CORR-79-0009
174427

A METHODOLOGY FOR TORNADO RISK ASSESSMENT

by

James R. McDonald, P.E.

Prepared for

University of California
Lawrence Livermore Laboratory
Livermore, California

April 1979

MCDONALD, MEHTA AND MINOR
Consulting Engineers
Lubbock, Texas

This document was prepared in conjunction with work accomplished under Contract No. DE-
DE-AC09-76SR00001with the U.S. Department of Energy.

FOREWORD

This report describes a methodology for tornado risk assessment. The methodology accounts for gradation of tornado damage across the width and along the length of the tornado path. The approach represents a refinement in the methodology presented previously by the author. The report contains a detailed explanation of the rationale and assumptions used in the risk analysis. Information contained in the report is presented in support of tornado risk assessments of selected facilities operated by the Department of Energy. The work is performed under University Purchase Order 9493503, University of California, Lawrence Livermore Laboratory, Livermore, California. Project monitor is Robert C. Murray, Structural Mechanics Group, Nuclear Test Engineering Division. Project manager for McDonald, Mehta and Minor is James R. McDonald, P.E.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

In order to make rational decisions on the degree of tornado protection required one needs to know the risk of experiencing a windspeed greater than some threshold value at a given location in one year. Thus, the probabilities of exceeding threshold values of windspeed in one year are collectively known as a tornado risk model. A risk model can be calculated using standard statistical methods and the tornado records of the geographical region surrounding the location of interest.

Once the risk model is determined, a management decision must be reached as to the appropriate level of risk for the particular facility under consideration. The appropriate level of risk depends on the consequence of failure, the risk to human life and the environment. Once a decision is made concerning the appropriate level of risk, the maximum horizontal design windspeed is obtained from the risk model. Other tornado parameters such as wind components, atmospheric pressure change and missile characteristics can be deduced from our understanding of tornado vortex mechanics.

The purpose of this report is to present a methodology for assessing tornado risks at a particular geographic location. The definition of a tornado risk is the probability of a point within a defined geographic region experiencing windspeeds greater than some threshold value in one year. The inverse of this probability is known as the mean recurrence interval. Mean recurrence interval is simply the average arrival rate of tornadoes within a region, when measured over a long period of time. This concept of risk is referred to as a point probability. The level of risk is independent of the size of a structure or the location of the structure within a defined geographic region.

A number of tornado risk models have been proposed, but when applied to the same tornado data set, the models give a wide range of results. A careful evaluation of each of the proposed models suggests reasons for the diverse results. Specific risk model methodologies have been proposed by Markee, et al. (1974), Dames & Moore (1975), Wen and Chu (1973), Garson, et al. (1975), Abbey and Fujita, (1975) and the author, McDonald, et al. (1975). Each of the above models uses apparently valid statistical formulations, yet Abbey (1975) showed that when the models are applied to the same tornado data set, windspeeds for a specified level of risk varied significantly. Windspeeds predicted by the risk models varied from 300 to 800 mph for a risk level of 1×10^{-7} occurrences per year (risk level of interest for nuclear power plants).

A careful study of the tornado risk models reveals that the scatter of results is largely due to the variety of ways that the tornado data are represented in the statistical formulation of the models. Table 1 breifly summarizes the statistical data representation utilized in each of the models. For specific details refer to Abbey (1975) or to references to the individual models.

The evaluation of the different models first involves the determination of how well the distributions fit the tornado data. Unless distributions are carefully selected, windspeeds associated with small probability levels (long return periods) can be unreasonably large.

The model by Markee, et al. assumes a mean tornado damage path area of 2.81 sq mi, based on Thom's (1963) study of Iowa and Kansas tornadoes. The area is assumed to be constant across the United States regardless of tornado intensity. Significant variations in tornado path area are known to exist (Howe, 1974).

TABLE 1

STATISTICAL REPRESENTATION OF TORNADO DATA IN TORNADO RISK MODELS

Model	Tornado Data Representation
Markee, et al. (1974)	. Mean damage area . Log-normal intensity distribution
Dames & Moore (1975)	. Intensity distribution represented by Gaussian, Gamma or Extreme Value Type II . Occurrence modeled by Poisson or Weibull process
Wen and Chu (1973)	. Bivariate log-normal distribution for area and intensity
Garson, et al.	. Multivariate log-normal joint probability density function for intensity, path length and path width
McDonald, et al. (1975)	. Empirical area-intensity relationship . Emperical occurrence-intensity relationship . Gradations of damage
Abbey and Fujita (1975)	. Empirical area-intensity relationship based on gradations of damage

Several of the models use a log-normal intensity distribution. Although the intensity distribution seems to fit the log-normal distribution for less intense tornadoes, larger percentages of tornadoes are predicted in the more intense intervals than have actually been observed. Hence for extremely small risk levels the log-normal distribution leads to unreasonably and unexpectedly high windspeeds. See Golden, (1976) for a discussion of upper bound values of windspeeds in tornadoes.

The distributions and processes used in the Dames & Moore model resulted in windspeed estimates which were deemed too high. For this reason all distributions were truncated at 350 mph.

The Abbey-Fujita risk model utilizes an empirically derived area-intensity relationship based on observed gradations of damage within the tornado path. The DAPPLE index gives the damage area per path length as a function of tornado intensity. The DAPPLE index is assumed to be invariant with respect to geographic region. Further, it is based on examination of a limited number of tornado damage paths. As the index is further refined, by examining many more tornado damage paths, greater confidence (in a qualitative rather than statistical sense) will be gained in this approach.

The tornado risk model methodology presented in this paper utilizes emperically derived relationships between area-intensity and occurrence-intensity. The emperical relationships are selected to accurately represent the available tornado data. The methodology accounts for gradation of windspeed across the path width and along the path length.

Section II of this report presents the primary data sources available for tornado risk analysis. The general methodology is described in Section III. Section IV presents details of the risk model calculations. A risk model is calculated to demonstrate the procedure in Section V. An evaluation of the risk model is made with respect to data sources, tornado characteristics, population effects and confidence limits in Section VI. The final Section presents a summary and conclusions.

II. DATA SOURCES

Unfortunately, tornado records have not been kept in the past with risk model analysis in mind. Risk analysis requires the time of occurrence, intensity, the initial touchdown point, the path length and path width. The occurrence and touch down points, at least back to 1959, have been systematically recorded, if the touch down was observed or if significant damage were done.

Until 1971 there was no method available for rating the intensity of tornadoes. Fujita (1971) introduced a rating scale whereby the intensity could be judged on the basis of appearance of damage. Known as the Fujita Scale, there are six intensity classifications ranging from F0 to F5. Weak tornadoes have lower ratings than strong ones.

The Pearson path length P_L and path width P_W scales indicate the length and mean width of the tornado damage path for damage done by winds greater than or equal to 75 mph. Each Pearson scale also has six catagories. Short narrow tornado paths have lower Pearson scale numbers than long wide ones.

Thus, a tornado can be conveniently catagorized by giving its FPP number. A tornado rated 3,2,3, for example, has an intensity of F3, a path length of P2 and a path width of P3. Table 2 defines the FPP classifications. Table 3 gives a word description of damage associated with each F-scale intensity classification. A range of windspeed is also associated with each F-scale classification.

A. AVAILABLE TORNADO RECORDS

Risk analysis requires a consistent and complete data set. Since risks are sometimes extrapoloated to probabilities of one in ten million,

TABLE 2

FUJITA-PEARSON (FPP) CLASSIFICATIONS

F- Scale: Maximum Windspeed

	F0	F1	F2	F3	F4	F5
Windspeed, mph	40-72	73-112	113-157	158-206	207-260	261-318

P-Scale: Path Length

	P0	P1	P2	P3	P4	P5
Path Length, mi	0.3-0.9	1.0-3.1	3.2-9.9	10.0-31.5	31.6-99	100-316

P-Scale: Path Width

	P0	P1	P2	P3	P4	P5
Path Width, yds	6-17	18-55	56-175	176-556	557-1759	1760-4963

TABLE 3

F-SCALE CLASSIFICATION OF TORNADOES BASED ON DAMAGE
Fujita (1971)

(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 uprotted; 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; structures 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.

(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.

TABLE 3 (cont.)

(F6) INCONCEIVABLE DAMAGE 319 mph to sonic speed

Should a tornado with the maximum windspeed in excess of F5 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.

it is obvious that a very long data record is desirable. Such a data set is not available, but the need for risk assessment nevertheless exists. Therefore, we use the best available data and realize that our results have a wide confidence band because of the data.

Storm Data, a publication of the Department of Commerce, NOAA, Enviromental Data Service, National Climatic Center, Asheville, North Carolina contains systematic records of various types of severe storms. The information includes:

(1) State, county, community

(2) Year, month, day, time

(3) Path length, path width

(4) Deaths, injuries

(5) Property damage class

(6) Crop damage class

(7) Narrative description of the damage

The publication is issued monthly. To extract tornado information from the publication over a long period of time is tedious and time consuming. It is possible, however, to systematically assign FPP ratings to the tornadoes, based on the information in Storm Data.

A computer tape containing tornado records back to 1950 has been assembled by the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri. Considerable effort has been expended to update and improve this tape. Storm Data, newspaper accounts and other information in the technical literature are used to update the information on specific tornadoes. Considerable information is tabulated for each tornado. Among others, the tape includes:

(1) Year, month, date, time, weather event

(2) Latitude and Longitude of beginning and ending points of tornado path

(3) Type of path, percent on ground, storm types and rotational sense

(4) Path length and mean path width

(5) Deaths, injuries, damage class, states and counties affected

(6) FPP scale

All catagories of data listed above are not complete at this time (1978).

Dr. T. Theodore Fujita, Department of the Geophysical Sciences, University of Chicago has assembled a tornado data tape which he refers to as the DAPPLE tape. His information comes from Storm Data, the news media and the files of storm damage investigation that he has personally assembled over a period of years. The DAPPLE tape contains

(1) Year, month, day and time

(2) F-scale

(3) Deaths and injuries

(4) Areas affected by tornado, identified as a one-degree square of latitude and longitude, each subdivided into 15 minute subboxes

(5) Path length, path types and direction within each subbox.

Copies of the NSSFC and DAPPLE tapes can be obtained from their sources.

Other random data are available in the literature. The three sources listed above are attempts at systematic accumulation of data and are most useful for tornado risk analysis.

B. QUALITY OF THE DATA

Since 1971, with the invention of the FPP scale, tornado data has been recorded in a systematic manner. The local Meteorologist-In-Charge of the National Weather Service has the responsibility of confirming tornado occurrences and assigning the proper FPP ratings. Prior to 1971, tornado data was collected on a less systematic basis.

There is no doubt that some biases exist in the data with respect to intensity, path length and path width ratings. In sparcely populated open country tornado occurrences are likely to go undetected and unrecorded.

The question arises, which data source should be used in developing a risk model? Should one be preferred over the other? The approach we suggest is to look at all three sources (NSSFC tape, DAPPLE tape and Storm Data), and make a rational judgement concerning a consistent data set. Either of the two tape sources may be appropriate, or some combination of the tapes and Storm Data.

III. METHODOLOGY

The tornado risk model is determined from statistical analyses of records of tornadoes that have occurred in the region surrounding the site of interest. The tornado data used are expressed in terms of the FPP scales. As discussed in the previous section, a consistent data set is first obtained. Then the risk model is computed following the steps outlined in this section.

Four basic steps are involved in the development of the tornado risk model:

(1) Determination of an 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 windspeeds in some windspeed interval.

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

A. AREA-INTENSITY RELATIONSHIP

The establishment of the area-intensity relationship requires a large sample of relatively complete tornado records. Because tornado records have been more accurately kept since 1971, a geographic region, which may contain several states, is defined and the period of record is taken from 1971. Factors considered in selecting this global region are:

(1) The region should generally surround the 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.

The Pearson scales for path length P_L and path width P_W are defined such that the mean damage area of a tornado rated 2,1 is the same as one rated 1,2. Thus the mean damage areas can be grouped into eleven categories A_i, where i = 0,10. The value of i is the sum of the P_L and P_W numbers. Tornadoes rated 2,1 and 1,2 both have mean damage areas corresponding to A_3 ($i = P_L + P_W$). The mean damage area for each area classification is given by

$$A_i = 10^{0.5(i-5)}. \quad (1)$$

All tornadoes in the global region are tabulated into an area-intensity matrix. The rows of the matrix correspond to the area classifications; the columns correspond to the F-scale classifications. Each element of the matrix is the number of tornadoes in the global region (1971-1975) that corresponds to the particular area-intensity classification. The form of the area-intensity matrix is illustrated in Table 4. The mean areas and windspeeds for the different classifications are also listed in Table 4.

The mean damage path area for each F-scale classification is calculated, using the data in the area-intensity matrix. The coordinates of mean windspeed for each F-scale classification and the corresponding

TABLE 4

AREA-INTENSITY MATRIX FORMAT

Area Classification	Number of Tornadoes F0	F1	F2	F3	F4	F5
A_0	*	*	*	*	*	*
A_1	*	*	*	*	*	*
A_2	*	*	*	*	*	*
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
A_i	*	*	*	*	*	*
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
A_{10}	*	*	*	*	*	*

Mean Windspeed, mph

F0	F1	F2	F3	F4	F5
56	92.5	135	182	233.5	289.5

Mean Area, sq mi

A0	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
0.00316	0.0100	0.0316	0.100	0.316	1.00	3.16	10.0	31.6	100.0	316

mean damage path area are plotted and an emperical relationship is derived by means of linear regression or other curve fitting techniques. A log-log plot sometimes gives a good fit. If, for example, a log-log plot is considered, then a linear regression analysis is performed to obtain an equation that best fits the data. The equation takes the form

$$\text{Log (Area)} = C_1 + C_2 \text{ Log (V)} \qquad (2)$$

where C_1, C_2 are regression coefficients and V is the windspeed (intensity). Equation (2) is the desired area-intensity relationship.

A number of standard statistical distribution functions have been considered, but none of those tried give a consistently good fit for different geographical regions. The tail end of some functions, corresponding to high tornado intensity, tend to give unreasonably large areas.

B. OCCURRENCE-INTENSITY RELATIONSHIP

A local region within the global region is defined to permit determination of an occurrence-intensity relationship. The size of the local region may range from a 1-degree to a 5-degree square, depending on the number of tornado occurrences and the topographical and meterological conditions in the vincinity of the site. Degree-squares are convenient because tornado touch down points are expressed in terms of latitude and longitude. If data from the DAPPLE tape are used, then 15-minute subboxes are the basic unit of area in the local region.

The longest possible period of record is used for the occurrence-intensity relationship. In this case a longer period of record for a smaller (local) region is considered better than the short period of record in a large global region as used for determining the area-intensity relationship. Generally records covering a 15-20 year period are available from the three data sources cited in Section II.

The number of tornadoes exceeding each F-scale classification is fitted to appropriate curves by means of regression analyses or curve fitting techniques. The emperically derived function gives a continuous relationship between area and intensity.

Various standard statistical distributions also have been tried, but none of them fit the occurrence-intensity data well. Various relationships are tried until goodness of fit tests indicate the best one. From the empirically derived curve the number of tornadoes per year per F-scale are obtained and are denoted λ_i. The set of λ's for all F-scale intervals is the occurrence-intensity relationship required for the risk analysis.

C. PROBABILITY OF WINDSPEEDS IN SOME F-SCALE INTERVAL

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

$$P(V=\overline{V}_j) = \frac{1}{A} \sum_{i=j}^{5} \lambda_i a_{ij} \qquad (3)$$

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 in the F-scale interval $\overline{V}_j$ in a tornado whose maximum windspeed is in the F-scale interval $\overline{V}_i$, $(i \geq j)$ (sq mi)

The F-scale intervals designated by $\overline{V}_i$ or $\overline{V}_j$ are

F-Scale Interval Windspeeds

	F0	F1	F2	F3	F4	F5
i or j	0	1	2	3	4	5
$\overline{V}_i$ or $\overline{V}_j$ (mph)	40-72	73-112	113-157	158-206	207-260	261-318

The integer i refers to the interval of maximum tornado windspeeds; the integer j refers to some interval less than or equal to i.

The magnitude of a_{ij} depends on the maximum intensity of the tornado, the gradation of damage along the length and across the width of the path and the mean damage path area. The lower portion of Figure 1 shows schematically the areas within the tornado damage path exposed to windspeeds of various magnitudes. (Note, that only half of the path area is shown.) These gradations occur because of variations of windspeed across the width and along the length of the path. Segments along the length of the path that have uniform F-scale intensities have been arranged in descending order. This rearrangement does not change the variation of windspeed within the path. It merely arranges the areas in a more convenient form for the mathematical calculations.

The velocity profile across the width of the path also is shown in Figure 1. Assuming a combined Rankine Vortex, the variation of the windspeed outside of the radius of maximum windspeed is given by

$$VR = \text{Constant} \quad (4)$$

At the radius of damaging winds, R_d, the windspeed is, by definition, 75 mph. Then

$$75\ R_d = C. \quad (5)$$

From Figure 1 the tornado radius corresponding to a windspeed of 75 mph is given by

$$R_{75} = \frac{a_i}{2L_i}, \quad (6)$$

where a_i is the mean damage path area and L_i is the mean path length of a tornado whose maximum intensity is F_i. An expression for the constant C can be written as

$$C = \frac{75a_i}{2L_i} \quad (7)$$

The tornado radius R_j corresponding to any windspeed V_j is

$$R_j = \frac{75a_i}{2L_iV_j} \tag{8}$$

From Figure 1 one half the area exposed to F_j windspeed along the path length where the maximum windspeed is F_k in a tornado whose maximum windspeed is F_i is given by

$$\begin{aligned}\frac{a_{ijk}}{2} &= (R_j - R_{j+1})\alpha_{ik}L_i \\ &= \frac{75a_i}{2L_i}\left[\frac{1}{V_j} - \frac{1}{V_{j+1}}\right]\alpha_{ik}L_i\end{aligned} \tag{9}$$

$$\begin{aligned}a_{ijk} &= 75a_i\alpha_{ik}\left[\frac{V_{j+1}-V_j}{V_jV_{j+1}}\right] \\ &= w_j\alpha_{ik}a_i \qquad (j<i)\end{aligned} \tag{10}$$

where

α_{ik} = the percent length of intensity F_k in a tornado of maximum intensity F_i

$$w_j = 75\left[\frac{V_{j+1}-V_j}{V_jV_{j+1}}\right] \tag{11}$$

The area of windspeed across the path width a_{ijj} is given by

$$\frac{a_{ijj}}{2} = R_j \alpha_{ij} L_i$$

$$= \frac{75 a_i}{2L_i} \left[\frac{1}{V_j} \right] \alpha_{ij} L_i \qquad (k=j) \qquad (12)$$

$$a_{ijj} = w_{jj} \alpha_{ij} a_i \qquad (13)$$

where $$w_{jj} = \frac{75}{V_j} \qquad (14)$$

From Figure 1 the following expressions can be written for a_{ij}.

$$a_{ij} = \left[w_j \sum_{k=j+1}^{i} \alpha_{ik} + w_{jj} \alpha_{ij} \right] a_i$$

$$= K_{ij} a_i \qquad (j<i) \qquad (15)$$

also

$$a_{ij} = w_{jj} \alpha_{ij} a_i$$

$$\qquad (j=i) \qquad (16)$$

$$= K_{ij} a_i$$

and

$$a_{ij} = 0 \qquad (j>i) \qquad (17)$$

The K_{ij} terms are constant for the assumed gradation of windspeed along the path length and the assumed velocity profile.

The gradations of F-scale damage along the path length are obtained from Fujita's assessment of damage produced by the Super Outbreak Tornadoes of April 3-4, 1974 (Fujita, 1975). The percent of the path length of a tornado that experiences windspeeds of intensity F_j in a tornado whose maximum intensity is F_i is designated α_{ij}. These individual elements can be summarized in the form of a lower triangular matrix. Details of the calculations for α_{ij} are given in Appendix B. The $[\alpha]$ matrix has the following form:

$$[\alpha] = \begin{bmatrix} 1.0 & 0 & 0 & 0 & 0 & 0 \\ 0.563 & 0.437 & 0 & 0 & 0 & 0 \\ 0.224 & 0.342 & 0.435 & 0 & 0 & 0 \\ 0.090 & 0.229 & 0.316 & 0.365 & 0 & 0 \\ 0.124 & 0.157 & 0.263 & 0.216 & 0.240 & 0 \\ 0.127 & 0.109 & 0.177 & 0.260 & 0.181 & 0.145 \end{bmatrix} \qquad (18)$$

Using Equations (15), (16) and (17), the K_{ij} terms also can be expressed in matrix form. Details of these calculations are given in Appendix C.

The $[K]$ matrix, thus, becomes

$$[K] = \begin{bmatrix} 1.875 & 0 & 0 & 0 & 0 & 0 \\ 1.420 & 0.455 & 0 & 0 & 0 & 0 \\ 1.067 & 0.512 & 0.291 & 0 & 0 & 0 \\ 0.927 & 0.482 & 0.280 & 0.174 & 0 & 0 \\ 0.962 & 0.421 & 0.261 & 0.128 & 0.087 & 0 \\ 0.965 & 0.387 & 0.228 & 0.160 & 0.077 & 0.042 \end{bmatrix} \quad (20)$$

The a_{ij} terms in Equation (3) also can be expressed in the form of a lower triangular matrix. Equation (3) is evaluated by multiplying each row i of the $[K]$ matrix by $a_i\lambda_i$. The summation in Equation (3) extends over each column of the modified $[K]$ matrix. Appendix A shows details of these calculations.

D. PROBABILITY OF WINDSPEEDS EXCEEDING INTERVAL VALUES

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

$$P(V \geq \overline{V}_j) = \sum_{j=j}^{n} P(V = \overline{V}_j) \quad (21)$$

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

E. EFFECT OF POPULATION DENSITY ON THE NUMBER OF UNREPORTED TORNADOES

The question arises -- Are all tornadoes that have occurred reported in our records? A logical answer to this question is, "Yes, if there are enough people around to observe them." How many people per square mile are necessary to assure that all tornadoes are observed? This is not a simple question to answer, because terrain, visibility and time of day all have an effect on the answer. One simple cannot select a single minimum value of population density and apply it to all situations.

In light of the above discussion a method of correcting the number of reported tornadoes based on the population density (persons per square mile) is proposed. The population correction is applied only to the occurrence-intensity statistics. The reasoning being that even though all tornadoes are not necessarily reported in the global region, if a sufficiently large sample has been used, the area-intensity relationship is essentially the same.

The population density of each 15-minute subbox in the local region is determined from the 1970 census.* The number of tornadoes that have occurred in each subbox is also determined. The mean number of tornadoes per subbox for all subboxes with population density greater than or equal to various population densities, starting with the largest values and decreasing to zero, are calculated. This information can be plotted as shown in Figure 2.

---

* The methodology described here presumes that the DAPPLE tape data is being used. Other data sources can be used, but the format is not as convenient.

In all cases that have been tested, the resulting curve begins to deviate from the mean, calculated for the high population density subboxes, at some arbitrary population density. Since zero population density in Figure 2 implies all subboxes with population greater than or equal to zero, the ordinate corresponding to zero population density gives the mean number of tornadoes for all subboxes in the local region. The difference in this mean and the mean corresponding to the high population subboxes is assumed to be due to unreported tornadoes. The number of unreported tornadoes is given by

$$X = (\bar{X}_h - \bar{X}_a)n \qquad (22)$$

where

- X is the number of unreported tornadoes
- $\bar{X}_h$ is the mean number of tornadoes per subbox in the high population density subboxes where all tornadoes are assumed to be reported
- $\bar{X}_a$ is the mean number of tornadoes in all subboxes, including the high population density ones
- n is the total number of subboxes in the local region.

The next step is to distribute the unreported tornadoes according to F-scale classification. The occurrence-intensity relationship is used for this purpose. Let N_i be the number of tornadoes with windspeeds equal to or exceeding the lower bound windspeed for F-scale rating i. Also let N_{i+1} be the number of tornadoes with windspeeds equal to or exceeding the lower bound windspeed for F-scale i+1. The number of

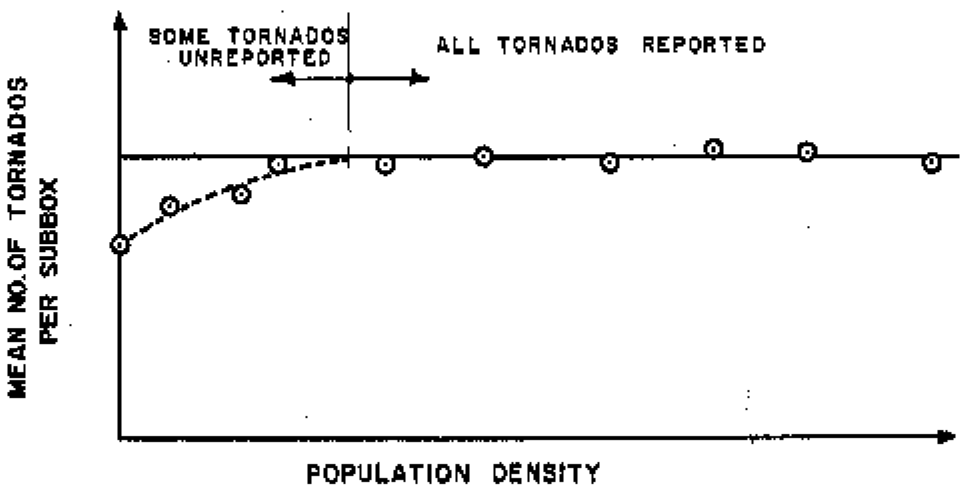


FIGURE 2. MEAN NUMBER OF TORNADOES PER SUBBOX VERSUS POPULATION DENSITY

tornadoes with windspeeds corresponding to F-scale i, then is $N_i - N_{i+1}$. The percentage of tornadoes in F-scale i is then $N_i - N_{i+1}$ divided by the total number of tornadoes in all F-scale classifications. The total number of unreported tornadoes is then distributed in proportion to the percentage in each F-scale classification.

IV. PROCEDURE

The step by step procedure for calculating risks is outlined in this section. The steps are further demonstrated with the example calculations in Appendix A.

A. AREA-INTENSITY RELATIONSHIP

(1) Select global region

(2) Assemble area-intensity matrix

(3) Determine mean damage-path area for each F-scale classification in the global region

(4) Choose appropriate function(s) to represent area-intensity relationship

(5) For F-scale class intervals use the mean windspeed and determine the mean damage path area a_i for the interval from the area-intensity function.

AREA-INTENSITY RELATIONSHIP

F0	F1	F2	F3	F4	F5
a_0	a_1	a_2	a_3	a_4	a_5

B. OCCURRENCE-INTENSITY RELATIONSHIP

(1) Select one or more local regions

(2) Determine the number of reported tornadoes equal to or exceeding each F-scale classification

(3) Plot number of reported tornadoes obtained in Step (2) versus the lower bound windspeed for each F-scale classification and determine an appropriate function or functions to represent the occurrence-intensity relationship

(4) Correct for population effects

(a) Determine number of persons per subbox from 1970 census information

(b) Determine the number of tornadoes that have occurred in each subbox

(c) Calculate the mean number of tornadoes per subbox for those subboxes with populations equal to or greater than some threshold value. Start with the subboxes with highest population density

(d) Find the point on the curve where population effects first affect the number of reported tornadoes (See Fig. 2)

(e) Calculate the mean number of tornadoes per subbox $\bar{X}_h$ for those subboxes with all tornadoes assumed to be reported and calculate the mean number of tornadoes in all subboxes $\bar{X}_a$

(f) Calculate the number of tornadoes not reported using Equation (22)

(g) Determine the percentage of tornadoes per F-scale from the occurrence-intensity relationship (Step B.3). Distribute the unreported tornadoes according to the percentages per F-scale

(h) Calculate a new occurrence-intensity relationship for all tornadoes as in Step B.3.

(i) Using the new occurrence-intensity relationship calculate the number of tornadoes per year for 50 mph intervals, λ_i

NUMBER OF TORNADOES PER YEAR IN EACH F-SCALE INTERVAL, λ_i

F0	F1	F2	F3	F4	F5
λ_0	λ_1	λ_2	λ_3	λ_4	λ_5

C. PROBABILITY OF WINDSPEEDS IN SOME F-SCALE INTERVAL

(1) Compute values of a_{ij} from Equations (15), (16), and (17)

(2) Determine area of local region

(3) Evaluate Equation (3) for each j

D. PROBABILITY OF WINDSPEEDS EXCEEDING INTERVAL VALUES

(1) Evaluate Equation (21) for all values of j

(2) Plot $P(V \geq \overline{V}_t)$ versus windspeed, which, by definition, is the tornado risk model

V. EVALUATION OF THE METHOD

Just how good is the risk model based on the methodology presented? Several factors that effect the outcome and our faith in the results. These include data source, tornado characteristics, population effects on reporting and confidence limits on the risk model prediction.

A. DATA SOURCE

There are no doubt biases in the data sources, as discussed in Section II. The three systematically assembled data sources considered in this study are genuine attempts to assemble the best available data. As demonstrated in the example calculations in Section V, the number of low intensity tornadoes do not have a significant effect on the tornado probabilities. The large high intensity tornadoes have the most significant impact on the magnitude of the risks.

The F-scale intensity ratings given in the data sources are based on appearance of damage. Windspeeds are associated with the F-scale ratings and are used directly in the risk model calculations. It is the author's opinion and a general concensus that the maximum windspeeds that actually occur in tornadoes and in the range 250-275 mph (Golden, 1976). Thus the windspeeds associated with the F4 and F5 classifications would appear to be too high. The probabilities will thus be conservative, if the windspeeds are indeed too high.

B. POPULATION EFFECTS

In a particular geographical region some tornadoes are likely to go undetected in areas of sparce population. The problem is we do not know the total number of unreported tornadoes that have occurred in the region. The total number of tornadoes, reported and unreported, is estimated from the mean number of tornadoes that have occurred in the subboxes with high population density. The assumption is thus made that the mean number of tornadoes per subbox for the entire local region is the same as the mean number for the high density subboxes. This assumption is true only if there is a sufficiently large number of high density subboxes so that the sample is indeed representative of the total set of all tornadoes. Each individual case should be carefully considered.

C. TORNADO CHARACTERISTICS

The risk assessment methodology presented herein accounts for the variation of windspeed along the length and across the width of the tornado damage path. The gradations of damage along the path length were established from results of a detailed study of the 148 tornadoes of the Super Outbreak of April 3-4, 1974 (Fujita, 1975). This data source based on a single extreme tornado outbreak, is somewhat limited. Confidence in the values of α will grow when the data set is expanded to contain other tornadoes not associated with the single outbreak. Because the Super Outbreak contained many tornadoes with a wide range of F-scale intensities, the results are believed to be conservative. The tornado risk assessment method developed by Abbey and Fujita (1975) also accounts for gradation of damage along the length and width of the path. Their variation function is based on the DAPPLE Index, which is also developed on the basis of the Super Outbreak Tornadoes of 1974.

The DAPPLE Index is expressed as a function of path length, whereas the approach presented in this report uses mean tornado damage path area as the independent variable.

D. CONFIDENCE LIMITS ON RISK MODEL PREDICTIONS

Confidence limits can be calculated for the risk model based on confidence of the fits of the regression analyses on the area-intensity and occurrence-intensity. This methodology is described in McDonald, et al. (1975) and will not be repeated here.

VI. SUMMARY AND CONCLUSIONS

A methodology for assessing tornado risks is presented in this report. Risk as defined here is the probability of any point within a defined geographical region experiencing windspeeds in excess of some threshold value in one year. As defined, this is a point probability that is independent of structure size and location within the defined geographic region.

The methodology uses available tornado records from the geographic region surrounding the site. Distribution functions which relate area-intensity and occurrence-intensity, are emperically derived from the data. These are then utilized in making the probability calculations. Attention must be paid to selection of the appropriate geographic region so that tornado characteristics are reasonably homogeneous in the region. The effects of low population density on the number of tornadoes that may go unreported is also taken into account.

The methodology presented here is an attempt to arrive at a rational method for assessing risks. It has been developed over a period of four years and has been tested at a number of specific locations.

What the risk model for a specific facility provides is an instrument which will enable authorities to establish an acceptable level of risk for their facility and thus deduce a criteria for design of new structures and the evaluation of existing ones. When the methodology is applied to several sites at different geographical locations, design criteria at a consistent level of risk can be established.

REFERENCES

Abbey, R.F. and Fujita, T.T., 1975: "Use of Tornado Path Length and Gradations of Damage to Assess Tornado Intensity Probabilities," Preprint Volume, Ninth Conference on Severe Local Storms, October 21-23, 1975, Norman, Oklahoma, published by American Meteorological Society, Boston, MA.

Dames and Moore, 1975: "A Meteorological and Engineering Approach to the Regionalization of Tornado Wind Criteria for Nuclear Power Plant Design" Technical report prepared for Division of Reactor Research and Development, Energy Research and Development Administration, Washington, D.C.

Garson, R.C., Catalan, J.M. and Carnell, C.A., 1975: "Tornado Design Winds Based on Risk," Journal of the Structural Division, Proceedings of ASCE, Volume 101, No. ST9, 1883-1897.

Golden, J.H., 1976: "An Assessment of Windspeeds in Tornadoes," Proceedings of a Symposium on Tornadoes: An Assessment of Technology and Implications for Man, Texas Tech University, Lubbock, Texas.

Fujita, T.T., 1971: "Proposed Characterization of Tornadoes and Hurricanes by Area and Intensity," Satellite and Mesometeorology Research Paper No. 91, The University of Chicago, Chicago, Illinois.

Fujita, T.T., 1975: "Super Outbreat Tornadoes of April 3-4, 1974," A map prepared by the University of Chicago, Chicago, Illinois.

Howe, G.M., 1974: "Tornado Path Sizes," Journal of Applied Meteorology, Volume 13, pp. 343-347.

Markee, E.H., Beckerley, J.G. and Sanders, K.E., 1974: "Technical Basis for Iterim Regional Tornado Criteria," WASH-1300, U.S. Atomic Energy Commission, Office of Regulation, Washington, D.C.

McDonald, J.R., Mehta, K.C. and Minor, J.E., 1975: "Development of Windspeed Risk Models for the Savannah River Plant Site," Technical report prepared for E.I. du Pont de Nemours and Company, Wilmington, Delaware by Institute for Disaster Research and Department of Civil Engineering, Texas Tech University, Lubbock, Texas.

37

APPENDIX A: SAMPLE CALCULATIONS

To further illustrate the methodology, a numerical example is presented in this section. The site location chosen is fictitious. The example is presented only to illustrate the method. The results are not interpreted.

A. AREA-INTENSITY RELATIONSHIP

(1) The global region selected is a rectangular box, 10 degrees by 12 degrees

(2) The area-intensity matrix is given on the next page. The information is assumed to come from the DAPPLE tape

(3) The mean area for each F-scale classification is calculated from the information in the area-intensity matrix

(4) The area and intensity coordinates are plotted and an appropriate function is fitted to the points. In this example a log-log plot is used. A regression analysis gives the following equation for the area-intensity relationship:

$$\text{Log (Area)} = 2.38 \text{ Log } (V) - 5.26$$

The coefficient of determination is $r^2 = 0.98$

(5) From the area-intensity function values of a_i are found to be

AREA-INTENSITY RELATIONSHIP, a_i, sq mi

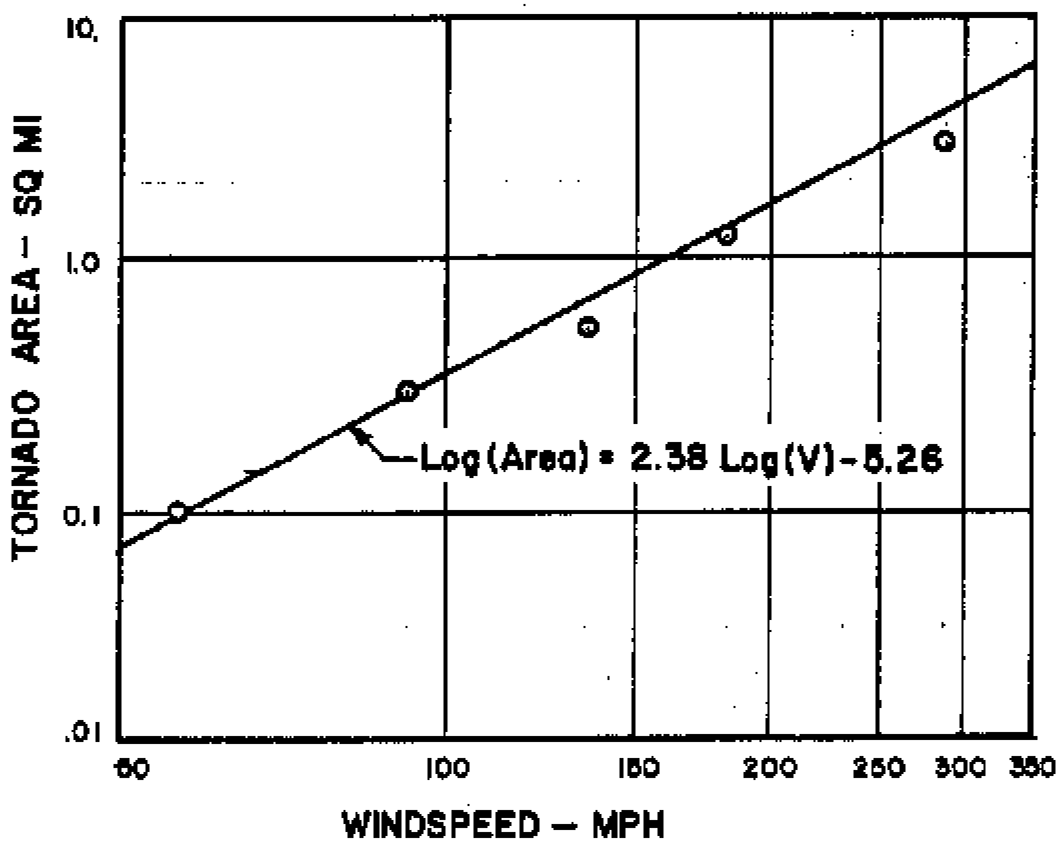
F0	F1	F2	F3	F4	F5
0.080	0.26	0.65	1.32	2.38	3.97

AREA-INTENSITY MATRIX (Step A.2)

Area Classification	Number of Tornadoes						Mean Area sq mi
	F0	F1	F2	F3	F4	F5	
A_0	118	43	9	0	0	0	3.16×10^{-3}
A_1	34	73	11	3	1	0	1.00×10^{-2}
A_2	21	63	22	5	1	0	3.16×10^{-2}
A_3	11	36	28	8	0	0	1.00×10^{-1}
A_4	12	25	44	15	2	0	3.16×10^{-1}
A_5	2	17	16	13	5	0	1.00×10^{0}
A_6	3	7	12	9	2	0	3.16×10^{0}
A_7	0	2	0	2	3	0	1.00×10^{1}
A_8	0	0	0	0	0	0	3.16×10^{1}
A_9	0	0	0	0	0	0	1.00×10^{2}
A_{10}	0	0	0	0	0	0	3.16×10^{2}
Totals	201	266	142	55	14	0	

MEAN AREA PER F-SCALE (Step A.3)

	F0	F1	F2	F3	F4	F5
Mean Area, sq mi	0.088	0.276	0.503	1.221	3.00	0
Median Windspeed, mph	56	92.5	135	182	233.5	289.5


TORNADO AREA - SQ MI
10.
1.0
0.1
.01
Log(Area) = 2.38 Log(V)-5.26
60
100
150
200
250
300
350
WINDSPEED — MPH

B. OCCURRENCE-INTENSITY RELATIONSHIP

(1) A fictitious 5-degree square local region is selected for this example

(2) The number of reported tornadoes in each F-scale classification are extracted from the DAPPLE tape

NUMBER OF TORNADOES PER F-SCALE (from DAPPLE Tape)

	F0	F1	F2	F3	F4	F5
No. in Interval	215	109	41	12	2	0
Cumulative	379	164	55	14	2	0
Lower Bound Windspeed, mph	40	73	113	158	207	261

(3) The cumulative number of tornadoes is plotted versus lower bound windspeed for each F-scale. A semi-log plot is used in this case (other plots were tried). Two equations are derived based on linear regression analyses. If y is the number of tornadoes exceeding some windspeed value V,

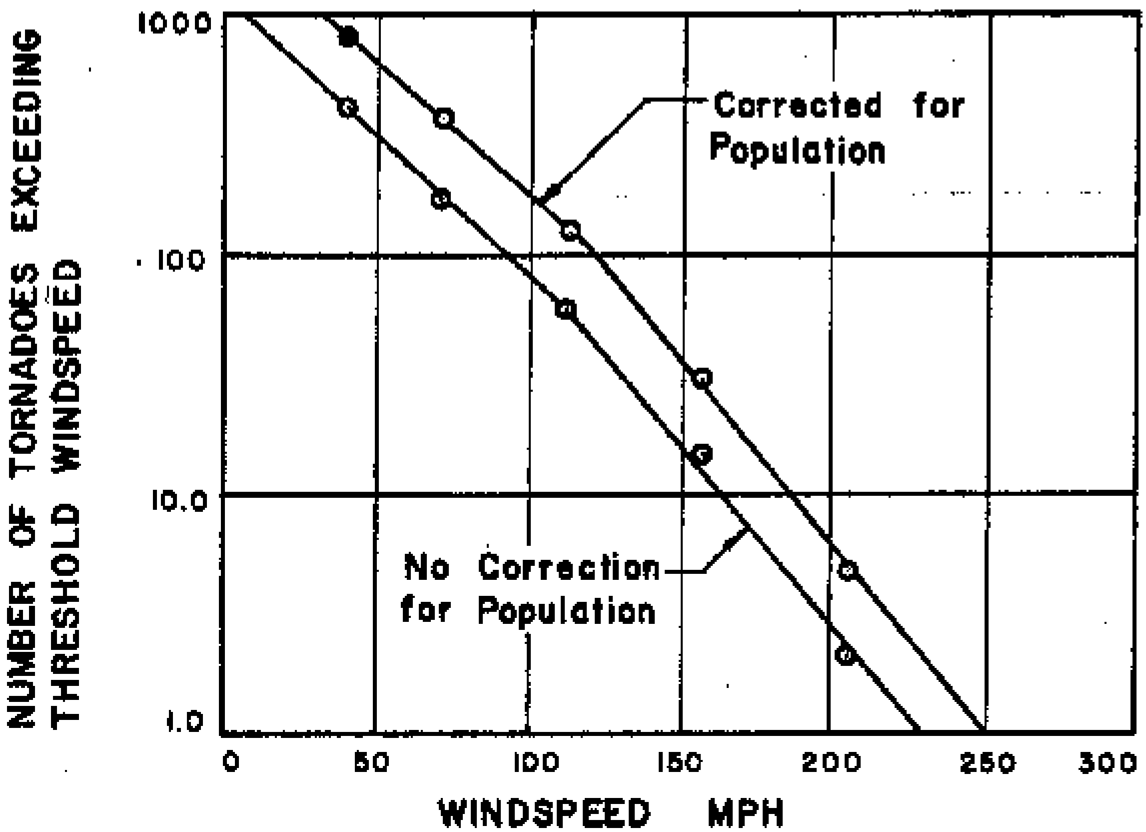
$$y = (2046)10^{-0.0110V} \qquad (V<113 \text{ mph})$$

$$y = (3212)10^{-0.0153V} \qquad (V\geq 113 \text{ mph})$$

(4) Correction for population effects

(a) The number of persons per subbox is obtained from the 1970 census data. The fifteen minute subboxes are drawn on a large scale map of the area. The county and city population (5000 or greater) are then attributed to the appropriate subboxes. The area of each subbox is given by,

$$A_{sb} = \frac{4780}{16} \cos \theta,$$



NUMBER OF TORNADOES EXCEEDING
THRESHOLD WINDSPEED
1000
100
10.0
1.0
0
50
100
150
200
250
300
WINDSPEED MPH
Corrected for
Population
No Correction
for Population

where θ is the latitude of the center of the subbox. The number of persons per subbox divided by the subbox area gives the population density.

(b) Next the number of tornadoes per subbox for the period 1959-1975 is determined from the DAPPLE tape

(c) The mean number of tornadoes per subbox for those subboxes with population density greater than or equal to some threshold value (see p.) is calculated.

(d) In this case all tornadoes appear to be reported, if the population density of the subbox is greater than or equal to 300 persons/sq mi.

(e) $\overline{X}_h = (2.00 + 2.13 + 1.94 + 2.00 + 2.03 + 1.98)/6$

$= 2.01$

$\overline{X}_a = 0.95$

(f) The number of tornadoes not reported is:

$x = (\overline{X}_h - \overline{X}_a)n$

$= (2.01 - 0.95)\ (400)$

$= 425$ tornadoes

(g) The percentage of tornadoes per F-scale is obtained from the occurrence-intensity relationship (Step B.3).

	F0	F1	F2	F3	F4	F5
Threshold Windspeed	40	73	113	158	207	261
Percent of Total	56.6	27.6	12.5	2.7	0.5	0.1
No. of Unreported Tornadoes	241	117	53	11.5	2	0.5
No. Reported Tornadoes	215	109	41	12	2	0
Total	456	226	94	23.5	5	0.5
Cumulative Total	804	348	122	28	4.5	0.5

(h) The new occurrence-intensity relationships are calculated from the information in Step B.4.g using linear regression analysis. The new relationships are

$y = (2219)10^{-0.0110V}$ $(V<118 \text{ mph})$

$y = (9094)10^{-0.0162V}$ $(V\geq 118 \text{ mph})$

(i) The number of tornadoes per year in F-scale windspeed intervals are determined.

NUMBER OF TORNADOES PER YEAR IN EACH F-SCALE INTERVAL, λ_i

F0	F1	F2	F3	F4	F5
26.32	12.89	5.94	1.23	0.204	0.028

C. PROBABILITY OF EXPERIENCING WINDSPEEDS IN EACH F-SCALE INTERVAL

(1) Compute values of $a_{ij}\lambda_i$

(2) Determine the area of the 5-degree square local region

$$A = 25(4780) \cos \theta ,$$

where θ is the latitude of the midpoint of the region, assumed to be 39.5° in this example. Therefore,

$$A = 92,210 \text{ sq mi}$$

(3) Evaluate Equation (3) for each j using results of Step C.2.

D. PROBABILITY OF WINDSPEEDS EXCEEDING INTERVAL VALUES

(1) Evaluate Equation (21) for all values of j

(2) These values are plotted to obtain the desired risk model.

The entire risk model analysis can be accomplished by computer. A sample output is shown on page 47.

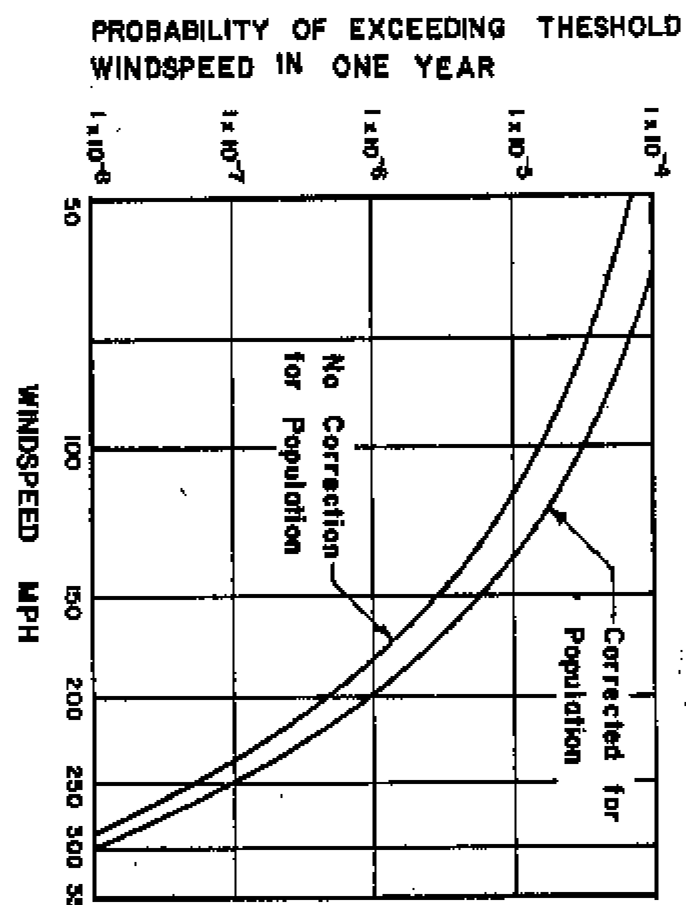
TORNADO RISK CALCULATIONS

Step C.1

i \ j	K_{ij} F0	F1	F2	F3	F4	F5	e_i	λ_i
F0	1.875						0.080	26.32
F1	1.420	0.454					0.26	12.89
F2	1.067	0.612	0.291				0.65	5.94
F3	0.927	0.482	0.280	0.174			1.32	1.23
F4	0.962	0.421	0.261	0.128	0.087		2.38	0.204
F5	0.965	0.387	0.228	0.160	0.077	0.042	3.97	0.028

TORNADO RISK CALCULATIONS (cont.)

		$a_{ij}\ \lambda_i$						
	i \ j	F0	F1	F2	F3	F4	F5	
	F0	3.948						
	F1	4.759	1.522					
	F2	4.120	1.977	1.124				
	F3	1.506	0.783	0.455	0.203			
	F4	0.467	0.204	0.127	0.062	0.042		
	F5	0.107	0.043	0.025	0.018	0.009	0.005	
$\sum_{i=j}^{5} a_{ij}\ \lambda_i$		14.906	4.529	1.731	0.363	0.051		Step C.1
A, sq mi		92,210	92,210	92,210	92,210	92,210	92,210	Step C.2
$P(V=\bar{V}_j)$ Eq. (3)		1.62×10^{-4}	4.91×10^{-5}	1.88×10^{-5}	3.94×10^{-6}	5.53×10^{-7}	5.42×10^{-8}	Step C.3
$P(V \geq \bar{V}_j)$ Eq. (21)		2.34×10^{-4}	7.24×10^{-5}	2.33×10^{-5}	4.55×10^{-6}	6.07×10^{-7}	5.42×10^{-8}	Step D.1
Windspeed (mph)		40	73	113	158	207	261	


PROBABILITY OF EXCEEDING THESHOLD WINDSPEED IN ONE YEAR
1 x 10^-8
1 x 10^-7
1 x 10^-6
1 x 10^-5
1 x 10^-4
No Correction for Population
Corrected for Population
50
100
150
200
250
300
350
WINDSPEED MPH

ASSESSMENT OF TORNADO RISK

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

TEST PROBLEM

K MATRIX

						A-I	LAM+I
1.075	0.000	0.000	0.000	0.000	0.000	0.081	13.898
1.420	0.488	0.000	0.000	0.000	0.000	0.267	4.860
1.067	0.812	0.291	0.000	0.000	0.000	0.484	1.380
0.937	0.482	0.280	0.174	0.000	0.000	1.331	0.380
0.762	0.421	0.241	0.128	0.087	0.000	1.405	0.086
0.785	0.387	0.228	0.140	0.077	0.042	4.007	0.007

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

1.713	0.000	0.000	0.000	0.000	0.000	
1.727	0.384	0.000	0.000	0.000	0.000	
0.872	0.419	0.338	0.000	0.000	0.000	
0.248	0.180	0.104	0.065	0.008	0.000	
0.130	0.057	0.038	0.017	0.013	0.000	
0.038	0.014	0.008	0.006	0.003	0.000	
-----	-----	-----	-----	-----	-----	
5.023	1.233	0.384	0.088	0.014	0.002	SUMMATION ALAM(J)
33190	33190	33190	33190	33190	33190	AREA OF LOCAL REGION-SQ MI
1.51E-004	3.68E-005	1.16E-005	2.65E-006	4.37E-007	4.87E-008	PROB OF WINDSPEED IN INTERVAL PJ
2.03E-004	5.16E-005	1.47E-005	3.13E-006	4.82E-007	4.87E-008	PROB OF EXCEED WINDSPEED IN INTERVAL PJ
40	73	113	158	207	261	LOWER BOUND WINDSPEED IN INTERVAL PJ