intensity be introduced. This concept was incorporated in subsequent work by Wen [5]. The assumptions made by Wen and Chu that average tornado damage path and peak windspeed is invariant with respect to geographical location has not been substantiated. In fact, studies by the authors have indicated that there is considerable variation from one geographic region to another [6, 7].

A second approach to the development of a tornado risk model was, in effect, presented by Markee, Beckerly and Sanders [8] in their document supporting the AEC Regulatory Guide 1.76 [9], although they did not specifically refer to it as a risk model. In this approach the assumption is made that the probability of strike occurrence and the probability of intensity occurrence are independent events. A mean damage path area of 2.82 sq. mi., based on Thom's work with Kansas and Iowa tornadoes [10], was used to determine probability of strike. This value of mean damage-path area is considerably larger than mean values found for specific geographic regions [11].

Because of inherent shortcomings in both approaches described above, an alternate method was used by the authors to develop the tornado windspeed risk models presented herein. The details of the development are described in subsequent chapters. In general, the approach is based on existing records of tornado occurrence in the geographic region surrounding the plant site. From these records a relationship between damage-path area and windspeed intensity is obtained. This data is then combined with an occurrence-intensity relationship to determine the probability of tornadic windspeeds exceeding any threshold value within a one-year period.

The work of Thom [12] is used to determine the risk model for extreme winds. The Frechet (Fisher-Tippet Type II) distribution of extreme winds is extrapolated to determine probability of straight winds exceeding any threshold value within a one-year period.

The remaining sections of this report present a summary of the investigations conducted and contain discussions of the techniques used for arriving at the tornado and extreme wind risk models. Tornado parameters, including those associated with wind, atmospheric pressure change and missiles, are presented in the last section of the report.

II. METEOROLOGICAL CONDITIONS

The Savannah River Facility lies about 110 mi northeast of the Atlantic Coast, not far from the fall line separating the gently sloping Coastal Plain from the higher ground of the Piedmont Plateau. This location enjoys a strongly modified seacoast climate with a measure of protection from continental cold air invasions.

The mean winds from April through August are from the sea at about 6 mph. During the fall, frontal passages allow air to be diverted southwestward along the coast. Through the remainder of the year the prevailing wind is northwesterly at 68 mph, with increasing frequency of frontal activity.

During the spring, thunderstorms may be triggered by frontal invasions of cooler air. These may be accompanied by strong straight winds in outflow regions with some damage resulting. Into summer, thunderstorms continue but are primarily due to localized heating and orographic forcing. Roughly two out of five days from June into September may experience thunderstorms; cooler temperatures in the fall however tend to suppress the air mass activity.

The thunderstorms, sometimes in squall lines, during the spring may occasionally spawn tornadoes. There have been relatively few tornadoes in South Carolina, however, over the the first half of this century the state recorded about four per year, primarily in the western and central portions.

Severe tropical storms have affected the area on an average of once every ten years, bringing the largest rainfall amounts, but generally presenting less wind damage than the more severe thunderstorms. The hurricanes, which usually develop from mid-summer into fall, may occasionally spawn tornadoes as well; again, however, the spring occurrences would be expected to be more severe.

III. DEVELOPMENT OF TORNADO RISK MODEL

The tornado risk model is determined from statistical analysis of records of tornadoes that have occurred in the region surrounding the Savannah River Plant site. The basic tornado data used in this study are expressed in terms of Fujita-Pearson Scales [13]. The Fujita Scale (F-scale) rates tornadoes on the basis of their maximum windspeed. The Pearson Scales rate tornadoes according to their path length (P_L) and average damage path width (P_W). Thus, a tornado can be given an FPP rating that describes its maximum windspeed and the extent of its damage path. The Fujita-Pearson (FPP) scale is described in Appendix A.

Each tornado since 1971 has been given an FPP rating by the Meteorologist-In-Charge (MIC) of the National Weather Service in the region where the tornado occurred. Where damage descriptions are available for tornadoes that occurred prior to 1971, it is possible to assign F-scale ratings to these storms. Records of damage path areas are very incomplete prior to 1971.

In this section the methodology for developing the tornado risk model is described in general terms. Then the specific details of developing the risk model for the Savannah River site are described. Finally the risk model is evaluated in terms of the uncertainties involved.

Methodology for Developing the Tornado Risk Model

The risk model is developed on the basis of Fujita-Pearson (FPP) Scales, since tornado intensities are expressed in terms of FPP-scales.

Four basic steps are involved:

1. Determination of a damage area-intensity relationship in a global region surrounding the plant site.
2. Determination of an occurrence-intensity relationship in a local region surrounding the plant site.
3. Calculation of the probability of a point in the local region experiencing windspeeds in some class interval.
4. Determination of the probability of windspeeds in the local region exceeding interval values.

A plot of the results of step four is the tornado risk model. Each of the four steps is described in the paragraphs below.

Damage Area-Intensity Relationship

A global region, which may contain several states, is defined for purposes of determining a damage area-intensity relationship. Factors considered in selecting a particular global region are:

1. The region should generally surround the plant site.
2. The region should generally contain the same type of terrain.
3. The region should have common meteorological conditions on a synoptic scale, as they relate to the formation of tornadoes.
4. The region should be of sufficient size to give an adequate sample size for determining the area-intensity relationship.

Existing tornado records give Fujita scale (F), Pearson path length (P_L), and Pearson path width (P_W) scales for most tornadoes in the three year period 1971-1973. From the P_L and P_W ratings, the damage area in square miles for each tornado is determined using the median length and width of each classification. Three years of relatively complete data in the global region are used to develop the damage area-intensity relationship instead of, say, 15 years of incomplete data in a local region.

Occurrence-Intensity Relationship

A local region within the global region is defined to promit determination of an occurrence-intensity relationship. The size of the local region may range from a 1-degree to a 5-degree square, (a 1-degree square is generally too small), depending on the number of tornado occurrences in the vicinity of the plant site.

The number of tornadoes exceeding each F-scale classification is obtained from the master list of tornado occurrences in the local region in the 15 year period from 1959-1973. This relationship is fitted to appropriate curves using regression analyses to give a continuous relationship between occurrence and intensity. From this curve the number of tornadoes occurring in arbitrary, but equal, class intervals are obtained and denoted λ_i. The set of λ's for all class intervals is the desired occurrence-intensity relationship.

Probability of Windspeeds in Some Class Interval

The probability that any point within the local region will experience a windspeed that is contained in the interval $\bar{V}_j$ from tornadoes whose maximum windspeeds are contained in the interval $\bar{V}_i$ is given by the expression

$$P(V=\bar{V}_j) = \frac{1}{A} \sum_{i=j}^{n} \lambda_i a_{ij} \qquad (1)$$

where A is the geographic area of the local region (sq mi)

λ_i is the occurrence-intensity relationship (tornadoes per year)

a_{ij} is the area within the damage path that experiences windspeeds $\overline{V}_j$ in a tornado whose maximum windspeed is in the class interval $\overline{V}_i$, ($i \geq j$) (sq mi)

n identifies the class interval containing the largest tornado windspeeds considered.

The intervals designated by $\overline{V}_i$ and $\overline{V}_j$ are defined for this study as

i or j	1	2	3	4	5	6	7
Windspeed interval (mph)	50-100	100-150	150-200	200-250	250-300	300-350	>350

The integer i refers to the class interval of maximum tornado windspeeds; the integer j refers to some class interval less than or equal to i. The magnitude of a_{ij} depends on the maximum intensity of the tornado and its mean damage path area. Assuming the windspeed model to be a Combined Rankin vortex, the values of a_{ij} are given by

$$a_{ij} = 75 a_i \left(\frac{V_{j+1} - V_j}{V_j \, V_{j+1}}\right) \qquad (j<i) \qquad (2)$$

$$a_{ij} = \frac{75}{V_j} \, a_i \qquad (j=i) \qquad (3)$$

where a_i is the mean damage area caused by winds greater than or equal to 75 mph by tornadoes whose maximum windspeeds are in the interval i. For 50 mph class intervals, Equation (2) becomes

$$a_{ij} = \frac{3750 \, a_i}{V_j \, V_{j+1}} \qquad (j<i) \qquad (4)$$

Derivations of Equation (2) and (3) are given in Appendix B.

'Probability of Windspeeds Exceeding Interval Values

The probability that a point within the local region will experience windspeeds greater than or equal to $\bar{V}_j$ is

$$P(V \geq \bar{V}_j) = \sum_{j=j}^{n} P(V = \bar{V}_j) \qquad (5)$$

A plot of $P(V \geq \bar{V}_j)$ versus windspeed is, by definition, the tornado risk model.

Development of Tornado Risk Model for the Savannah River Plant Site

Regions, both global and local, are first defined for purposes of determining an area-intensity relationship and an occurrence-intensity relationship respectively for the Savannah River site. Appropriate tornado records are then assembled in terms of FPP scales. Five local regions were defined and the tornado risk model for each one was developed. The risk models for the five local regions are compared and the one deemed most appropriate is selected as the recommended tornado risk model for the plant site. The final risk model is then evaluated in terms of the uncertainties of data, meteorological conditions, and the basic approach.

'Definition of Global and Local Regions

A global region containing the states of Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, Tennessee, South Carolina, Virginia, and West Virginia was defined for purposes of determining the damage area-intensity relationship. Complete data on tornado damage-path size are only available for a three year period 1971-

1973. Thus, a large geographic area is used with a relatively short reporting period. For the occurrence-intensity relationship a smaller (local) region is used with a 15 year reporting period (1959-1973).

The size of the local region must be carefully selected. Ideally the region should be chosen as small as possible, but because of the random distribution of tornado occurrences in an area, risk levels may be predicted that are too high (or too low), depending on the actual distribution of tornadoes in the area. In this study five local regions were defined .

Local Region I:	1-degree square	4000 sq mi
Local Region II:	2-degree square	16000 sq mi
Local Region III:	3-degree square	34300 sq mi
Local Region IV:	4-degree square	57800 sq mi
Local Region V:	5-degree square	86500 sq mi

The regions were defined on the basis of degree squares because the tornado records contain tornado touchdown points in terms of latitude and longitude. The ocean area was deducted from the total area of the degree square, since no tornado touchdown points were recorded over the ocean. Details of the calculations for the 5-degree square region are presented for illustration purposes. Development of the risk models based on the other local regions follows a similar pattern.

Tornado Records in the Savannah River Plant Regions

The technical literature and various sources of National Weather

Service records were reviewed for the purpose of establishing a master list of tornado occurrences in the local regions. A computer listing of all tornado occurrences in the United States has been assembled by the National Severe Storms Forecasting Center (NSSFC) in Kansas City, Missouri [14]. This tape contains the date, time, location, path length, path width, extent of damage, number of deaths and injuries for most tornadoes since 1950. Prior to 1971, the details are somewhat incomplete.

The data from the NSSFC tape was supplemented by records from Storm Data [15], a publication of the National Oceanic and Atmospheric Administration, Asheville, North Carolina. The Storm Data records go back to 1959. The most significant information contained in this publication are brief word descriptions of the damage caused by tornadoes. These word descriptions were used to assign Fujita Scale (F-scale) ratings to the tornadoes. Other sources of tornado records were checked to be sure that the master list was complete [16, 17, 18, 19]. Use of the records in developing the tornado risk model is described below.

Tornado Risk Model for the 5-Degree Square Local Region

A total of 389 tornado occurrences were recorded in the 5-degree square region in the fifteen year period 1959-1973. Their touch-down points and intensity in terms of F-scale are plotted in Figure 1. The average number of tornadoes per year in the region was 25.9. Figure 2 shows the number of tornadoes per year over the 15 year period. The largest number recorded in any one year was 57 in 1973. The

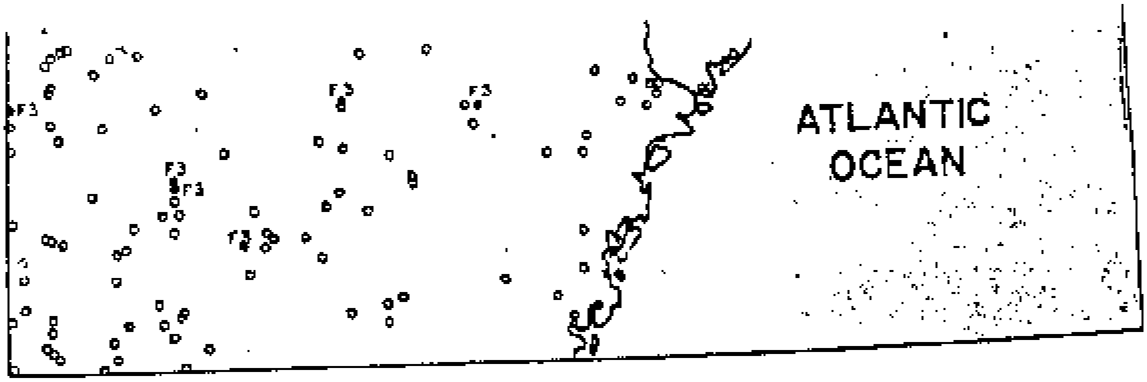


FIGURE 1. TORNADO OCCURRENCES AND INTENSITIES
SAVANNAH RIVER PLANT REGION

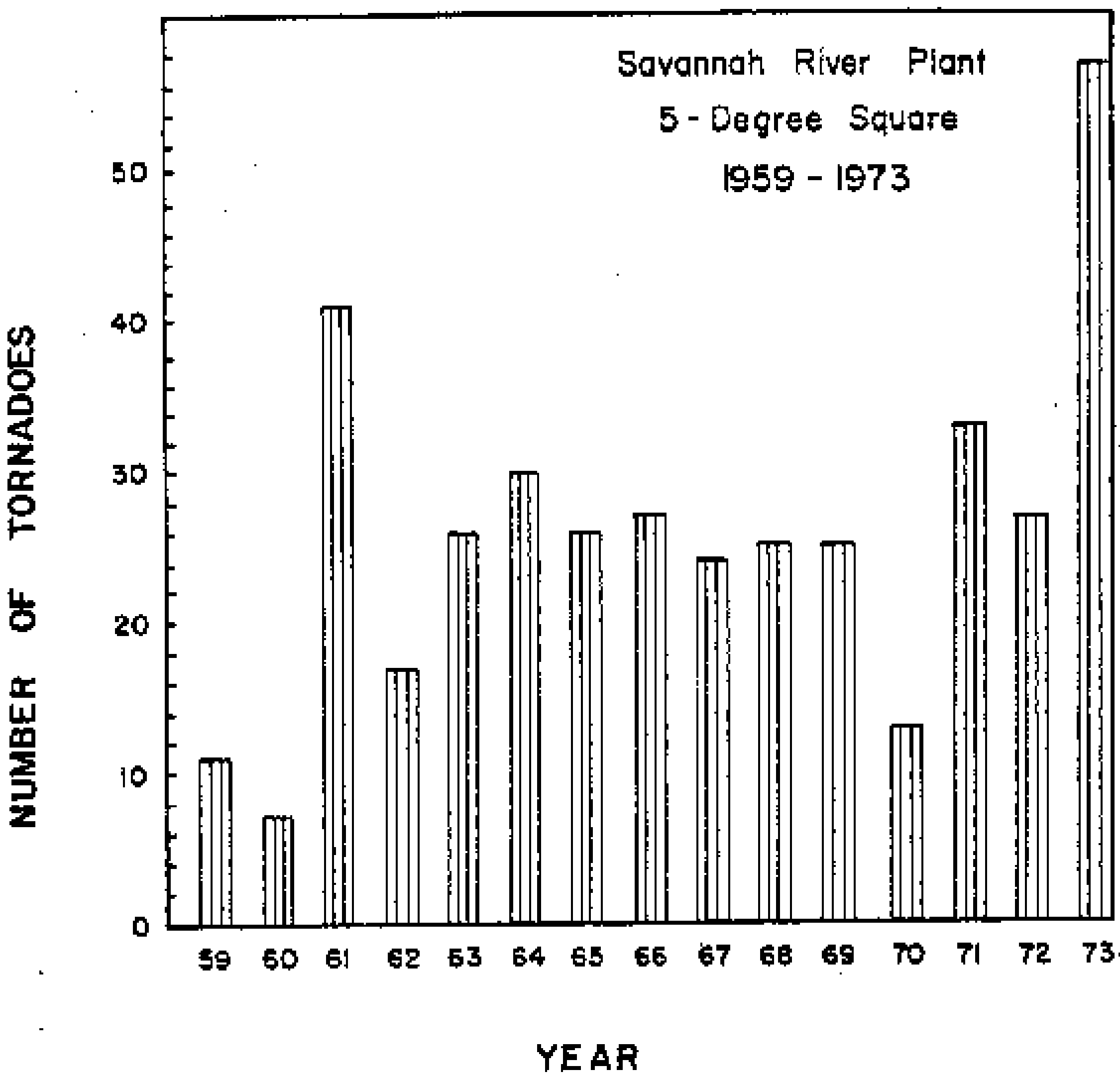


FIGURE 2. NUMBER OF TORNADOES PER YEAR

smallest number was 7 in 1960. Figure 3 shows the number of tornadoes in each F-scale classification. Of the 389 tornadoes that have occurred in the 5-degree region, 61 percent had maximum windspeeds less than 112 mph, while 92 percent has maximum windspeeds less than 157 mph. Table I lists all significant tornadoes that have occurred within the 5-degree region.

Table II lists the mean damage-path areas for each F-scale classification in the global region surrounding the Savannah River site. Examination of values of the standard deviation indicates that areas affected by individual tornadoes vary widely. In Figure 4 mean damage path area versus windspeed is plotted for each F-scale classification. An appropriate line is fitted through the points by means of a regression analysis in order to provide a relationship between mean damage-path area and windspeed. The curve thus obtained is the desired area-intensity relationship, a_i. Values of a_i for tornadoes whose maximum windspeeds are contained in the intervals $\bar{V}_i$ are given in Table III.

The cumulative number of tornadoes exceeding each F-scale classification is obtained from the master list of tornadoes that have occurred in the local region. This relationship is fitted to appropriate lines using regression analyses to obtain relationships between occurrence and intensity (See Figure 5). From this figure the number of tornadoes occurring in arbitrary, but equal class intervals is obtained. The number of tornadoes per year in each class interval, λ_i, are shown in Table IV for the 5-degree square local region.

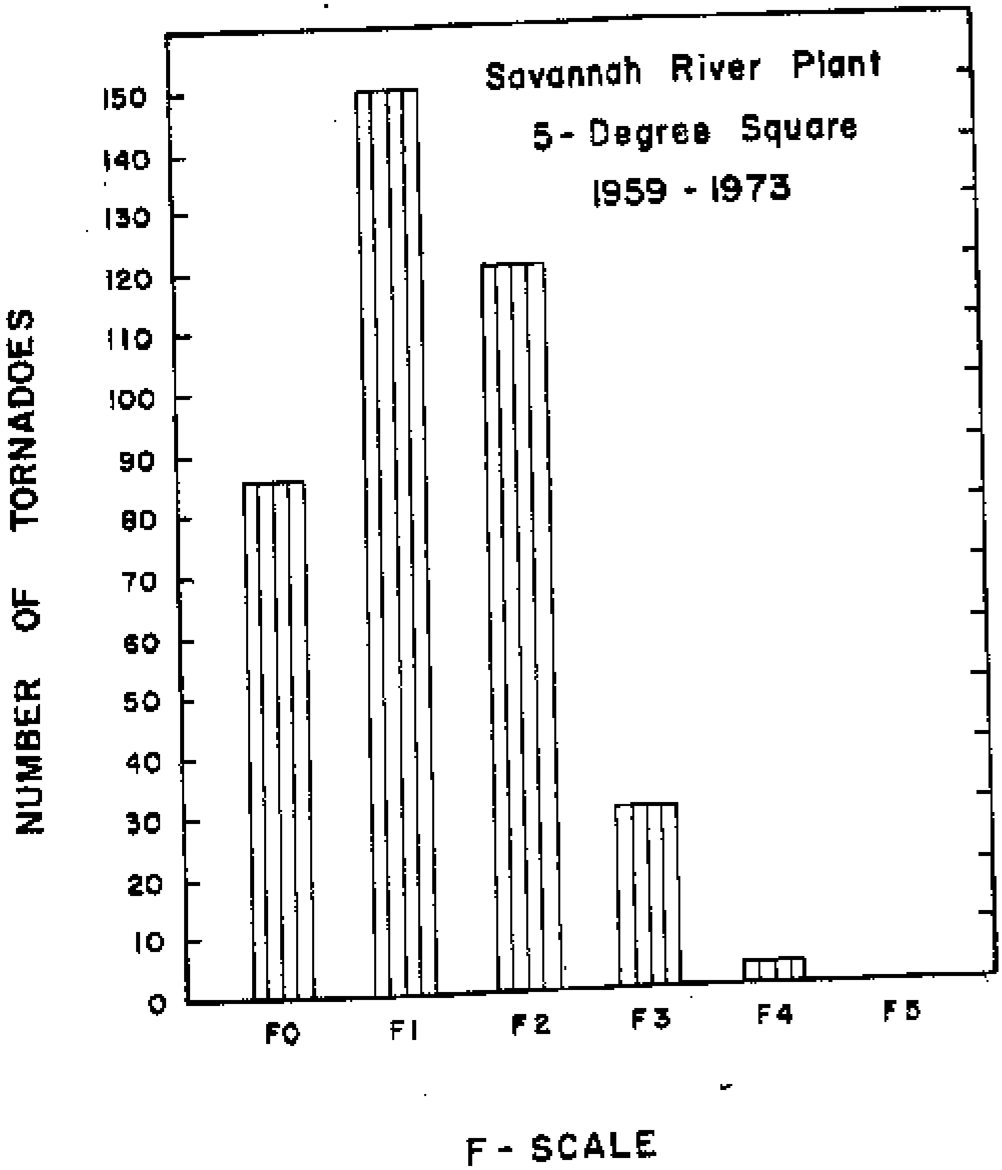


FIGURE 3. NUMBER OF TORNADOES IN EACH F-SCALE CLASSIFICATION

TABLE I

SIGNIFICANT TORNADOES IN 5-DEGREE LOCAL REGION

Date	Location	F	P_L	P_W	D*	I**	Comments
8/29/64	Richmond and Scotland Counties, NC	3	3	1	0	15	Tornado moved WNW. Demolished 2 churches, six house trailers and a dozen or more frame buildings; unroofed several brick business buildings.
10/7/65	Randolf County, NC	3	1	1	1	4	A small tornado; demolished a small brick and concrete block factory; blew down or broke off a few trees.
7/11/65	Near Mansfield, Newton County, GA	3	2	0	0	0	Tornado demolished one frame house; unroofed and heavily damaged a masonry house; trees were uprooted; storm moved westward.
2/13/66	Oglethorpe County, GA	3	2	3	0	1	Tornado demolished five large poultry houses; destroyed a new brick residence; overturned two house trailers; damaged roofs; trees were uprooted and twisted off.
5/16/66	Two mi S of Fitzgerald, GA	3	0	0	0	0	Tornado demolished two buildings; heavily damaged hangars at airport; damaged four airplanes in the hangars
11/11/68	North County near Doerum, GA	4	1	2	0	0	A residence was torn from its foundation and moved 50 yds; it was heavily damaged, but left more or less intact; a car and pickup were carried 100 yds by the winds

TABLE I (Con't)

SIGNIFICANT TORNADOES IN 5-DEGREE LOCAL REGION

Date	Location	F	P_L	P_W	D*	I**	Comments
9/18/69	Scotland, Robeson, Cumberland Counties, NC		4	3	0	0	Tornado touched down only occasionally for short distances; large trees blown down or broken off above ground; several frame buildings demolished; utility lines broken, poles blown down; mobile home carried 50 yds and destroyed.
4/19/69	Darlington, Chesterfield and Marlboro Counties, SC	3	4	2	0	3	Tornado touched ground several times along its 42 mi path; destroyed a poultry farm building and killed 1000 chickens; a trailer and 2 homes were demolished; further down path it touched down for 1 or 2 miles damaging houses, barns, trailers, power lines and trees; later it destroyed more houses and mobile homes; translational speed was estimated at 40 mph.
4/18/69	Coffee County, GA	3	3	-	0	27	Damage was almost continuous along the path which ranged up to almost a mile in width; 19 mobile homes were completely destroyed; 60 to 70 farm buildings demolished; timber losses were tremendous and telephone and power line damage was extensive.
4/9/70	Royston, GA	3	1	.2	0	0	Tornado destroyed several large poultry houses; one mobile home seemed to disintegrate; poultry house exploded outward and debris and trees were blown in all directions.

TABLE 1 (Con't)

SIGNIFICANT TORNADOES IN 5-DEGREE LOCAL REGION

Date	Location	F	P_L	P_W	D*	I**	Comments
7/22/70	Emanuel County, GA	3	1	3	1	2	Tornado demolished two houses and a barn; damaged two other houses; crops were flattened.
4/23/71	Sumpter, Dooly, and Crisp Counties GA	3	3	2	0	8	Tornado completely demolished a large brick home and several other smaller buildings; auto was carried end over end for 150 ft; extensive damage to cottages, trailer houses, boat houses and boats at a fishing camp; several farm homes and other buildings destroyed; hundred of trees sheared off or blown over; boards from a home were found sticking in the ground 7 mi away.
1/13/72	Jefferson and Burke Counties GA	3	3	3	0	21	Tornado destroyed two farm homes, several barns and a large amount of farm equipment; destroyed 2 mobile homes and the County Forestry Unit Equipment Shed; a fifteen acre pecan grove was flattened; many other trees were uprooted or broken off; power and telephone poles were down.
3/31/73	Abbeville and Greenwood Counties SC	4	3	3	7	30	Tornado moved ENE; 50 families left homeless; many other houses sustained minor damage; struck a motel; the entire motel, its furnishings and occupants, from the foundation upward, were carried across the highway toward the south and spread over a large field.

TABLE I (Con't)

SIGNIFICANT TORNADOES IN 5-DEGREE LOCAL REGION

Date	Location	F	P_L	P_W	D*	I**	Comments
3/31/73	North Central, GA	3	4	3	2	100	A devastating tornado moved ENE through central GA causing extremely heavy and almost continuous damage along a 75 mi path. A State Survey team estimated damage as follows: 400 homes destroyed, 1784 homes damaged, 32 businesses destroyed, 76 businesses damaged; damage to business property left 1500 jobless; 2600 were left homeless.
5/28/73	Walton, Oconee and Clarke Counties, GA	3	3	3	1	65	Destruction was very heavy near Athens, GA; destruction included 49 residences destroyed, 175 heavily damaged and 321 with minor damage; 6 business buildings destroyed, 17 businesses damaged.
12/13/73	Greenwood and Laurens Counties, SC	3	3	3	0	3	Tornado was in contact with ground 20 percent of time causing extensive damage.
12/13/73	Greenwood County, SC	4	0	1	2	0	Tornado was associated with the one described below. Touched down briefly in the Ninety Six Area causing extensive damage.
12/13/73	Greenwood and Newberry Counties, SC	3	3	3	0	26	Tornado was on ground 20 percent of the time, causing extensive damage to homes, utilities and industrial property; major damage was in the Ninety Six Area and Chappels Area.

TABLE I (Con't)

SIGNIFICANT TORNADOES IN 5-DEGREE LOCAL REGION

Date	Location	F	P_L	P_W	D*	I**	Comments
12/13/73	Newberry County, SC	3	1	3	1	0	Tornado hit Mid Carolinia School; damaged or destroyed 48 homes and 10 mobile homes; width of path suggests a double funnel along part of path.
12/13/73	Gainsville, GA	3	3	3	0	21	Fifty homes were severely damaged; 8 mobile homes destroyed.

* Deaths
** Injuries

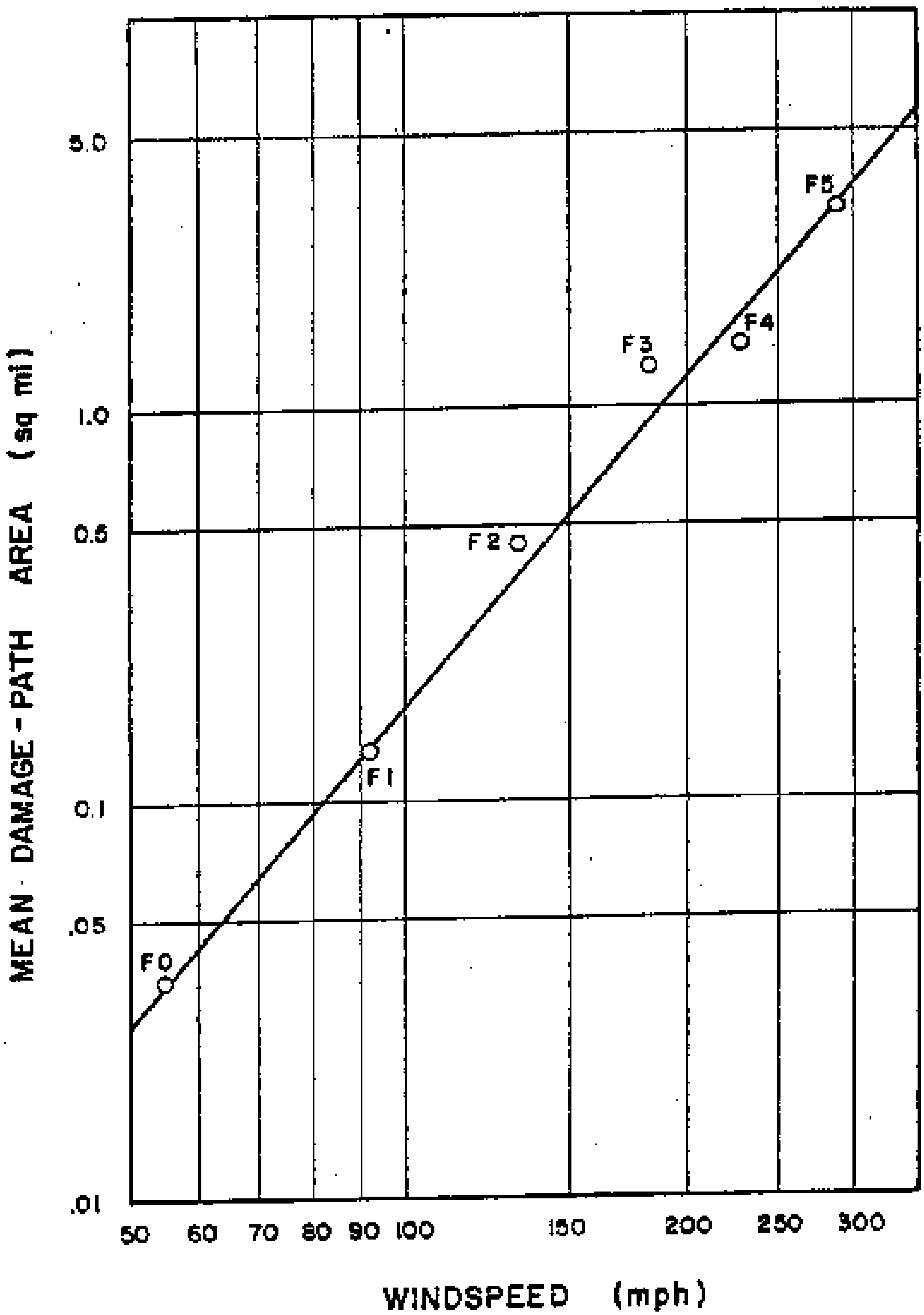


FIGURE 4. MEAN DAMAGE-PATH AREA VERSUS WINDSPEED

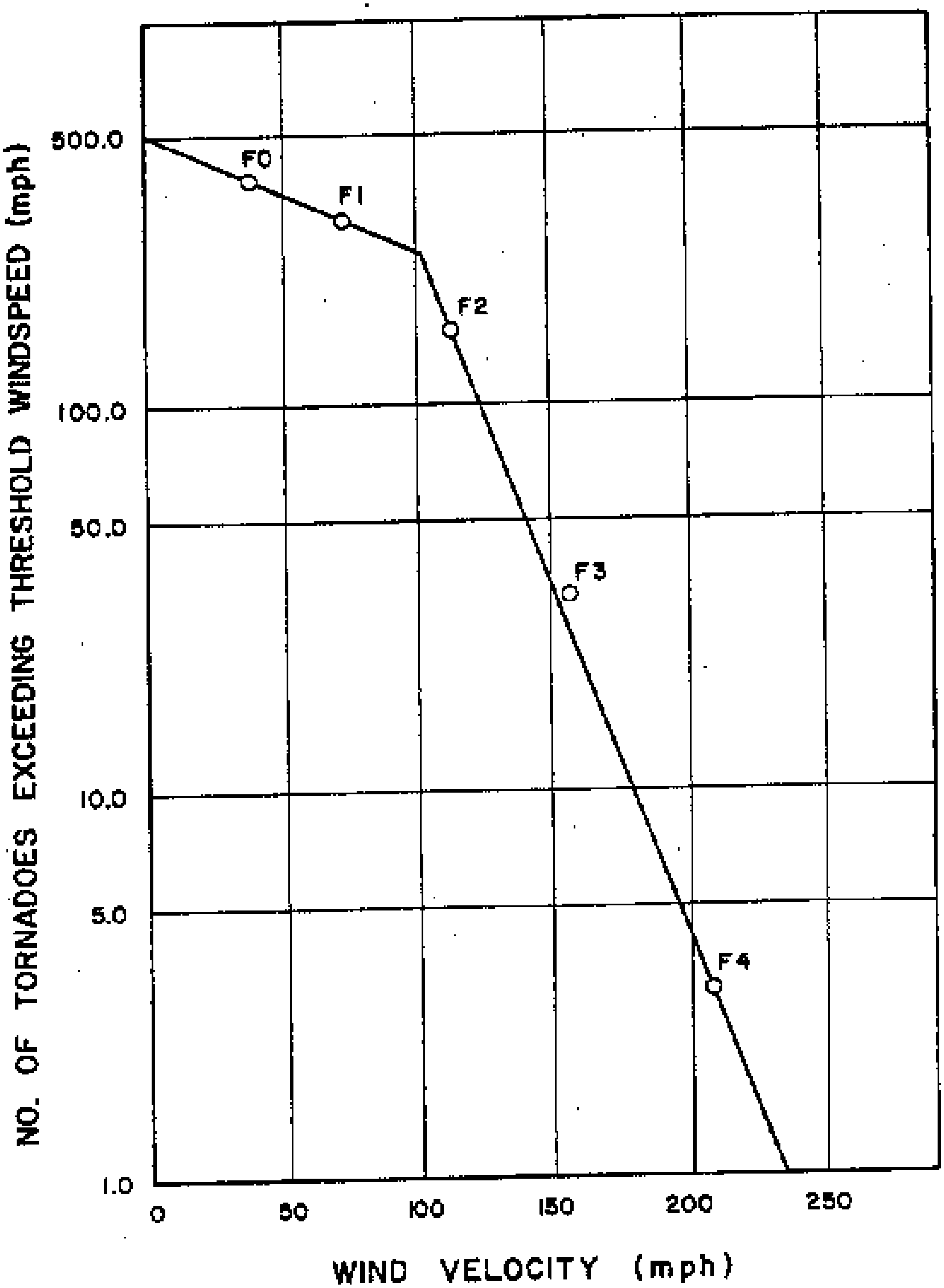


FIGURE 5. NUMBER OF TORNADOES EXCEEDING THRESHOLD WINDSPEED

TABLE II

MEAN DAMAGE-PATH AREA FOR EACH
F-SCALE CLASIFICATION IN GLOBAL
REGION SURROUNDING SAVANNAH RIVER SITE

	F0	F1	F2	F3	F4	F5
No. of Tornaodes	72	245	177	49	13	2
Mean Damage-Path Area (Sq mi)	0.036	0.140	0.463	1.261	1.485	3.169
Standard Deviation	0.077	0.349	1.246	1.714	1.412	0.003

TABLE III

MEAN DAMAGE-PATH AREA FOR TORNADOES
WITH MAXIMUM WINDSPEEDS IN THE
INTERVAL, $\bar{V}_i$

MEAN DAMAGE-PATH AREA a_i, Sq Mi

50-100	100-150	150-200	200-250	250-300	300-350	>350
0.0851	0.3411	0.8513	1.6858	2.9089	4.5809	6.7593

TABLE IV

NUMBER OF TORNADOES PER YEAR IN INTERVAL $\bar{V}_i$

λ_i (Tornadoes/Year)

50-100	100-150	150-200	200-250	250-300	300-350	>350
7.58	14.03	2.14	0.26	0.03	0.004	0.0005

Table V and VI then summarize the calculations required for obtaining the tornado risk model. The upper part of Table V lists the values of a_{ij} (Equation 2) for the selected class intervals. The lower part of the table gives the probable area exposed to wind speeds in the interval $\overline{V}_j$, from tornadoes whose maximum intensities are contained in the intervals $\overline{V}_i$ ($i \geq j$). The last line of Table VI gives the probabilities of exceeding the interval windspeeds $\overline{V}_j$, in one year, which is by definition, the tornado risk model.

Tornado Risk Models for Other Local Regions

Tornado risk models were computed for the five local regions surrounding the Savannah River Plant site. Table VII lists the number of tornadoes in each F-scale classification for each region. The tornado windspeed probabilities are summarized in Table VIII and the windspeed risk models for the five regions are shown in Figure 6. A decision then had to be made as to which risk model was most representative of the tornado risks in the vicinity surrounding the Savannah River Plant site.

The risk model for the 5-degree square is the one considered most appropriate for the Savannah River Plant site. There are no meteorological or topographical conditions associated with the locale that would lead one to expect a variation in tornado probabilities between say the 1-degree square and the 5-degree square. The differences between the various local regions must therefore be attributed to the variation of statistical data within the five local regions. In order to evaluate these differences, confidence limits were established for each of the five local regions. The two most significant statistical parameters are the area-intensity and the occurrence-intensity relationships. Confidence

TABLE V

PROBABLE AREA EXPOSED TO WINDSPEEDS V_j FROM TORNADOES OF INTENSITY V_i

V_i \ V_j	50-100	100-150	150-200	200-250	250-300	300-350	350	a_i
	a_{ij}, sq mi							
50-100	0.128							0.085
100-150	0.256	0.256						0.341
150-200	0.638	0.213	0.426					0.851
200-250	1.264	0.421	0.211	0.632				1.686
250-300	2.182	0.727	0.364	0.218	0.873			2.909
300-350	3.382	1.127	0.564	0.338	0.225	1.127		4.581
>350	5.069	1.690	0.845	0.507	0.338	0.241	1.448	6.759
V_i \ V_j	$\lambda_i a_{ij}$, sq mi/year							λ_i
50-100	0.967							7.58
100-150	3.588	3.588						14.03
150-200	1.366	0.455	0.911					2.14
200-250	0.332	0.111	0.055	0.166				0.26
250-300	0.070	0.023	0.012	0.0070	0.0281			0.03
300-350	0.013	0.0045	0.0022	0.0013	0.0009	0.0045		0.004
>350	0.0028	0.0009	0.0005	0.0003	0.0002	0.0001	0.0008	0.0005
$\Sigma \lambda_i a_i$	5.339	4.182	0.981	0.175	0.029	0.005	0.0008	

TABLE VI

COMPUTATIONS: TORNADO RISK MODEL

Operation	Windspeed Interval V_j, mph						
	50-100	100-150	150-200	200-250	250-300	300-350	>350
$\sum_{i=1}^{n} \lambda_i a_{ij}$ (sq mi/yr)	6.339	4.182	0.981	0.175	0.029	0.005	0.0008
A (sq mi)	86,500	86,500	86,500	86,500	86,500	86,500	86,500
$p(V=V_j)$ (Eqn. 1)	$7.33x10^{-5}$	$4.84x10^{-5}$	$1.13x10^{-5}$	$2.02x10^{-6}$	$3.38x10^{-7}$	$5.33x10^{-8}$	$9.31x10^{-9}$
$P(V \geq V_j$ Eqn. 5)	$1.35x10^{-4}$	$6.21x10^{-5}$	$1.38x10^{-5}$	$2.42x10^{-6}$	$4.01x10^{-7}$	$6.26x10^{-8}$	$9.31x10^{-9}$

TABLE VII

F-SCALE CLASSIFICATION OF TORNADOES IN THE FIVE LOCAL REGIONS

Region	F0	F1	F2	F3	F4	F5	Total
1-Degree	9	5	1	1	0	0	16
2-Degree	17	16	6	6	2	0	47
3-Degree	35	45	27	13	2	0	122
4-Degree	68	103	79	21	2	0	273
5-Degree	86	150	120	30	3	0	389

TABLE VIII

TORNADO RISK MODELS FOR LOCAL REGIONS

Interval	1-Degree Square	2-Degree Square	3-Degree Square	4-Degree Square	5-Degree Square
50-100	6.58×10^{-5}	1.04×10^{-4}	1.08×10^{-6}	1.36×10^{-4}	1.35×10^{-4}
100-150	2.30×10^{-5}	4.66×10^{-5}	4.85×10^{-5}	6.14×10^{-5}	6.21×10^{-5}
150-200	8.44×10^{-6}	2.16×10^{-5}	1.53×10^{-5}	1.39×10^{-5}	1.38×10^{-5}
200-250	2.98×10^{-6}	9.84×10^{-6}	4.21×10^{-6}	2.45×10^{-6}	2.42×10^{-6}
250-300	1.00×10^{-6}	4.32×10^{-6}	1.09×10^{-6}	4.06×10^{-7}	4.01×10^{-7}
300-350	3.18×10^{-7}	1.80×10^{-6}	2.68×10^{-7}	6.32×10^{-8}	6.26×10^{-8}
>350	9.39×10^{-8}	6.93×10^{-7}	6.17×10^{-8}	9.40×10^{-9}	9.31×10^{-9}

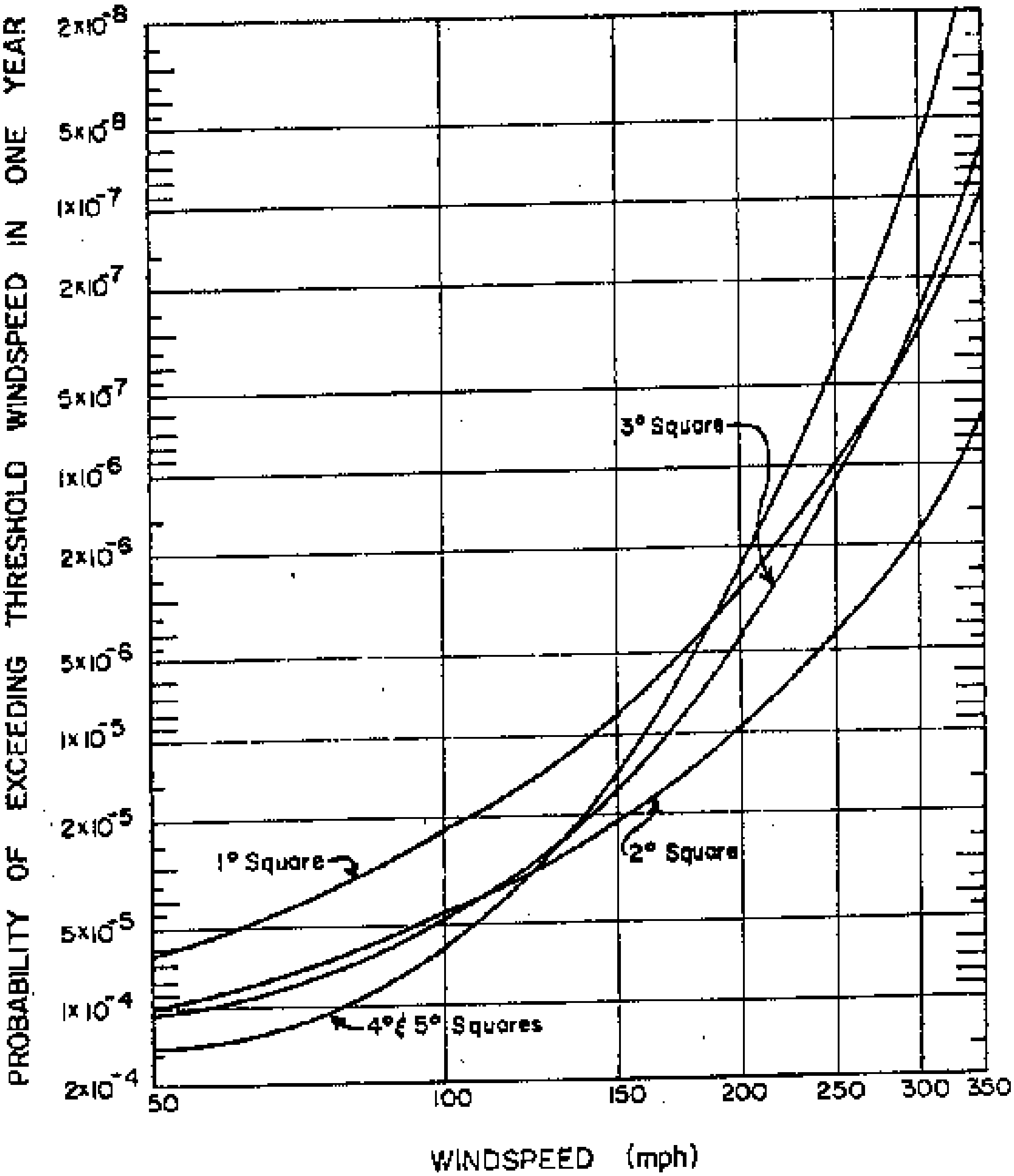


FIGURE 6. TORNADO RISK MODELS FOR THE FIVE LOCAL REGIONS

limits were established for the area-intensity relationship a_i and for the occurrence-intensity relationship λ_i. The upper and lower bound values of these two parameters, respectively, were then used to calculate the upper and lower confidence limits on the tornado risk model.

The area-intensity relationship is shown in Figure 4. The straight line shown in the figure represents the best-fit line based on a linear regression analysis using the six data points shown. A $(1-\alpha)100\%$ confidence interval for the mean response $\mu_{Y|x_0}$ (corresponding to a_i) is given by [20]

$$\hat{y}_0 - t_{\alpha/2} s \sqrt{\frac{1}{n} + \frac{(x_0-\bar{x})^2}{S_{xx}}} < \mu_{Y|x_0} < \hat{y}_0 + t_{\alpha/2} s \sqrt{\frac{1}{n} + \frac{(x_0-\bar{x})^2}{S_{xx}}} \qquad (6)$$

where

$\hat{y}_0$ = the estimated response from the regression equation at the point x_0

$t_{\alpha/2}$ = a value of the t distribution with n-2 degrees of freedom

s = sample variance

$\bar{x}$ = sample mean

n = sample size (6 in this case).

The term S_{xx} is given by

$$S_{xx} = \sum_{i=i}^{n} x_i^2 - \frac{\left(\sum_{i=k}^{n} x_i\right)^2}{n} \qquad (7)$$

The confidence limits for the occurrence-intensity relationship is obtained by calculating the confidence interval for the binomial parameter p. The relationship used is [20].

$$\hat{p} - z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}} < p < \hat{p} + z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}} \qquad (8)$$

where

$\hat{p}$ = the proportion of successes in a random sample of size n (in this case success means the occurrence of a tornado).

$\hat{q} = 1 - \hat{p}$

$z_{\alpha/2}$ = the value of the standard normal curve leaving an area $\alpha/2$ to the right.

n = sample size (In this case it is the total number of tornado occurrences in the 15 year recording period). The sample size should be greater than 30.

The upper and lower limit values of λ_i are obtained by multiplying the limits defined in Equation (8) times n and dividing by 15.

Confidence limits for the tornado risk models for the five local regions are included in Appendix C. These include 80 percent confidence limits for the 1-, 2-, 3-, 4- and 5-degree squares (Figures C1-C5) and 90 and 95 percent confidence limits for the 3- and 5-degree squares (Figures C6-C9). To illustrate the contribution of the area-intensity and the occurrence-intensity to the overall confidence limits, the 80 percent confidence limits for the 5-degree square were calculated first using the expected values of area with the upper and lower bound values of occurrence (Figure C10), then the expected values of occurrence were used with the upper and lower bound values of area (Figure C11). Comparison of Figures C10 and C11 shows that the occurrence-intensity relationship has the most significant effect on the width of the confidence band. Because the area-intensity relationship is based on the global region, it is the same regardless of the local region considered.

Clearly the 5-degree local region has the narrowest confidence band. The 95 percent confidence band for the 5-degree square is approximately the same as the 80 percent band for the 3-degree square. The rather close agreement between the risk models for the 4-degree and 5-degree regions tends to confirm that there is some minimum size geographical region that must be considered in order that the random distribution of strong and weak tornadoes in a global region not bias the risk model based on a local region. If, for example, a small local region is defined that includes a random concentration of intense tornadoes, the risk model based on the local region will predict probabilities that are too high. On the other hand, if there were an absence of tornado occurrences in the local region, the predicted risks would be too low. Therefore, based on a comparison of the confidence limits, the recommendation here is that the risk model for the 5-degree square region surrounding the plant site be used for determining the probability of tornado occurrence.

Evaluation of the Savannah River Plant Risk Model

Several additional uncertainties not accounted for in the confidence intervals affect the outcome of the tornado risk model. The tornado data itself is subject to some bias. The assignment of F-scale ratings to the tornadoes -- either by the NIC or by the authors after reviewing the damage descriptions in Storm Data -- is subject to some bias. The bias tends to be on the conservative side. Windspeed estimates based on F-scale ratings tend to be higher than those estimated by other means such as analysis of damaged structures [21].

The areas exposed to windspeeds $\overline{V}_j$ from tornadoes whose maximum intensities are $\overline{V}_i$ (A_{ij}, Equation 2) are obtained by assuming that the tornado windfield behaves as a Combined Rankine vortex. A precise definition of the tornado windfield is not known, but the assumption of a Combined Rankine vortex closely matches the windfield obtained by Hoecker at the 1000 ft level in his work with the Dallas tornado of 1957 [22]. Near the ground level the Rankine vortex assumption is conservative for the same maximum windspeed and radius of maximum wind.

Comparing windspeeds with those determined by Markee, Beckerly and Sanders [8], their model predicts windspeeds of 360 mph at the 10^{-7} level, whereas the model developed herein predicts 280 mph windspeeds at the same level of risk. The two methods are, however, based on completely different statistical approaches. The limitations of the present method are expressed in terms of confidence limits on the risk models. No such estimates of confidence have been presented by the authors of Reference 8.

IV. DEVELOPMENT OF EXTREME WIND RISK MODEL

The work of Thom [12] is used to evaluate the probability of extreme winds exceeding any threshold value of windspeed. Thom's data specifically excludes tornadoes from the data set.

Extreme Windspeed Records

Probability distributions of extreme winds developed by Thom are based on records of extreme annual fastest-mile windspeeds. The records cover a 21-year period (1945-1965) and were accumulated at 138 locations in the contiguous United States. The distributions are represented graphically in the form of contour maps that give annual extreme fastest-mile windspeeds for 2, 10, 25, 50 and 100-year mean recurrence intervals. These maps are used to determine an appropriate windspeed distribution at locations where data sets of annual extreme fastest mile windspeeds are not available.

Extreme Windspeed Distribution

Because winds are bounded at zero and are generally thought of as being unlimited above zero, Thom selected the Fisher-Tippett Type II distribution for the annual extreme fastest-mile windspeed. A transformation involving logarithms of the extreme windspeed can be made to obtain the Fisher-Tippett Type I distribution. This is the model actually used by Thom in his latest work. This mathematical model is also known as the Frechet Distribution Function. Based on Thom's work, the probability of exceeding a threshold windspeed V_j in one year is given by the expression

$$P(V \geq V_j) = 1 - F(V_j) \qquad (9)$$

where

$$F(V_j) = \exp[-(V_j/\beta)^{-\gamma}] \qquad (10)$$

both β and γ are constants chosen to fit the annual extreme fastest-mile speed distribution at the grographic location under consideration. The annual extreme fastest-mile windspeed is determined from the 2, 10, 25, 50 and 100-year recurrence interval maps for the location under consideration. These values are plotted on special Fisher-Tippett Type II probability paper. A regression analysis is performed to give the best fit straight line through the five points as shown in Figure 7. For the Savannah River Plant site the β and γ terms are found to be

$$\beta = 46.62$$

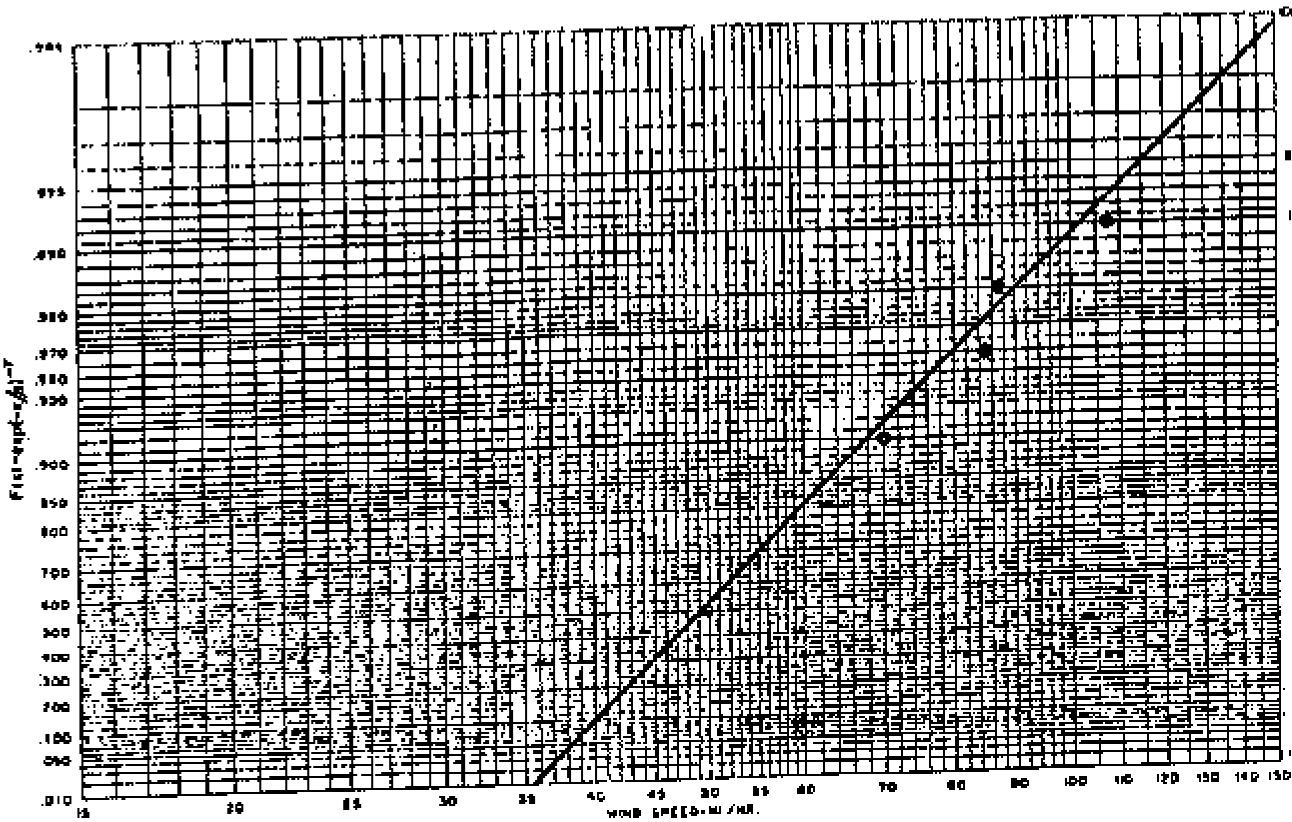
$$\gamma = 5.63$$

Equation (5) thus becomes

$$F(V_j) = \exp\,[-(V_j/46.62)^{-5.63}] \qquad (11)$$

Values of $P(V \geq V_j)$ are tabulated in Table IX.

The extrapolation of the straight windspeed curve into the region beyond measured values requires some discussion. There may be some upper bound on maximum straight windspeeds, but the value is not precisely known. The upper limit assumed for tornadoes is less than 300 mph [23, 24, 25]. This limit could be used for straight winds as well. Thus, in this study the upper limit windspeed for straight wind is assumed to approach the generally accepted upper limit windspeed for tornadoes.



MAXIMUM-VALUE PROBABILITY PAPER, FISHER-TIPPETT TYPE II DISTRIBUTION.

FIGURE 7. FISHER-TIPPETT TYPE II DISTRIBUTION FOR SAVANNAH RIVER PLANT SITE

V. RECOMMENDED TORNADO AND EXTREME WIND RISK MODELS

The recommended tornado risk model for the Savannah River Plant site is based on the 5-degree square local region. Values for the tornado risk model are given in Table IX and are plotted in Figure 8.

The extreme (straight) windspeed risk model is given by Equation (11). This equation can be rearranged into a more useful form where the design velocity is expressed as a function of the acceptable level of risk.

$$V_j = 46.62\,[-\ln\,(1-P(V \geq V_j)\,)]^{-1/5.63} \qquad (12)$$

Caution should be used in extrapolating maximum extreme wind velocities above the 200 mph value. Windspeeds in excess of 200 mph have been measured at the surface, but they occurred at a specific location atop Mt. Washington in New Hampshire. Hurricane windspeeds of 200 mph are occasionally reported, but these occur over water and at elevations of more than 100 ft. Arbitrary extrapolation of the Fisher-Tippett windspeed distribution could lead to unreasonable design parameters. Such an extrapolation is <u>not</u> recommended in this report.

TABLE IX

WINDSPEED PROBABILITIES FOR
SAVANNAH RIVER PLANT SITE
(5-Degree Square Local Region)

Windspeed (mph)	Extreme Wind Distribution	Tornado Distribution
50	4.90×10^{-1}	1.35×10^{-4}
100	1.35×10^{-2}	6.21×10^{-5}
150	1.38×10^{-3}	1.38×10^{-5}
- - - - -	- - - - -	- - - - -
200*	2.73×10^{-4}	2.42×10^{-6}
250	7.77×10^{-5}	4.01×10^{-7}
300	2.78×10^{-5}	6.26×10^{-8}
350	1.17×10^{-5}	9.31×10^{-9}

*Windspeed values below the dashed line are presented for comparison purposes only. They should not be considered in deriving appropriate design parameters for wind resistant construction at the Savannah River Plant.

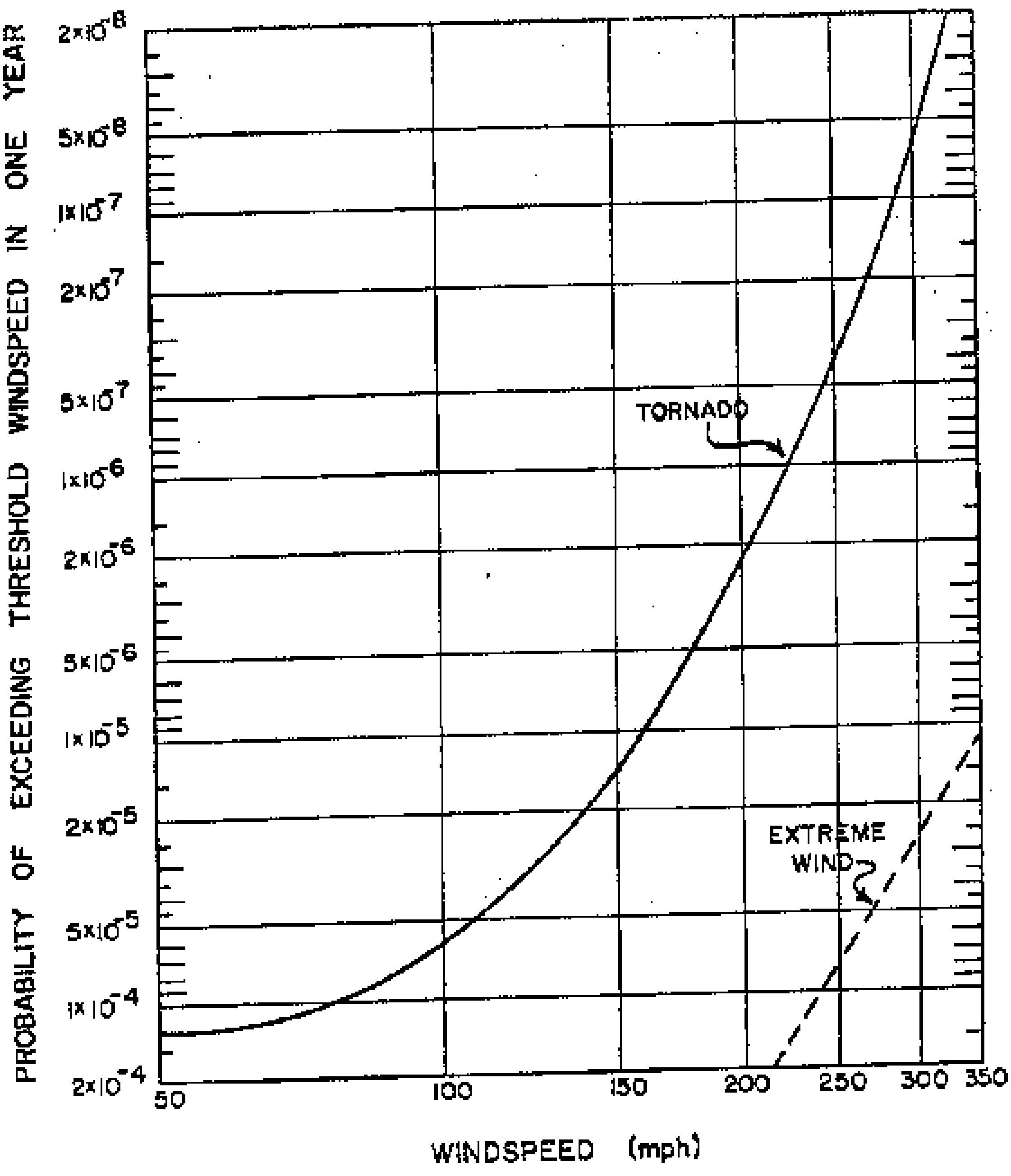


FIGURE 8. RECOMMENDED TORNADO RISK MODEL FOR THE SAVANNAH RIVER PLANT SITE

VI. RECOMMENDED TORNADO AND EXTREME WIND PARAMETERS FOR THE SAVANNAH RIVER PLANT SITE

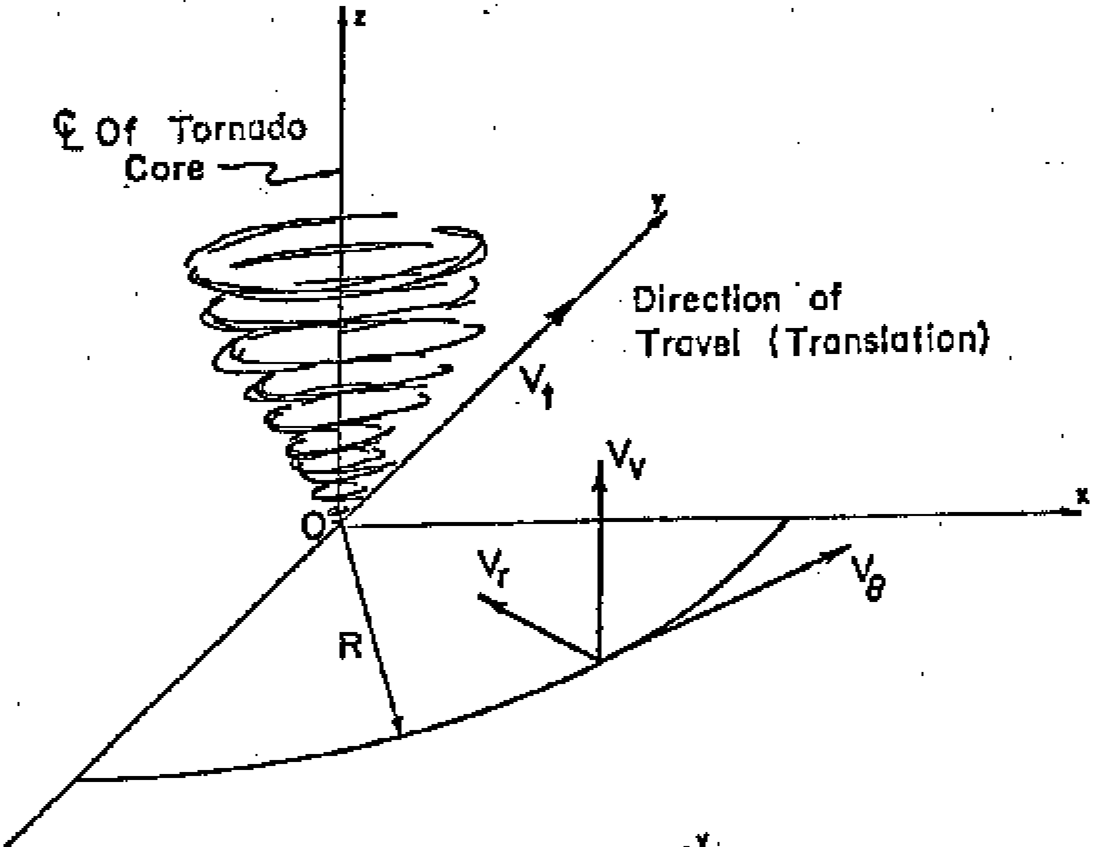
Determination of specific tornado and extreme wind parameters for any geographic location requires the tornado and extreme wind risk models and a definition of the acceptable level of risk for structures or facilities under consideration. The acceptable level of risk is defined by the responsible authorities at the plant site.

Wind Parameters

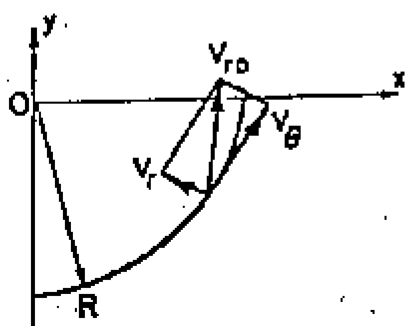
In the case of straight winds the only parameters needed besides maximum design windspeed is the characteristics of potential windborn missiles. Missile characteristics are treated at the end of this section.

The tornado parameters to be considered are maximum horizontal windspeed, atmospheric pressure change and windborn missiles. These parameters are derived from tornado vortex mechanics. The variation of wind velocity within the tornado vortex is referred to as the tornado wind field. The best currently available information on the tornado windfield is due to the work of Hoecker on the Dallas tornado of 1957 [22]. Hoecker found that at the 1000 ft. level the tangential windfield behaves similar to a Combined Rankine vortex. At elevation below 1000 ft. the wind profile deviates somewhat from the Rankine type vortex because of boundary layer effects and turbulence. Since the Rankine profile is conservative, compared to the Hoecker profile, it is used in this study.

Components of the 3-dimensional wind velocity vector as found



V_θ = Tangential Component
V_t = Translational Component
V_r = Radial Component
V_v = Vertical Component
V_{ro} = Rotational Component
V_{max} = Vector sum of $V_t + V_{ro}$



Rotational Component

FIGURE 9. THREE-DIMENSIONAL WIND VELOCITY VECTOR IN A TORNADO

in a tornado vortex is shown in Figure 9. The extreme wind and tornado parameters are shown in Table X for different values of maximum horizontal windspeeds. Table X also shows the relationship between various components of the wind velocity vector within the tornado vortex.

The radius of maximum winds must be assumed. Tornadoes with larger values of maximum winds are assumed to have larger radii of maximum winds. The values assumed in Table X follow a trend suggested in a paper by Fujita [29]. Based on an assumed value of R_{max} the radius of damaging winds, which is defined as the radius beyond which the winds are less than 75 mph, can be obtained. The equation given in Table X is not exact, but represents a good approximation.

Atmospheric Pressure Change Parameters

The atmospheric pressure change is obtained by integrating the cyclostrophic equation

$$p = \int \frac{\rho V_\theta^2 \, dr}{R} \qquad (13)$$

In this equation the tangential windspeed V_θ needs to be written as a function R to accomplish the integration. For our purposes the following relationships between V_θ and R have been assumed (Combined Rankine vortex).

$$V_\theta / R = C \qquad 0 < R < R_{max}$$

$$V_\theta R = C \qquad R_{max} < R < \infty$$

The radius of maximum tangential windspeed R_{max} is measured from the center of the tornado vortex. The maximum atmospheric pressure change

TABLE X

TORNADO AND EXTREME WIND PARAMETERS

Wind Component	Symbol	Equation	Maximum Values of Parameters					
Extreme Winds:								
Max. Horiz. Windspeed		(From Risk Model)	100	150	200	250	300	350
Tornadoes:								
Wind Velocity Components:								
Max. Horizontal, mph	V_{max}	(From Risk Model)	100	150	200	250	300	350
Translational, mph	V_t	(Assumed)	30	50	50	50	50	60
Rotational, mph	V_{ro}	$V_{max} - V_t$; $(V_r^2 + V_\theta^2)^{1/2}$; $1.12\ V_\theta$	70	100	150	200	250	290
Tangential, mph	V_θ	$0.89\ V_{ro}$	62	89	134	178	223	258
Radial, mph	V_r	$0.5\ V_\theta$	31	45	67	89	112	129
Vertical, mph	V_v	$0.67\ V_\theta$	41	59	89	118	149	173
Tornado Geometry:								
Radius of max. winds, ft	R_{max}	(Assumed)	125	150	175	200	250	300
Radius of damaging winds, ft	R_D	$\frac{R_{max}}{75}(V_{max})$	167	300	467	667	1000	1400
Total Pressure Change, psf	p	$\rho\ V_{\theta max}^2$	20	41	92	162	255	341
Rate of Pressure Change psf/sec	dp/dt	$\rho V_{\theta max}^2 (\frac{V_t}{R_{max}})$	7	20	38	59	75	100

(psf) is

$$p = \rho V_{\theta max}^{2} \tag{14}$$

where

ρ is the mass density of air (0.00238 slugs/ft^3)

$V_{\theta max}$ is the maximum tangential windspeed (ft/sec)

The rate of atmospheric pressure change is given by

$$\frac{dp}{dt} = \rho V_{\theta max}^{2} \frac{V_t}{R_{max}} \tag{15}$$

The values of maximum pressure change and maximum rate of pressure change for tornadoes of maximum design windspeeds are given in Table X.

Wind Generated Missile Parameters

Windborne missiles may be generated by either tornadoes or extreme winds. An inspection tour of the plant site was made by the principal investigator for the purpose of assessing classes of potential missiles at the site. A wide range of potential missiles were observed, including power poles, barrels, canyon jumpers, fence posts, guard railings, timbers and miscellaneous pieces of iron and debris. Potential missiles at the site could generally be lumped into one of four catagories for design purposes. Table XI lists the missiles that should be considered for design or evaluation of structures at the Savannah River Plant Site. The four missiles listed in the table are representative of the classes of missiles observed at the site and are most likely to control the design of walls and roof against missile impacts. Other missiles such as, 1 in. diameter x 3 ft. steel rod, 6 in. diameter x 15 ft. steel pipe, have been included in some lists of potential missiles [26]. The author's experiences in storm damage investigation shows that the likelihood of these missiles being accelerated in a tornado are extremely small. Therefore they have been excluded from the missile list.

Table XII gives the recommended horizontal missile velocities. The vertical velocities may be conservatively taken as 2/3 the horizontal missile velocities. This situation arises when a missile is carried to great heights by the winds and then is thrown out of the tornado wind-field and falls to the ground under the influence of gravity.

A computer program was written to calculate the time-history response of tornado generated missiles. A brief description of the program is contained in Appendix B. The program predicts conservative values of maximum horizontal velocities achieved by the missiles. Conservativisms are built into the program in the following ways:

1) The missiles are assumed to travel in a nontumbling mode.
2) The largest surface area of the missile is assumed to always be normal to the relative wind vector.
3) The vertical wind component is assumed to be constant with height.

The values of the horizontal missile velocities are summarized in Table XII. The values are essentially based on results of the computer program. The automobile is one exception. The program predicts higher values than those given in Table XII. However, the program does not account for the rolling and tumbling of an auto along the ground surface. The tumbling greatly retards the acceleration of the car because of frictional forces exerted on the car. Thus in the 350 mph maximum horizontal wind the automobile is expected to roll, tumble, and bounce at a maximum speed of 70 mph.

TABLE XI

WIND GENERATED MISSILE PARAMETERS

Missile	Weight (lb)	Maximum Projected Area (ft^2)	Minimum Cross Sectional Area (ft^2)
Timber Plank 4 in. x 12 in. x 12 ft	139	11.50	0.29
3 in. dia. std. Pipe x 10 ft	75.8	2.92	0.0155
Utility Pole 13.5 in. dia. x 35 ft	1490	39.4	0.99
Automobile	4000	100.0	20.0

TABLE XII

WINDBORNE MISSILE VELOCITIES

	Horizontal Missile Velocity, mph				Maximum Height, ft
Design Windspeed	200	250	300	350	
Timber Plank	90	100	125	175	200
3 in. dia. std. pipe	65	85	110	140	100
Utility pole	*	80	100	130	30
Automobile	*	25	45	70	30

*Missile will not be picked up or sustained by the wind.

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APPENDIXES

APPENDIX A: FUJITA-PEARSON TORNADO CLASSIFICATION

The Fujita Scale (F-Scale) is used to rate tornadoes according to their maximum estimated windspeed. The Pearson scales (PP-scales) enable one to rate tornadoes according to their path length (P_L) and average path width (P_W). Thus a tornado can be assigned an FPP rating which describes its maximum estimated windspeed and the extent of its damage path. The extent of the damage path is defined as that part of the path that experienced windspeeds greater than or equal to 75 mph.

Table AI identifies the quantitative meaning of the FPP scales. The FPP rating of a specific tornado consists of three numbers separated by commas. For example, 3, 2, 2 represents a typical FPP rating. The first number corresponds to the intensity scale rating, and, from Table AI implies a maximum estimated windspeed between 158 and 206 mph. The second number implies that the path length was between 3.2 and 9.9 miles. The third number means that the average damage-path width was between 56 and 175 yds.

The F-Scale assignment is based on observed damage along the Tornado path. Table AII gives a word description of each F-Scale category.

TABLE AI

TORNADO CLASSIFICATION [13]

Fujita Scale

Classification	Windspeed (mph)	Damage
F-	<40	Little or No
F0	40-72	Light
F1	73-112	Moderate
F2	113-157	Considerable
F3	158-206	Severe
F4	207-260	Devastating
F5	261-318	Incredible

Pearson Path Length

Classification	Path Length (mi)
P-	<0.3
P0	0.3-0.9
P1	1.0-3.1
P2	3.2-9.9
P3	10-31
P4	32-99
P5	100-315

Pearson Path Width

Classification	Path Width (yds.)
P-	<6
P0	6-17
P1	18-55
P2	56-175
P3	176-556
P4	0.3-0.9 mi
P5	1.0-3.1 mi

TABLE AII

F-SCALE CLASSIFICATION OF TORNADOES BASED ON DAMAGE [13]

(F-) LITTLE OR NO DAMAGE 40 mph or less

40 mph speed corresponds to Beaufort 8 or "Fresh Gale." Beaufort specification for use on land is "Breaks twigs off trees." Little damage is expected.

(F0) LIGHT DAMAGE 40-72 mph

This speed range corresponds to Beaufort 9 through 11. Some damage to chimneys or TV antennae; breaks branches off trees; pushes over shallow-rooted trees; old trees with hollow inside break or fall; sign boards damaged.

(F1) MODERATE DAMAGE 73-112 mph

73 mph is the beginning of hurricane windspeed or Beaufort 12. Peels surface off roofs; windows broken; trailer houses pushed or overturned; trees on soft ground uprooted; some trees snapped; moving autos pushed off the road.

(F2) CONSIDERABLE DAMAGE 113-157 mph

Roof torn off frame houses leaving strong upright walls standing; weak structure or outbuildings demolished; trailer houses demolished; railroad boxcars pushed over, large trees snapped or uprooted; light-object missiles generated; cars blown off highway; block structures and walls badly damaged.

(F3) SEVERE DAMAGE 158-206 mph

Roofs and some walls torn off well-constructed frame houses; some rural buildings completely demolished or flattened; trains overturned; steel framed hangar-warehouse type structures torn; cars lifted off the ground and may roll some distance; most trees in a forest uprooted, snapped, or leveled; block structures often leveled.

(F4) DEVASTATING DAMAGE 207-260 mph

Well-constructed frame houses leveled, leaving piles of debris; structure with weak foundation lifted, torn, and blown off some distance; trees debarked by small flying debris; sandy soil eroded and gravels fly in high winds; cars thrown some distances or rolled considerable distance finally to disintegrate; large missiles generated.

TABLE AII (continued)

(F5) INCREDIBLE DAMAGE 261-318 mph

Strong frame houses lifted clear off foundation and carried considerable distance to disintegrate; steel-reinforced concrete structures badly damaged; automobile-sized missiles fly through the distance of 100 yds. or more; trees debarked completely; incredible phenomena can occur.

(F6) INCONCEIVABLE DAMAGE 319 mph to sonic speed

Should a tornado with the maximum windspeed in excess of F6 occur, the extent and types of damage may not be conceived. A number of missiles such as ice boxes, water heaters, storage tanks, automobiles, etc., will fly through a long distance, creating serious secondary damage on structures. Assessment of tornadoes in these categories is feasible only through detailed survey involving engineering and aerodynamical calculations as well as meteorological models of tornadoes.

APPENDIX B: DERIVATION OF EXPRESSIONS FOR DAMAGE AREA a_{ij}

The various relationships between windspeeds and damage area are illustrated in Figure B1. Note that only half of the damage area is shown in the Figure. The mean damage area a_i is defined as the extent of damage caused by winds greater than or equal to 75 mph by tornadoes whose maximum windspeeds are in the interval i. Values for a_i come from the area-intensity relationship. Now the area within the damage path a_i that experiences windspeeds contained in the interval j is denoted as a_{ij}. The windspeed model is assumed to be a Combined Rankine vortex. The tornado windspeed is a function of the distance R from the tornado centerline. For values of R beyond the radius of maximum windspeed the relationship between V and R is

$$VR = \text{Constant} \tag{B1}$$

At the radius of damaging winds the wind velocity is by definition, 75 mph.

$$75\ R_d = C \tag{B2}$$

However, if L is the length of the tornado damage path,

$$R_{75} = a_i/2L \tag{B3}$$

and the expression for C is

$$C = 75\ a_i/2L \tag{B4}$$

The radius R_j corresponding to any windspeed V_j is thus

$$R_j = \frac{75\ a_i}{2L\ V_j} \qquad (B5)$$

Referring to Figure (B1),

$$\frac{a_{ij}}{2} = (R_j - R_{j+1})\ L \qquad (B6)$$

Writing Equation (B5) for R_j and R_{j+1} and substituting into Equation (B6), gives

$$\frac{a_{ij}}{2} = \frac{75\ a_i}{2L}\left[\frac{1}{V_j} - \frac{1}{V_{j+1}}\right] L \qquad (j<i)$$

$$a_{ij} = 75\ a_i \left(\frac{V_{j+1} - V_j}{V_j\ V_{j+1}}\right) \qquad (B7)$$

Clearly Equation (B7) is the same as Equation (2) in the text.

When j = i the area exposed to the maximum windspeed is designated a_{ii} (Ref. Fig. B1).

$$\frac{a_{ij}}{2} = \frac{a_{ii}}{2} = R_j\ L = \frac{75\ a_i\ L}{2L\ V_j}$$

$$a_{ij} = a_{ii} = \frac{75\ a_i}{V_j} \qquad (j=i) \quad (B8)$$

Equation (B8) is the same as Equation (3) in the text.

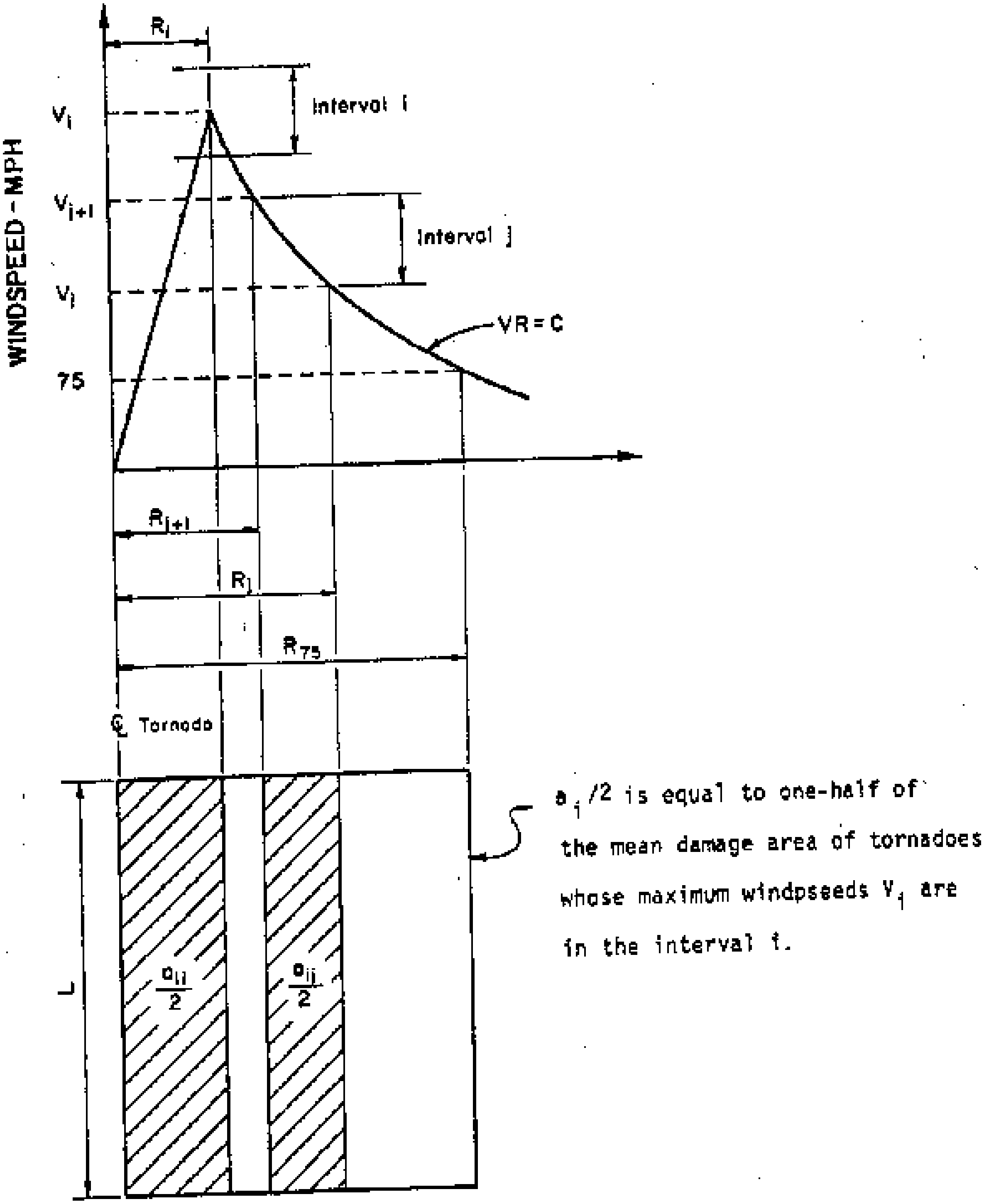

FIGURE B1. DAMAGE AREA EXPOSED TO WINDSPEEDS IN THE INTERVAL $_j$.

APPENDIX C: CONFIDENCE LIMITS FOR FIVE LOCAL REGIONS

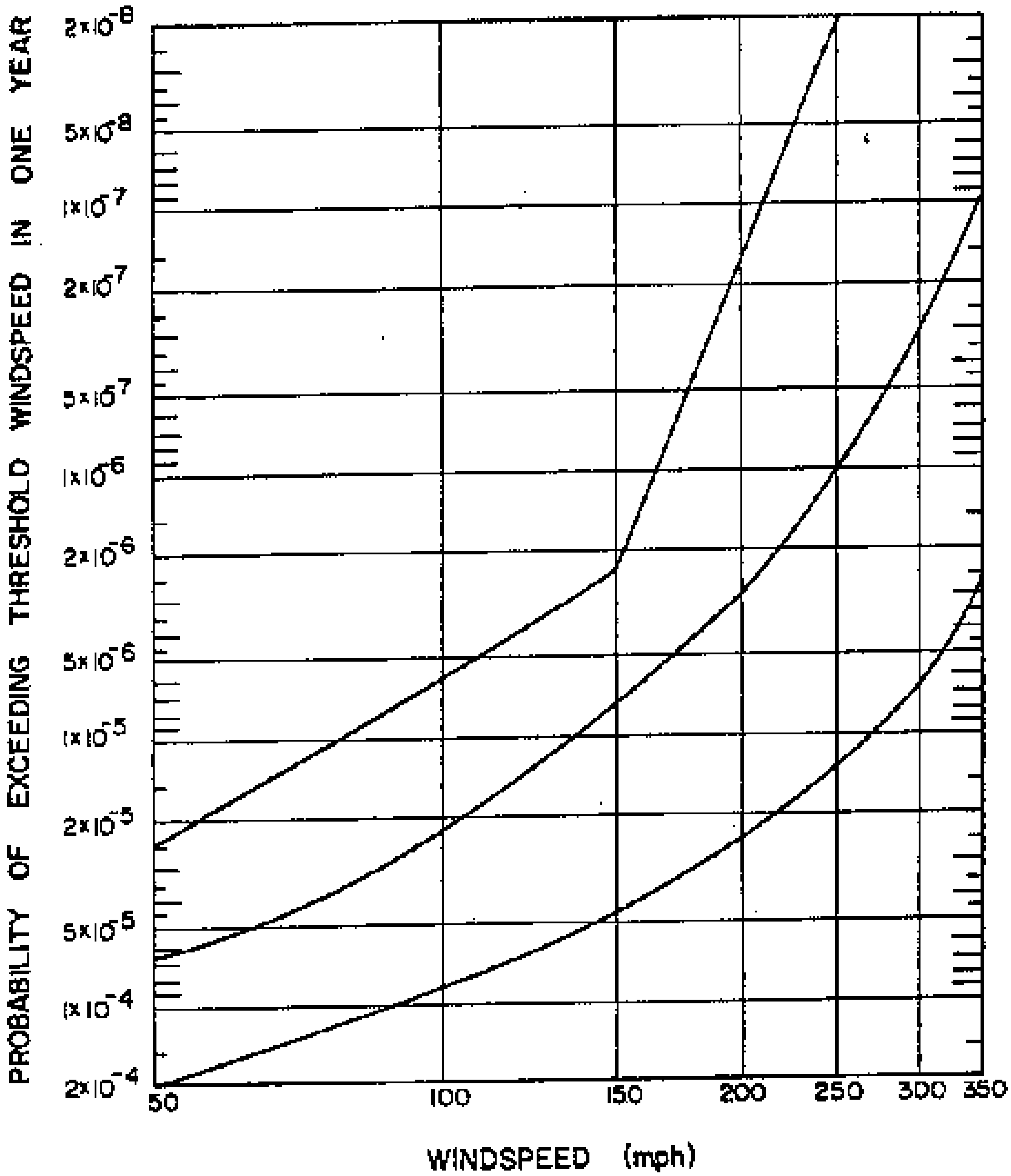

FIGURE C1. RISK MODEL: REGION 1 80% CONFIDENCE LIMITS

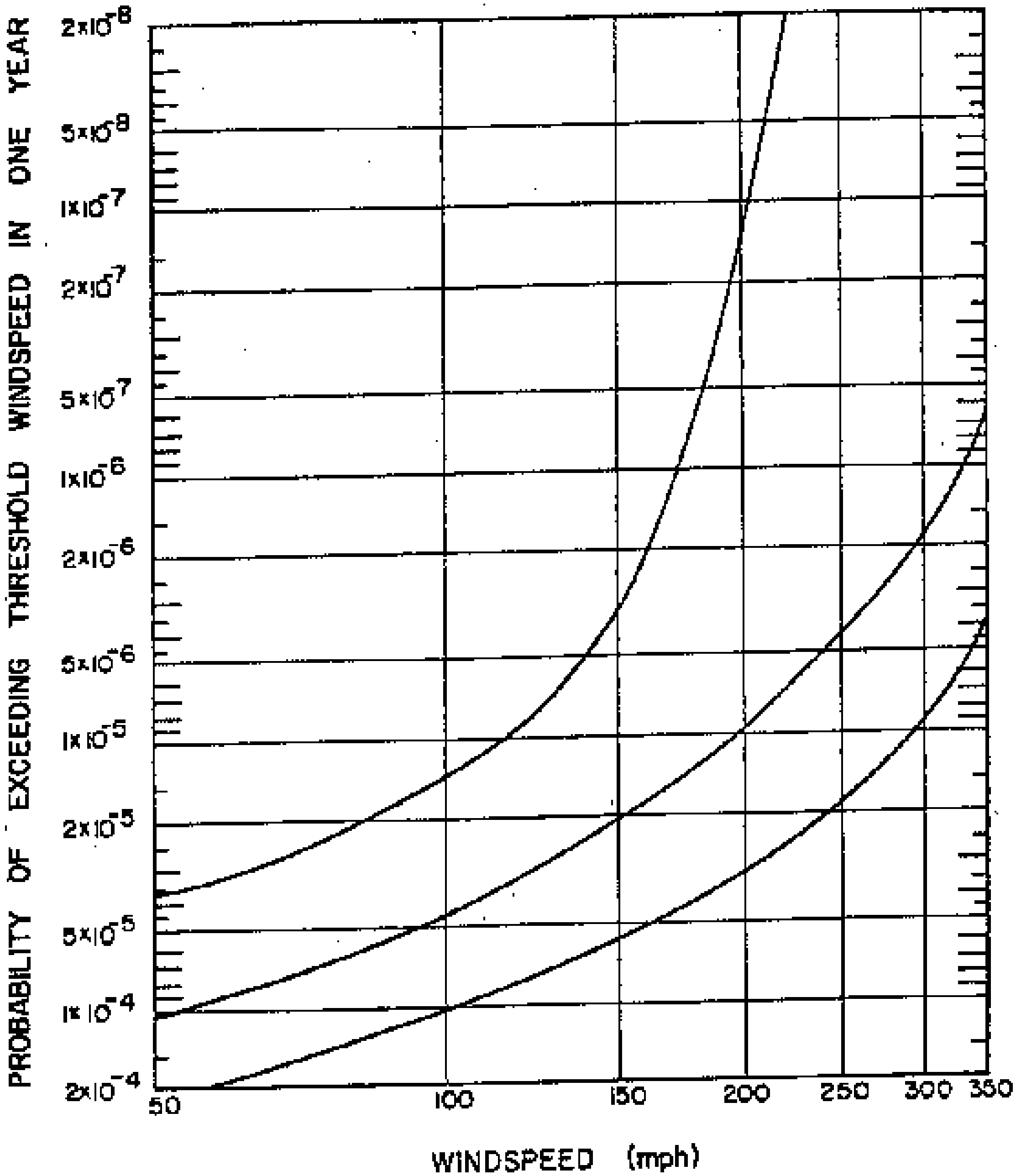

FIGURE C2. RISK MODEL: REGION 2 80% CONFIDENCE LIMITS

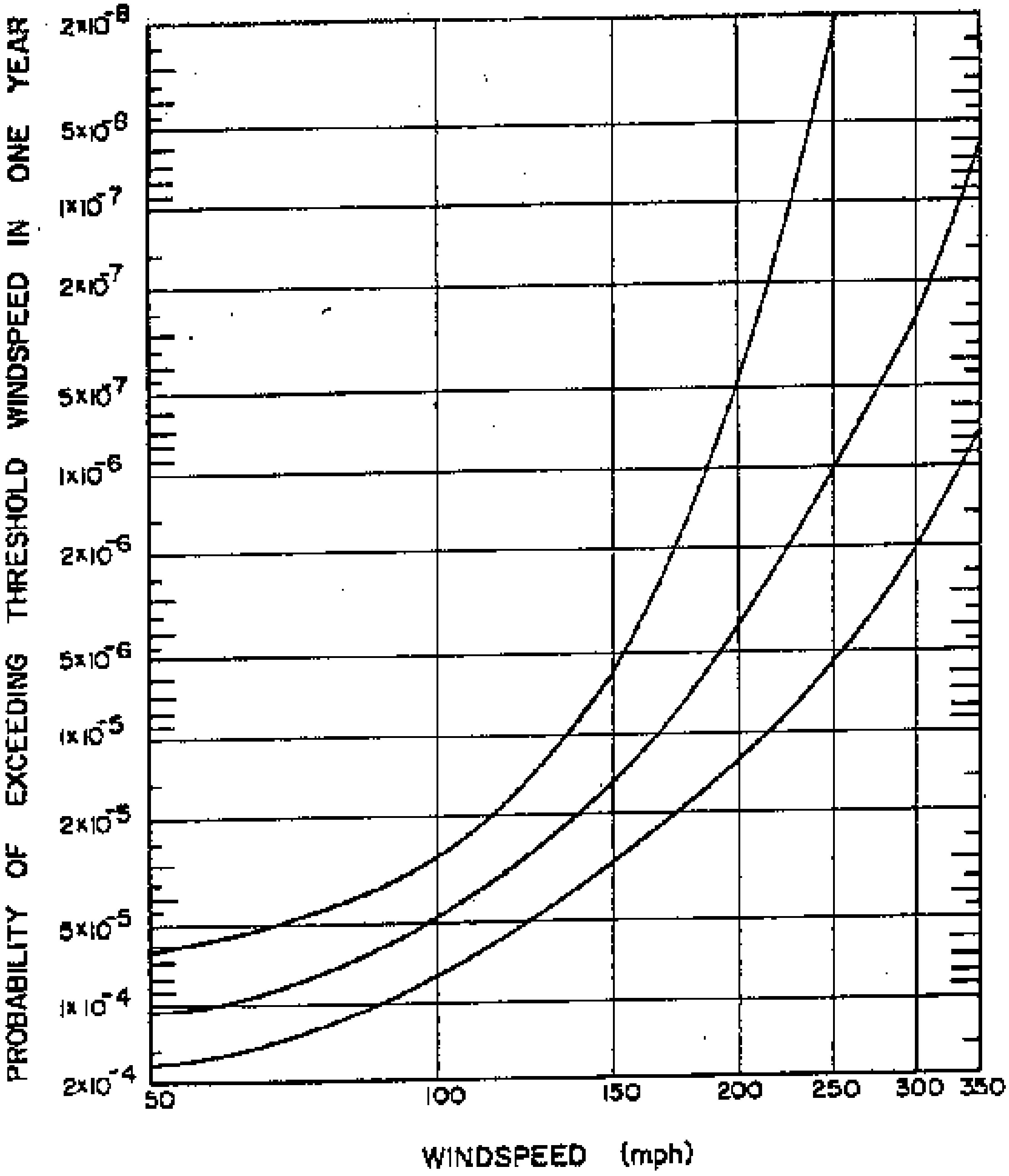

FIGURE C3. RISK MODEL: REGION 3 80% CONFIDENCE LIMITS

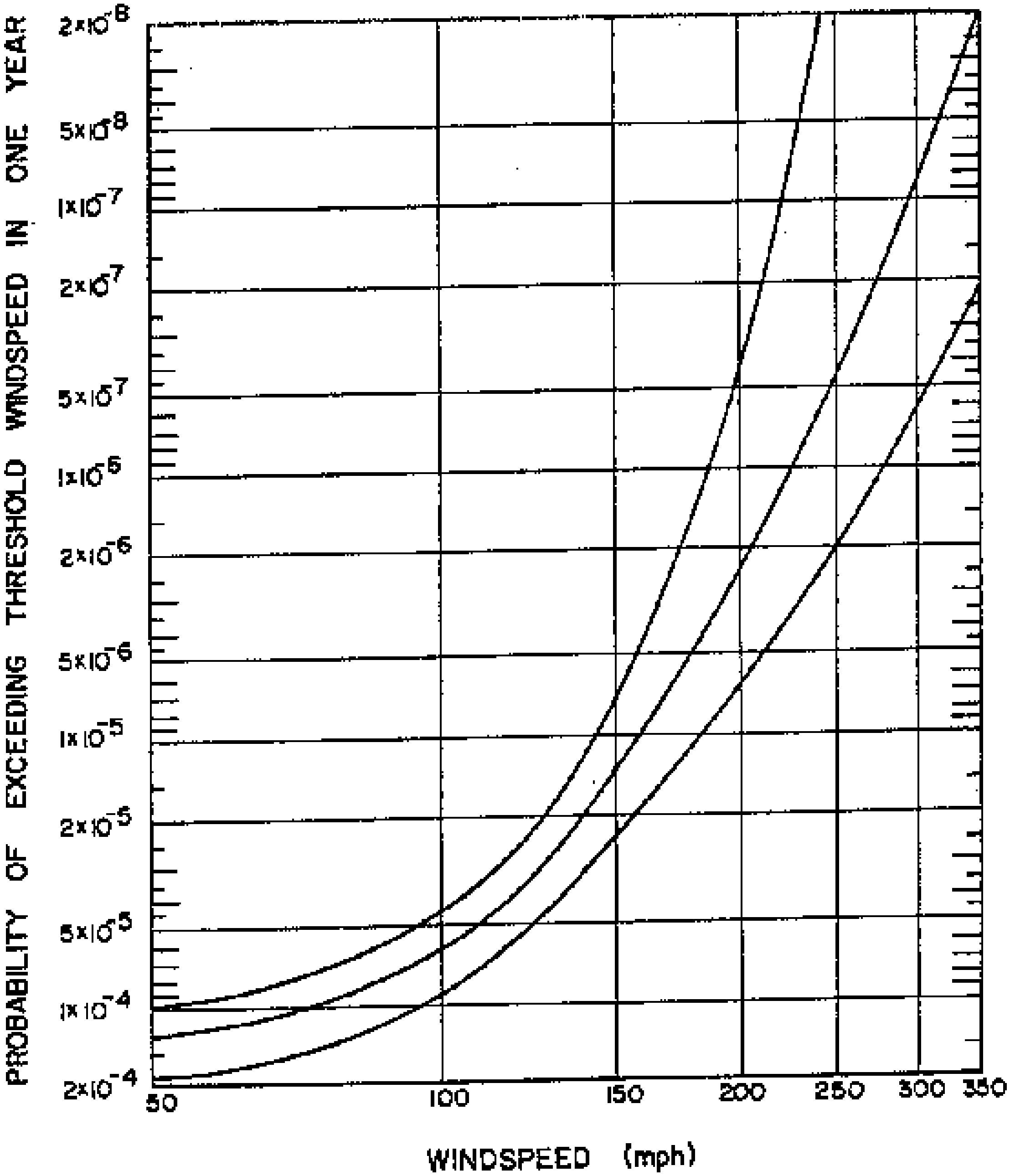

FIGURE C4. RISK MODEL: REGION 4 80% CONFIDENCE LIMITS

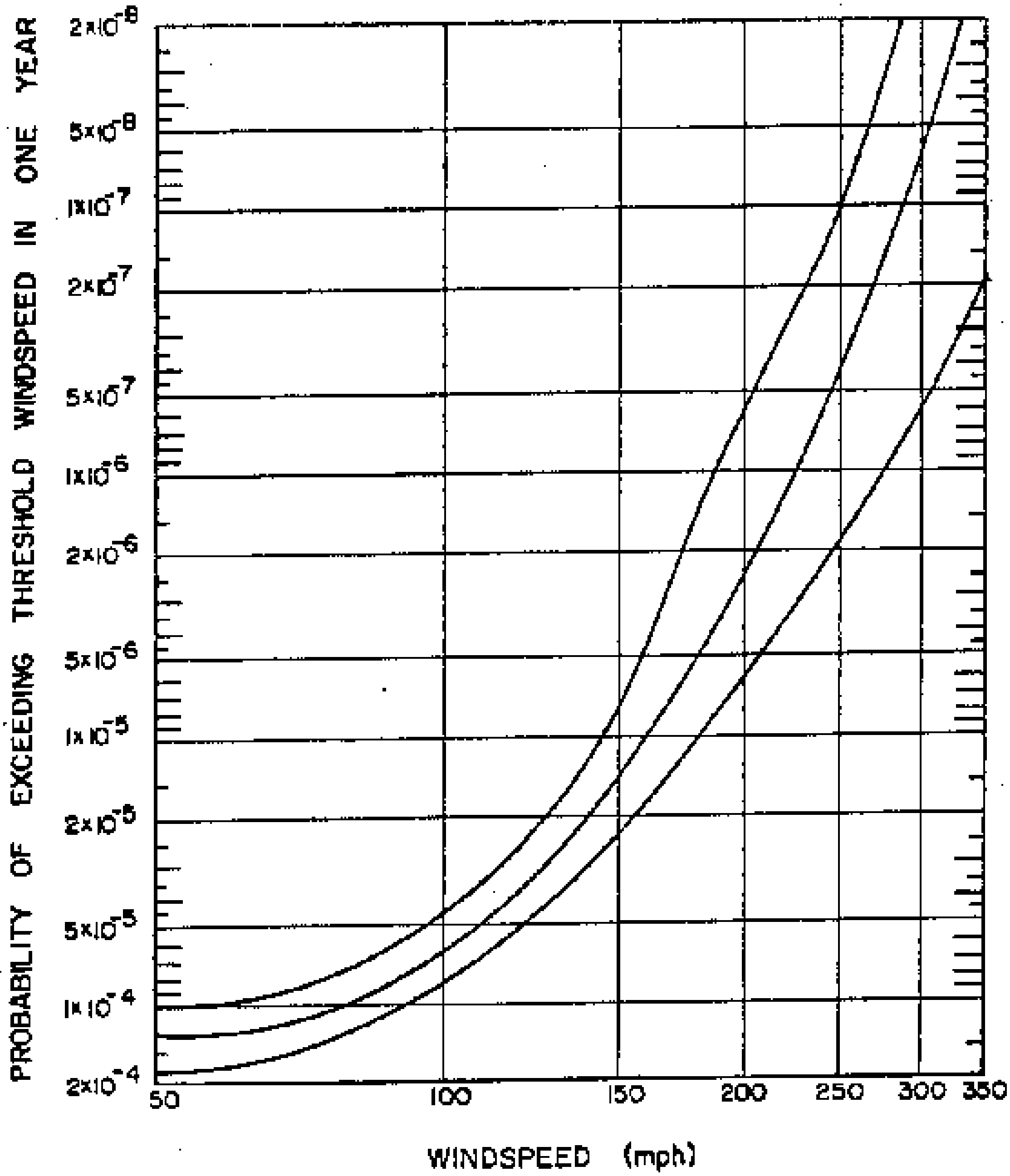

FIGURE C5. RISK MODEL: REGION 5 80% CONFIDENCE LIMITS

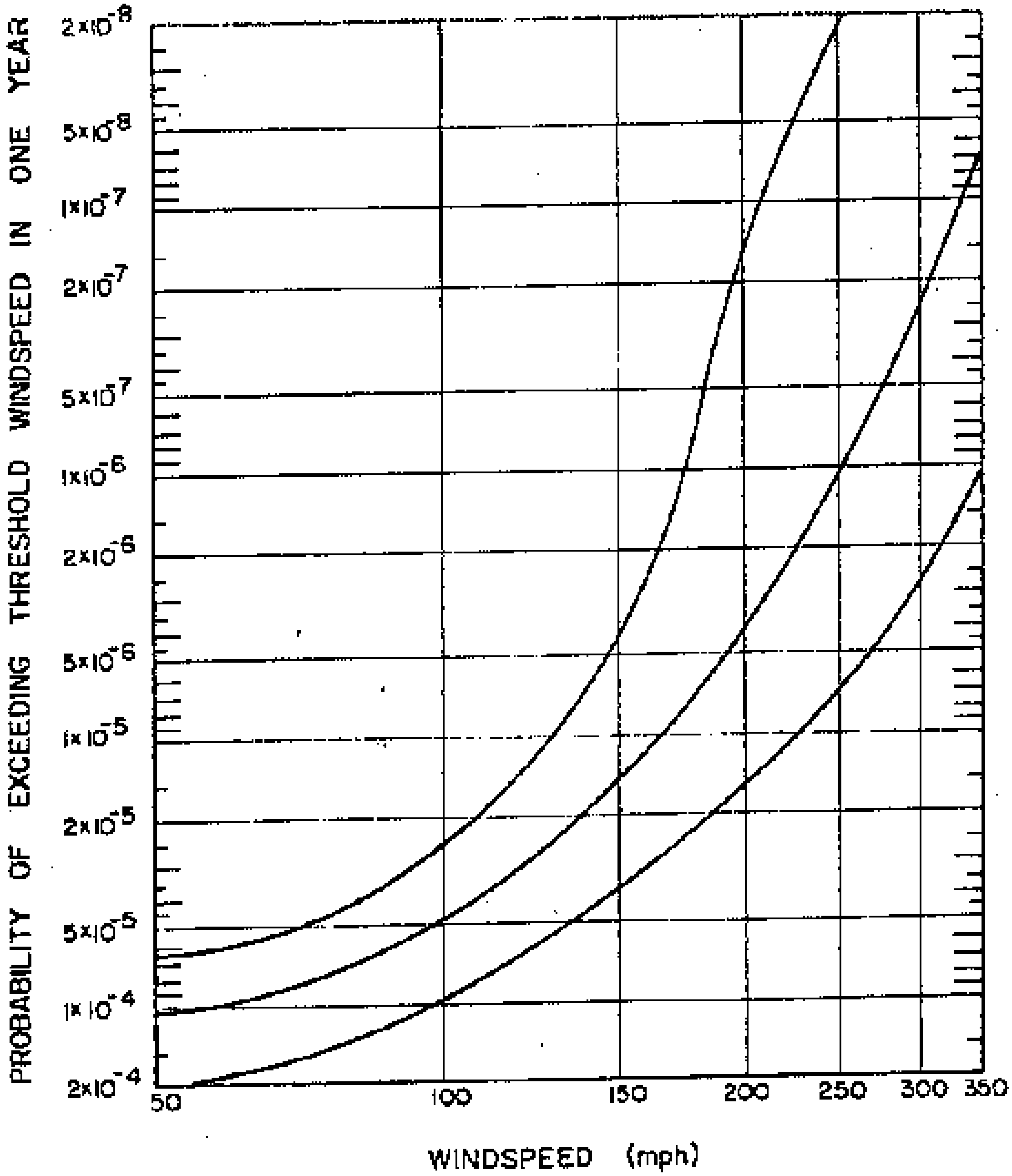

FIGURE C6. RISK MODEL: REGION 3 90% CONFIDENCE LIMITS

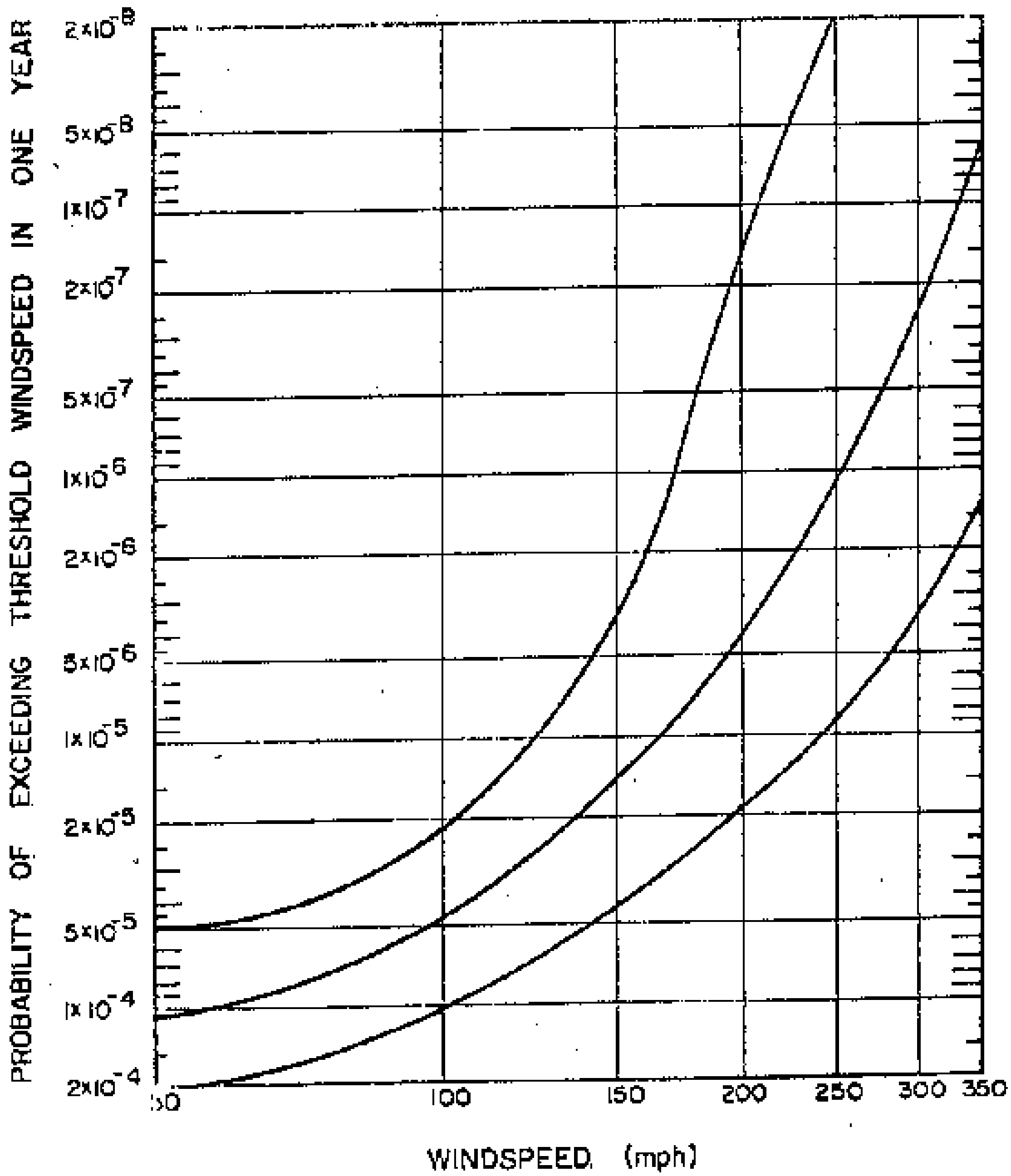

FIGURE C7. RISK MODEL: REGION 3 95% CONFIDENCE LIMITS

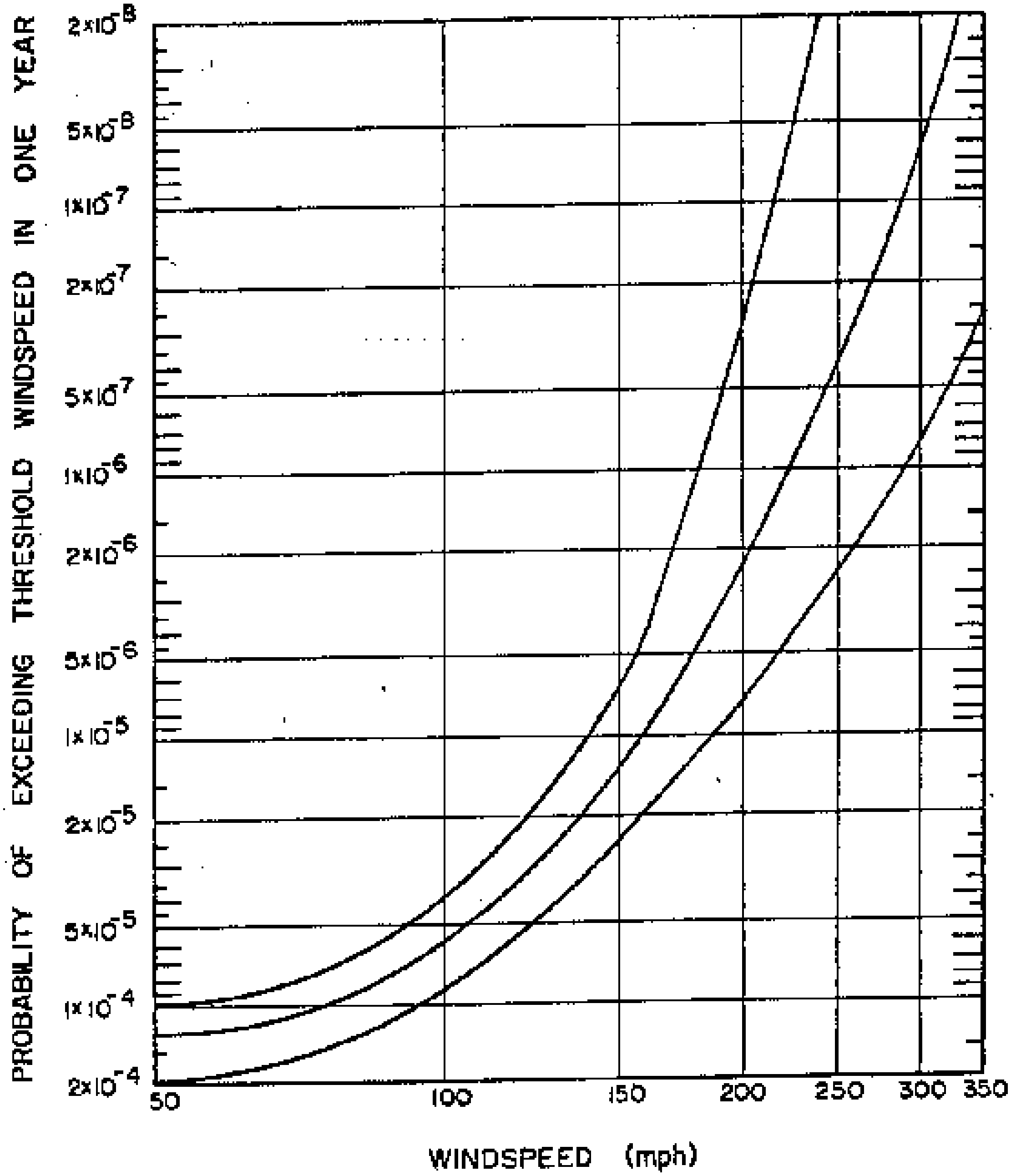

FIGURE C8. RISK MODEL: REGION 5 90% CONFIDENCE LIMITS

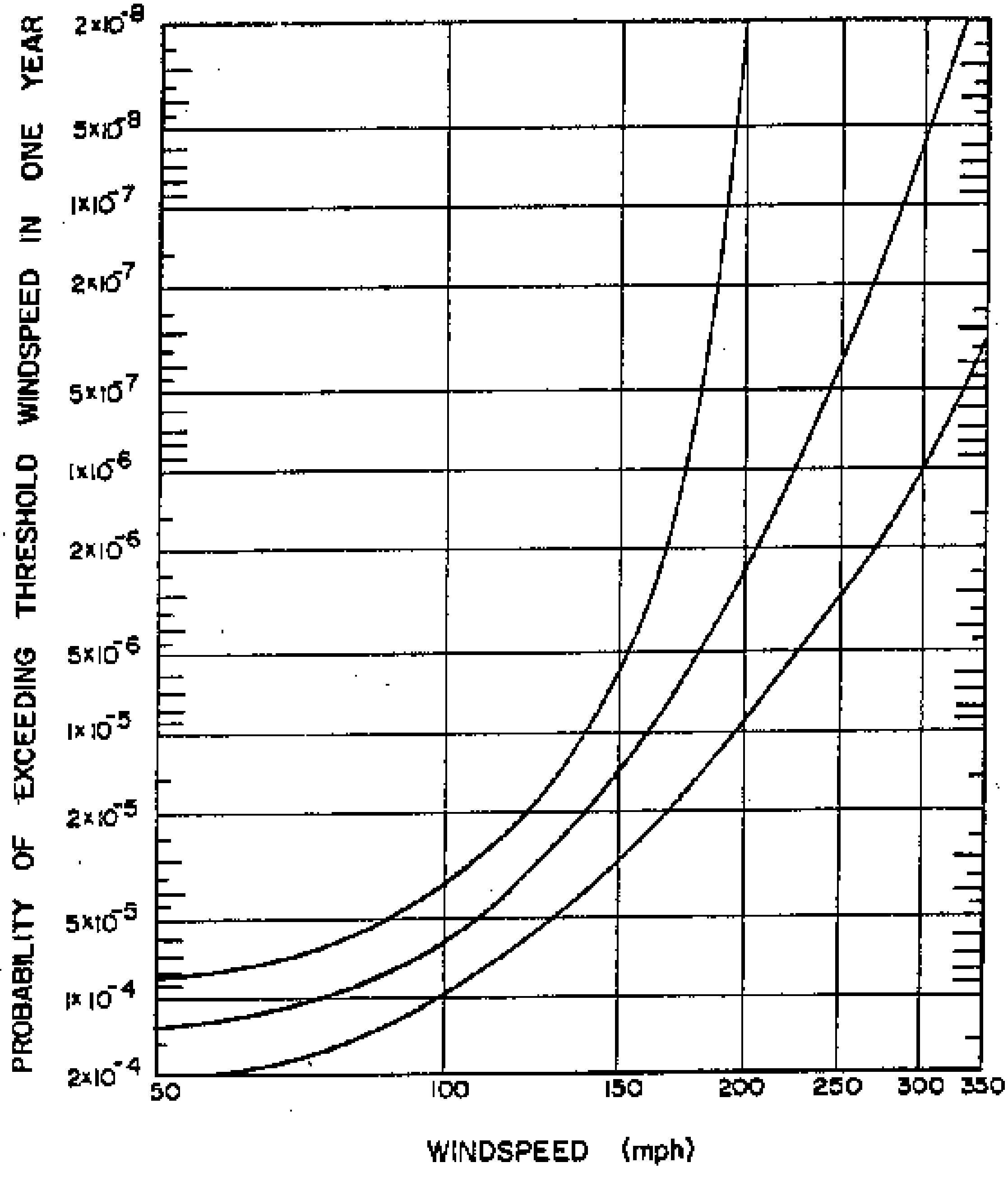

FIGURE C9. RISK MODEL: REGION 5 95% CONFIDENCE LIMITS

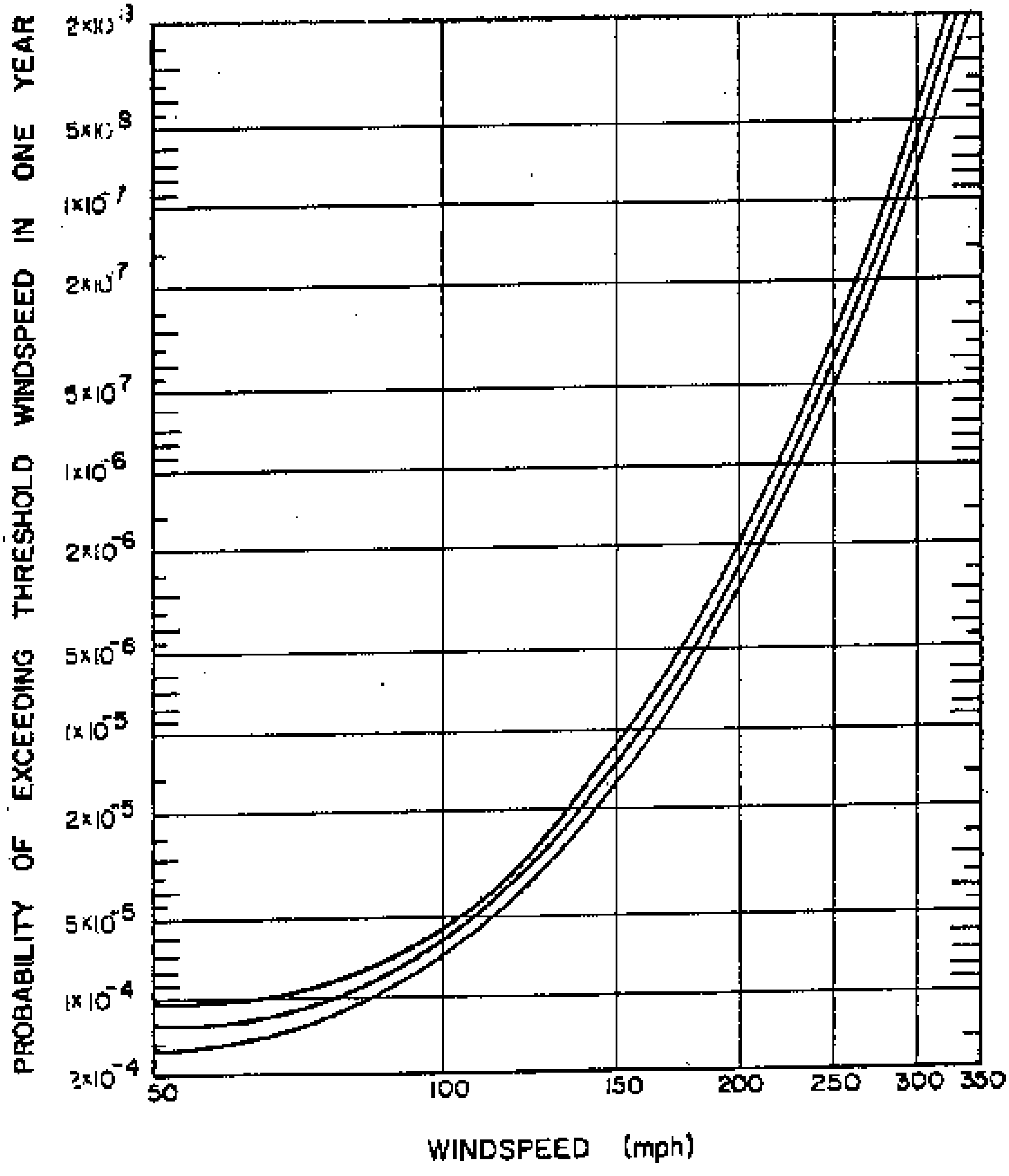

FIGURE C10. RISK MODEL: REGION 5 80% CONFIDENCE LIMITS.
EFFECT OF AREA-INTENSITY ALONE

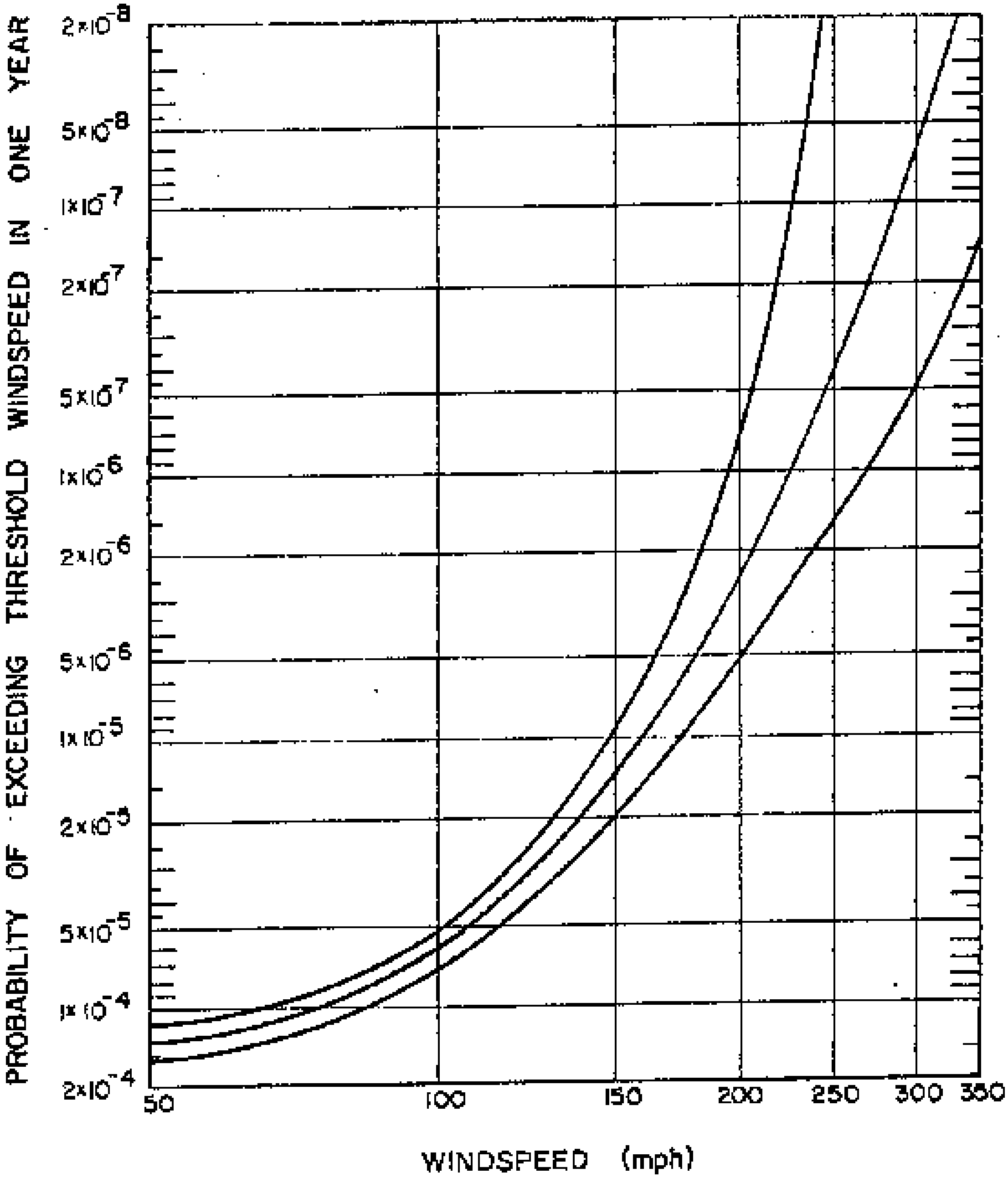

FIGURE C11. RISK MODEL: REGION 5 80% CONFIDENCE LIMITS. EFFECT OF OCCURRENCE-INTENSITY ALONE

APPENDIX D: TORNADO GENERATED MISSILES

A computer program has been written which calculates the time-history of motion of a missile that has been injected into a tornado windfield. The program calculates the trajectory of the missile along with the velocity and acceleration at any time after injection.

Aerodynamic Drag Coefficients

The missiles considered may be reasonably approximated as either rectangular parallelpipeds or right circular cylinders. The values for drag coefficients C_D are taken as 1.2 and 1.0 for parallelpipeds and cylinders respectively [27]. In order to introduce an element of conservatism the assumption is made that the missile travels in a non-tumbling mode, even though missiles are known to tumble in the wind field to some extent. Bates and Swanson [28] have suggested that the drag coefficients be modified by some numerical factor to account for tumbling. Their value of one-fourth may be unconservative in some instances (e.g., in the case of a cube). Thus for lack of a definitive value to use, a non-tumbling mode has been assumed.

Tornado Wind Field

The tornado wind field used to calculate missile trajectories is the same as that described in Section V. The tangential component of velocity is that of a Combined Rankine vortex.

For this wind field there is no variation in wind velocity with height. Thus the missile trajectory is dependent on the initial height only to the extent that the vertical components of all points on the trajectory change by the same amount as the change in initial height. A higher injection height also causes a longer trajectory before the missile strikes the ground.

Equations of Motion

The forces acting on a missile that has been injected into a tornado wind field is given by the equation

$$\bar{F} = C_d \, A \, \rho \, D^2 \, \bar{e}_w - m \, g \, \bar{e}_z \qquad \text{(D1)}$$

where

$\bar{F}$ = the total force acting on the missile

C_d = the drag coefficient

ρ = mass density of air

D = magnitude of the relative wind velocity vector

m = mass of the missile

g = acceleration due to gravity

$\bar{e}_w = \frac{\bar{D}}{D}$ = unit vector in the direction of the relative wind

$\bar{e}_z$ = unit vector in the vertical direction

From Newton's Second Law the drag force on the missile is equal to the mass times the acceleration

$$\bar{F} = ma$$

The acceleration of the missile can be determined from the above equation.

An orthogonal coordinate system was chosen such that the z-axis is the axis of revolution of the tornado. The tornado translation V_t is assumed to be constant along the x-axis.

An iterative procedure was used to determine the trajectory of a given missile. Basically, a finite difference approach is used in combination with an iterative procedure.