DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Natural Phenomena Hazards Modeling Project: Extreme Wind/Tornado Hazard Models for Department of Energy Sites

UCRL--53526-Rev.1

D. W. Coats

DE85 018156

R. C. Murray

Manuscript date: August 1985

LAWRENCE LIVERMORE NATIONAL LABORATORY
University of California • Livermore, California • 94550

Available from: National Technical Information Service • U.S. Department of Commerce
5285 Port Royal Road • Springfield, VA 22161 • \$11.50 per copy • (Microfiche \$4.50)

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

EP

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

PREFACE

The Lawrence Livermore National Laboratory (LLNL) under contract to the Office of Nuclear Safety (ONS), Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness, U.S. Department of Energy (DOE), is developing uniform design criteria for critical facilities at DOE sites throughout the United States. The criteria in question relate to a structure's ability to withstand earthquakes and strong winds from both tornadoes and other storms.

Work began on the project in September 1975, when representatives of LLNL's Structural Mechanics Group met with James Hill of DOE's Division of Operational and Environmental Safety to discuss the project's goals. In other meetings in late 1975 and early 1976, it was decided that a three-phase approach to the project was best. The first phase, completed in late 1978, involved information gathering. Sites were selected, their critical facilities were identified, and information about the facilities was gathered and summarized (Coats and Murray, 1978).

In the second phase, experts in seismic and wind hazards were asked to develop hazard models for each site. TERA Corporation, Berkeley, California, was selected to develop the seismic hazard models. McDonald, Mehta, and Minor, Consulting Engineers, Lubbock, Texas, and T. T. Fujita of the University of Chicago were both contracted to independently develop hazard models for tornadoes and high winds.

Once all the hazard models are developed, LLNL will support ONS in developing uniform hazard criteria for the DOE to use in evaluating the existing design criteria at the various sites and upgrading or modifying critical facilities.

The purpose of this report is to present the final wind/tornado hazard models and the methodology used to develop them. The final wind/tornado hazard models presented in this report are based on the site-specific wind/tornado hazard models produced by Drs. J. McDonald and T. Fujita, as part of the Natural Phenomena Hazards Study. Their reports have been distributed to DOE headquarters and field offices and should be used as reference material only. The wind/tornado hazard models contained in this report are the appropriate models for use in design and analysis. The final seismic hazard models have been published separately by TERA Corporation, and a complete summary of the seismic hazard methodology and the seismic hazard curves will be included in a separate UCRL publication.

CONTENTS

	<u>Page</u>
Preface	ii
Abstract	v
Acknowledgments	vii
Introduction	1
Tornado Hazard Modeling	6
Introduction	6
Tornado Records	6
Fujita's Methodology	9
Statistical Area--Distance Function	
for Range Weighting	10
Statistical Years	11
Gradation of Damage Along Path Length	12
Population Effects	13
Path Length Adjustments	16
Weighted Probability Computation by DAPPLE Method	16
Straight-Wind Hazard Modeling	18
Introduction	18
Methodology Used by McDonald	18
Tornado Parameters for Design and Evaluation	
of Facilities	21
Wind Parameters	21
Atmospheric Pressure Change	22
Windborne Missiles	25
Summary and Conclusions	28
References	29
Bibliography	31
Appendix A--Extreme Wind/Tornado	
Hazard Models for DOE Sites	35
Albuquerque Field Office Sites	36
Chicago Field Office Sites	45
Idaho Field Office Site	50
Oak Ridge Field Office Sites	52

Nevada Field Office Site	57
Richland Field Office Site	59
San Francisco Field Office Sites	61
Savannah River Field Office Site	67

ABSTRACT

Lawrence Livermore National Laboratory (LLNL) has developed seismic and wind hazard models for the Office of Nuclear Safety (ONS), Department of Energy (DOE). The work is part of a three-phase effort aimed at establishing uniform building design criteria for seismic and wind hazards at DOE sites throughout the United States. In Phase 1, LLNL gathered information on the sites and their critical facilities, including nuclear reactors, fuel-reprocessing plants, high-level waste storage and treatment facilities, and special nuclear material facilities. In Phase 2, development of seismic and wind hazard models, was initiated. These hazard models express the annual probability that the site will experience an earthquake or wind speed greater than some specified magnitude. This report summarizes the final wind/tornado hazard models recommended for each site and the methodology used to develop these models. Final seismic hazard models have been published separately by TERA Corporation. A complete summary of the seismic hazard methodology and seismic hazard curves will be included in a separate UCRL publication.

In the final phase, it is anticipated that the DOE will use the hazard models to establish uniform criteria for the design and evaluation of critical facilities.

ACKNOWLEDGMENTS

The authors would like to thank James R. Hill (DOE), the technical monitor for the Office of Nuclear Safety for his support and assistance. The support and assistance of the Office of Nuclear Safety, Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness, U.S. Department of Energy, is also gratefully acknowledged. Special thanks go to Drs. J. McDonald and T. Theodore Fujita for their valued technical contributions throughout the course of this project and to Dr. Robert Abbey for his advice and assistance. The wind hazard studies performed by Drs. McDonald and Fujita, formed the technical basis for the material presented herein (see Bibliography). Finally, thanks go to members of the DOE community, DOE contractors, NOAA, and the USNRC for their critical reviews of Dr. McDonald's and Dr. Fujita's work and for their assistance in establishing the final design windspeed curves. Thanks also go to Carol Meier (LLNL) for publications support.

INTRODUCTION

The Lawrence Livermore National Laboratory (LLNL) has been providing technical assistance to the Department of Energy's Office of Nuclear Safety (ONS), Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness, to develop seismic, extreme wind and tornado hazard curves for Department of Energy (DOE) sites throughout the country. (See Table 1 for a list of sites included in this study, and Fig. 1 for their geographic distribution.) Experts in seismic and wind hazards were asked to develop the hazard models for each site. TERA Corporation, Berkeley, California, was selected to develop the seismic hazard models. McDonald, Mehta, and Minor, Consulting Engineers, Lubbock, Texas, and T. T. Fujita of the University of Chicago were contracted to independently develop hazard models for tornadoes and high winds.

These consultants were selected based upon their nationally recognized expertise and their previous experience in hazard model development. Dr. Fujita's strength lies in the field of tornado hazard model development while Dr. McDonald's strengths lie in the development of straight-wind hazard models and engineering application of wind/tornado design parameters.

The hazard models produced have received widespread distribution for review and comment. This distribution included: DOE Field Offices; DOE site contractors; DOE headquarters; National Oceanic and Atmospheric Administration (NOAA); and the Nuclear Regulatory Commission (NRC), and the United States Geological Survey (USGS).

After review comments were evaluated and acted upon, final hazard model reports were issued. TERA Corporation has issued their final seismic hazard model reports in the form of individual binders for each DOE field office. These binders contain the final seismic hazard models developed, as well as a brief description of the methodology used to develop the hazard curves. A complete summary of the seismic hazard methodology and seismic hazard curves will be included in a separate UCRL publication.

The draft wind/tornado hazard models produced by McDonald and Fujita were updated to reflect review comments and reissued. Since both McDonald and Fujita had produced independent wind/tornado hazard curves for each DOE site, a resolution as to what form the final recommended wind/tornado hazard model should take was required. This resolution was reached in a meeting at DOE headquarters on June 8, 1982 (Thomasson, 1982). At this meeting it was unanimously decided to develop the final wind/tornado hazard model by using

the recognized strengths of McDonald's and Fujita's models. Specifically, the following recommendations were made and adopted:

- The McDonald site models for severe winds at subtornado wind speeds should be adopted because they are more realistic.
- The Fujita site models for tornado hazards should be adopted because they are more realistic.
- The McDonald tornado missile model, which uses Fujita's DBT-77 model as input, should be adopted.

In general, the wind speed differences between McDonald's and Fujita's wind/tornado hazard models were not significant from an engineering design point of view. Table 2 shows the maximum wind speed differences between McDonald and Fujita at the 10^{-7} probability level. These wind speed differences at this extremely low level of probability are not considered excessive in light of the differences in methodology between McDonald and Fujita.

Other points of interest discussed at the June 8, 1982 meeting were:

- Generally, for most critical structures the seismic design requirements are controlling so that design for severe winds to 150 mph are taken care of adequately.
- Tornado design parameters such as pressure drop and rate-of-pressure drop are not significant relative to structural design except for ventilation systems and design of structures with large plan areas.
- Straight winds modeling (of the severe winds curve) is insensitive to regional variation due to meteorological station locations since the models are based on fastest-mile winds which are governed by synoptic conditions.
- The significance of tornado generated missiles is greater for non-hardened structures. Therefore, for many DOE facilities, the specific missile characteristics critical for design and for safety evaluation are highly significant and are both site and region specific.

The final recommended wind/tornado hazard curves are presented in Appendix A. The remainder of this report contains a brief review of Fujita's tornado hazard methodology, McDonald's straight-wind hazard methodology, and the missile and wind parameters needed for design. It should be pointed out that at one site, the Pinellas, Florida site, the wind hazard assessment included the evaluation of hurricane winds.

TABLE 1. Project sites, with DOE field offices.

DOE field office	Sites
Albuquerque, NM	Bendix Plant Los Alamos National Scientific Laboratory Mound Laboratory Pantex Plant Rocky Flats Plant Sandia National Laboratories, Albuquerque Sandia National Laboratories, Livermore, CA Pinellas Plant, Florida
Chicago, IL	Argonne National Laboratory--East Argonne National Laboratory--West Brookhaven National Laboratory Princeton Plasma Physics Laboratory
Idaho	Idaho National Engineering Laboratory
Oak Ridge, TN	Feed Materials Production Center Oak Ridge National Laboratory, X-10, K-25 and Y-12 Paducah Gaseous Diffusion Plant Portsmouth Gaseous Diffusion Plant
Nevada	Nevada Test Site
Richland, WA	Hanford Project Site
San Francisco, CA	Lawrence Berkeley Laboratory Lawrence Livermore National Laboratory Lawrence Livermore National Laboratory, Site 300 Energy Technology and Engineering Center Stanford Linear Accelerator Center
Savannah, GA	Savannah River Plant

Fig. 1. DOE Sites for Wind/Tornado Hazard Analysis.

TABLE 2. Comparison of Fujita's and McDonald's wind speed (in miles per hour) with 10^{-7} probability.

Location	Method "A" (Fujita)	Method "B" (McDonald)	"B" Minus "A"
Bendix/Kansas City	292	310	18
Los Alamos	183	190	7
Mound	283	364	81
Pantex, Texas	271	297	26
Rocky Flats	204	228	24
Sandia, Albq.	175	191	16
Sandia, Livermore	164	165	1
Pinellas	268	244	-24
Argonne-East	276	318	42
Argonne-West	185	184	-1
Brookhaven	224	215	-9
Princeton (PPPL)	229	210	-19
Idaho (INEL)	185	184	-1
FMPC	287	364	77
Oak Ridge, X-10,K-25,Y-12	261	340	79
Paducah	289	340	51
Portsmouth	257	330	73
Nevada Test Site	152	136	-16
Hanford	179	177	-2
Berkeley (LBL)	168	165	-3
Livermore (LLNL)	164	165	1
Site 300 (LLNL)	164	182	18
ETEC	179	174	-5
Stanford (SLAC)	182	165	-17
Savannah River	283	283	0

INTRODUCTION

Tornado hazard is defined here as the annual probability that any point within a geographic region will experience wind speeds in excess of some threshold value. It is a point probability independent of a structure's size and location within the geographic region.

Our methodology for assessing these hazards uses the geographic region's available tornado records. Distribution functions that relate area to intensity and occurrence to intensity are empirically derived from the data for use in the probability calculations. The geographic region must be carefully defined so that tornado characteristics are reasonably homogeneous in the region. A number of factors which influence the number and path lengths of reported tornadoes, and the area of the local region in which tornadoes can spawn, are taken into account and are discussed in subsequent sections of this report.

The hazard model for a specific facility is an instrument that can be used to establish criteria for the design of new structures and the evaluation of existing ones. When the methodology is applied to several sites in different regions, design criteria can be established for a consistent level of hazard.

The tornado hazard model is determined from statistical analyses of records of tornadoes that have occurred in the region surrounding the site of interest. A consistent data set is first obtained. Then the hazard model is developed by sequentially determining the following relationships and effects:

- Distance function for range weighting.
- Statistical years.
- Gradation of damage along path length.
- Path length adjustments.

TORNADO RECORDS

Hazard analysis, in general, requires a consistent and complete data set. Since hazards are sometimes extrapolated to probabilities of one in ten million, a long data record is desirable, but unavailable. We used the best

available data and recognize that our results have a wide band of uncertainty because of the data.

Hazard analysis requires the time of occurrence, intensity, initial touchdown point, path length, and path width. The occurrence and touchdown points for tornadoes in which touchdown was observed or significant damage was done have been systematically recorded since 1959. However, no method was available for rating the intensity of tornadoes until 1971, when T. T. Fujita introduced a rating scale that relates intensity to observed damage. The Fujita Scale, shown in Table 3, has seven intensity classifications ranging from F0 to F6.

Table 4 shows the Pearson path length, P_L , and path width, P_W , scales, which 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 has six categories.

Thus, a tornado can be conveniently categorized by giving it a Fujita-Pearson (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.

Since the invention of the FPP scale in 1971, tornado data has been recorded in a systematic manner. The local meteorologist in charge of the National Weather Service is responsible for confirming tornado occurrences and assigning the proper FPP ratings.

Systematic sources of data on tornadoes are:

- Storm Data, a monthly publication of the Department of Commerce, National Oceanographic and Atmospheric Administration (NOAA), Environmental Data Service, National Climatic Center, Asheville, North Carolina, which contains systematic records of various types of severe storms.
- A data set containing tornado records back to 1950, which has been assembled and updated by the National Severe Storms Forecast Center (NSSFC) in Kansas City, Missouri.

TABLE 3. Fujita's 1971 F-scale classification of tornadoes based on damage.

Scale	Damage	Wind speed (mph)	Description of tornado
F0	Light	40-72	Corresponds to Beaufort 9 through 11. Some damage to chimneys, TV antennae, sign boards; tree branches broken; shallow-rooted trees pushed over; old, hollow trees break or fall.
F1	Moderate	73-112	The beginning of hurricane wind speed or Beaufort 12 is 73 mph. Surfaces peeled off roofs; windows broken; trailer houses moved or overturned; trees on soft ground uprooted; some trees snapped; moving autos pushed off roads.
F2	Considerable	113-157	Roofs torn off frame houses, leaving strong upright walls; weak structured outbuildings and trailer houses demolished; railroad boxcars pushed over; large trees snapped or uprooted; light-object missiles generated; cars blown off highways; block structures damaged badly.
F3	Severe	158-206	Roofs and some walls torn off well-constructed frame houses; some rural buildings demolished completely; trains overturned; steel-framed warehouse structures torn; cars lifted off ground and rolled some distance; most trees in a forest uprooted, snapped, or leveled; block structures often leveled.
F4	Devastating	207-260	Well-constructed frame houses leveled, leaving debris; structures with weak foundations lifted, torn, and blown some distance; trees debarked by small flying objects; sandy soil eroded and gravel flies; cars thrown or rolled some distance, finally disintegrating; large missiles generated.
F5	Incredible	261-318	Strong frame houses lifted off foundations and carried considerable distances to disintegrate; steel-reinforced concrete badly damaged; auto-sized missiles fly distances of 100 yds or more; trees debarked completely; incredible phenomena can occur.
F6	Inconceivable	319 to sonic	The extent and types of damage may not be conceived. Missiles such as iceboxes, water heaters, storage tanks, and automobiles fly long distances, creating serious secondary damage on structures. Assessment of damage is feasible only through detailed surveys involving engineering and aerodynamical calculations, as well as meteorological models of tornadoes.

TABLE 4. Tornado damage area parameters from Fujita-Pearson (FPP) classifications.

Index	F-scale wind speed (mph)	P-scale path length (mi)	P-scale path width (yds)
0	40-72	0.3-0.9	6-17
1	73-112	1.0-3.1	18-55
2	113-157	3.2-9.9	56-175
3	158-206	10.0-31.5	176-556
4	207-260	31.6-99	557-1759
5	261-318	100-316	1760-4963

- The Damage Area Per Path Length (DAPPLE) data set assembled by Fujita from Storm Data and personal files of storm damage reports. For each tornado, the DAPPLE data set records:
 - (1) Year, month, day and time.
 - (2) F-scale.
 - (3) Deaths and injuries.
 - (4) The areas affected by the tornado, with an area defined as a 1° -square of latitude and longitude, subdivided into $15'$ sub-boxes.
 - (5) Path length, path type, and direction within each sub-box.

FUJITA'S METHODOLOGY

Although McDonald and Fujita use the same data set for most of their calculations, their methodologies differ in several respects. Both use essentially the same formula for calculating the probability that a given velocity will be experienced in a local region. Fujita's expression for this probability is

$$P(F,V) = \frac{\text{Area of specific wind speed}}{\text{Statistical area x statistical year}} , \quad (1)$$

which is essentially the ratio of the area in which the velocity is expected to be V, divided by the total local area, times an annual rate of tornado occurrence.

Statistical Area--Distance Function for Range Weighting

A basic question in assessing the tornado risk concerns the selection of the statistical area around the specific site. If the selected area is too small, the computed probabilities are influenced by storms which do not represent the climatic average. On the other hand, the selection of an unusually large area around the site will result in the inclusion of storms which may not be related to the climatic conditions at the site.

To overcome such difficulties in site-specific evaluations, Fujita devised a weighting function which decreases gradually with the distance from the site, and is used to reduce the effects of distant tornadoes.

Distance Function, $F(D)$, is expressed by the equation

$$F(D) = \cos^m(0.9^\circ \times D) , \quad (2)$$

where m is a positive constant and D is the distance from the site in miles. This function is always 1.0 when $D = 0$, reaching zero at $D = 100$ miles. When the distance increases beyond 100 miles from the site, the distance function is assumed to be zero so that tornadoes outside the 100-mile circle do not influence probability computations.

Until 1979, m was either 0.5 or 2.0. Beginning in January 1980, three integers, 0, 1, 2, were to be used in reducing the effects of distant tornadoes. The selection of an m applicable to each site is made according to the following criteria:

- $m = 0$ for all sites for comparison purposes (i.e. no reduction).
- $m = 1$ for sites with few tornadoes.
- $m = 2$ for sites with many tornadoes.

Statistical Years

In developing his tornado model, Fujita uses data back to 1916. Fujita deals with the fact that tornado frequencies in the early years are only about one-tenth the current reporting rate by using the concept of a weighted statistical year, $\bar{Y}$, defined by

$$\bar{Y} = (n_0 - 1964) \frac{\frac{n_0 \sum N(n)}{1916}}{\frac{n_0 \sum N(n)}{1965}}, \quad (3)$$

where $N(n)$ denotes the annual tornado frequencies in the year n , and n_0 denotes the last year of statistics. Note that $N(n)$ is really $N(n, F)$ because annual tornado frequencies vary with the F scale. The weighted statistical years, therefore, vary as a function of F (see Table 5).

TABLE 5. Fujita's weighted statistical years for hazard computations, based on reported tornado frequencies between 1916 and 1978.

Scale	Statistical period (1916-1978) $\sum N(n)$	($n_0 = 1978$) (1965-1978) $\sum N(n)$	Actual years	Weighted years
F 0	5,718	3,260	63.0	24.6
F 1	8,645	4,453	63.0	27.2
F 2	7,102	2,762	63.0	36.0
F 3	2,665	850	63.0	43.9
F 4	673	209	63.0	45.1
F 5	127	30	63.0	59.2
F0 + F1	14,363	7,713	63.0	26.1
F2 + F3	9,767	3,612	63.0	37.9
F4 + F5	800	239	63.0	46.9

Table 5 reveals that the weighted statistical years of F0 tornadoes during a 63-yr period (1916-78) are only 24.6 yr, because these weak tornadoes were not confirmed efficiently in the early years. On the other hand, the weighted statistical years of F5 tornadoes are 59.2 yr because most tornadoes of extraordinary intensities were reported accurately, even in the early data-collection years.

Weighted statistical years of weak (F0 + F1), strong (F2 + F3), and violent (F4 + F5) tornadoes shown in Table 5 were used in computing the hazard probabilities in the site-specific evaluation.

Gradation of Damage Along Path Length

The tornado hazard assessment method developed by Abbey and Fujita (1975) accounts for gradation of damage along the length and width of the path in terms of mean damage path length, not mean damage area. Thus, Eq. (1) is rewritten as:

$$P(F,V) = \frac{L_F \times \text{DAPPLE} (F,V)}{A \times Y} \text{ year}^{-1} \quad (4)$$

where A is the statistical area; Y, the statistical year; L_F , the path length of F-scale tornadoes; and DAPPLE (F,V), the damage area per path length, which varies with F-scale and specified wind speed, V.

In 1975, Abbey and Fujita estimated DAPPLE values based on the Super Outbreak of tornadoes of 1974 at 50-mph intervals of maximum wind speeds for weak (F0 + F1), strong (F2 + F3), and violent (F4 + F5) tornadoes. Since then, Fujita computed DAPPLE values based on his Design-Basis Tornadoes, 1978 (DBT-78). Between September 1978 and February 1980, the mean values of DBT-78 DAPPLE and the initial Abbey/Fujita DAPPLE (AF-75) were used for hazard assessments.

Early in 1980, the mean DAPPLE was smoothed by using three empirical equations,

$$\text{DAPPLE} = 10^N \text{ in miles} \quad , \quad (5)$$

where

- $N = -0.00078 V^{1.496}$ for violent tornadoes,
- $N = -0.00263 V^{1.342}$ for strong tornadoes,
- $N = -0.00930 V^{1.293}$ for weak tornadoes,

V = the maximum wind speed in mph.

Table 6 shows the changes in DAPPLE values for violent, strong, and weak tornadoes.

Figure 2 is a plot of the DAPPLE relationships. Note that Fujita incorporates the dependence of damage area on F-scale and wind speed in a single standard statistical distribution.

Population Effects

Until 1979, Fujita used a population correction to account for a small reporting population, poor road system for post-storm damage assessment, and poor viewing conditions caused by obstructions such as thick forests. However, he abandoned this method in 1979 because he believed that the correction was excessively biased by local population concentrations.

TABLE 6. Improvement in DAPPLE values in miles. Fujita used AF-75 until August 31, 1978 and Mean DAPPLE, between September 1, 1978 and February 29, 1980. Smoothed DAPPLE values, which have been used since March 1, 1980, were computed by empirical equations.

Tornado category	Maximum total wind speed at 10-m AGL (mph)						
	50	100	150	200	250	300	350
<u>Violent</u>							
AF-75	0.51	0.14	0.036	0.0081	0.0016	0.00023	0.000016
DBT-78	0.43	0.16	0.050	0.0101	0.00014	0.00000	0.000000
Mean	0.47	0.15	0.043	0.0091	0.0009	0.00012	0.000008
Smoothed	5.35-01 ^a	1.71-01	3.94-02	6.92-03	9.64-04	1.09-04	1.03-05
<u>Strong</u>							
AF-75	0.43	0.062	0.0098	0.0012	0.000087	---	---
DBT-78	0.19	0.035	0.0037	0.0000	0.000000	---	---
Mean	0.31	0.049	0.0068	0.0006	0.000044	---	---
Smoothed	3.15-01	5.36-02	6.47-03	6.02-04	4.52-05	2.82-06	1.50-07
<u>Weak</u>							
AF-75	0.074	0.0028	0.000052	---	---	---	---
DBT-78	0.076	0.0000	0.000000	---	---	---	---
Mean	0.075	0.0014	0.000026	---	---	---	---
Smoothed	6.54-02	1.60-03	2.40-05	2.52-07	1.99-09	1.24-11	6.30-14

^a5.35-01 = 5.35×10^{-1} mile.

Fig. 2. Three curves of DAPPLE values for weak, strong, and violent tornadoes computed from empirical equations. Mean DAPPLE values used for obtaining these equations are shown with circles.

Path Length Adjustments

Beginning in February 1980, Fujita used four experimentally derived indexes to adjust and weight reported path lengths:

- Road Index. This index increases from 0 to 10 as the road networks in a local region change from those characteristic of a town to those in which roads are 10 or more miles apart.
- Forest Index. As the fractional area covered by forest increases, so does this index--from 0 to 10.
- Topography Index. This index varies from 0 to 10 as the terrain becomes steeper.
- Water Index. This index varies from 0 to 10 as the fractional area covered by water increases from nothing to the entire area.

Because not all tornadoes are observed and confirmed, the road and forest indexes are used to increase reported path lengths in a local region. The topography and water indexes are used to reduce the area of the local region to that in which tornadoes can spawn, develop, and dissipate. Steep areas and those covered by water (where waterspouts, not tornadoes, are formed) are eliminated.

Fujita also weights the path length through the use of a distance function that is based on the following two assumptions: (1) the larger the distance of a local region from the site, the smaller its weight; and (2) the smaller the adjusted area, the smaller the weight. An example of the second assumption is a local region containing a small island but not carrying as much weight as one that is 100% land.

Weighted Probability Computation by DAPPLE Method

In applying the DAPPLE method, L_F , A , and Y in Eq. (4) can be changed into their weighted values,

$$\begin{aligned} L_F & \text{ into } \sum L_F'' \\ A & \text{ into } A_s \sum G \end{aligned}$$

Y into $\bar{Y}$, the weighted statistical year,

where L_F'' is the range-corrected path length of F-scale tornadoes and is a function of the Road Index, the Forest Index, and the distance function $F(D)$. A_S is the area of the sub-box at the site, and G is a weighting function which is itself a function of the Topography Index, the Water Index, and the distance function $F(D)$.

Using this notation, we can now express Eq. (4) as

$$P(F,V) = \frac{DAPPLE(F,V) \times \Sigma L_F''}{\bar{Y} \times A_S \times \Sigma G} \text{ year}^{-1} \quad (6)$$

Equation (6) gives the probability of experiencing a windspeed of V associated with an F-scale tornado.

Since DAPPLE values are available for weak ($F0 + F1$), strong ($F2 + F3$) and violent ($F4 + F5$) tornadoes, statistical path lengths are computed not for each F scale tornado but for weak (w), strong (s), and violent (V) tornadoes. The probability of all tornadoes affecting the site can thus be computed as a sum,

$$P(V) = P(w,V) + P(s,V) + P(v,V) \quad (7)$$

INTRODUCTION

In the United States, 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 wind speeds. This distribution also has been used in Russia (Bernstein, 1968), Argentina (Riera and Reimudin, 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) is also based on the assumption that the extreme winds are modeled by the Type I distribution. The Type I distribution is used in the latest version of the American National Standards Institute, ANSI A58.1-1982 Standard.

METHODOLOGY USED BY McDONALD

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

The Type II distribution was used in earlier studies by McDonald. He has since switched to the Type I distribution because of the more reasonable wind speeds at the large mean recurrence intervals. All sites included in this study have been evaluated using the Type I distribution.

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

$$F(x) = \exp \{- \exp [-(x-u)/\sigma]\}. \quad (8)$$

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 are acceptably small for the 95 percent confidence level. The estimates for σ and u are given by

$$\bar{\sigma} = \frac{\sqrt{6}}{\pi} s, \quad (9)$$

$$\bar{u} = \bar{x} - 0.5772 \bar{\sigma}, \quad (10)$$

where $\bar{x}$ and s are the mean and standard deviation of the sample, respectively. Equation (8) can be inverted to give the estimated wind speed corresponding to a specified mean recurrence interval, N :

$$\bar{V}_N = \bar{x} + s(y - 0.5772) \frac{\sqrt{6}}{\pi}, \quad (11)$$

where

$$y = \left[\ln -\ln\left(1 - \frac{1}{N}\right) \right]. \quad (12)$$

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

$$SD(\bar{V}_N) = \left[\frac{\pi^2}{6} + 1.1396(y - 0.5772) \frac{\pi}{\sqrt{6}} + 1.1(y - 0.5772)^2 \right]^{1/2} \frac{\sqrt{6}}{\pi \sqrt{n}} s, \quad (13)$$

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

$$\bar{V}_N \pm Z_{\alpha/2} SD(\bar{V}_N), \quad (14)$$

is approximately $(1-\alpha)100$ percent, where $Z_{\alpha/2}$ is the value of the standard normal curve leaving an area of $\alpha/2$ to the right (Walpole and Myers, 1972) and $(1-\alpha)100$ percent defines the confidence interval.

A data set consisting of the annual extreme wind speeds is used to determine x and s parameters. The wind speed hazard probability model is then obtained from Eq. (11). The upper and lower bound confidence limits are estimated from Eq. (14).

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

$$P(V_N \geq V) = \frac{1}{N}. \quad (15)$$

In performing the calculations, wind speeds are corrected to the 10-m anemometer height. Results of the analyses are given in terms of fastest-mile wind speeds. A few of the sites had records listed in terms of fastest one-minute wind speeds. The fastest-one-minute wind speeds are converted to fastest-mile wind speeds to be consistent with the use of American National Standards Institute Standard ANSI A58.1. The two wind speeds differ because of the averaging time. A 60-mph fastest-mile wind speed has the same averaging time as a one-minute wind speed. A one-minute wind speed greater than 60 mph has a larger averaging time than the corresponding fastest-mile wind speed. Thus, a fastest-mile wind speed corresponding to a one-minute wind speed is larger than the one-minute windspeed. Above 60 mph, the relationship between fastest-mile wind speed and fastest-one-minute wind speed is, according to McDonald (1980),

$$V_{(F-M)} = 1.17V(1\text{-min}) - 10.34. \quad (16)$$

The straight winds obtained from the application of McDonald's methodology are expressed in terms of fastest-mile wind speeds. A gust factor as defined in ANSI A58.1 should be included in the calculations for the design wind loads.

An examination of the wind hazard curves contained in Appendix A reveals that several sites predict wind speeds less than 70 mph for the 50-year return period. In keeping with ANSI A58.1-1982, we recommend that the minimum design wind speed should be 70 mph.

TORNADO PARAMETERS FOR DESIGN AND EVALUATION OF FACILITIES

Once the maximum horizontal wind speed 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 parameters are obtained by indirect methods. The two most commonly used methods of tornado parameter measurements are photogrammetric analyses 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 cycloidal ground marks, debris patterns observed in the damage path, and height of the 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 McDonald 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 effects: wind, atmospheric pressure change, and missiles. The tornado parameters associated with these three factors are discussed in the following paragraphs.

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, yet representative, model of the tornado windfield. Hoecker found that at the 1000-ft level, the tangential windfield behaves similarly 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 Fig. 3. Associated tornado parameters for different values of maximum horizontal wind speeds are given in Table 7. 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 7 are not exact, but give a good approximation.

ATMOSPHERIC PRESSURE CHANGE

The atmospheric pressure change is obtained by integrating the cyclostrophic equation,

$$p = \int \frac{\rho v^2}{R} dR \quad (17)$$

Fig. 3. Three-dimensional wind velocity vector in a tornado.

TABLE 7. Design basis tornado parameters.

Wind component	Symbol	Equation	Maximum values of parameters						
<u>Wind velocity components:</u>									
Maximum horizontal, mph	$V_{\max}$	(from risk model)	100	150	200	250	300	350	
Translational, mph	V_t	(Assumed)	30	50	50	50	50	60	
Rotational, mph	V_{ro}	$V_{\max} - V_t$; $(V_r^2 + V_\theta^2)^{1/2}$; $1.12 V_\theta$	70	100	150	200	250	290	
Tangential, mph	V_θ	$0.89 V_{ro}$	62	89	134	178	223	258	
Radial, mph	V_r	$0.5 V_\theta$	31	45	67	89	112	129	
Vertical, mph	V_v	$0.67 V_\theta$	41	59	89	118	149	173	
<u>Tornado Geometry:</u>									
Radius of max. winds, ft	$R_{\max}$	(Assumed)	125	150	175	200	250	300	
Radius of damaging winds, ft	R_D	$\frac{R_{\max}}{75} (V_{\max})$	167	300	467	667	1000	1400	
Total pressure change, psf	p	$\rho V_{\theta \max}^2$	20	41	92	162	255	341	
Rate of pressure change, psf/sec	dp/dt	$\rho V_{\theta \max}^2 \left(\frac{V_t}{R_{\max}} \right)$	7	20	38	59	75	100	-

In this equation, the tangential wind speed, 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):

$$\begin{aligned} V_{\theta}/R &= C, & (0 < R < R_{\max}) \\ V_{\theta} R &= C, & (R_{\max} < R < \infty). \end{aligned} \tag{18}$$

The radius of maximum tangential wind speed, $R_{\max}$, is measured from the center of the tornado vortex. The maximum atmospheric pressure change (psf) is

$$p = \rho V_{\theta \max}^2 \tag{19}$$

where

ρ is the mass density of air ($0.00238 \text{ slugs/ft}^3$), and

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

The rate of atmospheric pressure change is given by

$$\frac{dp}{dt} = \rho V_{\theta \max}^2 \frac{V_t}{R_{\max}}. \tag{20}$$

The values of maximum pressure change and maximum rate of pressure change are given in Table 7.

WINDBORNE MISSILES

Table 8 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

TABLE 8. Wind generated missile parameters.

Missile	Weight (lb)	Projected Area (ft ²)	Cross Sectional Area (ft ²)
Timber plank 4 in. x 12 in. x 12 ft	139	11.50	0.29
3-in.-diameter standard steel pipe x 10 ft	75.8	2.29	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.

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). Experiences in storm damage investigations show that the likelihood of these missiles being accelerated in a tornado is extremely small. Therefore, they have been excluded from the missile list.

Table 9 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. Conservatism is 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 always assumed to 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 9. 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 9. 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 9. Windborne missile velocities.

Design wind speed	100	Horizontal missile* velocity (mph)					Maximum height (ft)
		150	200	250	300	350	
Timber plank	60	72	90	100	125	175	200
3-in.-diameter standard 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.

SUMMARY AND CONCLUSIONS

This report has presented a summary of the Tornado Hazard Model methodology used by Dr. T. Theodore Fujita and the Straight Wind Hazard Model methodology used by Dr. James McDonald as part of a DOE, Office of Nuclear Safety project to evaluate natural phenomena hazards at DOE sites throughout the country.

In addition to the above, a section on wind-generated missile parameters is included to assist the analyst in design.

The wind hazard curves presented in the Appendix are a compilation of the curves generated by Drs. Fujita and McDonald and are the curves recommended for use in the design of new facilities or the analysis of existing facilities. We believe that these curves represent the most realistic evaluation of wind hazards at DOE sites currently available, and we strongly recommend their use in analysis and design applications.

REFERENCES

- Abbey, R. F., Jr., and Fujita, T. T., 1975: "Use of Tornado Path Lengths and Gradations of Damage to Assess Tornado Intensity Probabilities," Preprints, Ninth Conference on Severe Local Storms, Norman, Oklahoma, October 21-23 (Published by American Meteorological Society, Boston, MS).
- Bernstein, M. F., 1968: "Theoretical Bases for the Method Adopted in A.G.S.R. for the Dynamic Design of Tall Slender Structures for Wind Effects," Int. Res. Seminar on Wind Effects on Buildings and Structures, Vol. III, Ottawa, Canada, 1967, University of Toronto Press, pp. 1-37.
- Coats, D. W., and Murray, R. C., 1978: "Natural Phenomena Hazards for Department of Energy Critical Facilities: Phase 1 - Site and Facility Information", Lawrence Livermore National Laboratory, UCRL-52599 Draft.
- 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.
- 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.
- Golden, J. H. and Davies-Jones, R. P., 1975: "Photogrammetric Windspeed Analysis and Damage Interpretation of the Union City, Oklahoma Tornado, May 14, 1973." Preprints for Second U.S. National Conference on Wind Engineering, Ft. Collins, Colorado.
- Hoecker, W. H., Jr., 1960: "Windspeeds and Airflow Patterns in the Dallas Tornado of April 1, 1957," Monthly Weather Review, Vol. 88, No. 5, pp. 167-180.
- McDonald, J. R., 1980: "Relationship Between Fastest-Mile Windspeed and Fastest One-Minute Windspeed," Technical Memo, Institute for Disaster Research, Texas Tech University, Lubbock, Texas.
- McDonald, J. R., 1975: "Flight Characteristics of Tornado Generated Missiles," Institute for Disaster Research, Texas Tech University, Lubbock, Texas.
- Mehta, K. C., 1976: "Wind speed Estimates: Engineering Analyses," Proceedings of the Symposium on Tornadoes: Assessment of Knowledge and Implications for Man, Lubbock, Texas, June 1976 (published by Texas Tech University).
- National Building Code of Canada, 1975: Canadian Structural Design Manual, Supplement No. 11, Associate Committee on National Building Code and National Research Council of Canada, Ottawa, Canada.
- Riera, J. D. and Reimundin, J. C., 1970: "Sobre la Distribucion de Velocidades Maximas de Viento en la Republica Argentina," Simposio Sobre Acciones en Estructuras, University NAC. de Tucman, Argentina.

- Salgado, J. M. and Filho, V., 1975: "Velocidades Maximas do viento no Brasil," Master's Thesis, Univ. Fed. do Rio Grande do Sul, Porto Alegre, Brasil.
- Simiu, E. and Filliben, J. J., 1975: "Statistical Analysis of Extreme Winds," Technical Note No. 868, National Bureau of Standards, Washington, D.C.
- Simiu, E. and Scanlan, R. H., 1978: Wind Effects on Structures, John Wiley & Sons, New York, New York.
- Thom, H. C. S., 1960: "Distribution of Extreme Winds in the United States," Journal of the Structural Division, ASCE, Vol. 86, No. ST4, Proc. Paper 2433, pp. 11-24.
- Thomasson, W. N., 1982: Memorandum Summarizing the June 8, 1982 Severe Winds and Tornado Hazards Review Meeting.
- U.S. Nuclear Regulatory Commission, 1975: Standard Review Plan, Office of Nuclear Reactor Regulation, Washington, D.C.
- Zipser, R. A., 1976: "Photogrammetric Studies of a Kansas Tornado and a Hawaiian Tornado Waterspout," M.S. Thesis, Dept. of Meteorology, Univ. of Oklahoma, Norman, Oklahoma.

BIBLIOGRAPHY

- McDonald, J. R., "A Methodology for Tornado Risk Assessment," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (April, 1979).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Los Alamos National Laboratory Site, Los Alamos, New Mexico," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Pantex, Texas Site," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Hazard Probabilities at the Bendix Plant, Kansas City, Missouri," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Sandia Laboratory Site, Albuquerque, New Mexico," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (September, 1980).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Rocky Flats, Colorado Site," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (May, 1983-Revised June, 1985).
- McDonald, J. R., "Assessment of Tornado, Hurricane and Straight Wind Hazard Probabilities at the Pinellas Plant, Florida," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (June, 1983).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Idaho National Engineering Laboratory/Argonne-West Site," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (February, 1980).
- McDonald, J. R., "Assessment of Tornado, and Straight Wind Hazard Probability at the Nevada Test Site, Nevada," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Hazard Probabilities at the Lawrence Berkeley Laboratory, Stanford Linear Accelerator and Livermore/Sandia Laboratories," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Hazard Probabilities at the Liquid Metals Engineering Center, California," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).

- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Hanford Engineering Works Site," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1979).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Savannah River Plant Site, Aiken, South Carolina," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Oak Ridge, Tennessee Site," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Paducah Gaseous Diffusion Plant Site, Paducah, Kentucky," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Portsmouth Gaseous Diffusion Plant, the Mound Laboratory, and the Fernald Materials Production Center," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (May, 1980).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Risks at the Argonne National Laboratory, Argonne, Illinois," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (June, 1979).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Hazard Probabilities at the Brookhaven National Laboratory, Long Island, New York," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- McDonald, J. R., "Assessment of Tornado and Straight Wind Hazard Probabilities at the Princeton Plasma Physics Laboratory, Princeton, New Jersey," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (October, 1982).
- Fujita, T. T., "Workbook of Tornadoes and High Winds for Engineering Applications," SMRP Research Paper 165, Department of the Geophysical Sciences, the University of Chicago (September, 1978).
- Fujita, T. T., "Tornado and High-Wind Hazards at Los Alamos Laboratory, New Mexico," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).
- Fujita, T. T., "Tornado and High-Wind Risks at Pantex Plant, Texas," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).
- Fujita, T. T., "Tornado and High-Wind Hazards at Bendix, Kansas City Plant, Missouri," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (December, 1981).

Fujita, T. T., "Tornado and High-Wind Hazards at Sandia Laboratory, New Mexico," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).

Fujita, T. T., "Tornado and High-Wind Hazards at Sandia Laboratory, New Mexico," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).

Fujita, T. T., "Tornado and High-Wind Risks at Rocky Flats, Colorado," report prepared for Lawrence Livermore National Laboratory, Livermore, CA.

Fujita, T. T., "Tornado and High-Wind Hazards at Pinellas Plant Site, Florida," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (January, 1983).

Fujita, T. T., "Tornado and High-Wind Risks at Idaho National Engineering Laboratory and Argonne National Laboratory, Idaho," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).

Fujita, T. T., "Tornado and High-Wind Hazards at Nevada Test Site, Nevada," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1981).

Fujita, T. T., "Tornado and High-Wind Hazards at Livermore Laboratory, California," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).

Fujita, T. T., "Tornado and High-Wind Hazards at Lawrence Berkeley Laboratory and Stanford Linear Accelerator Sites in California," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).

Fujita, T. T., "Tornado and High-Wind Hazards at Liquid Metal Engineering Center, California," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (December, 1981).

Fujita, T. T., "Tornado and High-Wind Risks at Hanford Project Site, Washington," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).

Fujita, T. T., "Tornado and High-Wind Hazards at Savannah River Plant, South Carolina," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1980).

Fujita, T. T., "Tornado and High-Wind Risks at Oak Ridge National Laboratory, Tennessee," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).

Fujita, T. T., "Additional Studies on Oak Ridge," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (January, 1980).

Fujita, T. T., "Tornado and High-Wind Risks at Paducah Gaseous Plant, Kentucky," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).

- Fujita, T. T., "Tornado and High-Wind Risks at FMPC, Portsmouth, and Mound Sites, Ohio," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1979).
- Fujita, T. T., "Tornado and High-Wind Risks at Argonne National Laboratory, Argonne, Illinois," report prepared for Lawrence Livermore National Laboratory, Livermore, CA.
- Fujita, T. T., "Tornado and High-Wind Hazards at Brookhaven National Laboratory Site, New York," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1981).
- Fujita, T. T., "Tornado and High-Wind Hazards at Princeton Plasma Physics Laboratory, New Jersey," report prepared for Lawrence Livermore National Laboratory, Livermore, CA (1981).

APPENDIX A

Extreme Wind/Tornado Hazard Models for DOE Sites

Albuquerque Field Office Sites

Wind/Tornado Hazard Curves

Wind Hazard at the Bendix, Kansas City Plant, Missouri

Wind Hazard at the Los Alamos National Laboratory, New Mexico

Wind Hazard at the Mound Laboratory, Ohio

Wind Hazard at the Pantex Plant, Texas

Wind Hazard at the Rocky Flats Plant, Colorado

Wind Hazard at the Sandia National Laboratory, New Mexico

Wind Hazard at the Sandia National Laboratory, California

Wind Hazard at the Pinellas Plant, Florida

Chicago Field Office Sites

Wind/Tornado Hazard Curves

Wind Hazard at the Argonne National Laboratory, Illinois

Wind Hazard at the Argonne National Laboratory, Idaho

Wind Hazard at the Brookhaven National Laboratory, New York

Wind Hazard at the Princeton Plasma Physics Laboratory, New Jersey

Idaho Field Office Site

Wind/Tornado Hazard Curve

Wind Hazard at the Idaho National Engineering Laboratory, Idaho

Oak Ridge Field Office Sites

Wind/Tornado Hazard Curves

Wind Hazard at the Feed Materials Production Center, Ohio

Wind Hazard at the Oak Ridge National Laboratory, X-10, K-25,
and Y-12 Sites, Tennessee

Wind Hazard at the Paducah Gaseous Diffusion Plant, Kentucky

Wind Hazard at the Portsmouth Gaseous Diffusion Plant, Ohio

Nevada Field Office Site
Wind/Tornado Hazard Curve

Wind Hazard at the Nevada Test Site, Nevada

Richland Field Office Site

Wind/Tornado Hazard Curve

Wind Hazard at the Hanford Site, Washington

San Francisco Field Office Sites

Wind/Tornado Hazard Curves

Wind Hazard at the Lawrence Berkeley Laboratory, California

Wind Hazard at the Lawrence Livermore National Laboratory, California

Wind Hazard at the Lawrence Livermore National
Laboratory--Site 300, California

Wind Hazard at the Energy Technology and
Engineering Center, California

Wind Hazard at the Stanford Linear Accelerator Center, California

Savannah River Field Office Site

Wind/Tornado Hazard Curve

Wind Hazard at the Savannah River Plant, South Carolina