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ASSESSMENT OF TORNADO AND STRAIGHT WIND RISKS

at the

SAVANNAH RIVER PLANT SITE
AIKEN, SOUTH CAROLINA

by

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Medowres, J.R.

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I. INTRODUCTION

The purpose of this report is to assess tornado and straight wind risks at the Savannah River Plant site, which is located near Aiken, South Carolina. Windspeed risk, which includes both tornadic and straight winds, is the probability of a point within a defined geographical region experiencing windspeeds greater than or equal to some threshold value in one year. A windspeed risk model is a plot of probability of exceeding threshold windspeed in one year versus windspeed. A windspeed risk model is used to define criteria for design and evaluation of facilities based on an appropriate level of risk.

The author previously performed a risk analysis for the Savannah River site (McDonald et al., 1975). Since that time additional data has been assembled and the risk model methodology has been improved considerably. Comparisons of the present model and the one published previously are presented in Section 5.E of this report.

The Savannah River site is located on the east bank of the Savannah River approximately 20 miles south of Augusta, Georgia and 13 miles south of Aiken, South Carolina. The site is located at latitude $33^{\circ}\ 15'$ N and longitude $81^{\circ}\ 40'$ W. It covers an area of approximately ~~280~~ 300 square miles.

Annual extreme windspeed data are not available from the site in a form suitable for use in the analysis. The closest location where straight wind data are available is Augusta, Georgia. This data set is used for the straight wind risk calculation. Confidence limits are also calculated for the straight wind risks.

Section II of this report briefly describes the risk analysis methodology for both tornadoes and straight winds. Section III presents the data and the rational for the tornado risk model calculations. Section IV describes the data and approach for the straight wind risk model calculations. The final windspeed risk model, which includes both the tornado and straight wind models, are contained in Section V. Tornado parameters for design and evaluation of facilities are presented in Section VI. Appropriate conclusions regarding the tornado and straight wind risks are summarized in the final section of the report.

II. RISK ANALYSIS METHODOLOGY

A. TORNADOES

The methodology for tornado risk assessment is given in detail in a companion document, "A Methodology for Tornado Risk Assessment," (McDonald, 1979). Contained in the document are a literature review, a discussion of tornado data sources, detailed descriptions and derivations of the method of analysis and example calculations. Evaluations of the method with respect to data sources, tornado characteristics, population effects and confidence limits are also included. These details are not repeated herein. For completeness and reference, an outline of the basic steps involved in the methodology is given in Table 1.

Confidence limits on the expected probabilities are obtained by calculating confidence intervals on the area-intensity relationship and the occurrence-intensity relationship. A $(1-\alpha)100\%$ confidence interval for a single response y_0 is given by

$$\hat{y}_0 - t_{\alpha/2}\, s\sqrt{1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}} < y_0 < \hat{y}_0 + t_{\alpha/2}\, s\sqrt{1+\frac{1}{n}+\frac{(x_0-\bar{x})^2}{S_{xx}}} \qquad (1)$$

TABLE 1

BASIC STEPS IN RISK MODEL METHODOLOGY

(1) Determination of area-intensity relationship in a global region surrounding the site.

(2) Determination of an occurrence-intensity relationship in a local region surrounding the site.

(3) Calculation of the probability of a point in the local region experiencing windspeed in some windspeed interval.

(4) Determination of probability of windspeeds in the local region exceeding interval values.

where $\hat{y}_o$ in this case is the estimated tornado path area corresponding to windspeed x_o, $t_{\alpha/2}$ is a value of the t-distribution with n-2 degrees of freedom, $\overline{x}$ is the mean tornado path area and s is an estimator for the standard deviation (Walpole and Myers, 1972). A (1-α)100% confidence interval for the binomial parameter p is approximately

$$\hat{p}-Z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}} < p < \hat{p} + Z_{\alpha/2}\sqrt{\frac{\hat{p}\hat{q}}{n}} \quad (2)$$

where p is the proportion of success (occurrence of a tornado of a certain intensity) in a random sample of size n. The term $\hat{q}$ is equal to $1 - \hat{p}$ and $Z_{\alpha/2}$ is the value of the standard normal curve leaving an area of α/2 to the right (Walpole and Myers, 1972).

The confidence intervals thus defined are used in the risk calculations to obtain confidence intervals on the estimated probability values.

B. STRAIGHT WINDS

In the U. S. the work of Thom (1960) has been used to evaluate the probability of straight winds exceeding some threshold value in one year. Thom selected the Type II extreme value distribution (Fisher-Tippett Type II) to represent the annual extreme fastest mile windspeeds. This distribution also has been used in Russia (Bernstein, 1968), Argentina (Riera and Reimundin, 1970) and Brazil (Salgado and Filho, 1975). Recently Simiu and Filliben (1975) found that in most cases of well-behaved wind climates the Type I extreme value distribution fits the wind data better than the Type II distribution. The National Building Code of Canada (1975) also assumes that the extreme winds are modeled by the Type I distribution. The Type I distribution will be used in the revised version of the American National Standards Institute, ANSI A58.1-1972 Standard.*

In all the cases compared by the author the Type II distribution predicts higher windspeeds for a given mean recurrence interval than the Type I distribution. At recurrence intervals of less than 100 years, the differences are not large. The windspeeds predicted by the Type I distribution for large recurrence intervals (500-10,000 yr) appear to give more reasonable values of windspeed. The values are not significantly larger than upper bound windspeeds expected in extratropical storms.

The Type II distribution was used in earlier studies by the author. In light of the recent research by Simiu et al. (1978) and the more reasonable windspeeds at large mean recurrence intervals, the Type I distribution is used for estimating straight wind risks at the Savannah River site.

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*A "hurricane factor" is used in the calculation of design wind pressures.

The cummulative distribution function for the Type I extreme value distribution (Gumbel distribution) is

$$F(x) = \exp\{-\exp\left[-(x-u)/\sigma\right]\} \quad (3)$$

The u and σ terms are referred to as location and scale parameters, respectively. The method of moments is one approach for determining estimators for the Type I distribution. Simiu and Scanlan (1978) state that the differences in results from this method and other more accurate methods is acceptably small for the 95 percent confidence level. The estimates for σ and u are given by

$$\bar{\sigma} = \frac{\sqrt{6}}{\pi} s \quad (4)$$

$$\bar{u} = \bar{x} - 0.5772\bar{\sigma} \quad (5)$$

where $\bar{x}$ and s are the mean and standard deviation of the sample, respectively. Equation (3) can be inverted to give the estimated windspeed corresponding to a specified mean recurrence interval N.

$$\overline{V}_N = \overline{x} + s(y-0.5772)\frac{\sqrt{6}}{\pi} \qquad (6)$$

where

$$y = \ln\left[-\ln(1 - \frac{1}{N})\right] \qquad (7)$$

Inherent in these estimates are sampling errors, the standard deviation of which can be estimated by the following equation:

$$SD(\overline{V}_N) = \left[\frac{\pi^2}{6} + 1.1396(y-0.5772)\frac{\pi}{\sqrt{6}} + 1.1(y-0.5772)^2\right]^{1/2} \frac{\sqrt{6}}{\pi}\frac{s}{\sqrt{n}} \qquad (8)$$

where n is the sample size. The probability that $\overline{V}_N$ is contained in the interval

$$\overline{V}_N \pm Z_{\alpha/2}\, SD(\overline{V}_N) \qquad (9)$$

is approximately $(1-\alpha)100$ percent.

A data set consisting of the annual extreme windspeeds is used to determine the $\bar{x}$ and s parameters. The windspeed risk model is then obtained from Equation (6). The upper and lower bound confidence limits are estimated from Equation (9).

The probability of exceeding some threshold value of windspeed is the inverse of mean recurrence interval, i.e.

$$P(V_N \geq V) = \frac{1}{N} \qquad (10)$$

III. ASSESSMENT OF TORNADO RISKS

In this section the data, the rationale and the assumptions that are involved in the tornado risk calculations for the Savannah River site are presented. Before discussing the essential features of the calculations, a general discussion of tornado occurrences in the region containing the site is presented.

A. TORNADO OCCURRENCES IN THE REGION CONTAINING THE SITE

The discussion centers on a rectangular region bounded by latitudes 32° and 35° and longitudes 80° and 83°. The Savannah River site is located in the approximate center of the region (See Figure 1).

1. Tornado Records

The source of tornado records for this study is the DAPPLE tornado tape assembled by Dr. Ted Fujita of the University of Chicago. This data source was selected in preference to the other available tornado data tape, which has been assembled by the National Severe Storms Forecasting Center in Kansas City, Missouri. Because the DAPPLE tape has all tornadoes fully rated, and because both Dr. Fujita and the author are independently developing risk models for the Savannah River site, the models can be compared on the basis

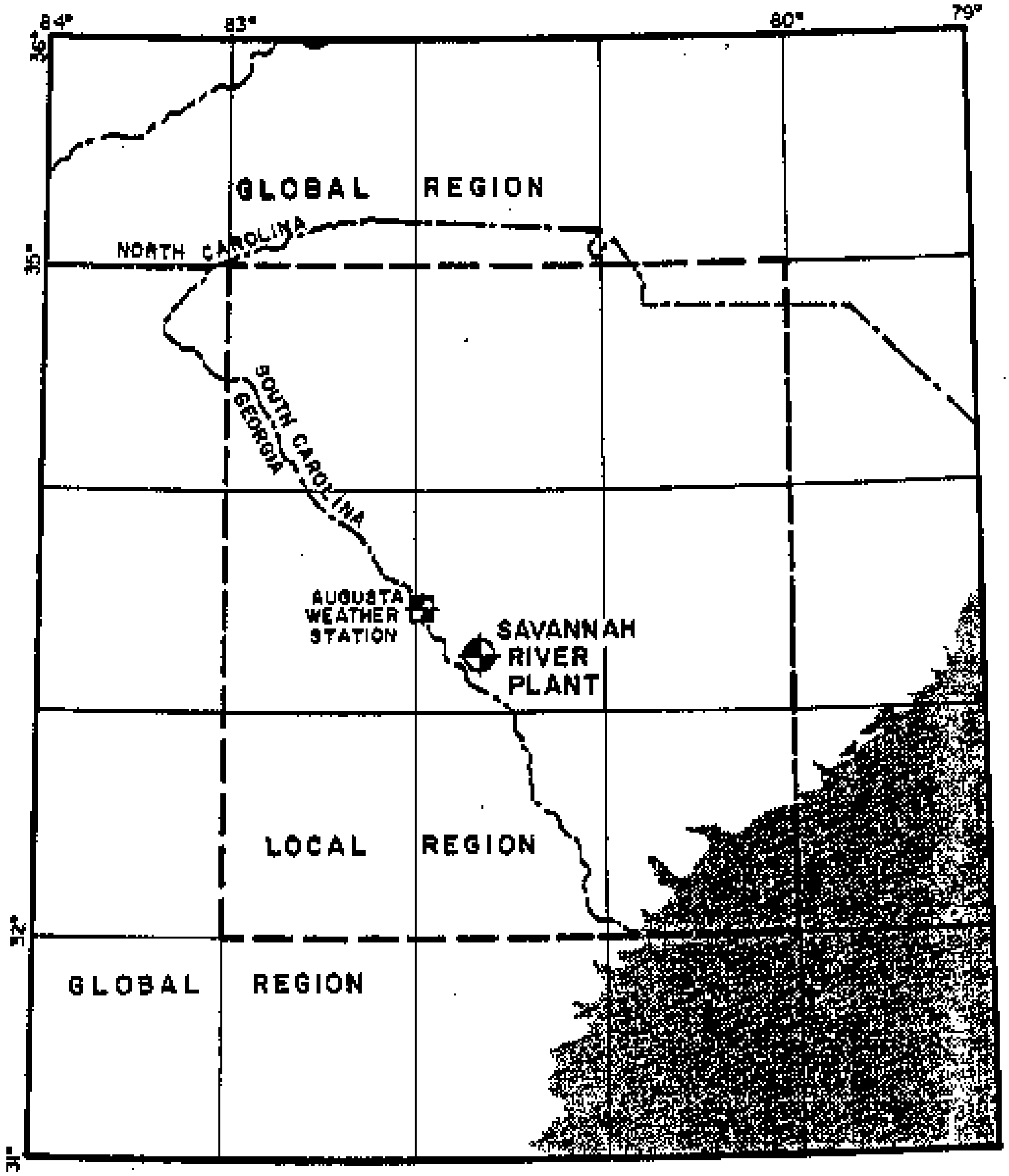


FIGURE 1. LOCAL AND GLOBAL REGIONS

of a common data set. The Fujita-Pearson scales are used to classify tornadoes according to intensity, path length and path width (Fujita, 1971).

2. Tornado Climatology

The characteristics of tornado occurrences in the local region are described in this section. The tornado statistics are obtained from the DAPPLE tape and cover a 29 year period from 1950 to 1978. The tornado records prior to 1950 are believed to be less complete than those after 1950 because of a greater public awareness of tornadoes and because more systematic methods of gathering data are used.

Table 2 shows the number of reported tornadoes per year by F-scale in the local region containing the site. A total of 248 tornado occurrences are recorded on the DAPPLE tape for an average of 8.55 tornadoes per year. The most tornadoes recorded in a single year was 20 in 1973.

The most active month for tornadoes is May, with the majority occurring between March and June. Table 3 shows the number of tornadoes per month by F-scale that have occurred during the reporting period.

3. Geographical Distribution of Tornadoes in the Region

The number of tornado touchdowns per 15-minute subbox is obtained from the DAPPLE tape. Figure 2 (a-e) gives a breakdown

TABLE 2

NUMBER OF REPORTED TORNADOES PER YEAR BY F-SCALE

Year	Number of Tornadoes F0	F1	F2	F3	F4	F5	Total
1950	0	1	0	0	0	0	1
1951	0	0	0	0	0	0	0
1952	0	1	4	1	0	0	6
1953	3	0	0	0	0	0	3
1954	6	3	1	0	0	0	10
1955	0	4	2	1	0	0	7
1956	1	3	2	0	0	0	6
1957	1	2	4	1	1	0	9
1958	3	1	2	0	0	0	6
1959	2	0	0	0	0	0	2
1960	0	1	1	0	0	0	2
1961	6	5	1	3	0	0	15
1962	3	2	2	0	0	0	7
1963	4	2	3	0	0	0	9
1964	6	6	0	0	0	0	12
1965	9	4	1	0	0	0	14
1966	2	2	2	0	0	0	6
1967	0	5	2	0	0	0	7
1968	0	1	3	1	0	0	5
1969	3	2	1	1	0	0	7
1970	1	0	2	3	0	0	6
1971	0	8	4	0	0	0	12
1972	3	6	2	1	0	0	12
1973	1	8	7	2	2	0	20
1974	1	13	1	1	0	0	16
1975	2	9	6	0	0	0	17
1976	1	11	4	0	0	0	16
1977	0	10	1	0	0	0	11
1978	0	3	1	0	0	0	4
Total	58	113	59	15	3	0	248

TABLE 3

NUMBER OF REPORTED TORNADOES PER MONTH BY F-SCALE

	Number of Tornadoes						
Month	F0	F1	F2	F3	F4	F5	Total
January	1	5	6	1	0	0	13
February	3	9	3	2	0	0	17
March	6	15	8	3	1	0	33
April	16	9	12	3	1	0	41
May	5	33	10	2	1	0	51
June	6	11	3	1	0	0	21
July	8	8	2	1	0	0	19
August	6	6	3	0	0	0	15
September	3	5	5	0	0	0	13
October	0	3	3	0	0	0	6
November	3	5	3	0	0	0	11
December	1	4	1	2	0	0	8
Total	58	113	59	15	3	0	248

83° 80° 35°

0	0	2	0	2	0	0	1	0	0	0	0
0	0	2	0	0	0	0	1	0	1	0	1
0	0	0	0	0	1	0	0	0	0	1	1
0	0	0	1	0	0	1	0	1	0	0	1
0	0	0	0	0	0	0	2	0	0	2	0
0	0	0	1	0	0	1	3	0	2	0	2
0	0	0	0	0	0	1	1	2	0	4	1
0	0	1	0	0	0	2	0	0	1	0	0
0	0	0	0	0	0	0	2	0	3	1	1
0	0	0	0	0	2	0	0	0	0	0	0
0	1	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	3	0	2	0	0

32° 83° 80°

a) F0 Tornadoes

83° 80° 35°

0	2	4	0	1	0	0	2	0	1	3	0
1	1	0	1	0	0	0	1	1	1	0	0
0	2	0	1	1	1	0	0	0	2	2	1
1	0	0	0	0	1	0	2	1	0	0	3
2	0	2	1	1	1	0	1	3	2	2	1
0	0	1	1	0	1	1	0	2	0	0	3
0	2	0	1	1	2	2	3	3	0	1	0
2	0	1	0	0	0	0	0	0	0	0	4
0	0	0	1	3	0	0	1	0	3	0	1
1	1	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	3	2	0	1	2	0	0
1	0	1	2	2	0	0	3	0	0	0	0

32° 83° 80°

b) F1 Tornadoes

FIGURE 2. NUMBER OF TORNADO TOUCHDOWNS PER 15-MINUTE SUBBOX BY F-SCALE

83° 35° — 80° 35°

1	1	0	1	0	0	1	0	0	0	1	1
0	0	1	0	0	0	0	0	2	0	0	0
1	1	1	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	2	1	1	0	1	0
0	0	0	0	0	1	0	0	1	0	0	0
0	1	0	0	0	0	0	0	0	0	2	0
0	1	1	0	0	0	2	0	1	1	1	0
0	0	0	0	1	0	0	0	0	0	0	0
2	1	0	0	1	2	0	0	0	0	0	0
0	1	2	1	0	0	0	0	0	0	0	0
0	0	0	1	1	1	2	0	0	0	0	0
0	2	4	2	0	0	0	4	0	1	0	0

83° 32° — 80° 32°

c) F2 Tornadoes

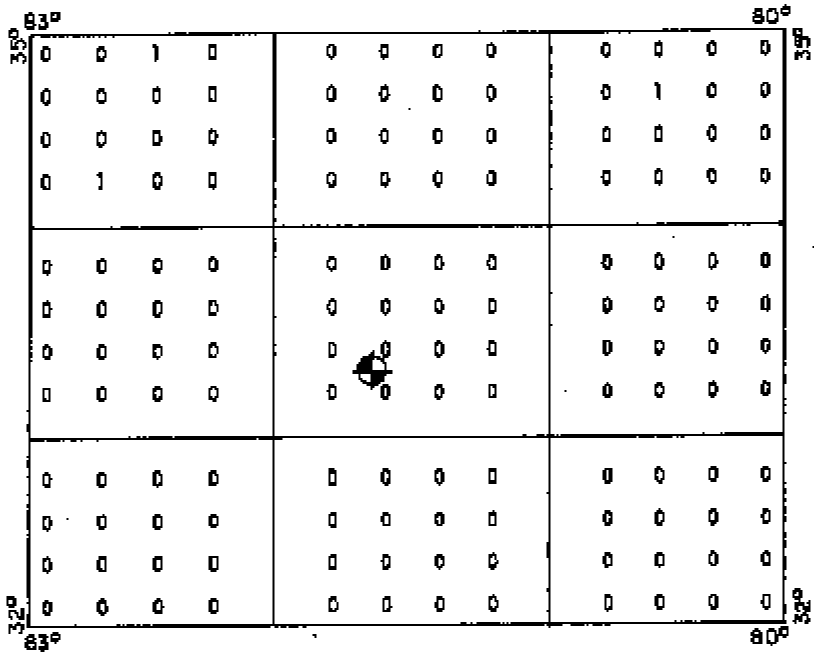
83° 35° — 80° 35°

0	0	0	0	0	0	0	0	0	2	0	0
0	0	0	0	1	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
0	1	0	1	0	1	0	0	0	0	0	0
0	0	0	0	0	1	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0
0	0	1	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	0	2	0	0	0

83° 32° — 80° 32°

d) F3 Tornadoes

FIGURE 2. NUMBER OF TORNADO TOUCHDOWNS PER 15-MINUTE SUBBOX BY F-SCALE (continued)



e) F4 Tornadoes

FIGURE 2. NUMBER OF TORNADO TOUCHDOWNS PER 15-MINUTE SUBBOX BY F-SCALE

of the number of tornado touchdowns per 15-minute subbox by F-scale classification. The total number of tornado touchdowns per subbox is shown in Figure 3. There have been no tornadoes reported with a F5 rating.

4. Estimate of Number of Unreported Tornadoes

Figure 4 shows the number of persons per sq mi (population density) in each 15-minute subbox of the local region. These values were obtained for each county from the 1970 census data. If cities with population greater than or equal to 5000 were located in a county, the city population was subtracted from the county population to obtain a county rural population. By dividing by the county area, the number of rural persons per sq mi was determined. An image of the 15-minute subboxes was laid over the county maps and a weighted mean rural population per sq was then determined for each subbox. If a city with population greater than or equal to 5000 was located in the subbox, the city population was accounted for in determining the population per sq mi of the subbox. The scale of the maps used and the nonuniform distribution of population within the counties contribute to some unknown amount of error in these caculations. The error is estimated to be less than 25 percent.

83° 35° — 80° 35°

1	3	7	1	3	0	1	3	0	3	4	1
1	1	3	1	1	0	0	2	3	3	0	1
2	3	1	1	1	2	0	0	0	2	3	3
1	2	0	2	0	2	3	3	3	0	1	4
2	0	2	1	1	3	0	3	4	2	4	1
0	1	1	2	0	1	2	3	2	2	2	5
0	3	1	1	0	2	5	4	6	1	6	1
2	0	2	0	2	0	2	0	0	1	0	4
2	1	1	1	5	2	0	3	0	6	1	2
1	2	3	1	0	3	0	0	0	0	0	0
1	1	0	1	1	4	4	0	1	2	0	0
1	2	5	5	2	0	0	10	2	3	0	0

83° 32° — 80° 32°

FIGURE 3. TOTAL NUMBER OF TORNADO TOUCHDOWNS PER 15-MINUTE SUBBOX

83° 35° — 80° 35°

74	146	457	232	320	60	67	221	64	112	66	42
144	125	203	86	85	80	36	56	90	61	38	35
79	110	62	94	74	69	30	26	38	52	38	64
81	36	39	149	37	32	85	123	134	90	59	64
30	35	26	29	32	61	93	661	123	120	177	60
22	33	56	65	84	72	72	55	41	40	46	42
20	38	98	133	377	62	38	36	106	51	49	31
24	26	30	37	31	27	27	34	32	42	49	39
25	26	27	19	22	29	26	28	22	45	55	225
82	22	45	19	25	29	29	22	31	44	71	75
22	23	23	37	84	25	28	22	34	73	7	0
20	10	72	36	36	19	49	585	43	6	0	0

83° 32° — 80° 32°

FIGURE 4. NUMBER OF PERSONS PER SQ MILE PER 15-MINUTE SUBBOX

The number of reported tornadoes per subbox is then correlated with the population density per subbox to obtain an estimate of the number of tornadoes that may not have been reported. Details of these calculations are presented in Appendix A. (pp 62-67)

B. AREA-INTENSITY RELATIONSHIP

The global region selected for deriving the area-intensity relationship is defined as the area bounded by latitudes 31° to 36° and longitudes 79° to 84°. Figure 1 shows the global region and its position relative to the Savannah River site. The area-intensity data are taken from the DAPPLE tape and include all reported tornadoes from 1971-1978. Details of the area-intensity relationship calculations are presented in Appendix A. (pp 58-60)

The mean tornado damage path areas for each F-scale classification were determined from tornado records of the global region. A linear regression analysis, based on a log-log plot of area versus tornado windspeed, is performed to obtain a continuous functional relationship between area and intensity. Confidence intervals are obtained from the regression analysis and are used later to estimate confidence intervals on the estimated tornado probabilities. Details of these calculations are given in Appendix A. (pp 58-60)

C. OCCURRENCE-INTENSITY RELATIONSHIP

Development of the occurrence-intensity relationship is somewhat more complicated than the area-intensity relationship. The size of the local region must be carefully selected and the number of unreported tornadoes must be estimated.

Table 4 summarizes the number of tornadoes in the local region per F-scale. The data are taken from the DAPPLE tape for the period 1950-1978.

The number of unreported tornadoes is estimated, based on the technique described above. The number of unreported tornadoes is distributed per F-scale in the same proportion as the reported ones. The occurrence-intensity relationship is then expressed as a continuous functional relationship. (pp. 61, 68, 69, 70) Confidence limits are obtained for the binomial parameter p, which is the proportion of the tornadoes of a certain F-scale intensity in the random sample of size n. (pp 69, 71)

D. TORNADO RISK MODEL CALCULATIONS

Details of the tornado risk model calculations are given in Appendix A. (pp 69, 73-75) The probability of tornadic windspeeds in each F-scale windspeed interval V_j is calculated using the following equation:

TABLE 4

NUMBER OF TORNADOES IN THE LOCAL REGION

	Number of Tornadoes					
	F0	F1	F2	F3	F4	F5
Number of Reported Tornadoes	58	113	59	15	3	0
Estimated Number of Unreported Tornadoes	17.3	32.9	18.8	4.1	0.8	0.1
Total Number of Tornadoes	75.3	145.9	77.8	19.1	3.8	0.1

Local Region

Latitude $32^{\circ} - 35^{\circ}$

Longitude $80^{\circ} - 83^{\circ}$

Period of Record 1950-1978

Area of Region 34,453 sq mi

$$P(V = \overline{V}_j) = \frac{1}{A} \sum_{i=j}^{6} \lambda_i a_{ij} \tag{11}$$

where A is the area of the local region, λ_i is the number of tornadoes per year in F-scale windspeed interval i (occurrence-intensity relationship) and a_{ij} is the path area that is exposed to windspeed in the interval j of a tornado whose maximum windspeed is in the interval i. The probability of tornado windspeeds exceeding interval values in one year is then calculated.

$$P(V \geq \overline{V}_j) = \sum_{j=j}^{6} P(V=\overline{V}_j) \tag{12}$$

These latter quantities, by definition, constitute the tornado risk model for the local region. A plot of the probability of exceeding threshold windspeed in one year versus windspeed is a convenient way to display the tornado risk model. The tornado risk model is summarized in Section V.

IV. ASSESSMENT OF STRAIGHT WIND RISKS

This section deals with the determination of straight wind risks for the Savannah River Plant site. The data and the rationale required for the analysis are presented. Calculation details are given in Appendix B. The results are summarized in Section V.

A. WINDSPEED RECORDS

Records of annual extreme windspeeds are not available at the site. The closest weather station with the needed data is Augusta, Georgia, which is approximately 20 mi northwest of the site. The basic wind climate at Augusta is essentially the same as that for the site. The set of annual extreme fastest one-minute windspeeds recorded at Augusta were used as the data set. After developing the straight wind probability model, the one-minute windspeeds are converted to fastest-mile windspeeds in order to be consistent with the wind load provision of ANSI A58.1.

Table 5 lists the set of annual extreme fastest one-minute windspeeds for the Augusta weather station site (NOAA, 1978). The maximum value recorded in the 29 year period of record is 83 mph. The minimum value is 32 mph. Table 6 shows the annual extreme fastest one-minute windspeeds by

TABLE 5

ANNUAL EXTREME FASTEST ONE-MINUTE WINDSPEEDS
AT AUGUSTA, GEORGIA

Year	Windspeed* (mph)	Direction	Date
1950	83	SW	5/28
1951	34	W	2/7
1952	42	E	7/25
1953	73	NE	6/10
1954	44	NW	8/28
1955	48	S	5/29
1956	48	W	7/15
1957	31	W	11/30+
1958	36	NW	11/28
1959	36	NW	9/29+
1960	36	W	7/22
1961	48	N	6/11
1962	41	NW	4/11
1963	40	W	11/29
1964	43	S	5/21
1965	67	E	6/10
1966	37	NW	5/27+
1967	52	W	5/8
1968	43	NW	7/16
1969	43	NE	7/8
1970	52	NW	7/16
1971	34	SW	7/11
1972	56	SW	3/2
1973	37	NW	11/21
1974	49	W	3/21
1975	37	W	7/6+
1976	32	NW	3/9
1977	43	S	10/2
1978	39	SW	1/26

* Windspeeds corrected to 10 m anemometer height.

\+ Windspeed occurred more than once during the year.

TABLE 6

ANNUAL EXTREME ONE-MINUTE WINDSPEEDS BY MONTH AT AUGUSTA, GEORGIA

Spring			Summer		
M	A	M	J	J	A
56	41	83	73	49	44
49		52	67	42	
32		48	52	36	
		43	48		
		37	43		
			43		
			37		
			34		

Fall			Winter		
S	O	N	D	J	F
36	43	31		39	34
		36			
		40			
		37			

month. Generally the peaks occur during the late spring and early summer, with a secondary peak in November. As shown in Table 7, wind direction associated with the maxima varies primarily from S to NW with W and NW being the most predominant directions.

B. STRAIGHT WIND RISK MODEL CALCULATIONS

The annual extreme fastest one-minute windspeed values given in Table 5 are used to determine the straight wind risk model. The sample mean $\bar{x}$ is 45.0, the sample standard deviation s is 12.1, and the sample size n is 29 years. Substituting appropriate values into Equations (6) and (8), the estimated windspeed and the standard deviation of the estimator are obtained for any mean recurrence interval N. Results of the straight wind risk calculations are summarized in Section V and Appendix B.

TABLE 7

ANNUAL EXTREME ONE-MINUTE WINDSPEEDS
BY DIRECTION AT AUGUSTA, GEORGIA

Wind Direction							
S	SW	W	NW	N	NE	E	SE
48	83	52	52	48	73	67	
43	56	49	44		43	42	
43	39	48	43				
	34	40	41				
		37	37				
		36	37				
		34	36				
		31	36				
			32				

V. SUMMARY OF TORNADO AND STRAIGHT WIND RISKS

Risk Models are calculated for both tornadoes and straight winds. Details of these calculations are presented in Appendixes A and B. The final windspeed risk model is a combination of the tornado and straight wind risk models. At windspeeds below a certain value the windspeeds are more likely to be from straight winds. Above this value the windspeeds are more likely to originate from tornadoes.

The probability of the occurrence of a straight wind or tornado can be calculated by methods described earlier in the report. For design or evaluation purposes, one needs to know the type of storm that controls the criteria. In the case of a tornado the atmospheric pressure change and missiles must be taken into account in addition to the wind effects. Because of this the union of the two events is not of particular interest.

A. TORNADO RISKS

Tornado risks are calculated for the local region surrounding the Savannah River site. Table 8 summarizes the tornado risks. The probability of exceeding threshold wind-speeds in one year versus windspeed is plotted in Figure 5 along with the 95 percent confidence limits.

TABLE 8

SUMMARY OF TORNADO RISKS
WITH 95 PERCENT CONFIDENCE LIMITS

Mean Recurrence Interval	Risk Probability Per Year	Tornado Windspeeds, mph		
		Expected Value	Lower Limit	Upper Limit
10,000	1.0×10^{-4}	58	30	83
100,000	1.0×10^{-5}	142	113	174
1,000,000	1.0×10^{-6}	207	170	242
10,000,000	1.0×10^{-7}	283	230	333

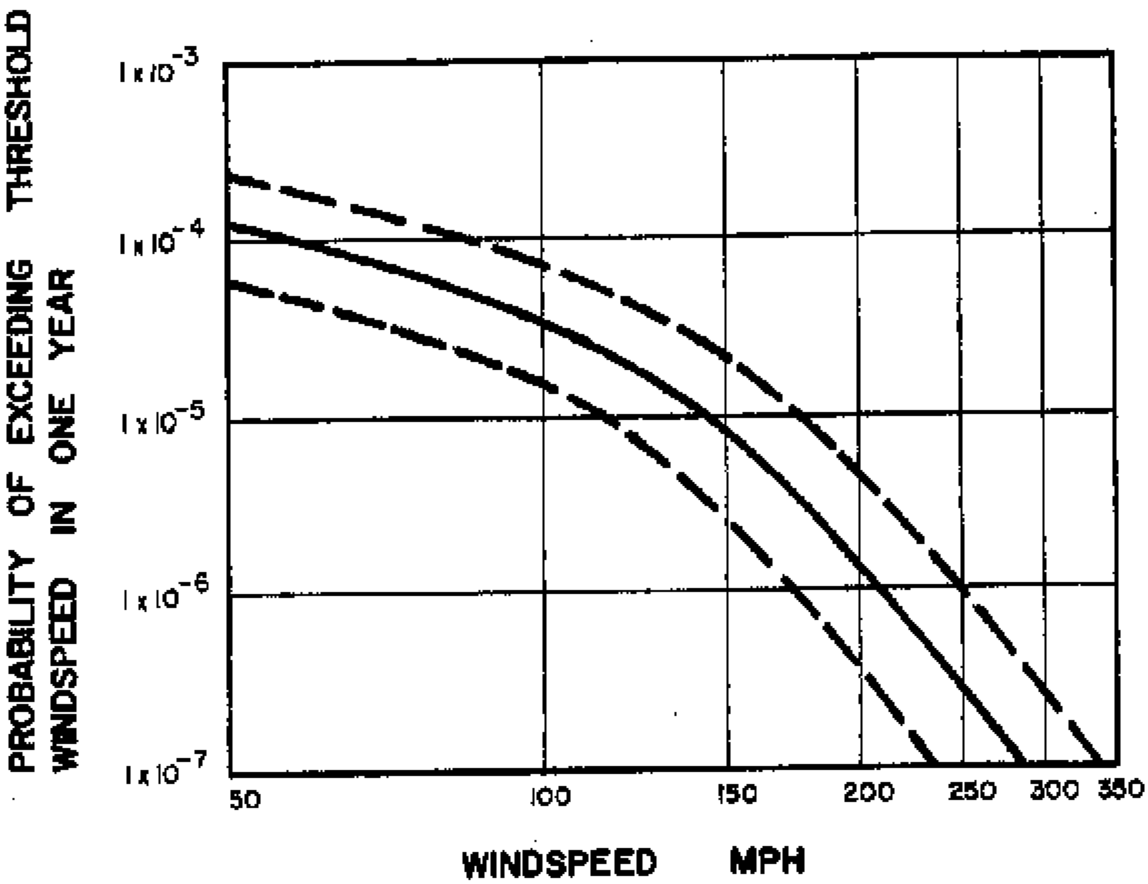


FIGURE 5. TORNADO RISK MODEL WITH 95 PERCENT CONFIDENCE LIMITS

Tornado windspeeds are referenced to 30 ft above ground level. According to Fujita (1971), F-scale intensity is based on fastest one-quarter mile winds. However, because of the translational speed of a tornado, winds acting on a structure may be of considerably less duration.

B. STRAIGHT WIND RISKS

Annual extreme fastest one-minute windspeeds recorded at the Augusta, Georgia weather station are used to calculate the straight wind risk model. The Type I extreme value distribution is selected for the model. Reasons for preference of the Type I over the Type II are discussed in Section II.

The fastest one-minute windspeeds are converted to fastest-mile windspeeds in order to be consistent with the use of ANSI A58.1. The difference in the two is due to the averaging time. A 60 mph fastest-mile windspeed has the same averaging time as a one-minute windspeed. A one-minute windspeed that is greater than 60 mph has a larger averaging time than the corresponding fastest-mile windspeed. Thus a fastest-mile windspeed corresponding to a one-minute windspeed is larger than the one-minute windspeed. Above 60 mph the relationship between fastest-mile windspeed and fastest one-minute windspeed is (McDonald, 1980)

$$V_{(F-M)} = 1.17^{V(1-min)} - 10.34 \tag{13}$$

Table 9 summarizes the straight wind risks. The probability of exceeding threshold windspeeds in one year versus windspeed is plotted in Figure 6 along with 95 percent confidence limits.

C. FINAL WINDSPEED RISK MODEL

The tornado and straight wind models are combined in Figure 7 to obtain the final windspeed risk model. At windspeeds less than approximately 172 mph (risk level of 3.6×10^{-6}) the straight wind model governs. For windspeeds greater than 172 mph the tornado model dominates. Table 10 summarizes the final windspeed risks.

The straight winds obtained from the Augusta weather station data are expressed in terms of fastest-mile windspeeds. A gust factor as defined in ANSI A58.1 should be included in the calculations for the design wind loads.

D. SENSITIVITY STUDY OF TORNADO RISK MODEL

The sensitivity of the tornado risk model to various parameters is presented herein for use in comparing results with models that are developed by others. Factors that can significantly affect the tornado risk model are:

TABLE 9

SUMMARY OF STRAIGHT WIND RISKS
WITH 95 PERCENT CONFIDENCE LIMITS

Recurrence Interval	Probability Per Year	Fastest One-Minute Windspeeds,* mph: Expected Value	Lower Limit	Upper Limit
10	1.0×10^{-1}	61(61)	52(51)	70(72)
20	5.0×10^{-2}	68(69)	56(55)	79(82)
50	2.0×10^{-2}	76(79)	62(62)	91(96)
100	1.0×10^{-2}	83(87)	66(67)	100(107)
200	5.0×10^{-3}	90(95)	70(72)	109(117)
500	2.0×10^{-3}	98(105)	75(78)	121(132)
1,000	1.0×10^{-3}	105(113)	79(82)	130(142)
10,000	1.0×10^{-4}	127(139)	93(99)	160(177)
100,000	1.0×10^{-5}	148(163)	106(114)	190(212)
1,000,000	1.0×10^{-6}	170(189)	120(130)	220(248)

* Values in parentheses are fastest-mile windspeeds. See Equation (13) for relationship between fastest-mile windspeed and fastest one-minute windspeed.

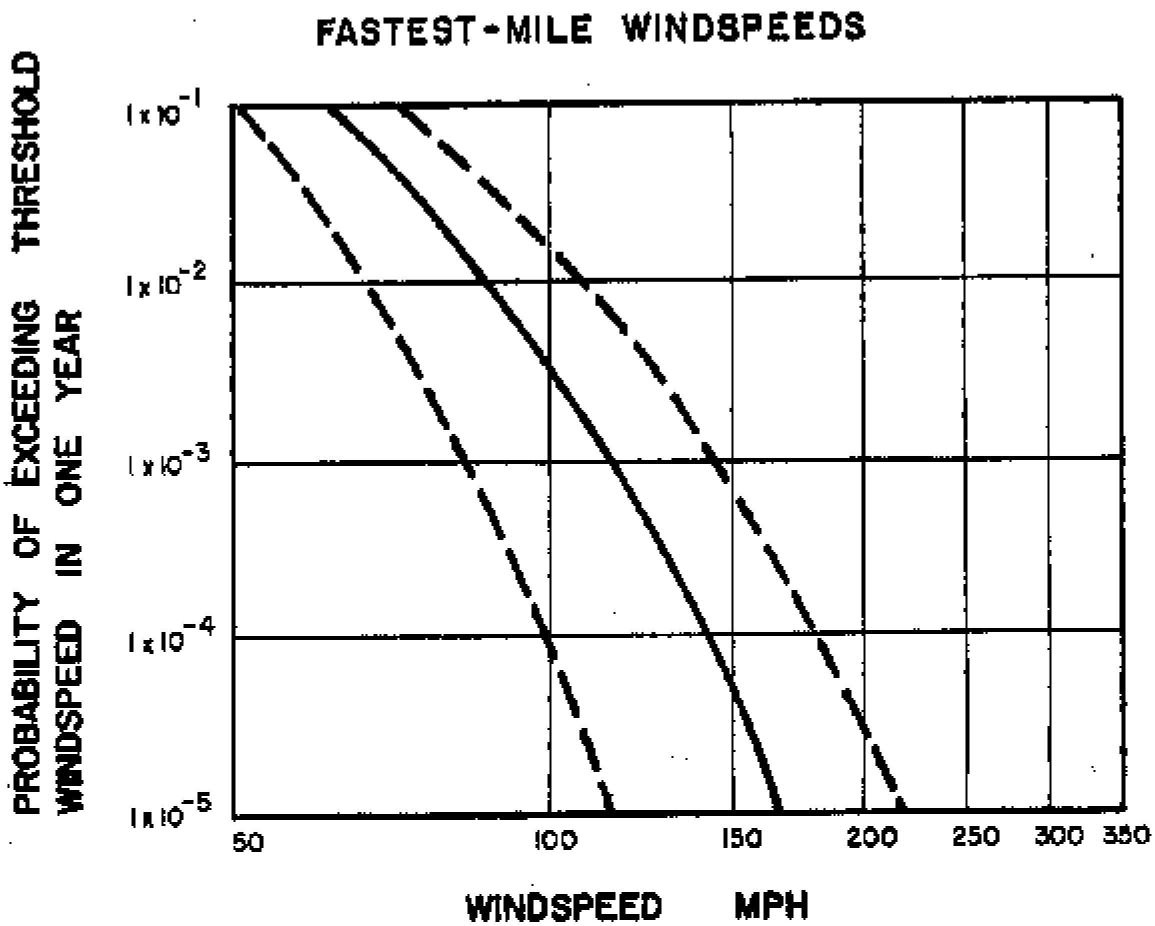


FIGURE 6. STRAIGHT WIND RISK MODEL WITH 95 PERCENT CONFIDENCE LIMITS

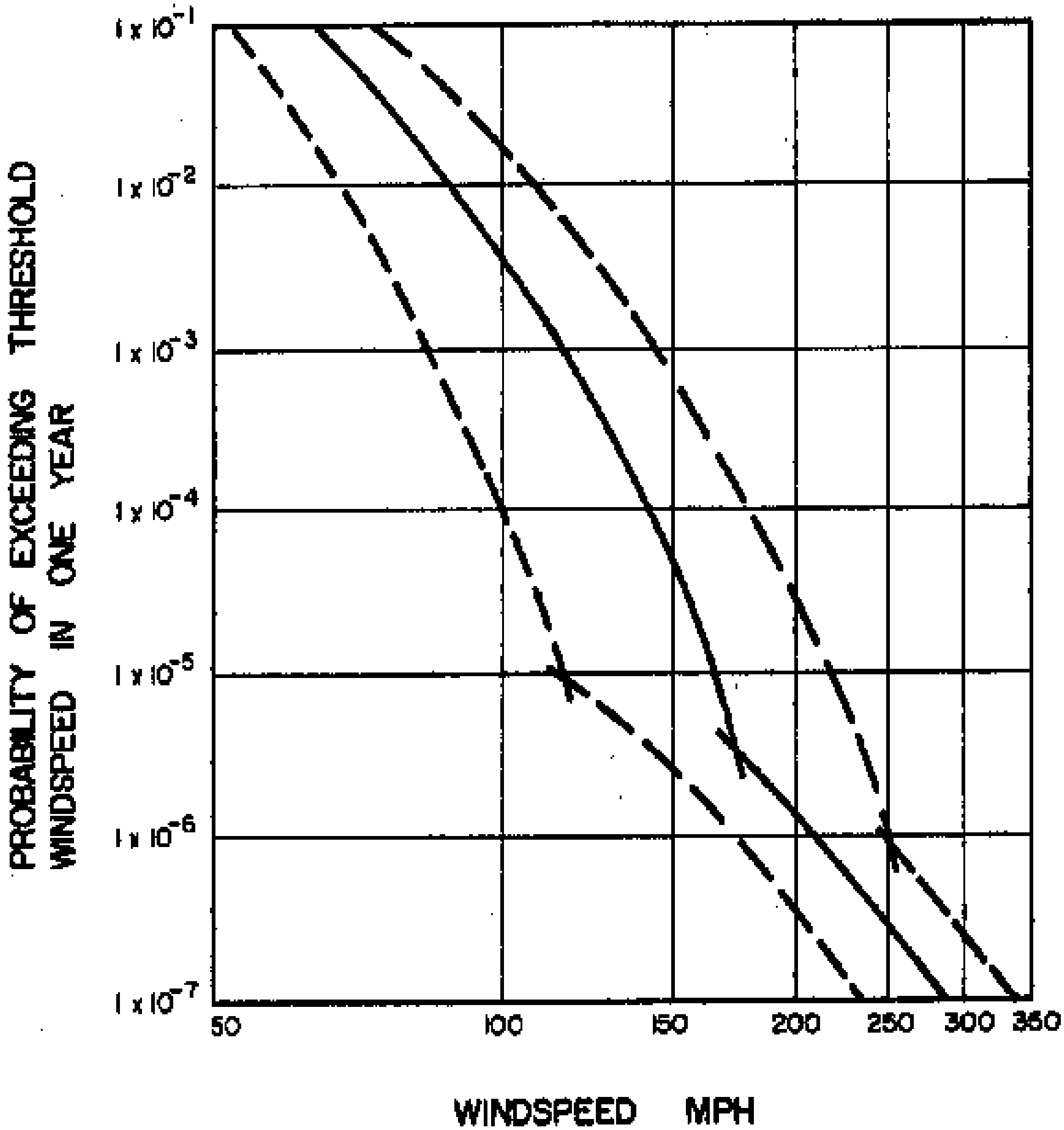


FIGURE 7. WINDSPEED RISK MODEL WITH 95 PERCENT CONFIDENCE LIMITS

TABLE 10

SUMMARY OF WINDSPEED RISKS WITH 95 PERCENT CONFIDENCE LIMITS FOR SAVANNAH RIVER PLANT

Mean Recurrence Limit	Risk Probability Per Year	Windspeeds, mph			Type of Storm
		Expected Value	Lower Limit	Upper Limit	
100	1.0×10^{-2}	87	67	107	Straight Wind
1,000	1.0×10^{-3}	113	82	142	Straight Wind
10,000	1.0×10^{-4}	139	99	177	Straight Wind
100,000	1.0×10^{-5}	163	114	212	Straight Wind
1,000,000	1.0×10^{-6}	207	170	242	Tornado
10,000,000	1.0×10^{-7}	283	230	333	Tornado

(1) Selection of global region

(2) Selection of local region

(3) Selection of period of record

(4) Estimation of unreported tornadoes

(5) Use of gradations of damage

In this study the global region is selected as a 5-Degree square region surrounding the site. The region covers what is believed to be a homogeneous region of tornado characteristics. The large number of tornadoes recorded in the region (251) contributes to the relatively narrow confidence bands on the area-intensity relationship.

1971-1978? (also see Table B1)

The local region is selected as a 3-Degree square region surrounding the site. The region is believed to be a homogeneous area with respect to tornado occurrence. The number of tornadoes recorded contributes to relatively narrow confidence bands on the occurrence-intensity relationship.

The 1971 to 1978 period for determining the area-intensity relationship and the 1950 to 1978 period for determining the occurrence-intensity relationship are believed to be optimum for the quality of the data on available tornado tapes. Since 1971 tornado records have been kept on a more systematic basis than prior to that time. Information on path length and path width are more accurate and more complete than in the records prior to 1971. Thus a relatively large global region and a recent period of record is selected for determining the area-intensity relationship. One could argue that the 19 year period of record for the occurrence-intensity relationship is too short. Why not use the 63 years of data contained on the DAPPLE tape? Studies of the numbers of tornadoes per year in the U.S. show that the annual number took a significant jump around 1950 because of increased public awareness of the phenomena resulting from issuance of the watches and warnings by the National Weather Service. A superoutbreak such as the one that occurred on April 3-4, 1974 might be missed, but the missing data prior to 1950 seems to outweigh the chance of not considering the severe outbreaks.

The relatively small number of estimated unreported tornadoes (74) has little effect on the final tornado hazard probability model. The differences can be seen in Figure 8.

Because of the land use, the type of terrain and the population density, one would expect relatively few tornadoes to go unreported in the local region. This fact is born out by the results of the correlation between population density

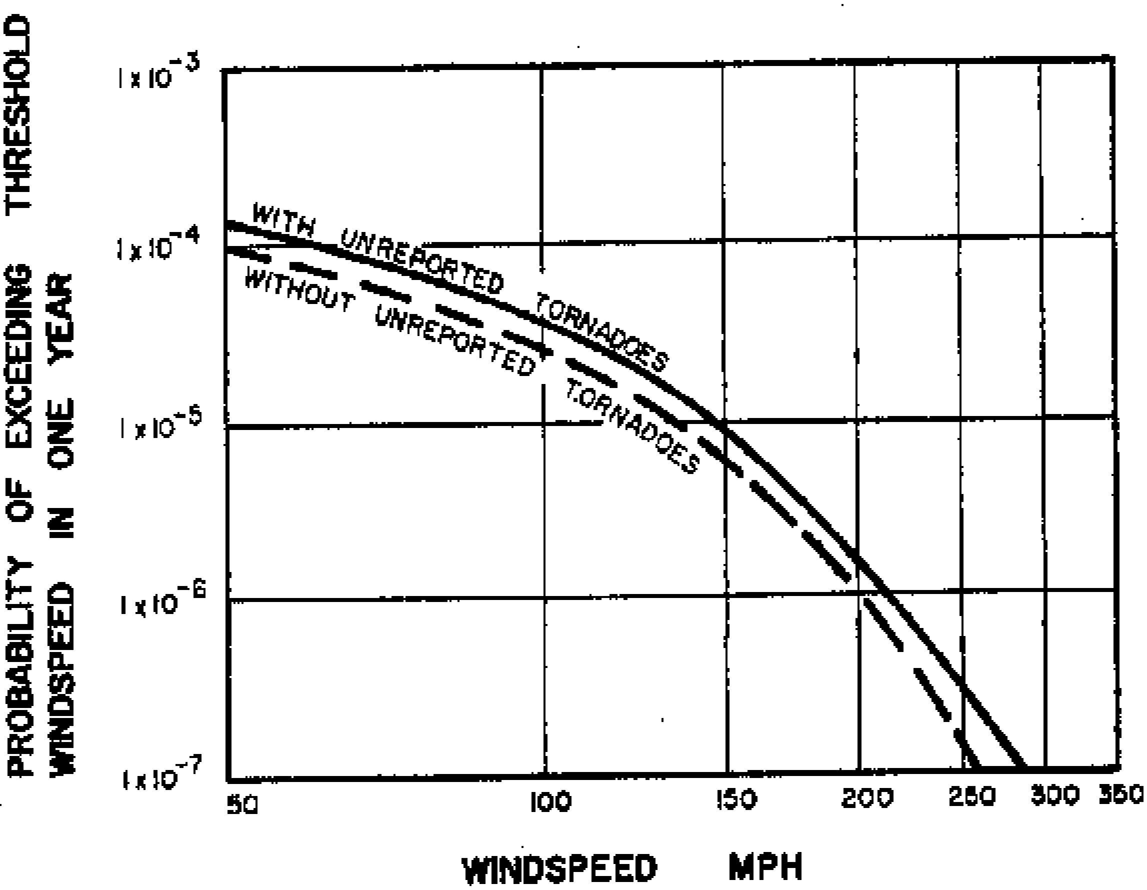


FIGURE B. EFFECT OF UNREPORTED TORNADOES ON RISK MODEL and number of tornadoes per subbox. The estimated 74 unreported tornadoes in the 29 year reporting period is 30 percent of the total number of reported tornadoes (248).

Consideration of gradations of damage both along the length and across the path is realistic and represents a better approach to risk model analysis than those used by the author previously.

These considerations are not discussed in this document. However, see item (2)c. below.

E. COMPARISON OF PRESENT WINDSPEED RISK MODEL WITH EARLIER ONE

The author developed a risk model earlier (McDonald, et al., 1975) for the Savannah River site. The windspeed model included probabilities of both straight winds and tornadoes. The two models are compared in Figure 9.

There has been considerable change in philosophy, in technique and in the data sets since 1975. The present windspeed risk model differs from the earlier one in several ways.

(1) Straight wind risk model
   a. Different source and period of windspeed records
   b. Type I rather than Type II windspeed distribution function

(2) Tornado risk model
   a. Different source and period of tornado records
   b. Account for unreported tornadoes in the records
   c. Consideration of gradations of damage along length of tornado path

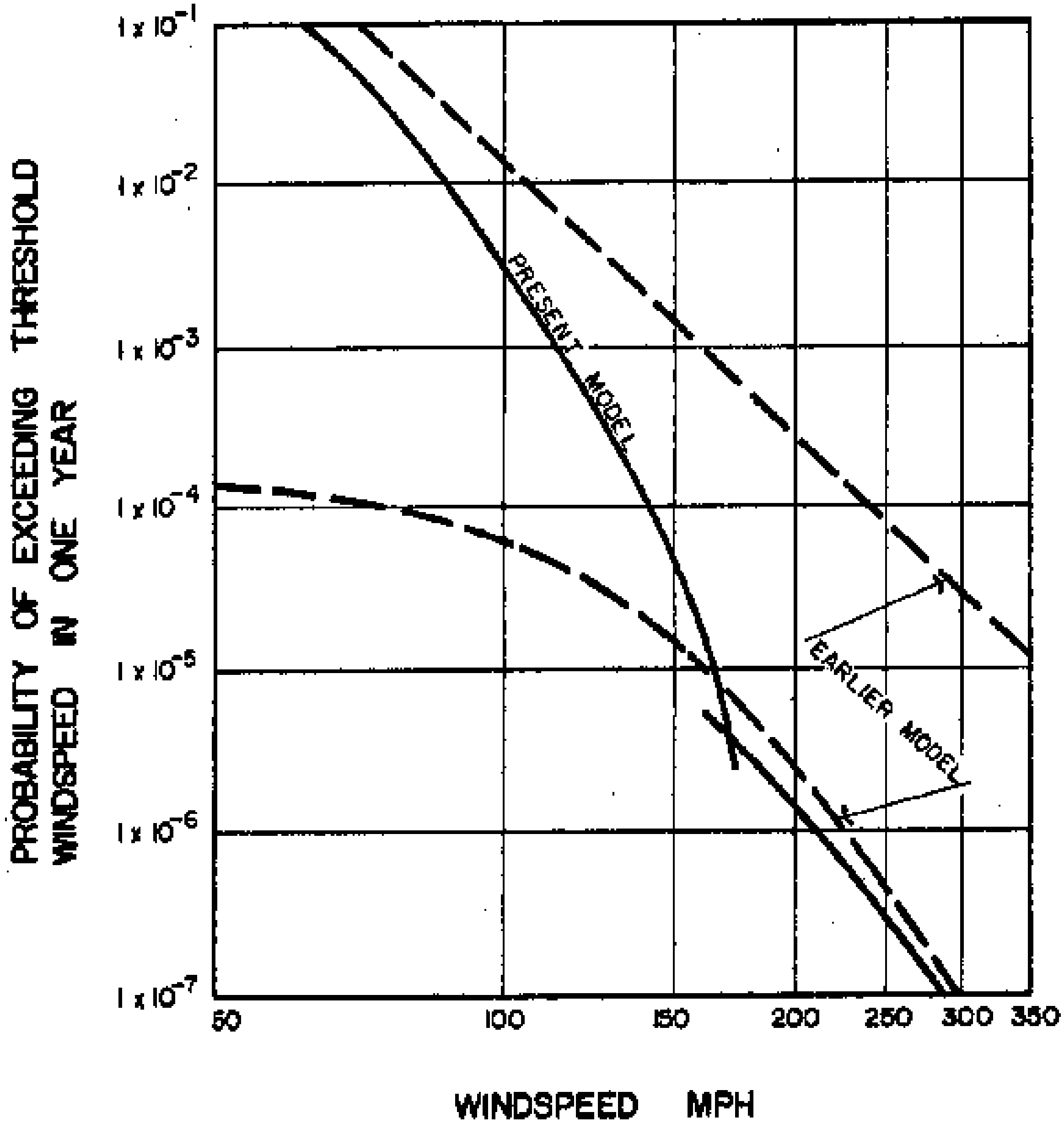


FIGURE 9. COMPARISON OF PRESENT WINDSPEED RISK MODEL WITH EARLIER ONE

Each of these differences are considered an improvement of the earlier risk model methodology. There is a major difference in the results of the straight wind models. The tornado models are reasonably similar.

The difference in the straight wind models is due to the fact that the Type I distribution converges to lower windspeeds at small probability levels. The risks based on the Type II distribution dominated the tornado risks in the earlier model even in this tornado prone region. This fact supports the contention that the Type I distribution is preferable to the Type II at low probability levels.

The two tornado hazard probability models give fairly similar results. This fact is coincidental. The local region, the period of record, the data set and even the methodology are different in the two models. Obviously some of the differences are self-compensating.

VI. TORNADO PARAMETERS FOR DESIGN AND EVALUATION OF FACILITIES

Once the maximum horizontal windspeed is determined from the tornado risk model, other tornado vortex parameters are defined based on tornado vortex mechanics. Because direct measurements of tornado parameters are virtually impossible to obtain, numerical values of tornado vortex parameter are obtained by indirect methods. The two most commonly used methods of tornado parameter measurements are photogrammetric analysis of movies of tornado funnels (Golden, 1976) and engineering calculations of the tornadic forces required to produce observed damage (Mehta, 1976). Other methods that have been used include the geometry of cyloidal ground marks, debris patterns observed in the damage path, and height of cloud base above ground level.

The various tornado parameters and their functional relationships make up what is known as a tornado windfield model. Numerous tornado windfield models can be found in the literature. The two basic types are 1) meteorological models, which attempt to model the prototype through physical parameters of temperature, pressure and vorticity of the parent thunderstorm, and 2) engineering models which attempt to represent upperbound forces that can be exerted on a structure by a tornado. The tornado model proposed in this study is the latter type. It has been developed and refined by the author over a period of seven years, based on relatively simple physical relationships and on observed damage patterns produced by tornadoes. Tornadoes exert forces on structures through three principal mechanisms: wind, atmospheric pressure change and missiles. The tornado parameters associated with these three factors are discussed in the paragraphs below.

A. WIND PARAMETERS

The variation of wind velocity within the tornado vortex is referred to as the tornado windfield. One of the earliest significant studies of tornado windfield parameters was performed by Hoecker (1960) on the Dallas tornado of 1957. More recent studies are available (Golden, and Davies-Jones, 1975; Zipser, 1976), but for engineering purposes, the work of Hoecker gives a simple, but representative, model of the tornado windfield. Hoecker found that at the 1000 ft level the tangential windfield behaves similar to a Combined Rankine Vortex. At elevations below 1000 ft the wind profile deviates somewhat from the Rankine-type vortex because of boundary layer effects and turbulence. Since the Combined Rankine profile is conservative and mathematically simple, it is the basis for the windfield model proposed in the design criteria.

Components of the 3-dimensional wind velocity vector are shown in Figure 10. Associated tornado parameters for different

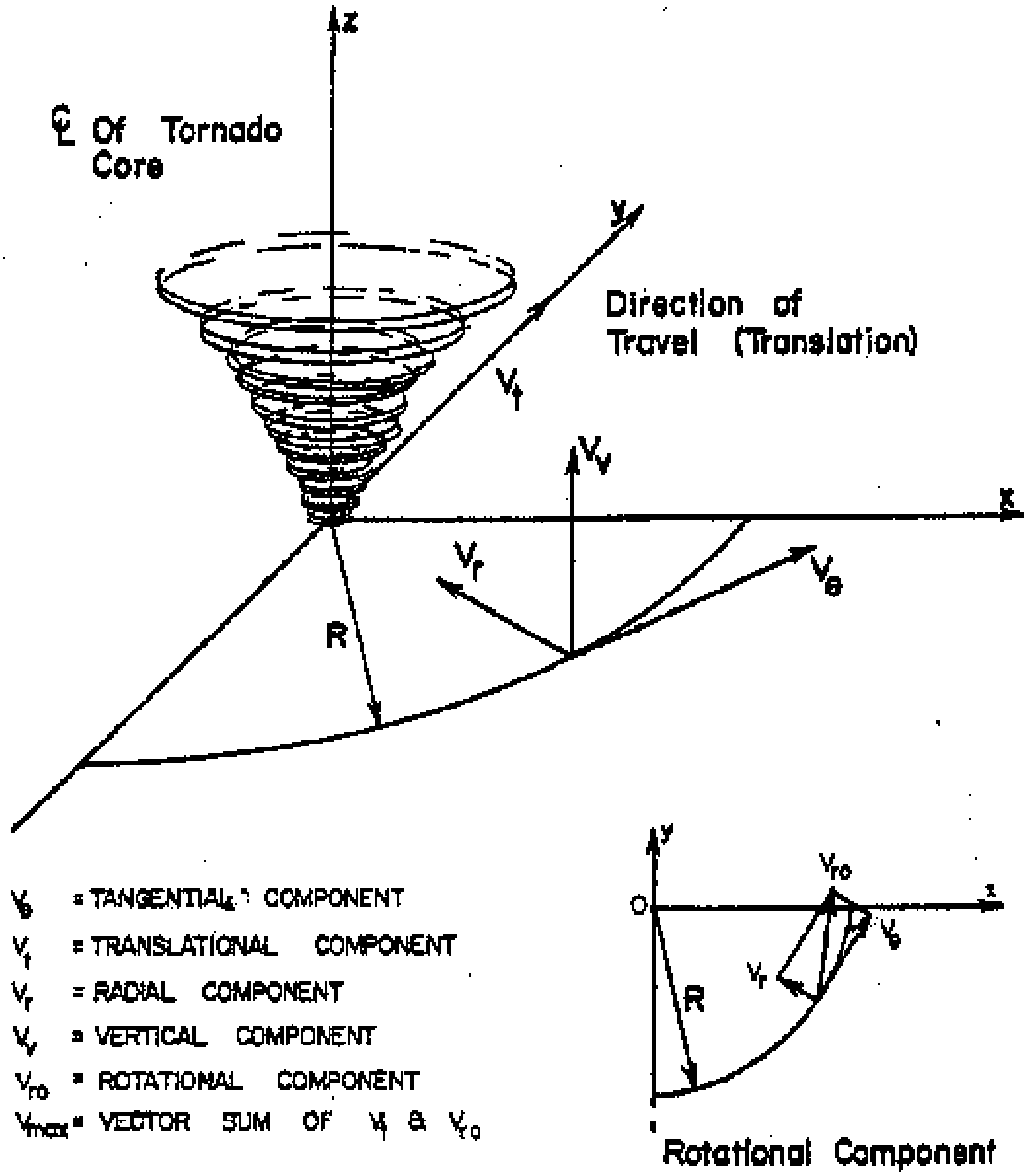


FIGURE 10. THREE-DIMENSIONAL WIND VELOCITY VECTOR IN A TORNADO

values of maximum horizontal windspeeds are given in Table 11. The table also shows the functional relationships 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 tend to have larger radii of maximum winds. These trends are born out in tornado statistics. 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 equations given in Table 11 are not exact, but give a good approximation.

B. ATMOSPHERIC PRESSURE CHANGE

The atmospheric pressure change is obtained by integrating the cylostrophic equation

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

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

TABLE 11

DESIGN BASIS TORNADO PARAMETERS

Wind Component	Symbol	Equation	Maximum Values of Parameters					
Wind Velocity Components:								
Max. Horizontal, mph	V_{max}	(From Risk Model)	100	150	200	250	300	360
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	268
Radial, mph	V_r	$0.5V_\theta$	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_0	$\frac{R_{max}}{75}(V_{max})$	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

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

$$V_\theta R = C \qquad (R_{max}<R<\infty) \tag{14}$$

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

$$p = \rho V_{\theta max}^2 \tag{15}$$

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

$$\frac{dp}{dt} = \rho V_{\theta max}^2 \frac{V_t}{R_{max}} \tag{16}$$

The values of maximum pressure change and maximum rate of pressure change are given in Table 11.

C. WINDBORNE MISSILES

Table 12 lists the tornado generated missiles that should be considered for design or evaluation of structures. The four missiles listed in the table are those most likely to be picked up by the winds 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 (USNRC, 1975). 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 13 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 windfield and falls to the ground under the influence of gravity.

A computer program developed at Texas Tech University (McDonald, 1975), calculates the time-history response of missiles generated by the tornado windfield model. 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 non-tumbling 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 13. 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 13. 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 between the car and the ground. Thus, the automobile is expected to roll, tumble and bounce at the speeds indicated in the table.

TABLE 12

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. Steel 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

*Value given is metal area. In penetration calculations the gross cross sectional area may be used.

TABLE 13

WINDBORNE MISSILE VELOCITIES

	Horizontal Missile* Velocity, mph						
Design Windspeed	100	150	200	250	300	350	Maximum Height, ft
Timber plank	60	72	90	100	125	175	200
3 in. Dia. Std. Pipe	40	50	65	85	110	140	100
Utility Pole	**	**	**	80	100	130	30
Automobile	**	**	**	25	45	70	30

*Vertical velocities are taken as 2/3 the horizontal missile velocity. Horizontal and vertical velocities should not be combined vectorially.

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

VII. CONCLUSIONS

A windspeed risk model which accounts for both tornadoes and straight winds has been developed from weather records in the region surrounding the Savannah River plant site. Straight winds dominate for probabilities greater than 3.6×10^{-6}. Tornadoes control for probabilities smaller than this value (See Figure 7).

The following conclusions are drawn from the study;

(1) Tornado windspeeds associated with the 1×10^{-7} probability level is 283 mph.

(2) The population density and land use contribute to the relatively small number of unreported tornadoes in the region.

(3) The homogeneous meteorological and topographical conditions in the region surrounding the site lend a qualitative confidence to the results of this study.

(4) The relative agreement of the previous tornado risk model with the current one is because some of the differences are self-compensating.

(5) The differences in the straight wind models are primarily due to the distribution functions used.

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APPENDIX A

TORNADO RISK CALCULATION DETAILS

A. AREA INTENSITY RELATIONSHIP

Global Region

Latitude $31^{\circ} - 36^{\circ}$

Longitude $79^{\circ} - 84^{\circ}$

Years 1971-1978

DAPPLE Tornado Tape UT1678

TABLE AI

AREA-INTENSITY MATRIX

Area Interval	Number of Tornadoes* F0	F1	F2	F3	F4	F5	Mean Area (sq mi)
0	11	11	7	0	0	0	0.316E-02
1	10	54	4	0	0	0	0.100E-01
2	1	45	10	0	0	0	0.316E-01
3	1	36	13	1	0	0	0.100E 00
4	1	29	14	2	0	0	0.316E 00
5	0	6	7	4	0	0	0.100E 01
6	0	2	2	2	1	0	0.310E 01
7	0	0	0	0	1	0	0.100E 02
8	0	0	0	0	0	0	0.316E 02
9	0	0	0	0	0	1	0.100E 03
10	0	0	0	0	0	0	0.316E 03
Totals	24	183	57	9	2	0	

* Those tornadoes outside the dashed lines are considered outliers and have been eliminated from the data set.

Mean Area Per F-Scale

	F0	F1	F2	F3	F4	F5
Area, sq mi	0.0243	0.1480	0.3407	1.2280	6.5800	--
Median Windspeed, mph	56	92.5	135	182	233.5	289.5

Area-Intensity Function

Linear regression analysis of the above area-intensity data, based on a log-log plot, yields the following functional relationship:

$$\text{Log (Area)} = 3.0488 \text{ Log } V - 6.8595 \qquad \text{(A1)}$$

The coefficient of determination for the regression analysis is

$$r^2 = 0.98$$

Area-Intensity Relationship

Using Equation (A1) to obtain the expected mean area and Equation (1) to obtain the upper and lower bound confidence limits, the following information regarding the area-intensity relationship is obtained:

	F0	F1	F2	F3	F4	F5
Expected mean area a_i, sq mi	0.0295	0.1364	0.4319	1.0738	2.2954	4.4207
Lower limit a_i, sq mi	0.0211	0.0979	0.3096	0.7680	1.6365	3.1405
Upper limit a_i, sq mi	0.041	0.190	0.602	1.501	3.222	6.223
Median Windspeed, mph	56	92.5	135	182	233.5	289.5

The above data are plotted in Figure A1

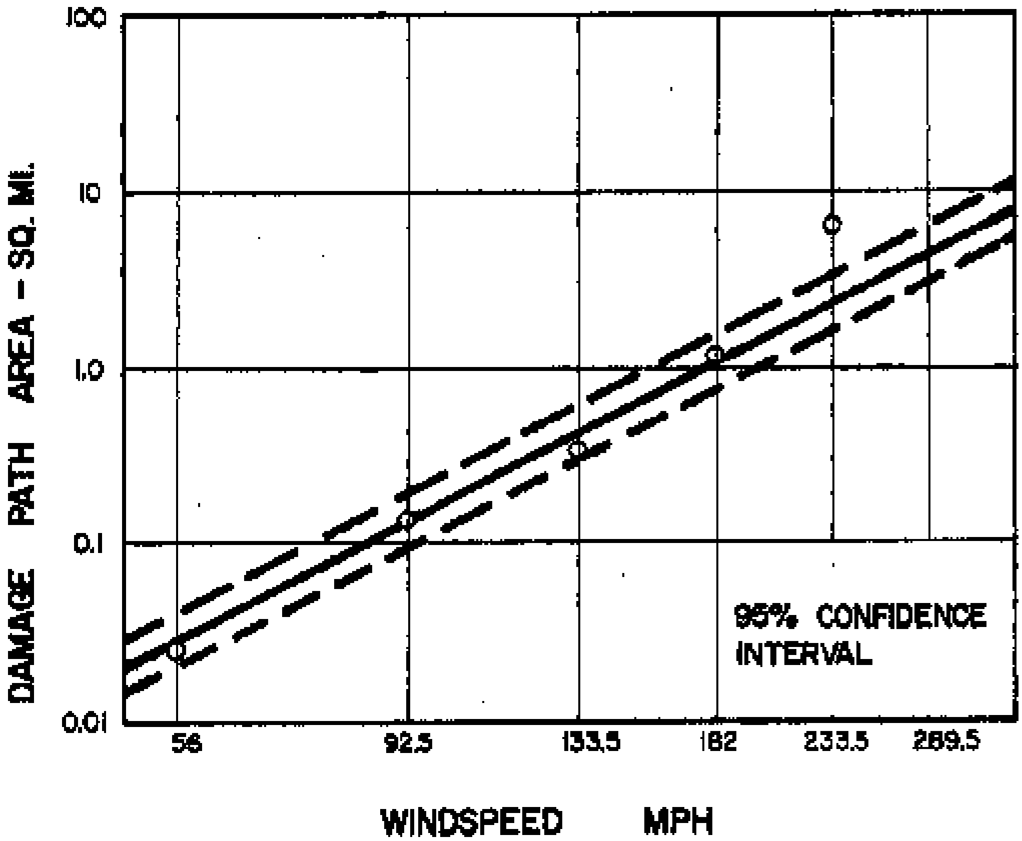

FIGURE A1. AREA-INTENSITY RELATIONSHIP WITH 95 PERCENT CONFIDENCE LIMITS

B. OCCURRENCE-INTENSITY RELATIONSHIP

Local Region

Latitude $32^0 - 35^0$

Longitude $80^0 - 83^0$

DAPPLE Tape UT1678

Years 1950 - 1978

Area = 35,874 - 1,421 (area of ocean)

= 34,453 sq mi

Number of Reported Tornadoes

	Number of Tornadoes					
	F0	F1	F2	F3	F4	F5
Number of Reported Tornadoes	58	113	59	15	3	0
Cumulative Number	248	190	77	18	3	0
Lower Bound Windspeed, mph	40	73	113	158	207	261

Occurrence-Intensity Relationship Based on Reported Tornadoes

Linear regression analysis of the above data yields:

$$y = (341.52)10^{-0.0035x} \quad (x \leq 92 \text{ mph})$$

$$y = (3956.49)10^{-0.0150x} \quad (x \geq 92 \text{ mph}) \qquad \text{(A2)}$$

where y is the cumulative number of tornadoes with windspeeds greater than or equal to x.

The two regression lines based on reported tornadoes are shown in Figure A3.

Unreported Tornadoes Because of Sparce Population in the Local Region.

The number of persons per sq mi per 15-minute subbox is tabulated in Figure 4. The number of tornadoes per 15-minute subbox is given in Figure 3. The estimated number of unreported tornadoes is obtained from a correlation between population density and number of tornadoes per subbox.

In order to get an estimate of the total number of unreported tornadoes, the number of tornadoes per year in the local region from 1950-1978 is examined in Figure A2.

A linear regression analysis is performed using the data from 1950-1978. The positive slope of the regression line indicates that the annual number of reported tornadoes increases with time. This suggests that there are tornadoes missing from the data set. The tornadoes are undetected because of

(1) Sparce population density
(2) Land use
(3) Terrain characteristics

In connection with the population density, the estimated number of unreported tornadoes is arrived at as follows: a correlation between population density and number of tornadoes per 15-minute subbox is shown in Table A2.

Select $\bar{x}_h = 2.24$

With $\bar{x}_a = 1.72$

$N = (2.24 - 1.72)144$

$= 74$ unreported tornadoes

The ~~74~~ 2.24 value selected for $\bar{x}_h$ implies that all tornadoes are reported in subboxes with population greater than 74 persons per sq mi. A total of 74 unreported tornadoes is 30 percent of the 248 reported tornadoes. This value seems consistent with the land use, which consists of 17 percent crops and managed woodlands in a terrain made up of alternating hills and valleys. The mean number of tornadoes per year is 11.1.

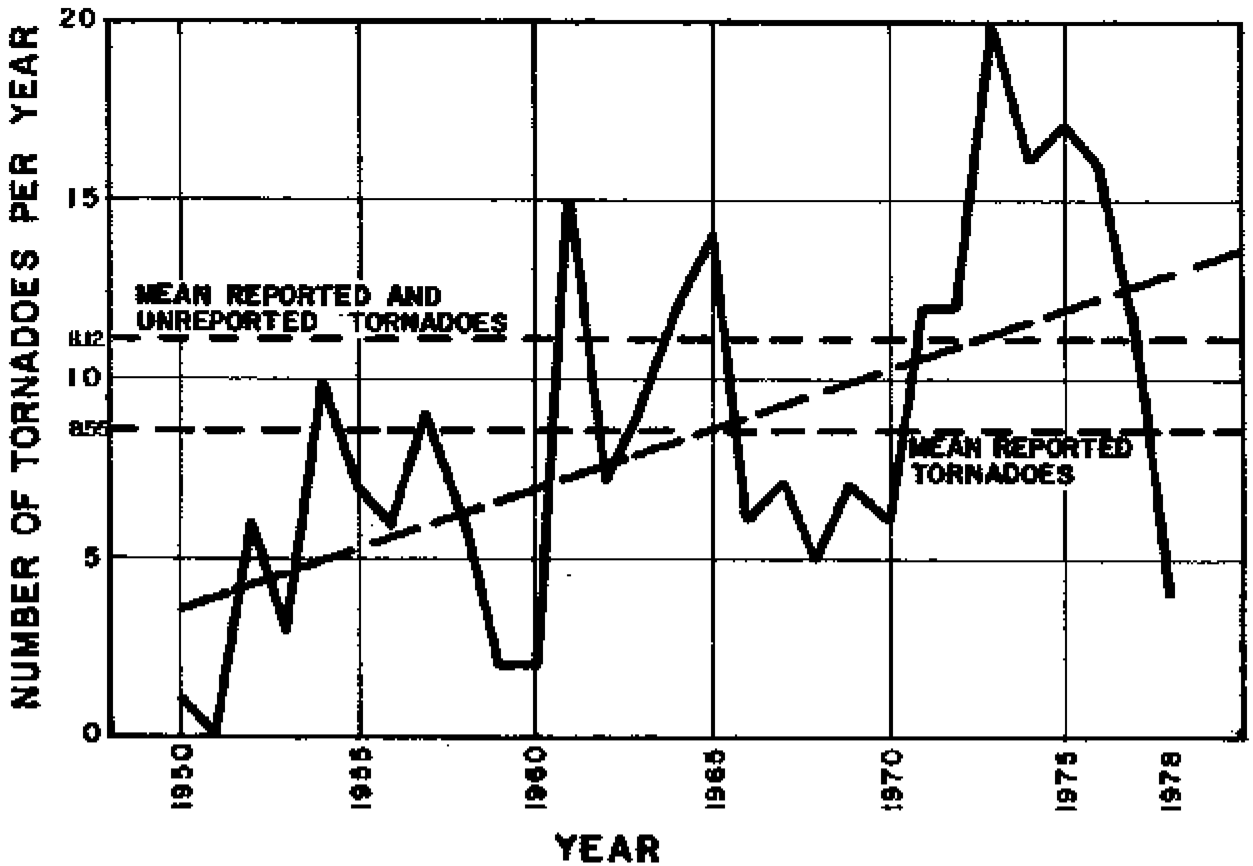

FIGURE A2. NUMBER OF REPORTED TORNADOES PER YEAR

TABLE A2

CORRELATION BETWEEN POPULATION DENSITY
AND NUMBER OF TORNADOES PER SUBBOX

Subbox	Population Density	No. of Tornadoes	Cumulative Tornadoes	Tornadoes Per Subbox
1	661	3	3	3.00
2	585	10	13	6.50
3	457	7	20	6.67
4	377	1	21	5.25
5	320	3	24	4.80
6	232	1	25	4.17
7	225	2	27	3.86
8	221	3	30	3.75
9	203	3	33	3.67
10	177	4	37	3.70
11	149	2	39	3.55
12	146	3	42	3.50
13	144	1	43	3.31
14	134	2	46	3.29
15	133	1	47	3.13
16	125	1	48	3.00
17	123	3	51	3.00
18	123	4	55	3.06
19	120	2	57	3.00
20	112	3	60	3.00
21	110	3	63	3.00
22	106	6	69	3.14
23	98	1	70	3.04
24	94	1	71	2.96
25	92	0	71	2.84
26	90	3	74	2.85
27	90	0	74	2.74
28	86	1	75	2.68
29	85	3	78	2.69
30	85	1	79	2.63
31	84	0	79	2.55
32	84	1	80	2.50
33	82	1	81	2.45
34	81	1	82	2.41
35	80	0	82	2.34

TABLE A2

(continued)

Subbox	Population Density	No. of Tornadoes	Cumulative Tornadoes	Tornadoes Per Subbox	
36	79	2	84	2.33	
37	75	0	84	2.27	
38	74	1	85	2.24	← $\bar{x}_h$
39	74	1	86	2.21	
40	73	2	88	2.20	
41	72	1	89	2.17	
42	72	2	91	2.17	
43	72	5	96	2.23	
44	71	0	96	2.18	
45	69	2	98	2.18	
46	66	2	100	2.17	
47	65	2	102	2.17	
48	64	3	105	2.19	
49	64	0	105	2.14	
50	62	1	106	2.12	
51	62	2	108	2.12	
52	61	3	111	2.13	
53	60	1	112	2.11	
54	59	1	113	2.09	
55	57	1	114	2.07	
56	55	1	115	2.05	
57	55	3	118	2.07	
58	55	1	119	2.05	
59	55	4	123	2.08	
60	54	4	127	2.12	
61	52	2	129	2.11	
62	51	3	132	2.13	
63	51	1	133	2.11	
64	50	0	133	2.08	
65	49	6	139	2.14	
66	49	0	139	2.11	
67	49	0	139	2.07	
68	46	2	141	2.07	
69	45	6	147	2.13	
70	45	3	150	2.14	

TABLE A2

(continued)

Subbox	Population Density	No. of Tornadoes	Cumulative Tornadoes	Tornadoes Per Subbox
71	44	0	150	2.11
72	43	2	152	2.11
73	42	1	153	2.10
74	42	1	154	2.08
75	42	5	159	2.12
76	41	2	161	2.12
77	40	2	163	2.12
78	39	0	163	2.09
79	39	4	167	2.11
80	38	5	172	2.15
81	38	0	172	2.12
82	38	3	175	2.13
83	38	3	178	2.14
84	38	0	178	2.12
85	37	0	178	2.09
86	37	0	178	2.07
87	36	4	182	2.09
88	36	0	182	2.07
89	36	2	184	2.07
90	36	2	186	2.07
91	35	1	187	2.05
92	35	0	187	2.03
93	35	5	192	2.06
94	34	1	193	2.05
95	34	0	193	2.03
96	33	1	194	2.02
97	32	1	195	2.01
98	32	0	195	1.99
99	32	2	197	1.99
100	31	0	197	1.97
101	31	2	199	1.97
102	31	1	200	1.96
103	30	2	202	1.96
104	30	2	204	1.96
105	30	0	204	1.94

TABLE A2

(continued)

Subbox	Population Density	No. of Tornadoes	Cumulative Tornadoes	Tornadoes Per Subbox
106	29	1	205	1.93
107	29	3	208	1.94
108	29	0	208	1.93
109	29	2	210	1.93
110	28	3	213	1.94
111	28	4	217	1.95
112	27	2	219	1.96
113	27	1	220	1.95
114	27	0	220	1.93
115	27	1	221	1.92
116	26	1	222	1.91
117	26	0	222	1.90
118	25	2	224	1.90
119	25	0	224	1.88
120	25	0	224	1.87
121	25	4	228	1.88
122	25	0	228	1.87
123	25	2	230	1.87
124	24	3	232	1.87
125	23	1	233	1.86
126	23	0	233	1.85
127	22	2	235	1.85
128	22	0	235	1.84
129	22	0	235	1.82
130	22	4	239	1.84
131	22	0	239	1.82
132	22	1	240	1.82
133	22	0	240	1.80
134	20	0	240	1.79
135	20	1	241	1.79
136	19	1	242	1.78
137	19	0	242	1.77
138	19	1	243	1.76
139	10	2	245	1.76
140	7	0	245	1.75
141	6	3	248	1.76
142	0	0	248	1.75
143	0	0	248	1.73
144	0	0	~~148~~ 248	1.72 ← $\bar{x}_a$

Distribution of Unreported Tornadoes

	Number of Tornadoes					
	F0	F1	F2	F3	F4	F5
Number of Reported Tornadoes from DAPPLE Tape	58	113	59	15	3	0
Number of Reported Tornadoes from Regression Analysis	58.00	110.28	62.89	13.74	2.62	0.48
Percent in Interval	0.234	0.445	0.254	0.055	0.011	0.002
Estimated Number of Unreported Tornadoes	17.31	32.91	18.76	4.10	0.78	0.14
Total Number of Tornadoes	75.30	143.18	81.65	17.84	3.40	0.62
Cummulative Total	322.00	246.69	103.51	21.86	4.02	0.62
Windspeed, mph	40	73	113	158	207	261

Occurrence-Intensity Relationship Based on Reported and Unreported Tornadoes

$$y = (444.71)10^{-0.0035x} \qquad (x<92 \text{ mph})$$

$$y = (5{,}137.48)10^{-0.0150x} \qquad (x \geq 92 \text{ mph}) \qquad \text{(A4)}$$

Occurrence-Intensity Relationship

Using Equation (A4) to obtain the expected number of tornadoes $\hat{n}$ and Equation (2) to obtain the upper and lower bound confidence limits, the following information regarding occurrence-intensity is obtained.

	F0	F1	F2	F3	F4	F5
Expected No. of Tornadoes in the Interval $\hat{n}$	75.30	143.18	81.65	17.84	3.40	0.62
Lower limit $\hat{n}$	60.41	125.70	66.35	9.80	--	--
Upper limit $\hat{n}$	90.19	160.66	96.95	25.89	6.99	2.17
Expected No. of Tornadoes per year, λ_i	2.60	4.94	2.82	0.62	0.12	0.021
Lower limit λ_i	2.08	4.33	2.29	0.34	--	--
Upper limit λ_i	3.11	5.54	3.34	0.89	0.24	0.07
Windspeed, mph	40	73	113	158	207	261

The expected values of the above occurrence-intensity relationship are plotted in Figure A3 for comparison with the one which neglects unreported tornadoes. The occurrence-intensity relationship used in the model calculations along with the 95 percent confidence limits is shown in Figure A4.

C. TORNADO PROBABILITY CALCULATIONS

The Tornado probabilities are calculated using Equation (11) and (12) and the technique described in McDonald (1979). Calculations are done by computer. The following four pages summarize the computer calculations.

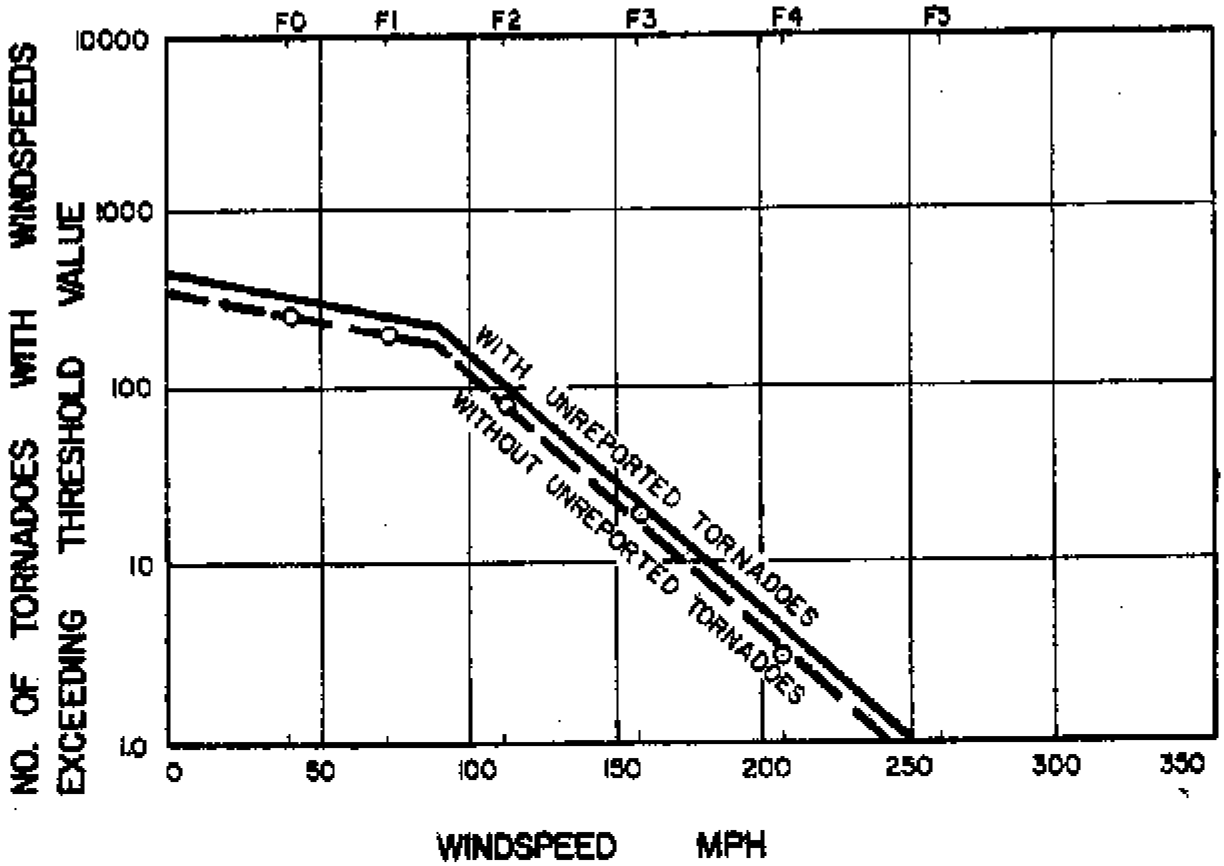

FIGURE A3. OCCURRENCE-INTENSITY RELATIONSHIPS WITH AND WITHOUT UNREPORTED TORNADOES

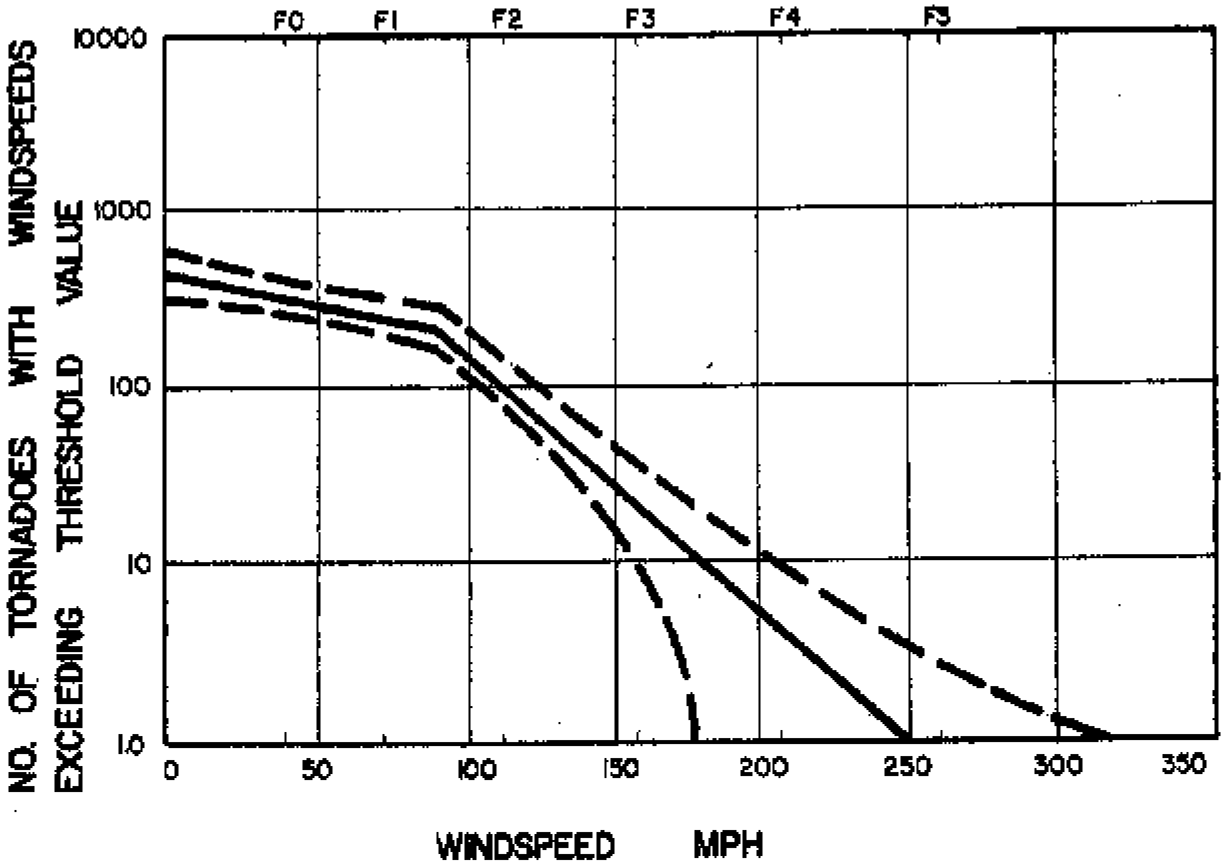

FIGURE A4. OCCURRENCE-INTENSITY RELATIONSHIP WITH 95 PERCENT CONFIDENCE LIMITS

COMPUTER PRINTOUTS

ASSESSMENT OF TORNADO RISK

PROGRAM BY JAMES R. MCDONALD,P.E. (4/3/79)

SAVANNAH RIVER EXPECTED VALUES

K MATRIX

						A-I	LAM-I
1.875	0.000	0.000	0.000	0.000	0.000	0.030	1.998
1.420	0.455	0.000	0.000	0.000	0.000	0.136	3.805
1.067	0.512	0.291	0.000	0.000	0.000	0.432	2.172
0.927	0.482	0.280	0.174	0.000	0.000	1.074	0.475
0.962	0.421	0.261	0.128	0.007	0.000	2.295	0.091
0.965	0.387	0.238	0.160	0.077	0.042	4.425	0.014

ALAM(I,J)=K(I,J)*A(I)*LAM(I)

0.111	0.000	0.000	0.000	0.000	0.000	
0.737	0.236	0.000	0.000	0.000	0.000	
1.001	0.480	0.273	0.000	0.000	0.000	
0.473	0.246	0.143	0.089	0.000	0.000	
0.200	0.087	0.054	0.027	0.018	0.000	
0.061	0.024	0.014	0.010	0.005	0.003	
-----	-----	-----	-----	-----	-----	
2.582	1.074	0.484	0.125	0.023	0.003	SUMMATION ALAM(J)
34453	34453	34453	34453	34453	34453	AREA OF LOCAL REGION-SQ MI
7.49E-005	3.12E-005	1.41E-005	3.64E-004	6.66E-007	7.71E-008	PROB OF WINDSPEED IN INTERVAL FJ
1.25E-004	4.96E-005	1.84E-005	4.39E-006	7.43E-007	7.71E-008	PROB OF EXCEED WINDSPEED IN INTERVAL F
40	73	113	158	207	261	LOWER BOUND WINDSPEED IN INTERVAL FJ

ASSESSMENT OF TORNADO RISK

PROGRAM BY JAMES R. MCDONALD,P.E. (4/3/79)

SAVANNAH RIVER UPPER LIMIT (95% confidence)

K MATRIX

						A-I	LAM-I
1.875	0.000	0.000	0.000	0.000	0.000	0.041	3.110
1.420	0.455	0.000	0.000	0.000	0.000	0.190	5.540
1.067	0.512	0.291	0.000	0.000	0.000	0.602	3.343
0.927	0.482	0.280	0.174	0.000	0.000	1.501	0.893
0.962	0.421	0.261	0.128	0.087	0.000	3.220	0.241
0.968	0.387	0.228	0.160	0.077	0.043	6.223	0.075

ALAM(I,J)=K(I,J)*A(I)*LAM(I)

0.239	0.000	0.000	0.000	0.000	0.000	
1.495	0.479	0.000	0.000	0.000	0.000	
2.147	1.030	0.586	0.000	0.000	0.000	
1.243	0.646	0.375	0.233	0.000	0.000	
0.747	0.327	0.203	0.099	0.068	0.000	
0.449	0.180	0.106	0.074	0.036	0.020	
-----	-----	-----	-----	-----	-----	
6.319	2.662	1.270	0.407	0.103	0.020	SUMMATION ALAM(J)
34453	34453	34453	34453	34453	34453	AREA OF LOCAL REGION-SQ MI-
1.83E-004	7.73E-005	3.69E-005	1.18E-005	3.00E-006	5.67E-007	PROB OF WINDSPEED IN INTERVAL FJ

3.13E-004	1.29E-004	5.22E-005	1.54E-005	3.57E-006	5.67E-007	PROB OF EXCEED WINDSPEED IN INTERVAL FJ
40	73	113	158	207	261	LOWER BOUND WINDSPEED IN INTERVAL FJ

ASSESSMENT OF TORNADO RISK

PROGRAM BY JAMES R. MCDONALD,P.E. (4/3/79)

SAVANNAH RIVER LOWER LIMIT (95% Confidence)

K MATRIX

						A-I	LAM-I
1.875	0.000	0.000	0.000	0.000	0.000	0.031	2.083
1.420	0.455	0.000	0.000	0.000	0.000	0.098	4.335
1.067	0.512	0.291	0.000	0.000	0.000	0.310	2.288
0.927	0.482	0.280	0.174	0.000	0.000	0.768	0.338
0.962	0.421	0.241	0.139	0.087	0.000	1.637	0.037
0.965	0.387	0.229	0.160	0.077	0.043	3.141	0.007

ALAM(I,J)=K(I,J)*A(I)*LAM(I)

0.082	0.000	0.000	0.000	0.000	0.000	
0.403	0.193	0.000	0.000	0.000	0.000	
0.737	0.362	0.206	0.000	0.000	0.000	
0.241	0.125	0.073	0.045	0.000	0.000	
0.058	0.023	0.016	0.006	0.005	0.000	
0.021	0.009	0.005	0.004	0.002	0.001	
-----	-----	-----	-----	-----	-----	
1.742	0.716	0.300	0.056	0.007	0.001	SUMMATION ALAM(J)
34453	34453	34453	34453	34453	34453	AREA OF LOCAL REGION-SQ MI
6.11E-005	2.08E-005	8.70E-006	1.64E-006	2.03E-007	2.68E-008	PROB OF WINDSPEED IN INTERVAL FJ
8.28E-005	2.13E-005	1.04E-005	1.87E-006	2.29E-007	2.68E-008	PROB OF EXCEED WINDSPEED IN INTERVAL FJ
40	73	113	158	207	261	LOWER BOUND WINDSPEED IN INTERVAL FJ

ASSESSMENT OF TORNADO RISK

PROGRAM BY JAMES R. MCDONALD,P.E. (4/3/79)

SAVANNAH RIVER EXPECTED VALUE (Without unreported tornadoes)

K MATRIX

						A-I	LAN-I
1.875	0.000	0.000	0.000	0.000	0.000	0.030	2.597
1.420	0.458	0.000	0.000	0.000	0.000	0.134	4.937
1.067	0.512	0.291	0.000	0.000	0.000	0.432	2.816
0.927	0.482	0.280	0.174	0.000	0.000	1.074	0.615
0.962	0.421	0.261	0.128	0.087	0.000	2.295	0.117
0.965	0.387	0.228	0.160	0.077	0.042	4.421	0.021

ALAM(I,J)=K(I,J)*A(I)*LAM(I)

0.144	0.000	0.000	0.000	0.000	0.000	
0.956	0.306	0.000	0.000	0.000	0.000	
1.298	0.623	0.354	0.000	0.000	0.000	
0.612	0.318	0.185	0.115	0.000	0.000	
0.259	0.113	0.070	0.034	0.023	0.000	
0.092	0.037	0.022	0.015	0.007	0.004	
-----	-----	-----	-----	-----	-----	
3.360	1.397	0.631	0.165	0.031	0.004	SUMMATION ALAM(J)
34453	34453	34453	34453	34453	34453	AREA OF LOCAL REGION-SQ MI
9.75E-005	4.04E-005	1.83E-005	4.78E-006	8.71E-007	1.14E-007	PROB OF WINDSPEED IN INTERVAL FJ
1.62E-004	6.46E-005	2.41E-005	5.78E-006	1.01E-006	1.14E-007	PROB OF EXCEED WINDSPEED IN INTERVAL FJ
40	73	113	158	207	261	LOWER BOUND WINDSPEED IN INTERVAL FJ

APPENDIX B

STRAIGHT WIND RISK CALCULATION DETAILS

The data in Table 5 are used for the straight wind risk calculations. Equations (6) and (7) are used to calculate the windspeed associated with any arbritrary mean recurrence interval. The upper and lower confidence limits are then obtained from Equation (9). For a 95 percent confidence level the value of $a_{\alpha/2}$ = 1.96. The computer calculations are summarized on the next page. Windspeeds are expressed as fastest one-minute windspeeds.

Year	Windspeed	Year	Windspeed
1950	83	1965	67
1951	34	1966	37
1952	42	1967	52
1953	73	1968	43
1954	44	1969	43
1955	48	1970	52
1956	48	1971	34
1957	31	1972	56
1958	36	1973	37
1959	36	1974	49
1960	36	1975	37
1961	48	1976	32
1962	41	1977	43
1963	40	1978	39
1964	43		

Mean is 44.97

Standard Deviation is 12.13

STRAIGHT WIND RISK ANALYSIS

Program by: J. R. McDonald
8/30/79 Latest Rev. 8/30/79

PROBLEM ID: ANNUAL EXTREME FASTEST ONE-MINUTE WINDSPEEDS - AUGUSTA, GEORGIA

ANALYSIS BASED ON 29 YEARS OF DATA, 95 PERCENT CONFIDENCE LEVEL AND A Z OF 1.96

Mean Recurrence Interval	Probability	Y	VN	SD	VNL	VNU
2	5.00E-01	0.37	43	2	39	47
5	2.00E-01	1.50	54	3	47	61
10	1.00E-01	2.25	61	5	52	70
20	5.00E-02	2.97	68	6	56	79
50	2.00E-02	3.90	76	8	62	91
100	1.00E-02	4.60	83	9	66	100
200	5.00E-03	5.30	90	10	70	109
500	1.00E-03	6.21	98	12	75	121
1000	1.00E-03	6.91	105	13	79	130
2000	5.00E-04	7.60	111	14	83	139
5000	2.00E-04	8.52	120	16	89	151
10000	1.00E-04	9.21	127	17	93	160
100000	1.00E-05	11.51	148	21	106	190
1000000	1.00E-06	13.80	170	26	120	220
10000000	1.00E-07	15.94	190	30	132	248