Appendix 4

Structural Integrity of Spent Fuel Pool Structures Subject to Tornados and High Winds

Tornado or high winds damage, resulting from missile generation, can affect the structural integrity of the spent fuel pool or affect the availability of nearby support systems, such as power supplies, cooling pumps, heat exchangers and water makeup sources, and may also affect recovery actions. A set of site specific evaluations for tornados and high winds was documented in NUREG/CR-5042, "Evaluation of External Hazards to Nuclear Power Plants in the United States," Lawrence Livermore National Laboratory, December 1987. It is noted that the study was performed to assess core damage frequencies at operating plants. The methodology for the assessment of tornado risk developed In NUREG/CR-2944, "Tornado Damage Risk Assessment," Brookhaven National Laboratory, September 1982, was used for this evaluation.

The National Climatic Data Center (NCDC) in Asheville, N.C., keeps weather records for the U.S. for the period 1950 to 1995 (Ref: http://www.ncdc.noaa.gov/). These data are reported as the annual average number of (all) tornadoes per 10,000 square mile per state, and the annual average number of strong-violent (F2 to F5) tornadoes per square mile per state, as shown in Figures 1 and 2.

A comparison of the site specific evaluations (from NUREG/CR-5042) and general regional values from the NCDC database is presented in Table 1. The NCDC data was reviewed and a range of frequencies per square mile per year was developed based on the site location and neighboring state (regional) data. In general, the comparison of the NUREG/CR-5042 tornado frequencies for all tornadoes to the NCDC tornado frequencies for all reported tornadoes showed good agreement between the two sets of data.

The Storm Prediction Center (SPC) raw data, for the period 1950 to 1995, was used to develop a data base for this assessment. There have been about 121 F5, and 924 F4, tornadoes recorded between 1950 and 1995 (an additional four in the 1996 to 1998 period). It was estimated that about 30% of all reported tornadoes were in the F2 to F3 range and about 2.5% were in the F4 to F5 range.

DOE-STD-1020-94, "Natural Phenomena Hazards Design and Evaluation Criteria for Department of Energy Facilities," January 1996, Department of Energy, provides some insights into wind generated missiles:

- For site where tornadoes are not considered a viable threat, to account for objects or debris a 2x4 inch timber plank weighing 15 lbs is considered as a missile for straight winds and hurricanes. With a recommended impact speed of 50 mph at a maximum height of 30 ft above ground, this missile would break annealed glass, perforate sheet metal siding and wood siding up to to 3/4-in thick. For weak tornadoes, the timber missile horizontal speed is 100 mph effective to a height of 100 ft above ground and a vertical speed of 70 mph. A second missile is considered: a 3-in diameter steel pipe weighing 75 lbs with an impact velocity of 50 mph, effective to a height of 75 ft above

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ground and a vertical velocity of 35 mph. For the straight wind missile, an 8-in concrete masonry unit (CMU) wall, single wythe (single layer) brick wall with stud wall, or a 4-inch concrete (reinforced) is considered adequate to prevent penetration. For the tornado missile, an 8- to 12-in CMU wall, single wythe brick wall with stud wall and metal ties, or a 4- to 8-inch concrete (reinforced) slab is considered adequate to prevent penetration (depending on the missile). (Refer to DOE-STD-1020-94 for additional details.)

- For sites where tornadoes are considered a viable threat, to account for objects or debris the same 2x4 inch timber is considered but for heights above ground to 50 ft. The tornado missiles are (1) the 15 lbs, 2x4 inch timber with a horizontal speed of 150 mph effective up to 200 ft above ground, and a vertical speed of 100 mph; (2) the 3-inch diameter, 75 lbs steel pipe with a horizontal speed of 75 mph and a vertical sped of 50 mph effective up to 100 ft above ground; and (3) a 3,000 lbs automobile with ground speed up to 25 mph. For the straight wind missile, an 8-in CMU wall, single wythe brick wall with stud wall, or a 4-inch concrete (reinforced) is considered adequate to prevent penetration. For the tornado missile, an 8 in CMU reinforced wall, or a 4- to 10-inch concrete (reinforced) slab is considered adequate to prevent penetration (depending on the missile). (Refer to DOE-STD-1020-94 for additional details.)

The winds associated with hurricanes and other storms are generally less intense and lower in magnitude than those associated with tornadoes. Generally, high winds from wind storms and hurricanes are considered to be the controlling wind level at a higher frequency but at a lower magnitude.

Recommended values for risk-informed assessment of spent fuel pool

The tornado strike probabilities for each F-scale interval was determined from the SPC raw data on a state-averaged basis. For each F-scale, the probability was obtained from the following equation, for the point strike probability:

$$P_{fs} = \left(\frac{\Sigma_N < a >_T}{A_{ob}} \right) \times \frac{1}{Y_{int}} \qquad \text{Equation 1}$$

where:

P_{fs} = strike probability for F-scale (fs)
$<a>_T$ = tornado area, mi^2
A_{ob} = area of observation, mi^2 (state land area)
Y_{int} = interval over which observations were made, years
Σ_N = sum of reported tornados in the area of observation

The tornado area, $<a>_T$, was evaluated at the mid-point of the path-length and path-width intervals shown in Table 2a, based on the SPC path classifications. For example, an F2 tornado with a path-length scale of 2 has an average path length of 6.55 miles and with a path-width scale of 3 has an average width of 0.2 miles.

The tornado area, $\langle a \rangle_T$, was then modified using the method described in NUREG/CR-2944 (based on Table 6b, page 19 and Table 7b, page 21) to correct the area calculation based on observations of the variations in a tornado's intensity along its path length and path width, see Figure 3. Table 2b provides the path-length correction data. Table 2c provides the path-width correction data. The corrected effective area has a calculated $\langle a \rangle_T$ of about 0.28 mi^2. The combined variation in intensity along the length and across the width of the tornado path is shown in Table 2d (Table 15b from NUREG/CR-2944). For example, an F2 tornado with a path-length scale of 2 and a path-width scale of 3 has a calculated $\langle a \rangle_T$ of about 0.28 mi^2. The total area is reapportioned using Table 2d to assign 0.11 mi^2 to the F0 classification, 0.13 mi^2 to the F1 classification and 0.04 mi^2 to the F2 classification.

The risk regionalization scheme used in NUREG/CR-2944, as shown in Figure 4 was used to determine the exceedance probability for each region identified. A continental U.S. average was also determined. Included in Figure 4 are the approximate location of commercial LWRs and independent spent fuel storage facilities.

The SPC raw data for each state was used to determine the F-scale, path-length and path-width characteristics of the reported tornadoes. The effective tornado strike area was corrected using the data from NUREG/CR-2944. Equation 1 was used for each state and the summation and averaging of the states within each region (A, B, C and D, as well as a continental USA average) performed. The results for the exceedance probability per year for each F-scale are shown in Table 3, and graphically presented in Figure 5. The SPC data analysis is summarized in Table 4.

Significant pool damage

An F4 to F5 tornado would be needed to consider the possibility of damage to the spent fuel pool from a tornado missile. The likelihood of the exceedance of this size tornado is estimated to be 5.6×10^{-7} per year (for Region A), or lower. In addition, the spent fuel pool is a multiple-foot thick concrete structure and, based on the DOE-DOE-STD-1020-94 information, it is very unlikely that a tornado missile would penetrate the spent fuel pool.

Support system availability

An F2 or larger tornado would be needed to consider damage to a support system, such as power supplies, cooling pumps, heat exchangers and water makeup sources. The likelihood of the exceedance of this size tornado is estimated to be 1.5×10^{-5} per year (for Region A), or lower.

Table 1 - Tornado and high wind data summary

	NUREG/CR-5042 Data				NCDC data	
Site	Tornado frequency (per mi^2-year)	Tornado strike frequency (per year)	High wind damage frequency (per year)	Tornado damage frequency (per year)	Frequency 1950-1995 average for F0-F5 (per mi^2-year)	Frequency 1950-1995 average for F2-F5 (per mi^2-year)
Indian Pt. 2	1.00×10^{-4}	1.00×10^{-4}	2.50×10^{-5}	$<1.0 \times 10^{-7}$	$1.2\text{-}2.2 \times 10^{-4}$	$0.2\text{-}0.7 \times 10^{-4}$
Indian Pt. 3	1.00×10^{-4}	1.00×10^{-4}	1.80×10^{-5}	$<1.0 \times 10^{-7}$	$1.2\text{-}2.2 \times 10^{-4}$	$0.2\text{-}0.7 \times 10^{-4}$
Limerick 1-2	1.13×10^{-4}	2.30×10^{-4} (<F1)	9.00×10^{-9}	$<1.0 \times 10^{-8}$	$2.2\text{-}3.4 \times 10^{-4}$	$0.7\text{-}1.3 \times 10^{-4}$
Millstone 3	1.87×10^{-4}	1.87×10^{-4}	Low	$<1.0 \times 10^{-7}$	$2.8\text{-}3.4 \times 10^{-4}$	$0.2\text{-}1.1 \times 10^{-4}$
Oconee 3	2.50×10^{-4}	3.50×10^{-3} 1 mi rad.	Low	$<1.0 \times 10^{-9}$	$2.8\text{-}3.4 \times 10^{-4}$	$0.7\text{-}0.9 \times 10^{-4}$
Seabrook 1-2	1.26×10^{-3}	7.75×10^{-5}	$<3.89 \times 10^{-8}$	2.06×10^{-9} LOSP & RWST	$1.8\text{-}3.8 \times 10^{-4}$	$0.4\text{-}1.1 \times 10^{-4}$
Zion ½	1.00×10^{-3}	1.00×10^{-3}	N.A.	$<1.0 \times 10^{-8}$	$3.4\text{-}5.4 \times 10^{-4}$	$1.2\text{-}2.0 \times 10^{-4}$
GSI A-45 PRAs	Regional Local		w/o recovery of offsite power			
ANO 1	5.18×10^{-4} 4.37×10^{-4}	1.53×10^{-3}	5.69×10^{-6}	2.53×10^{-4}	$3.7\text{-}7.5 \times 10^{-4}$	$1.7\text{-}2.4 \times 10^{-4}$
Point Beach 1-2	6.98×10^{-4} 4.11×10^{-4}	5.38×10^{-4}	1.00×10^{-5}	5.00×10^{-5}	$3.4\text{-}4.7 \times 10^{-4}$	$1.2\text{-}1.5 \times 10^{-4}$
Quad Cities 1-2	5.18×10^{-4} 5.44×10^{-4}	1.04×10^{-3}	$<<1.0 \times 10^{-8}$	5.08×10^{-7}	$3.4\text{-}5.4 \times 10^{-4}$	$1.2\text{-}2.0 \times 10^{-4}$
St. Lucie 1	6.98×10^{-4} 1.20×10^{-3}	1.70×10^{-4}	$<<1.0 \times 10^{-8}$	1.61×10^{-8}	8.4×10^{-4}	1.2×10^{-4}
Turkey Pt. 3	3.37×10^{-4} 5.83×10^{-3}	1.70×10^{-4}	3.30×10^{-5}	2.54×10^{-6}	8.4×10^{-4}	1.2×10^{-4}

Table 2a - Tornado characteristics

F-scale	Damage and wind speed	Path-length scale		Path-width scale	
		Scale	Length (mi)	Scale	Width (yds)
0	Light Damage (40-72 mph)	0	< 1.0	0	< 18
1	Moderate Damage (73-112 mph)	1	1.0 - 3.1	1	18 - 55
2	Significant Damage (113-157 mph)	2	3.2 - 9.9	2	56 - 175
3	Severe Damage (158-206 mph)	3	10.0 - 31.9	3	176 - 527
4	Devastating Damage (207-260 mph)	4	32 - 99.9	4	528 - 1759
5	Incredible Damage (261-318 mph)	5	100 >	5	1760 >

Table 2b - Variation of intensity along length based on fraction of length per tornado(*)

Local tornado state	Recorded tornado state					
	F0	F1	F2	F3	F4	F5
PL-F0	1	0.383	0.180	0.077	0.130	0.118
PL-F1		0.617	0.279	0.245	0.131	0.125
PL-F2			0.541	0.310	0.248	0.162
PL-F3				0.368	0.234	0.236
PL-F4					0.257	0.187
PL-F5						0.172

(*) - Table 6b from NUREG/CR-2944

Table 2c - Variation of intensity along width based on fraction of width per tornado(*)

Local tornado state	Recorded tornado state					
	F0	F1	F2	F3	F4	F5
PW-F0	1	0.418	0.154	0.153	0.152	0.152
PW-F1		0.582	0.570	0.310	0.264	0.262
PW-F2			0.276	0.363	0.216	0.143
PW-F3				0.174	0.246	0.168
PW-F4					0.122	0.183
PW-F5						0.092

(*) - Table 7b from NUREG/CR-2944

Table 2d- Combined variation in intensity along length and across width of tornado path(*)

Local tornado state	True maximum tornado state					
	F0	F1	F2	F3	F4	F5
CV-F0	1.0	0.641	0.380	0.283	0.298	0.286
CV-F1		0.359	0.471	0.433	0.358	0.333
CV-F2			0.149	0.220	0.209	0.195
CV-F3				0.064	0.104	0.116
CV-F4					0.031	0.054
CV-F5						0.016

(*) - Table 15b from NUREG/CR-2944

Table 3 - Exceedance probability for each F-scale

NUREG/CR-2944 Region	Exceedance probability (per year)					
	F0	F1	F2	F3	F4	F5
A	7.4E-05	4.4E-05	1.5E-05	3.5E-06	5.6E-07	3.1E-08
B	5.6E-05	3.3E-05	1.1E-05	2.5E-06	3.7E-07	2.1E-08
C	2.9E-05	1.5E-05	4.1E-06	8.9E-07	1.3E-07	4.7E-09
D	3.6E-06	1.6E-06	3.9E-07	8.7E-08	1.6E-08	---
USA	3.5E-05	2.0E-05	6.1E-06	1.4E-06	2.2E-07	1.0E-08

Table 4 - SPC data analysis summary by state

	NUREG/CR -2944 Region					Tornado F-scale							Point strike probability (per year)						Land Area
State	A	B	C	D	Years	F0	F1	F2	F3	F4	F5	Total	F0	F1	F2	F3	F4	F5	(mi^2)
AL	X	X			46	165	364	323	129	36	14	1031	2.9e-05	3.2e-05	1.3e-05	3.7e-06	6.9e-07	4.3e-08	50750
AZ				X	44	90	57	11	2	0	0	160	6.7e-07	2.9e-07	3.6e-08	1.8e-09	0	0	113642
AR	X				46	198	298	331	149	31	0	1007	3.2e-05	3.5e-05	1.3e-05	2.4e-06	1.9e-07	0	52075
CA				X	45	142	58	21	2	0	0	223	5.1e-07	2.7e-07	6.0e-08	2.7e-09	0	0	155973
CO			X	X	46	616	441	99	15	1	0	1172	4.4e-06	2.0e-06	4.2e-07	3.9e-08	3.3e-11	0	103730
CT			X		46	9	29	20	5	2	0	65	1.1e-05	1.1e-05	3.6e-06	8.5e-07	2.2e-07	0	4845
DE			X		42	20	23	11	1	0	0	55	2.6e-05	1.5e-05	1.5e-06	6.4e-09	0	0	1955
DC*					1	1	0	0	0	0	0	1	1.3e-04	0	0	0	0	0	61
FL		X	X		46	1156	665	293	30	4	0	2148	1.5e-05	8.6e-06	2.2e-06	2.8e-07	2.0e-08	0	53997
GA		X			46	147	537	266	65	17	0	1032	2.9e-05	3.0e-05	1.2e-05	3.4e-06	4.3e-07	0	57919
ID				X	42	63	53	8	0	0	0	124	4.7e-07	1.9e-07	1.4e-08	0	0	0	82751
IN	X				46	246	336	263	108	77	8	1038	3.3e-05	3.5e-05	1.5e-05	5.2e-06	1.2e-06	6.7e-08	35870
IA	X				46	478	506	421	119	74	9	1607	3.7e-05	3.7e-05	1.4e-05	3.1e-06	6.1e-07	2.5e-08	55875
IL	X				46	431	440	316	113	39	3	1342	3.0e-05	2.7e-05	9.8e-06	2.5e-06	3.3e-07	2.1e-08	55875
KS	X	X			46	1111	610	404	168	54	16	2363	3.5e-05	3.0e-05	1.1e-05	3.0e-06	5.8e-07	1.1e-07	81823
KY	X				46	79	168	133	65	35	3	483	1.6e-05	1.7e-05	6.9e-06	1.8e-06	3.1e-07	1.4e-08	39732
LA		X			46	225	620	268	123	16	2	1254	2.4e-05	2.2e-05	6.9e-06	1.4e-06	1.2e-07	1.9e-08	43566
ME				X	42	21	44	17	0	0	0	82	1.8e-06	1.1e-06	1.7e-07	0	0	0	30865
MD			X		46	49	92	26	5	0	0	172	1.5e-05	9.2e-06	9.4e-07	8.2e-09	0	0	9775
MA			X		45	24	72	31	8	3	0	138	1.2e-05	1.1e-05	4.3e-06	1.6e-06	3.7e-07	0.0e+00	7838
MI		X	X		45	195	308	210	57	30	7	807	1.4e-05	1.4e-05	5.2e-06	1.4e-06	2.8e-07	1.4e-08	56809
MN		X	X		46	372	336	158	53	28	6	953	1.4e-05	1.2e-05	3.5e-06	7.2e-07	1.3e-07	6.6e-09	79617
MS	X	X			46	226	468	369	136	59	10	1268	4.4e-05	4.4e-05	1.7e-05	5.0e-06	1.0e-06	1.3e-08	46914
MO	X				46	298	577	334	109	48	1	1367	1.8e-05	1.6e-05	5.3e-06	1.3e-06	2.3e-07	2.6e-11	68898
MT				X	44	174	42	33	4	0	0	253	1.0e-06	7.0e-07	2.3e-07	2.2e-08	0	0	145556
NE		X	X		46	827	585	255	105	42	4	1818	2.9e-05	2.9e-05	1.2e-05	3.5e-06	3.5e-07	1.6e-08	76878
NV				X	34	41	8	0	0	0	0	49	2.9e-07	4.0e-08	0	0	0	0	109806
NH				X	45	24	34	15	2	0	0	75	4.7e-06	2.4e-06	4.7e-07	1.1e-08	0	0	8969

Table 4 - SPC data analysis summary by state

	NUREG/CR -2944 Region					Tornado F-scale							Point strike probability (per year)						Land Area
State	A	B	C	D	Years	F0	F1	F2	F3	F4	F5	Total	F0	F1	F2	F3	F4	F5	(mi²)
NJ			X		45	43	58	23	4	0	0	128	1.7e-05	6.6e-06	7.9e-07	7.1e-09	0	0	7419
NM			X		46	261	104	31	4	0	0	400	1.5e-06	5.2e-07	8.0e-08	1.1e-09	0	0	121365
NY				X	44	101	106	35	21	5	0	268	7.6e-06	6.1e-06	2.3e-06	8.8e-07	2.2e-07	0	47224
NC			X		46	153	321	143	44	26	0	687	1.5e-05	1.4e-05	4.9e-06	1.5e-06	2.5e-07	0	48718
ND			X		46	490	211	91	28	7	3	830	4.7e-06	3.2e-06	1.1e-06	3.6e-07	9.1e-08	1.1e-08	68994
OH	X				46	157	321	166	53	27	9	733	2.1e-05	1.8e-05	5.6e-06	1.3e-06	3.0e-07	2.8e-08	40953
OK	X				46	845	808	626	209	83	9	2580	4.1e-05	3.9e-05	1.4e-05	3.6e-06	7.0e-07	5.5e-08	68679
OR				X	45	31	15	3	0	0	0	49	2.9e-07	1.5e-07	3.1e-08	0	0	0	96003
PA			X		46	93	220	143	26	22	2	506	9.4e-06	9.0e-06	3.3e-06	9.3e-07	2.0e-07	5.4e-09	44820
RI			X		23	3	4	1	0	0	0	8	1.9e-05	1.3e-05	1.7e-06	0	0	0	1045
SC		X			46	136	234	100	31	15	0	516	1.9e-05	1.9e-05	6.8e-06	1.8e-06	3.0e-07	0	30111
SD		X	X		46	651	259	197	57	7	1	1172	9.7e-06	8.1e-06	3.0e-06	7.7e-07	1.5e-07	1.2e-08	75898
TN	X				46	107	241	139	76	29	4	596	2.2e-05	2.2e-05	8.3e-06	2.1e-06	2.0e-07	1.7e-10	41220
TX		X	X		46	2632	1837	1067	317	76	5	5934	1.6e-05	1.3e-05	4.3e-06	1.1e-06	1.8e-07	3.8e-09	261914
UT				X	43	53	19	6	1	0	0	79	5.1e-07	3.2e-07	1.0e-07	2.8e-08	0	0	82168
VT				X	41	7	14	12	0	0	0	33	3.3e-06	2.0e-06	3.4e-07	0	0	0	9249
VA			X		45	84	132	68	28	6	0	318	8.5e-06	7.0e-06	2.0e-06	4.4e-07	7.1e-08	0	39598
WA				X	41	24	17	12	3	0	0	56	4.9e-07	9.6e-08	2.3e-08	3.6e-09	0	0	66582
WV			X		45	27	36	16	8	0	0	87	2.2e-06	2.4e-06	9.7e-07	2.5e-07	0	0	24087
WI		X	X		46	204	378	276	62	24	5	949	2.6e-05	2.4e-05	7.9e-06	1.4e-06	2.5e-07	3.3e-08	54314
WY				X	46	247	145	43	8	1	0	444	2.5e-06	1.2e-06	3.1e-07	7.1e-08	1.9e-08	0	97105
Sum						13776	13251	7834	2553	924	121	38459							3536342

* - DC was not included in the exceedance analysis.

Figure 1

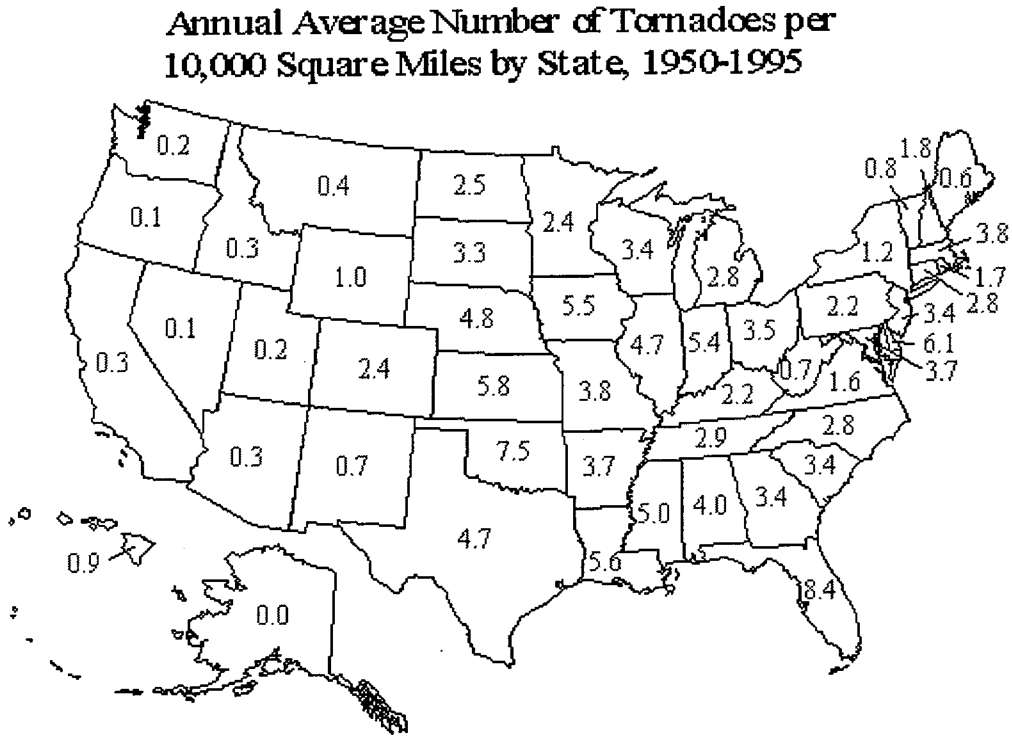


Figure 2

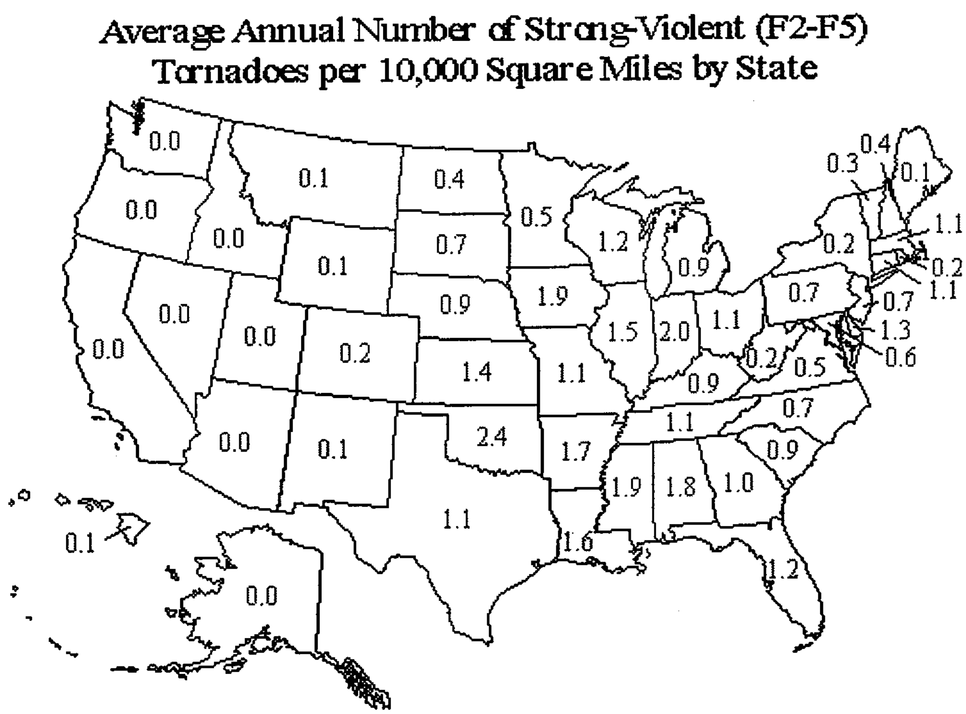


Figure 3 - Sketch of hypothetical F2 tornado illustrating variations

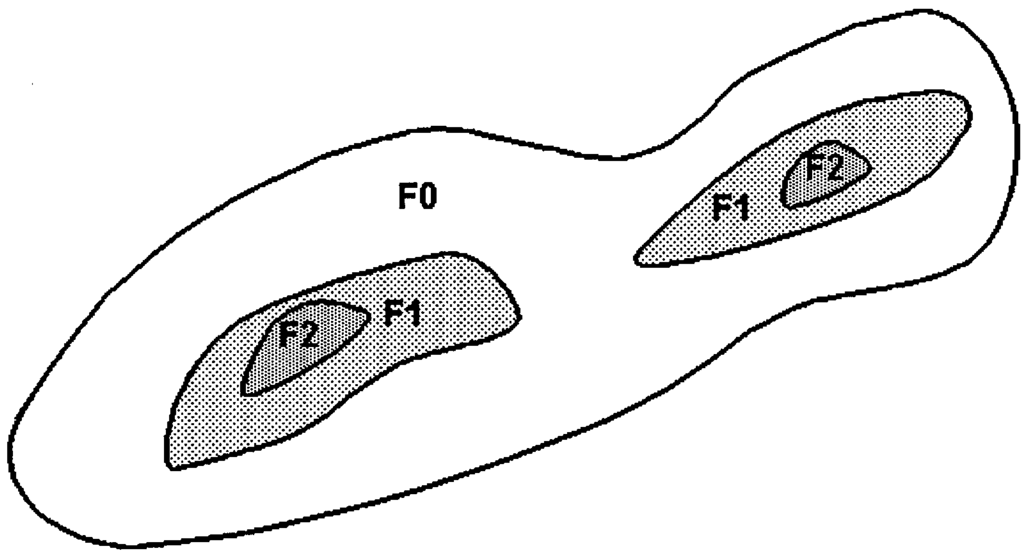


Figure 4 - Tornado risk regionalization scheme (from NUREG/CR-2944)

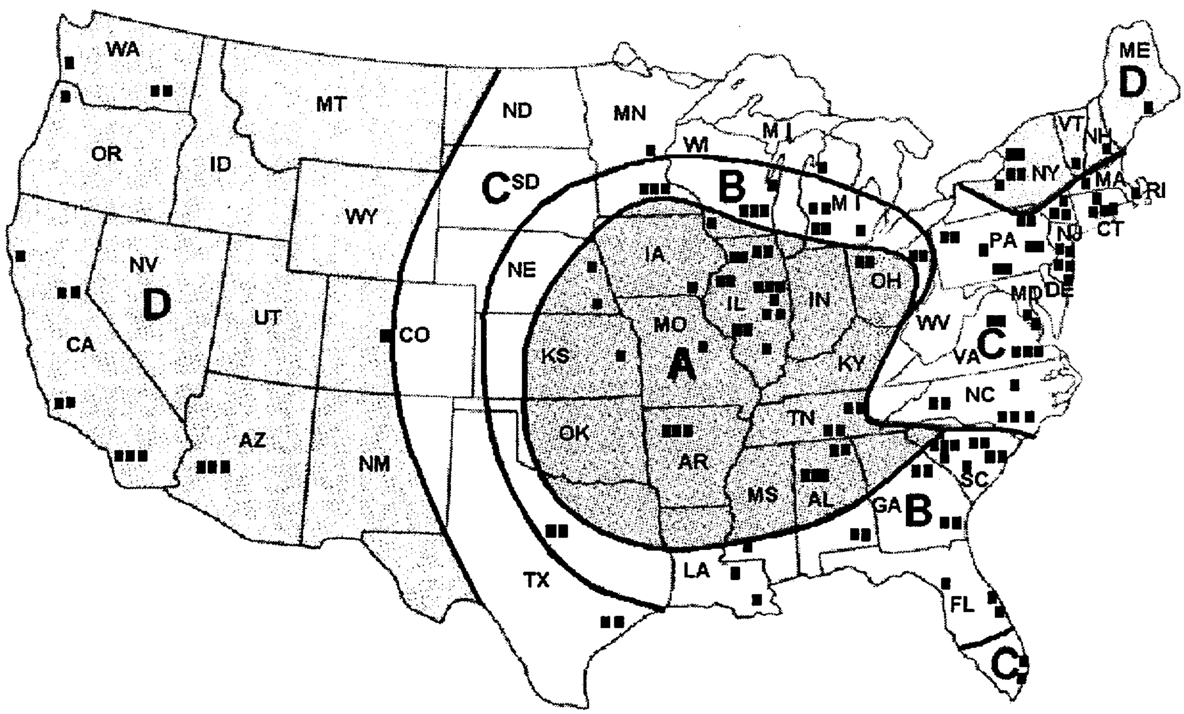
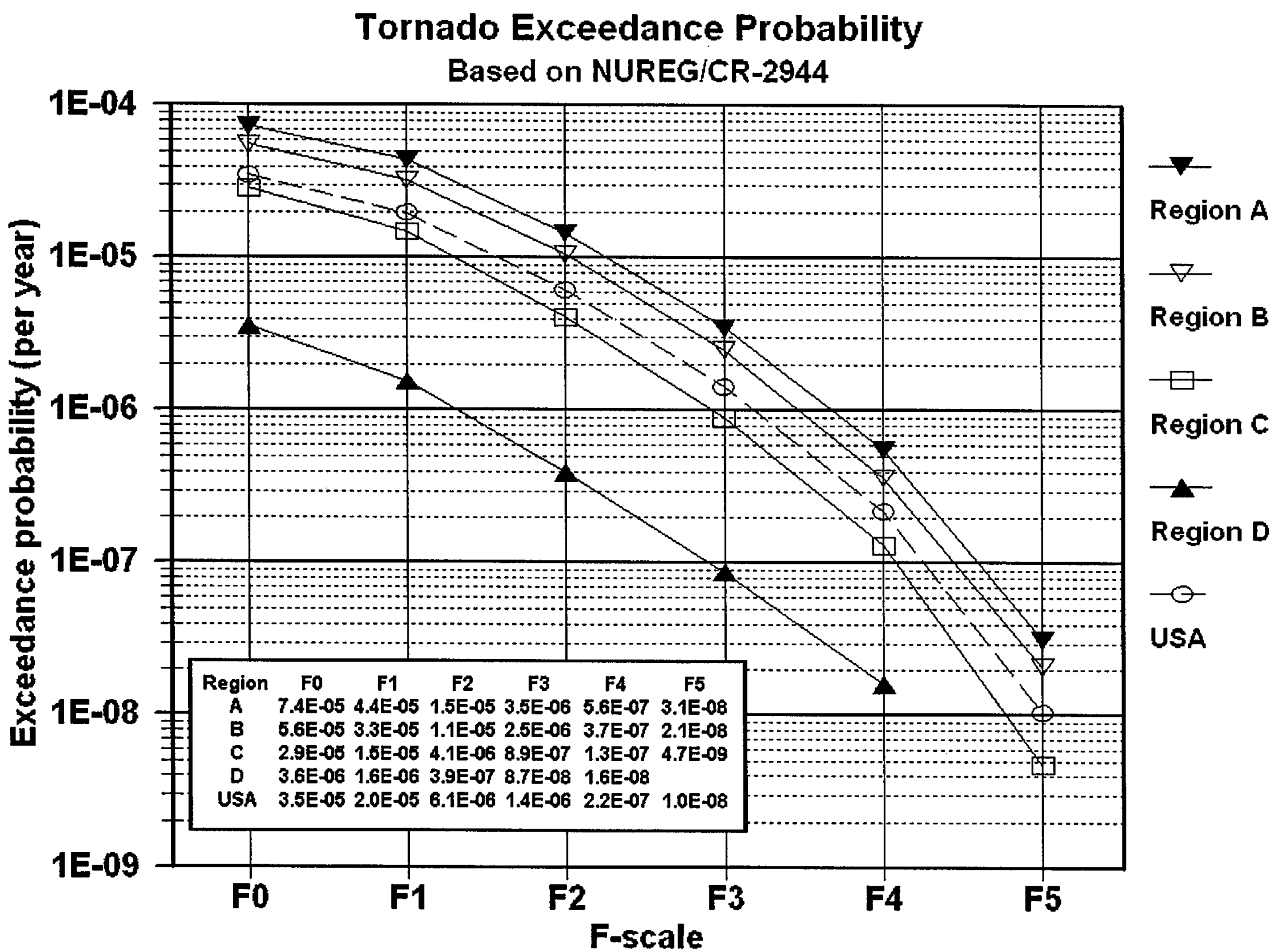


Figure 5 - Tornado exceedance probability for each F-scale



Region	F0	F1	F2	F3	F4	F5
A	7.4E-05	4.4E-05	1.5E-05	3.5E-06	5.6E-07	3.1E-08
B	5.6E-05	3.3E-05	1.1E-05	2.5E-06	3.7E-07	2.1E-08
C	2.9E-05	1.5E-05	4.1E-06	8.9E-07	1.3E-07	4.7E-09
D	3.6E-06	1.6E-06	3.9E-07	8.7E-08	1.6E-08	
USA	3.5E-05	2.0E-05	6.1E-06	1.4E-06	2.2E-07	1.0E-08