

## Appendix 4

### Structural Integrity of Spent Fuel Pool Structures Subject to Tornadoes 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 tornadoes 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 speed 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:

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

where:

- $P_{fs}$  = strike probability for F-scale (fs)
- $<a>_T$  = tornado area, mi<sup>2</sup>
- $A_{ob}$  = area of observation, mi<sup>2</sup> (state land area)
- $Y_{int}$  = interval over which observations were made, years
- $\sum_N$  = sum of reported tornadoes 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<sup>2</sup>. 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<sup>2</sup>. The total area is reapportioned using Table 2d to assign 0.11 mi<sup>2</sup> to the F0 classification, 0.13 mi<sup>2</sup> to the F1 classification and 0.04 mi<sup>2</sup> 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  $5.6 \times 10^{-7}$  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  $1.5 \times 10^{-5}$  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 <sup>2</sup> -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 <sup>2</sup> -year)	Frequency 1950-1995 average for F2-F5 (per mi <sup>2</sup> -year)
Indian Pt. 2	1.00x10 <sup>-4</sup>	1.00x10 <sup>-4</sup>	2.50x10 <sup>-5</sup>	<1.0x10 <sup>-7</sup>	1.2-2.2x10 <sup>-4</sup>	0.2-0.7x10 <sup>-4</sup>
Indian Pt. 3	1.00x10 <sup>-4</sup>	1.00x10 <sup>-4</sup>	1.80x10 <sup>-5</sup>	<1.0x10 <sup>-7</sup>	1.2-2.2x10 <sup>-4</sup>	0.2-0.7x10 <sup>-4</sup>
Limerick 1-2	1.13x10 <sup>-4</sup>	2.30x10 <sup>-4</sup> (<F1)	9.00x10 <sup>-9</sup>	<1.0x10 <sup>-8</sup>	2.2-3.4x10 <sup>-4</sup>	0.7-1.3x10 <sup>-4</sup>
Millstone 3	1.87x10 <sup>-4</sup>	1.87x10 <sup>-4</sup>	Low	<1.0x10 <sup>-7</sup>	2.8-3.4x10 <sup>-4</sup>	0.2-1.1x10 <sup>-4</sup>
Oconee 3	2.50x10 <sup>-4</sup>	3.50x10 <sup>-3</sup> 1 mi rad.	Low	<1.0x10 <sup>-9</sup>	2.8-3.4x10 <sup>-4</sup>	0.7-0.9x10 <sup>-4</sup>
Seabrook 1-2	1.26x10 <sup>-3</sup>	7.75x10 <sup>-5</sup>	<3.89x10 <sup>-8</sup>	2.06x10 <sup>-9</sup> LOSP & RWST	1.8-3.8x10 <sup>-4</sup>	0.4-1.1x10 <sup>-4</sup>
Zion ½	1.00x10 <sup>-3</sup>	1.00x10 <sup>-3</sup>	N.A.	<1.0x10 <sup>-8</sup>	3.4-5.4x10 <sup>-4</sup>	1.2-2.0x10 <sup>-4</sup>
GSI A-45 PRAs	Regional Local		w/o recovery of offsite power			
ANO 1	5.18x10 <sup>-4</sup> 4.37x10 <sup>-4</sup>	1.53x10 <sup>-3</sup>	5.69x10 <sup>-6</sup>	2.53x10 <sup>-4</sup>	3.7-7.5x10 <sup>-4</sup>	1.7-2.4x10 <sup>-4</sup>
Point Beach 1-2	6.98x10 <sup>-4</sup> 4.11x10 <sup>-4</sup>	5.38x10 <sup>-4</sup>	1.00x10 <sup>-5</sup>	5.00x10 <sup>-5</sup>	3.4-4.7x10 <sup>-4</sup>	1.2-1.5x10 <sup>-4</sup>
Quad Cities 1-2	5.18x10 <sup>-4</sup> 5.44x10 <sup>-4</sup>	1.04x10 <sup>-3</sup>	<<1.0x10 <sup>-8</sup>	5.08x10 <sup>-7</sup>	3.4-5.4x10 <sup>-4</sup>	1.2-2.0x10 <sup>-4</sup>
St. Lucie 1	6.98x10 <sup>-4</sup> 1.20x10 <sup>-3</sup>	1.70x10 <sup>-4</sup>	<<1.0x10 <sup>-8</sup>	1.61x10 <sup>-8</sup>	8.4x10 <sup>-4</sup>	1.2x10 <sup>-4</sup>
Turkey Pt. 3	3.37x10 <sup>-4</sup> 5.83x10 <sup>-3</sup>	1.70x10 <sup>-4</sup>	3.30x10 <sup>-5</sup>	2.54x10 <sup>-6</sup>	8.4x10 <sup>-4</sup>	1.2x10 <sup>-4</sup>

**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<sup>(\*)</sup>**

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<sup>(\*)</sup>**

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<sup>(\*)</sup>**

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	1.6E-05	4.3E-06	9.5E-07	1.4E-07	4.5E-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**

State	Y <sub>int</sub> (Eq.1)	Number of observation							Point Strike Probability (per year)						Areas (square miles)		
		F0	F1	F2	F3	F4	F5	Total	F0	F1	F2	F3	F4	F5	Land (A <sub>ob</sub> )	Water	Total
AL	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	1673	52423
AZ	44	90	57	11	2	0	0	160	6.7E-07	2.9E-07	3.6E-08	1.8E-09	0	0	113642	364	114006
AR	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	1107	53182
CA	45	142	58	21	2	0	0	223	5.1E-07	2.7E-07	6.0E-08	2.7E-09	0	0	155973	7734	163707
CO	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	371	104100
CT	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	698	5544
DE	42	20	23	11	1	0	0	55	2.6E-05	1.5E-05	1.5E-06	6.4E-09	0	0	1955	535	2489
DC*	1	1	0	0	0	0	0	1	1.3E-04	0	0	0	0	0	61	7	68
FL	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	11761	65758
GA	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	1522	59441
ID	42	63	53	8	0	0	0	124	4.7E-07	1.9E-07	1.4E-08	0	0	0	82751	823	83574
IN	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	550	36420
IA	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	401	56276
IL	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	55593	2325	57918
KS	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	459	82282
KY	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	679	40411
LA	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	8277	51843
ME	42	21	44	17	0	0	0	82	1.8E-06	1.1E-06	1.7E-07	0	0	0	30865	4523	35387
MD	46	49	92	26	5	0	0	172	1.5E-05	9.2E-06	9.4E-07	8.2E-09	0	0	9775	2633	12407
MA	45	24	72	31	8	3	0	138	1.2E-05	1.1E-05	4.3E-06	1.6E-06	3.7E-07	0	7838	2717	10555
MI	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	40001	96810
MN	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	7326	86943
MS	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	1520	48434
MO	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	811	69709
MT	44	174	42	33	4	0	0	253	1.0E-06	7.0E-07	2.3E-07	2.2E-08	0	0	145556	1490	147046
NE	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	481	77358
NV	34	41	8	0	0	0	0	49	2.9E-07	4.0E-08	0	0	0	0	109806	761	110567
NH	45	24	34	15	2	0	0	75	4.7E-06	2.4E-06	4.7E-07	1.1E-08	0	0	8969	382	9351
NJ	45	43	58	23	4	0	0	128	1.7E-05	6.6E-06	7.9E-07	7.1E-09	0	0	7419	1303	8722
NM	46	261	104	31	4	0	0	400	1.5E-06	5.2E-07	8.0E-08	1.1E-09	0	0	121365	234	123598



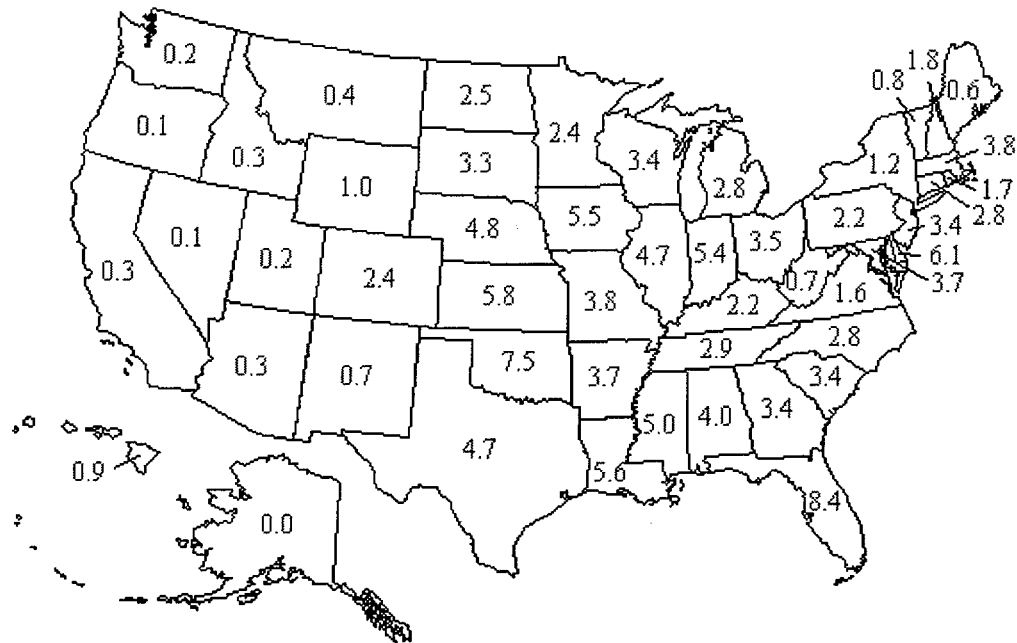
**Table 4 - SPC data analysis summary by state**

State	Y <sub>int</sub> (Eq.1)	Number of observation							Point Strike Probability (per year)						Areas (square miles)		
		F0	F1	F2	F3	F4	F5	Total	F0	F1	F2	F3	F4	F5	Land (A <sub>ob</sub> )	Water	Total
NY	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	7251	54475
NC	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	5103	53821
ND	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	1710	70704
OH	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	3875	44828
OK	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	1224	69903
OR	45	31	15	3	0	0	0	49	2.9E-07	1.5E-07	3.1E-08	0	0	0	96003	2383	98386
PA	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	1239	46058
RI	23	3	4	1	0	0	0	8	1.9E-05	1.3E-05	1.7E-06	0	0	0	1045	500	1545
SC	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	1896	32007
SD	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	1224	77121
TN	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	926	42146
TX	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	6687	268601
UT	43	53	19	6	1	0	0	79	5.1E-07	3.2E-07	1.0E-07	2.8E-08	0	0	82168	2736	84904
VT	41	7	14	12	0	0	0	33	3.3E-06	2.0E-06	3.4E-07	0	0	0	9249	366	9615
VA	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	3171	42769
WA	41	24	17	12	3	0	0	56	4.9E-07	9.6E-08	2.3E-08	3.6E-09	0	0	66582	4721	71303
WV	45	27	36	16	8	0	0	87	2.2E-06	2.4E-06	9.7E-07	2.5E-07	0	0	24087	145	24231
WI	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	11190	65503
WY	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	714	97818
Sum		13776	13251	7834	2553	924	121	38459							3536342	251083	3787425

- DC was not included in the exceedance analysis.

**Figure 1**

**Annual Average Number of Tornadoes per  
10,000 Square Miles by State, 1950-1995**



**Figure 2**

**Average Annual Number of Strong-Violent (F2-F5)  
Tornadoes per 10,000 Square Miles by State**

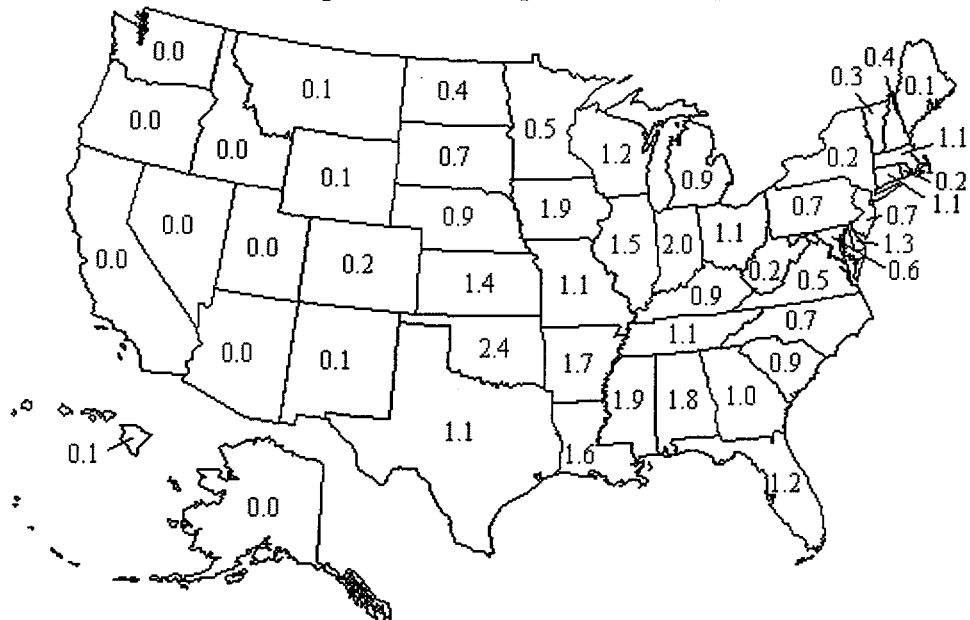


Figure 3 - Sketch of hypothetical F2 tornado illustrating variations

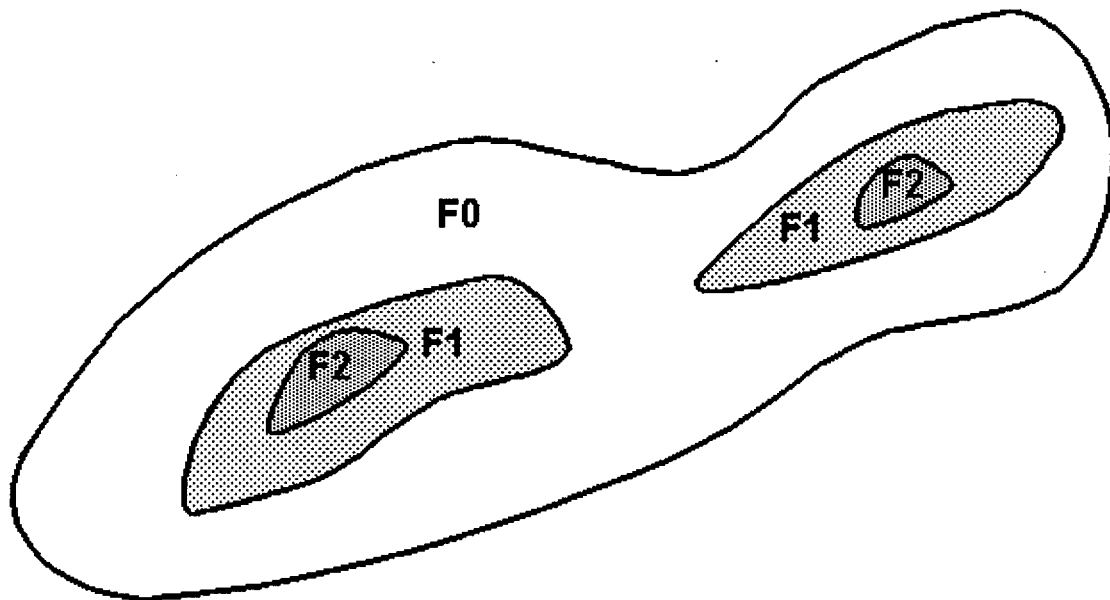
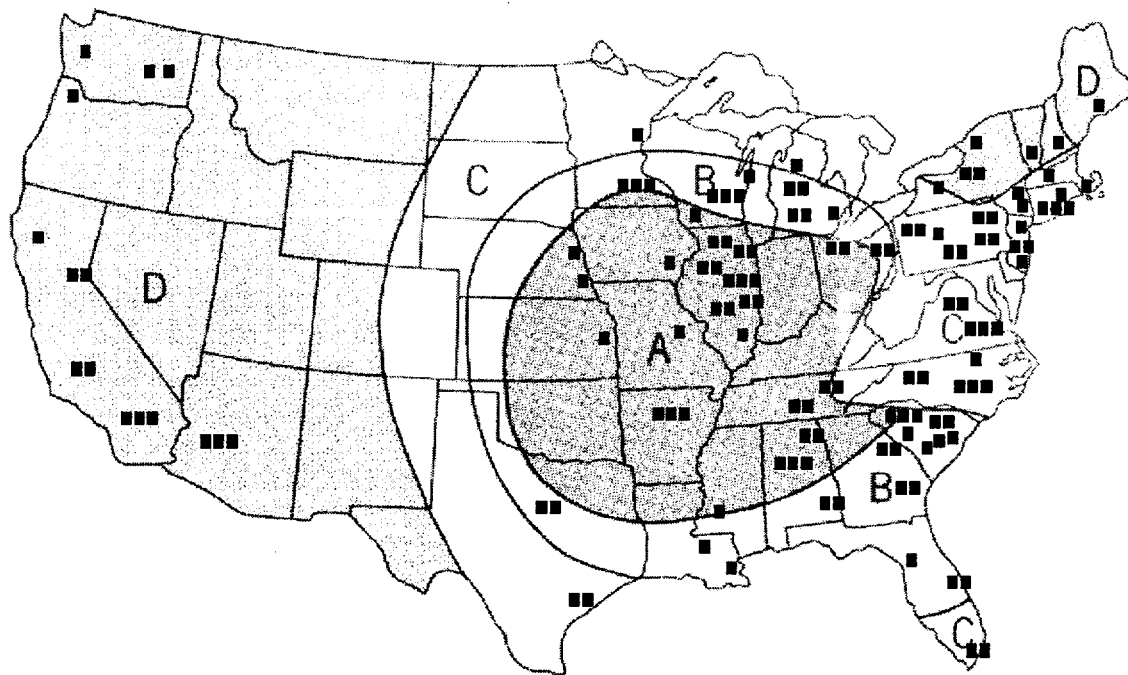
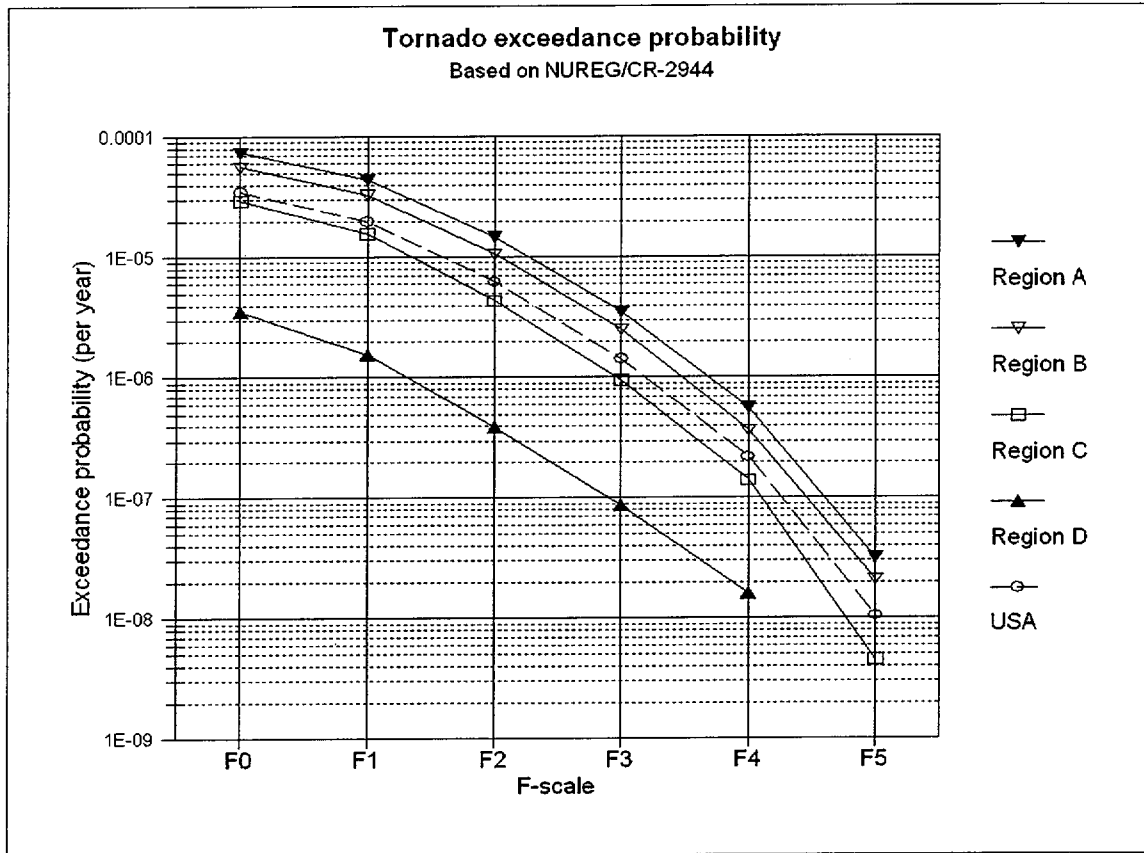


Figure 4 - Tornado risk regionalization scheme (from NUREG/CR-2944)



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