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DISCLAIMER

Probability, winds, tornado, earthquake, meteorite,

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PROBABILITIES OF NATURAL EVENTS OCCURRING AT SAVANNAH RIVER PLANT

INTRODUCTION

Safety Analysis Reports (SARs) require consideration of the risks of incidents caused by natural events. The natural events of interest to SRP/SRL safety analysts generally include high-velocity straight winds, tornadoes, earthquakes, and meteorites. Probabilities for these events to occur at SRP have been independently studied by several investigators. However, the results of their studies have never been evaluated systematically. Therefore, there is a need for an extensive review and an objective critique of these independent studies.

This memorandum documents the comprehensive evaluation of probability models of natural events which are applicable to SRP site. The probability curves selected for these natural events are recommended to be used by all SRP/SRL safety analysts. This will ensure a consistency in analysis methodology for postulated SAR incidents involving natural phenomena.

SUMMARY

Several reports related to the probabilities of natural events occurring at SRP were reviewed. A probability curve is selected for each natural event and its use is recommended to be used for future SARs. The selections are mainly based on the evaluation of data sources and analysis methodologies.

1. For high-velocity straight winds, McDonald's probability curve is selected because it had a more representative data base and used a well recognized mathematical model.

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2. Fujita's tornado probability curve is preferred because a more realistic approach to account for the unreported tornadoes was used. To account for the effect of structure size, the correction factors determined by Twisdale and Hardy are recommended.

3. The more rigorous approach to determining earthquake frequencies in the Blume's report, make Blume's earthquake probability curves the curves of choice.

4. None of the reviewed reports addressed point probabilities of meteorite impact at SRP. Point probabilities of meteorite impact were therefore calculated.

The recommended methods for determining straight high-wind and tornado probabilities are in agreement with the analysis methodology recently recommended to the Department of Energy by Lawrence Livermore National Laboratory.[1] The selected earthquake possibility curve was approved by Du Pont's Earthquake Advisory Panel in 1982.[2]

DISCUSSION

The natural events normally considered in the SARs are: 1) high-velocity straight winds; 2) tornadoes; 3) earthquakes; and 4) meteorites. Probabilities for these events to occur at SRP have been independently evaluated by several investigators. However, the results of their evaluations have never been systematically reviewed. Since these natural phenomena are rare events in the vicinity of SRP, there is some subjectivity in choosing probability models suitable for the SRP site. Nevertheless, this review attempts to identify probability models having reliable data sources and sound analysis methodologies which are suitable for SRP.

High-Velocity Straight Winds

High-velocity straight wind probabilities for SRP site have been investigated by Fujita[3] and McDonald[4]. Figure 1 shows the results of these two independent studies. For wind speeds greater than 100 mph, the probabilities derived by McDonald are significantly higher than that from Fujita. The discrepancies are mainly due to the differences in data source and analysis methodology.

Fujita Approach. Fujita used the monthly and yearly high-wind data recorded at Macon, Georgia from 1950-1978. The point probabilities were calculated by using the frequency of a given wind speed divided by the total number of years. The monthly and yearly cumulative probability curves were plotted on logarithmic scale versus wind speed (see Appendix A). These two curves merge and Fujita constructs a tangent to the merged curve. This tangent line is his probability model for extrapolating linearly to higher wind speeds.

McDonald Approach. McDonald used the annual extreme wind speed data recorded at Augusta, Georgia for the period 1950-1978. The cumulative probability curve was obtained by inverting the Fisher-Tippett Type I extreme value distribution function,[10] which has been adopted in the latest version of the American National Standards Institute, ANSI A58.1-1982 Standard. The parameters of the distribution function were estimated from the observed data. Details are included in Appendix B.

Critique. McDonald's method of determining straight wind probabilities is preferred for the following reasons:

(1) Macon is 120 miles away from SRP site, whereas, Augusta is only 20 miles away. Therefore, Augusta's data seems to be more representative for SRP site than those from Macon.

(2) The largest observed wind speed in Fujita's analysis is 62 miles per hour. The data set used by McDonald contains wind speed as high as 83 miles per hour (fastest one-minute wind speed) or 87 miles per hour (fastest-mile wind speed). For the purpose of extrapolating, McDonald's analysis seems to be more reliable than Fujita's.

(3) McDonald uses a well received distribution function which fits well on extreme wind speed data. Such a mathematically rigorous approach permits a more valid extrapolation to higher wind speeds and calculation of 95% confidence intervals. On the other hand, Fujita takes a more empirical approach which is deficient from these standpoints.

Tornadoes

Tornado probabilities for SRP site have also been investigated by Fujita[3] and McDonald[4]. It can be seen from Figure 2 that the probabilities obtained by Fujita are consistently greater than that from McDonald. The discrepancies are mainly due to the different approaches to account for unreported tornadoes.

Fujita Approach. The data base used by Fujita consists of all reported tornadoes within 100 miles of SRP site for the period 1916-1978. For the calculations of tornado probabiities, Fujita evaluated several indicies (road, forest, topography, water, and time indicies) and a distance function. Appendix C shows the details of Fujita's computations.

McDonald's Approach. McDonald calculated tornado probabilities using area-intensity and occurrence-intensity relationships. The number of unreported tornadoes was estimated by using the correlation between the reported tornado frequencies and population densities. The small number of reported tornadoes in the area with light population density is due to many tornadoes not reported. The detailed computations are included in Appendix D.

Critique. Fujita's methodology of computing tornado probabilities is recommended for the following reasons:

(1) The tornado probabilities derived by Fujita are SRP site-specific; while McDonald's tornado probabilities are determined assuming the tornado frequency is uniformly distributed in his local region.

(2) McDonald's approach of estimating the unreported tornado frequencies could be conceptually wrong if the population density is indeed uncorrelated to the frequency of tornadoes including both reported and unreported (see Appendix E).

(3) It can be shown (see Appendix E) that the tornado probabilities by Fujita and McDonald are almost the same if certain degrees of conservatism are incorporated into McDonald's method. Therefore, Fujita's probability curve seems to be reasonable.

An analysis[14] of tornado occurrence and windspeed frequencies for the SRP has been recently performed by Twisdale and Hardy using a state-of-the-art type effort. They developed point, area, and site tornado windspeed frequency curves by analyzing the 1950-1982 of National Severe Storm Forecast Center (NSSFC) and 1983-1984 tornado data records. The point probabilities estimated by them are not significantly different from the point probabilities determined by Fujita, and therefore support the use of Fujita's methodology (consistent with other DOE sites). However, Fujita's tornado risk models (recommended to DOE by LLNL) omitted the effect of structure size. This is probably because most investigators[11,12,13] consider that the probability for a tornado to strike a structure is only twice its point probability, even when the structure reaches a size of about 10^5 square feet; the correction factors, however, could be as high as 8.[14] Therefore, it is recommended that the correction factors (Figures 2A-2F) determined by Twisdale and Hardy be used in SAR accident analyses. By doing so, the risks associated with tornadoes would be a little higher (albeit insignificant), however, it provides conservatism in evaluating tornado risks.

Earthquakes

Earthquake probabilities for the SRP site have been investigated by Blume[5] and D'Appolonia.[6] A comparison of their probability curves is shown in Figure 3. Both Blume and D'Appolonia used the same frequency model:

$$\log N_I = a + bI, \qquad (1)$$

where N_I is the frequency of the earthquake with Modified Mercalli Intensity (MMI) I or greater in a specified area per year, and a,b are two parameters to be determined. However, they used different data sets and earthquake attenuation equations.

Blume's Approach. The data set used includes all the earthquakes with MMI scale VII or greater, within three tectonic regions (Applachian mountain and coastal plain tectonic provinces and Charleston seismic zone) in the past century. The probability of exceeding a given peak ground acceleration (PGA) g occurring on the SRP site, denoted by Pg, is calculated by:

$$Pg = \sum_I P\,(PGA \geq g \mid MMI = I) \times P(MMI = I). \qquad (2)$$

The conditional probability in this equation is computed by an integration of a lognormal density function which was established by Murphy and O'Brien in 1977. The probability P (MMI=I) is estimated by the frequency obtained from Equation (1). Appendix F shows the detailed computations.

D'Appolonia's Approach. The data sets used are all the earthquakes with MMI scale IV or greater within the same three tectonic regions from 1737 to 1978. The probability that the SRP site will experience a MMI scale I to I+1 earthquake is computed by:

$$\sum_i \left[10^{a_i + b_i I} - 10^{a_i + b_i (I+1)}\right] A_i,$$

where A_i is the area of the ith grid elements in the regions, and a_i, b_i are parameters of Equation (1) and can be determined from the data set.

Critique. Blume's report is recommended for the following reasons:

1. Since the Charleston earthquake in 1886, people's awareness of earthquake have increased. Because Blume included data from the past century, the earthquake probabilities derived are more reliable.

2. Blume's data base consists only of earthquakes with MMI VII or greater. The earthquakes of higher intensity are of primary interest to SRP safety analyses, therefore, Blume's analysis is more reliable for extrapolation.

3. Blume used Bollinger's attenuation equation which was based on the 1886 Charleston earthquake, while D'Appolonia used Gupta and Nuttli's equation which was derived from central U.S. data. The SRP site is closer to Charleston then to the central U.S., therefore, the attenuation used by Blume is preferred for SRP use.

4. Blume's analysis transformed the earthquake data (in MMI scale) into PGA, which is lognormally distributed. In this manner, the earthquake data can be refined to an extent that the Blume's earthquake probabilities are statistically significant.

Meteorites

The risk associated with meteorite impact has been studied by Blake[7] and Poe[8]. In their studies, Blake and Poe used Hawkins' frequency equation[9]:

Stone meteorite: $\log_{10} N = -3.73 - \log_{10} m$,

Iron meteorite: $\log_{10} N = -5.61 - 0.7 \log_{10} m$,

where m = the mass of the meteorite in kg (before entry into the earth's atmosphere),

N = the number of meteorites with mass m or greater falling on an 1-km^2 area in a year.

Blake calculated the probabilities of annual fatalities from meteorite impact. Poe computed the frequencies of meteorite strikes on the SRP facility (1.9×10^5 ft^2 surface area) per year. Neither Blake nor Poe investigated the point probability of meteorite impact (by direct and/or indirect strike) in a year.

Blake's Approach. The main objective of Blake's study is to find meteorite kill probabilities. However, his finding pertinent to meteorite damage probabilities is the relationship among the meteorite weight (before entering the earth's atmosphere), the meteorite impact weight and the lethal area.

Poe's Approach. The impact frequency of a meteorite striking some geographic area of the world was calculated by the following equation:

$$\text{probability} = 1 - \left(1 - \frac{a}{A}\right)^f,$$

where a = the damage area,
A = the area of the earth surface = 5.48×10^{15} ft^2,
f = the frequency of the event per year.

Since the stone meteorite hazard is considered to be much less than that of iron meteorites, the risk associated with stone meteorite was not investigated.

Critique. The meteorite impact frequencies obtained by Poe seem to be erroneous in that the probability increases with respect to the meteorite mass m for $m > 10^9$ tons. As described in Appendix H, the function $\sum_{k=1}^{\infty} \frac{1}{k} \left(\sqrt{b} + \sqrt{S}\right)^{2k} b^{-2.05}$ can be used to evaluate the probability of meteorite impact on a structure of area S. This function is decreasing with respect to the lethal area b. Furthermore, the lethal area of a meteorite is an increasing function of its mass. Therefore, the probability of a structure impacted by a meteorite of larger mass should be less than that from smaller mass.

Meteorite Impact Probabilities. The probability that a certain point of the SRP site will be struck by a meteorite with mass of m tons or greater (before entry of the earth's atmosphere) in a year was shown in Appendix G to be no greater than:

$$\left(2.50\ m^{-1/30} - 0.56\right) \times 10^{-10};$$

and the error is at most 4×10^{-12}. Figure 4 shows the exceedance probabilities of meteorite impact as a function of its weight.

The probability that a structure with an area S ft^2 will be struck by a meteorite of mass m or greater (before entry of the earth's atmosphere) per year was shown in Appendix H to be at most

$$\begin{cases} (q - 0.32) \times 10^{-10} & \text{if } S > 4976.744\ m^{2/3} \\ [q + 0.03294 \times t - 0.60] \times 10^{-10} & \text{if } S < 4976.744\ m^{2/3}, \end{cases}$$

where $q = 2.50\ m^{-1/30} + 6.48\ m^{-11/30}$ and $t = \left(\frac{70.546\ m^{1/3} + \sqrt{S}}{70.546\ m^{1/3}}\right)^{3.1}$; and the maximum error is 2.8×10^{-11}.

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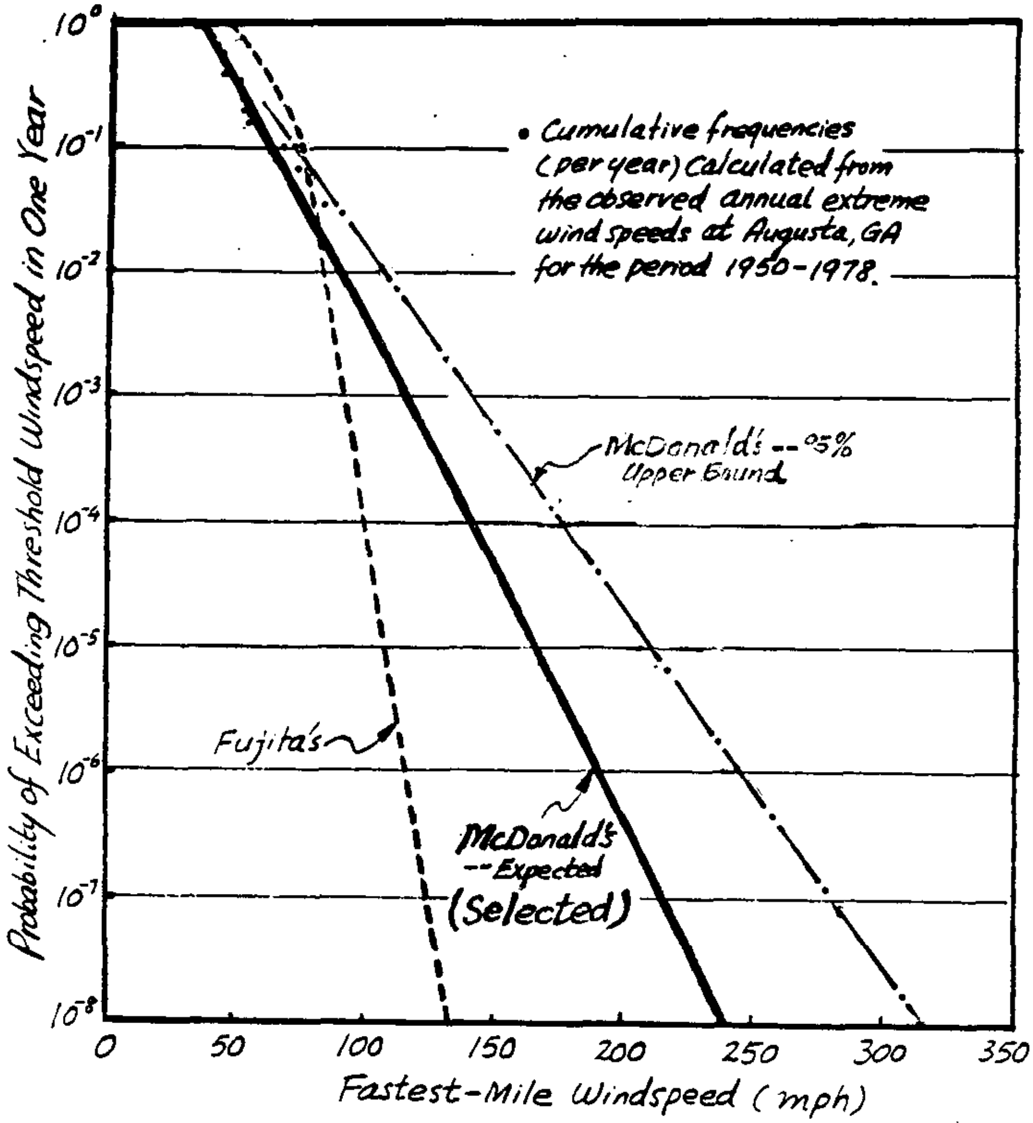

FIGURE 1. High-Velocity Straight Wind Probabilities

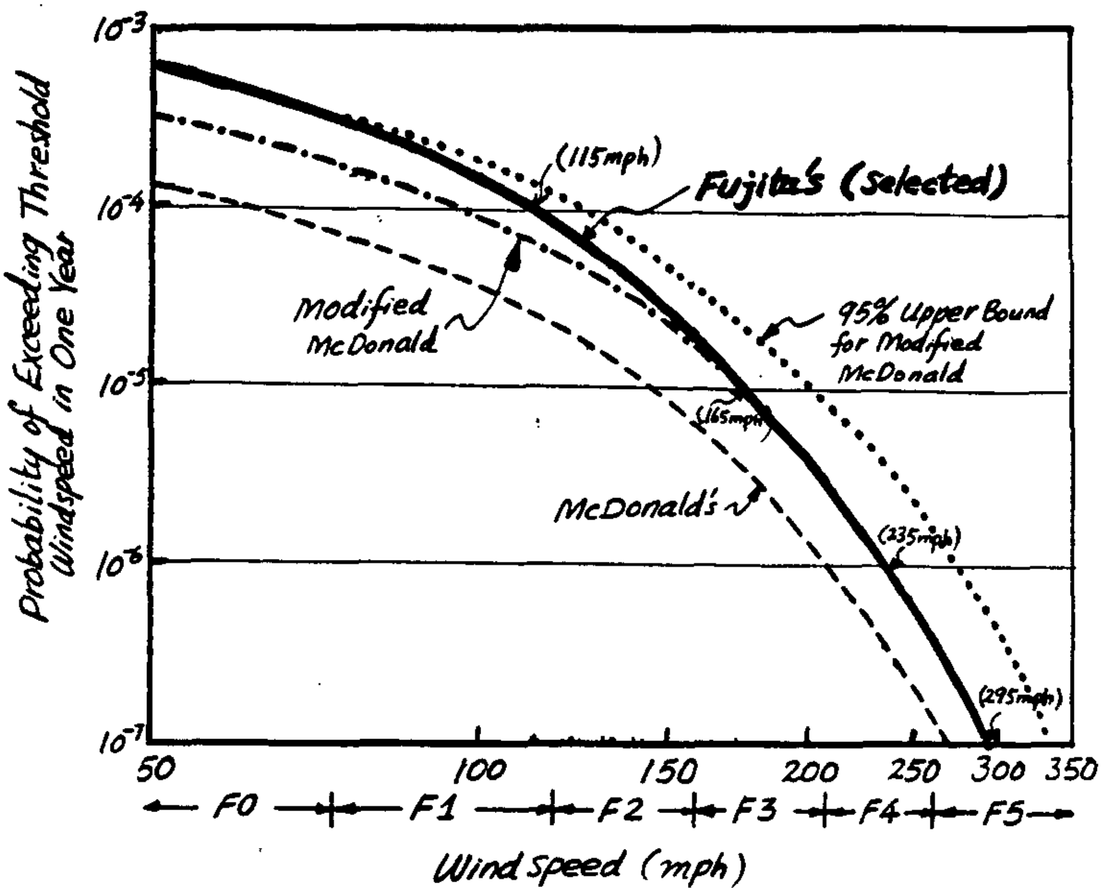

FIGURE 2. Tornado Probabilities

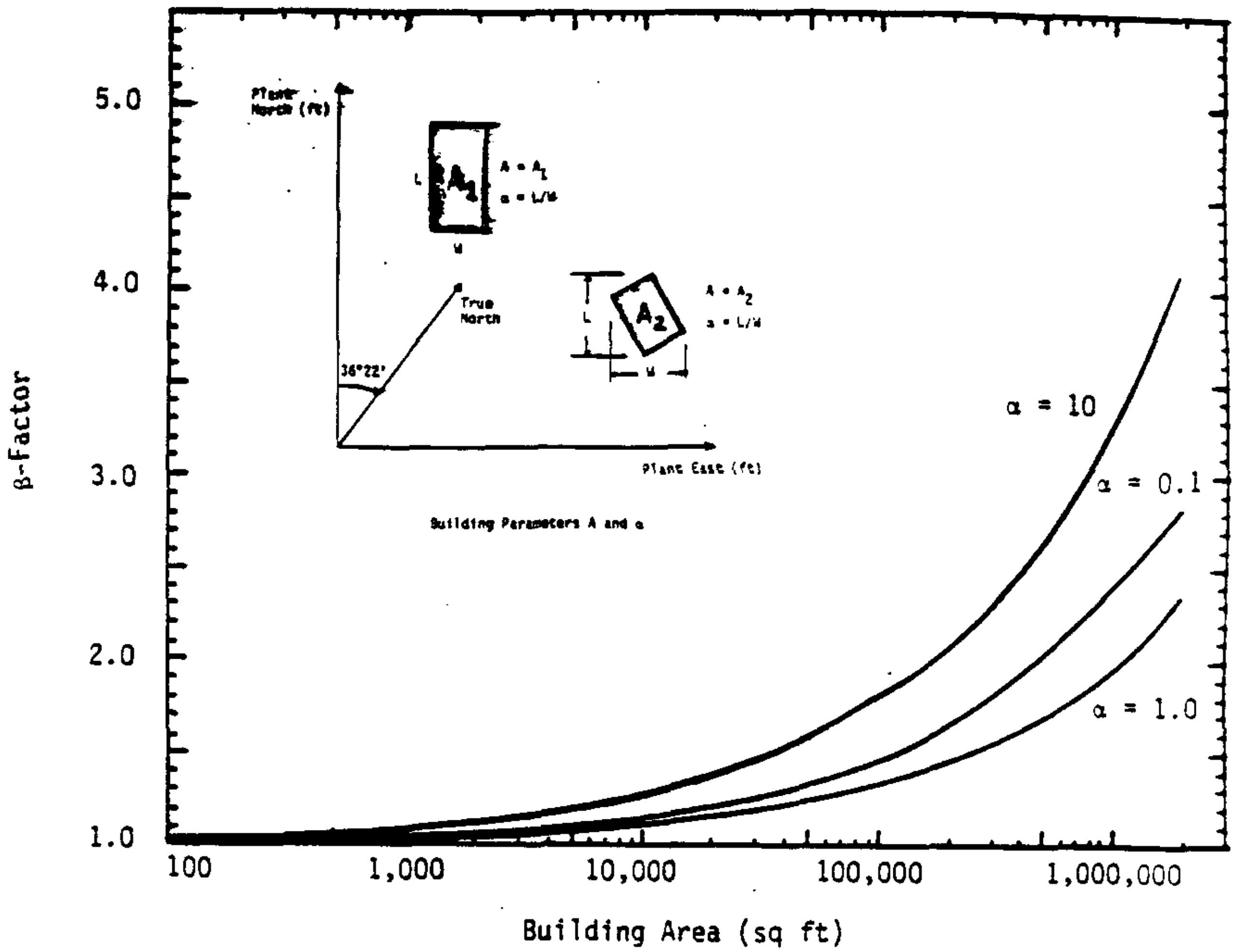

Figure 2A. β-Factors for V^* > 73 mph

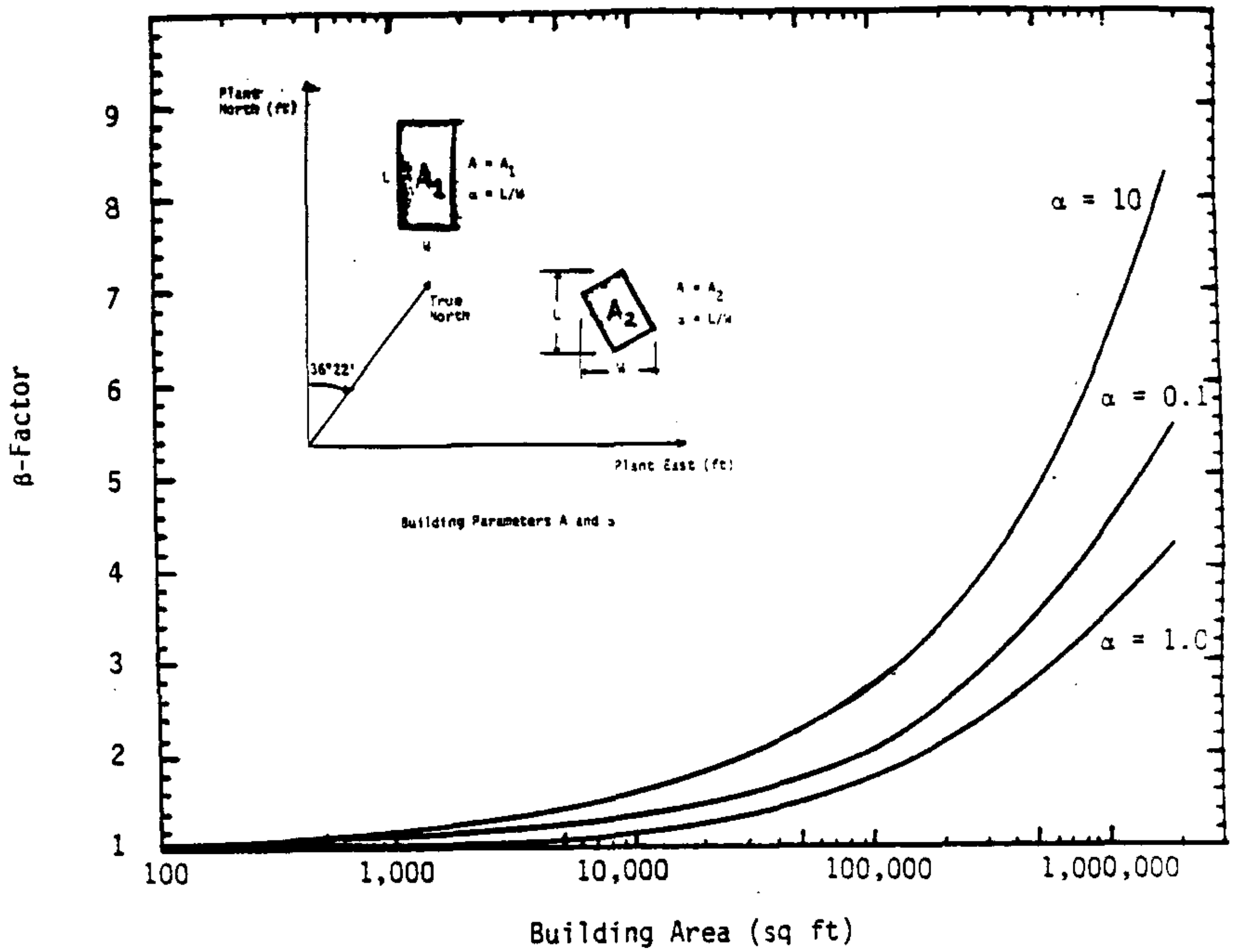

Figure 2B. β-Factors for V^* > 100 mph

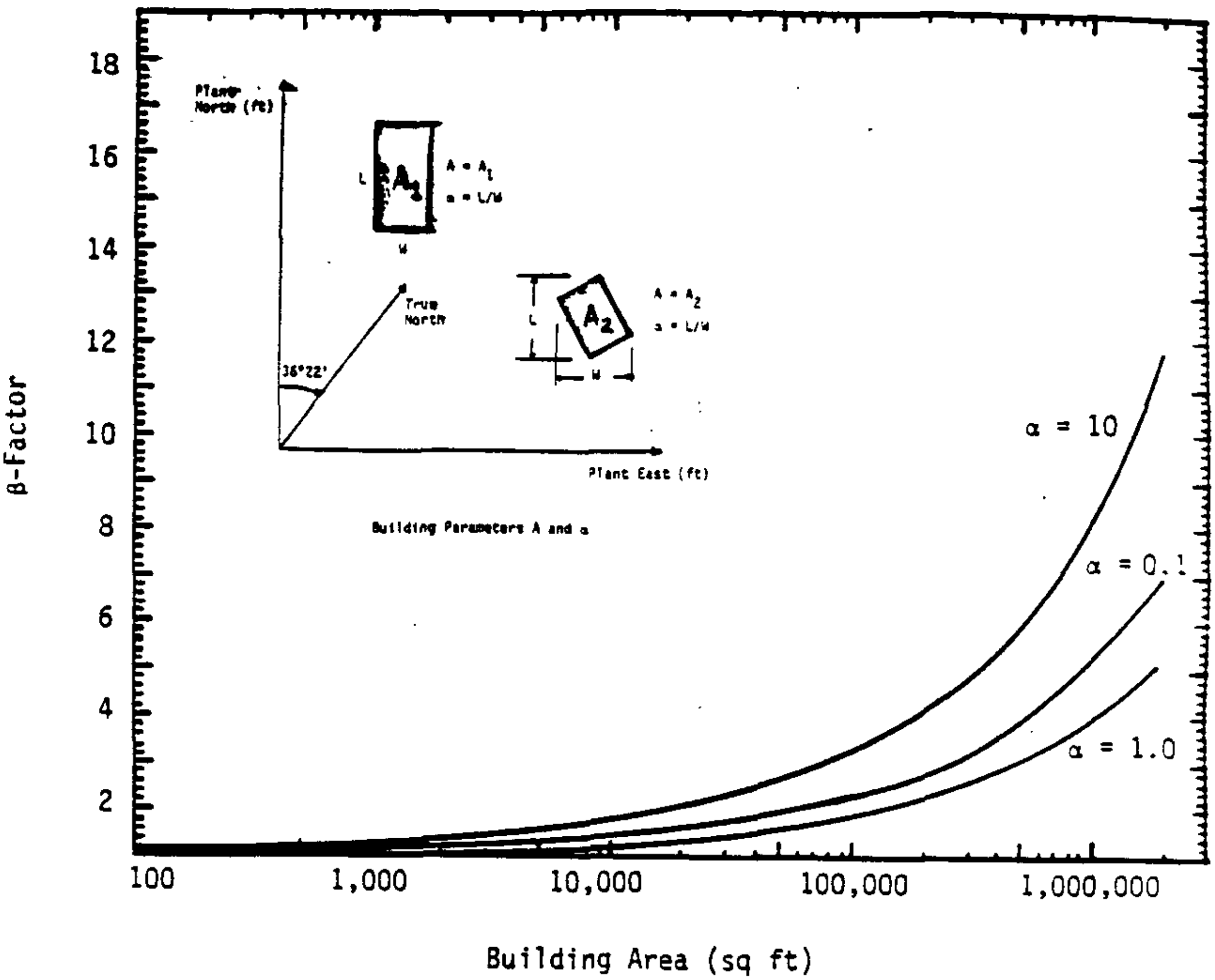

Figure 2c. β-Factors for V^* > 150 mph

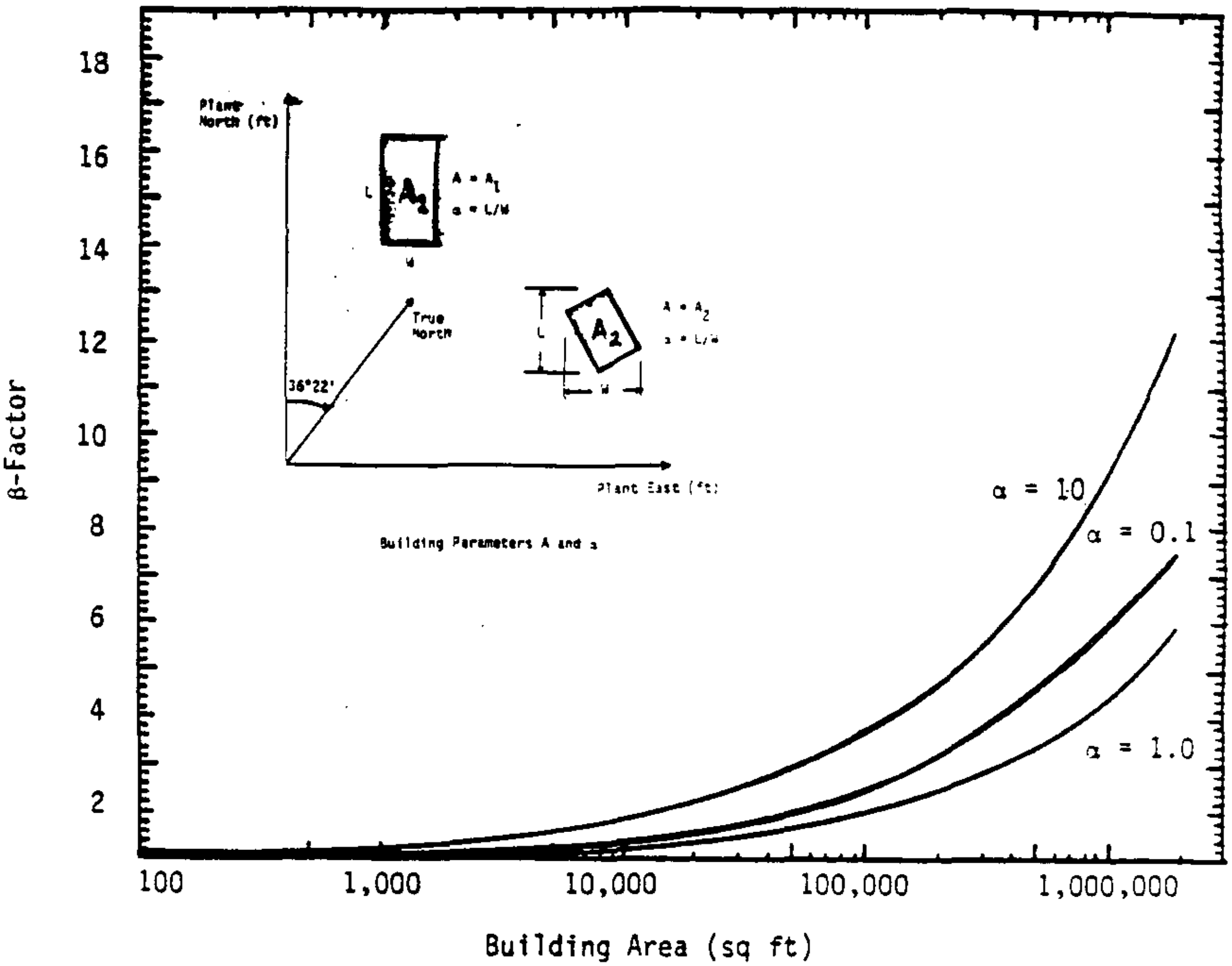

Figure 2D. β-Factors for V^* > 200 mph

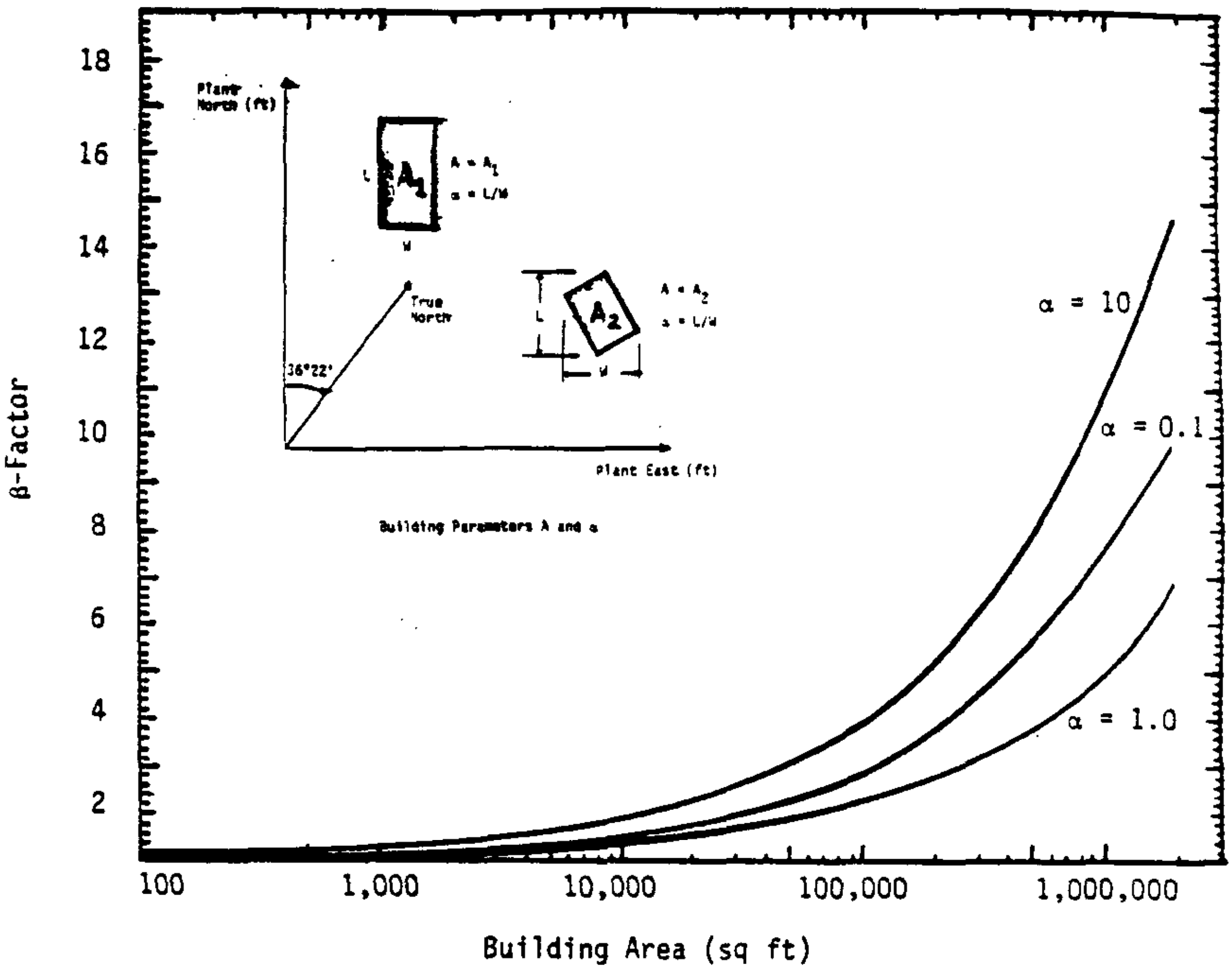

Figure 2E. β-Factors for V^* > 250 mph

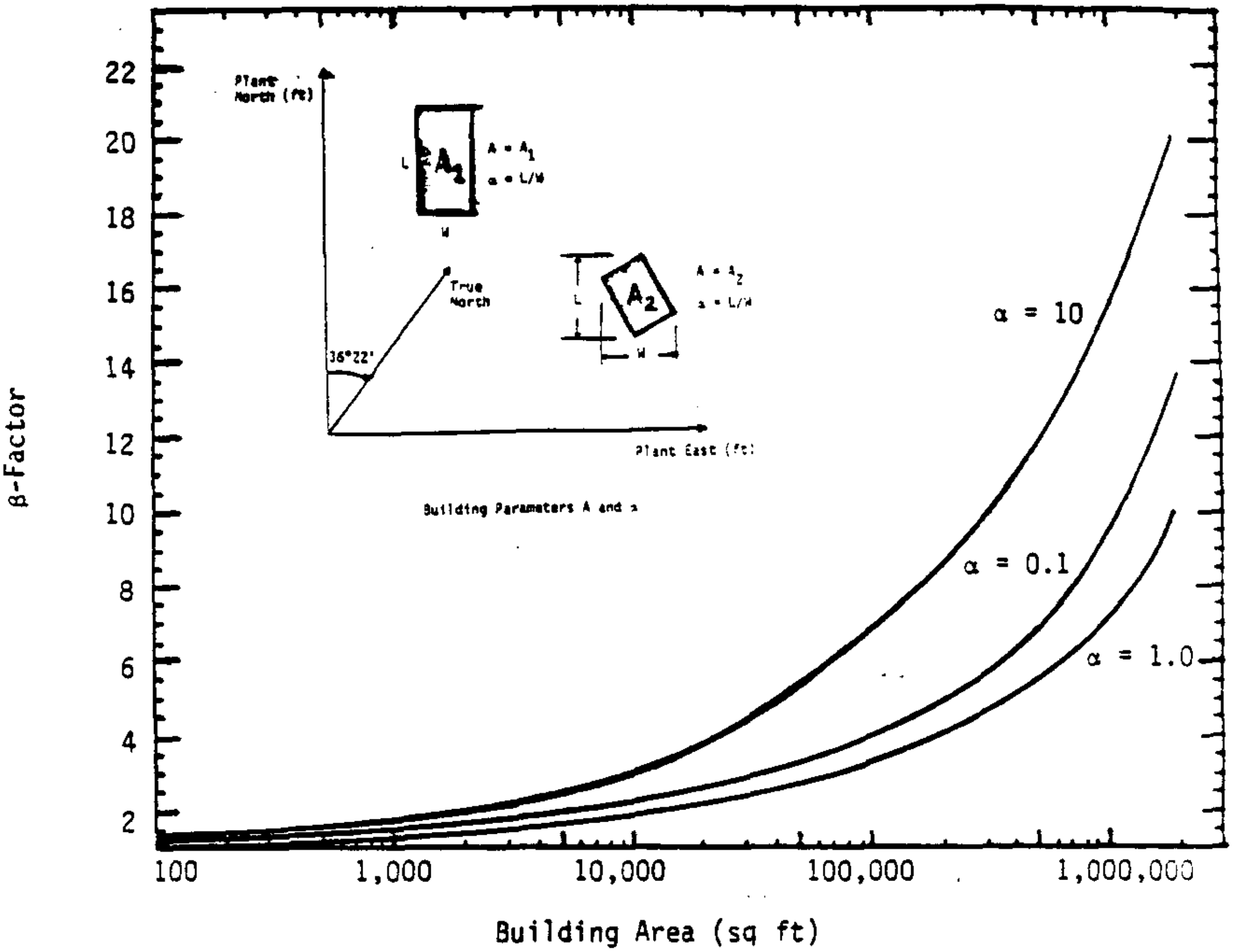

Figure 2F. β-Factors for V^* > 300 mph

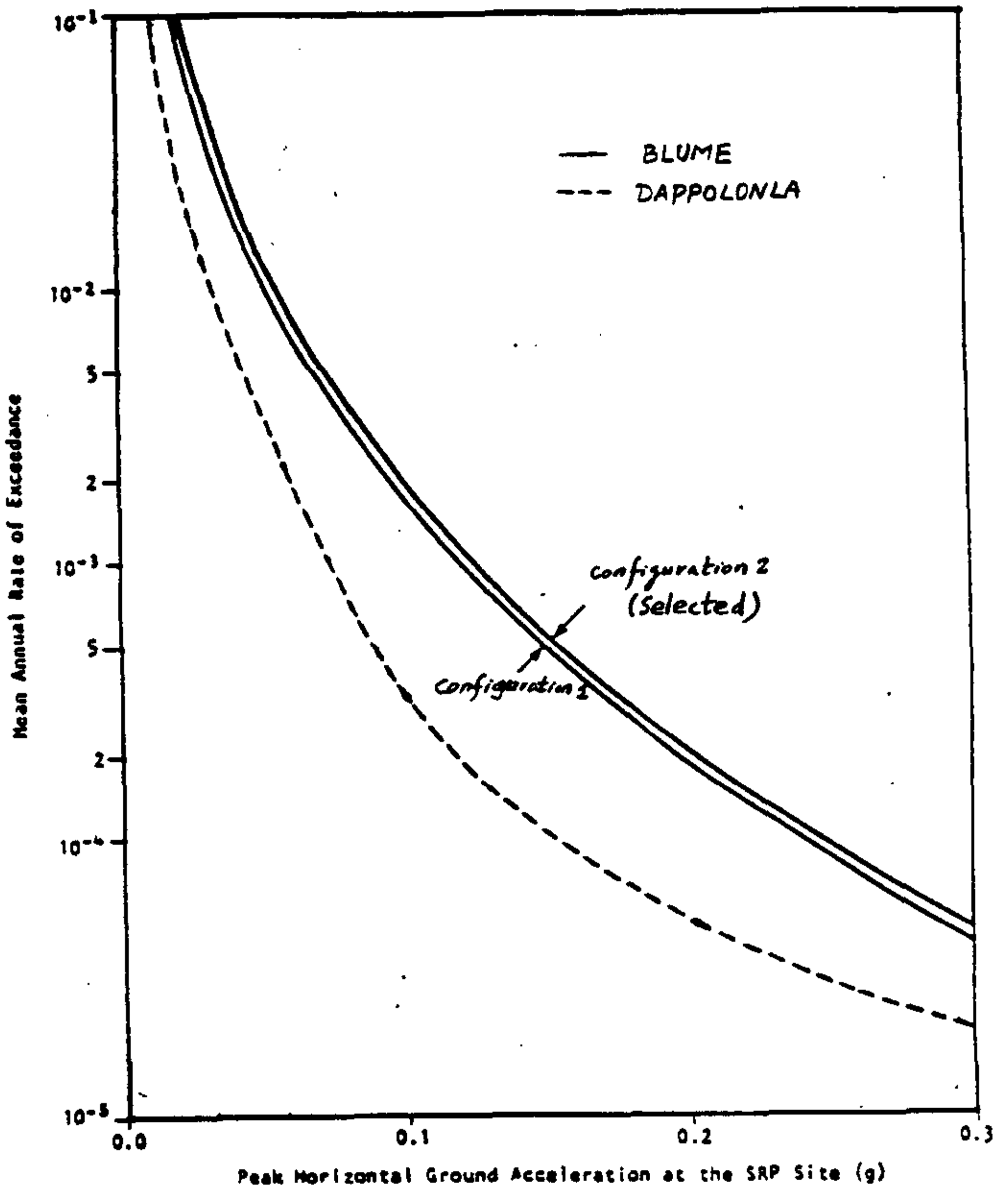

FIGURE 3. Comparison of Earthquake Probabilities of Blume and D'Appolonia

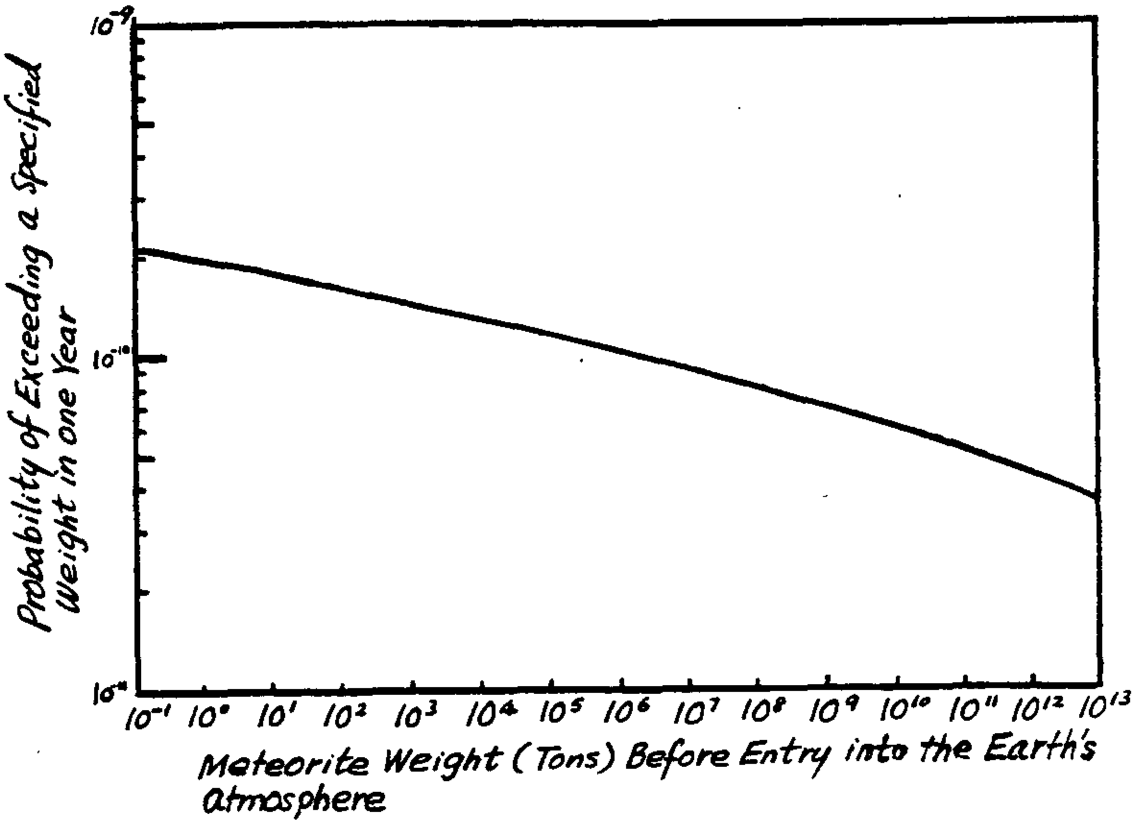

FIGURE 4. Meteorite Impact Probabilities

APPENDIX A

Fujita's Computation of High-Wind Probabilities

The data sources used by Fujita in computing high-wind probabilities are the 1950-1978 records of winds from NOAA's (National Oceanographic and Atmospheric Administration) climatological station at Macon, Georgia.

Since the height of the anemometer was changed in 1963, from 74 feet AGL (above the ground level) to 23 feet AGL, both monthly and yearly fastest-mile wind speed data are adjusted to 10 m (33 feet) AGL by using the site specific relation:

$$W_{10} = \left(\frac{10}{H}\right)^{0.148} W_H,$$

where W_H denotes the wind speed at H-meter AGL.

Table A1 shows the frequencies, cumulative frequencies, and exceedance probabilities of both monthly and yearly wind speed data. The exceedance probabilities in logarithmic scale vs. the wind speeds were plotted in Figure A1. The straight line which was tangent to those two probability curves was used as a logical extrapolation for high-wind probabilities:

$$W(P) = 52.2 - 6.9 \log P,$$

where W(P) denotes the wind speed (mph) with probability P (per year).

TABLE A1

Probability (per year) of the Fastest-Mile Winds of the Month and of the Year at Macon, Georgia (1950-1978)

Freq. = frequency
Cu. Freq. = cumulative frequency
Prob. = probability per year

Wind	Winds of the Month			Winds of the Year		
Speed, mph	Freq.	Cu. Freq.	Prob.*	Freq.	Cu. Freq.	Prob.
17	1	348	12.0	-	-	-
18	3	347	12.0	-	-	-
19	6	344	11.9	-	-	-
20	2	338	11.7	-	-	-
21	1	336	11.6	-	-	-
22	10	335	11.6	-	-	-
23	20	325	11.2	-	-	-
24	14	305	10.5	-	-	-
25	19	291	10.0	-	-	-
26	25	272	9.38	-	-	-
27	37	247	9.52	-	-	-
28	14	210	7.24	-	-	-
29	5	196	6.76	-	-	-
30	29	191	6.59	-	-	-
31	21	162	5.59	-	-	-
32	22	141	4.86	1	29	1.000
33	13	119	4.10	1	28	0.966
34	22	106	3.66	-	-	-
35	15	84	2.90	-	-	-
36	3	69	2.38	-	-	-
37	13	66	2.28	2	27	0.931
38	5	53	1.83	1	25	0.862
39	1	48	1.66	-	-	-
40	7	47	1.62	2	24	0.527
41	2	40	1.38	-	-	-
42	10	38	1.31	3	22	0.759
43	-	-	-	-	-	-
44	4	28	0.966	2	19	0.655
45	2	24	0.828	1	17	0.586
46	3	22	0.759	1	16	0.552
47	1	19	0.655	1	15	0.517
48	1	18	0.620	-	-	-
49	2	17	0.586	2	13	0.482

* Defined as cumulative frequency of monthly winds divided by statistical years

TABLE A1, Contd

Wind Speed, mph	Winds of the Month Freq.	Cu. Freq.	Prob.	Winds of the Year Freq.	Cu. Freq.	Prob.
50	2	15	0.517	1	12	0.413
51	2	13	0.448	2	11	0.379
52	1	11	0.379	-	-	-
53	5	10	0.345	4	9	0.310
54	1	5	0.172	1	5	0.172
55	-	-	-	-	-	-
56	-	-	-	-	-	-
57	1	4	0.138	1	4	0.138
58	-	-	-	-	-	-
59	2	3	0.103	2	3	0.103
60	-	-	-	-	-	-
61	-	-	-	-	-	-
62	1	1	0.034	1	1	0.034

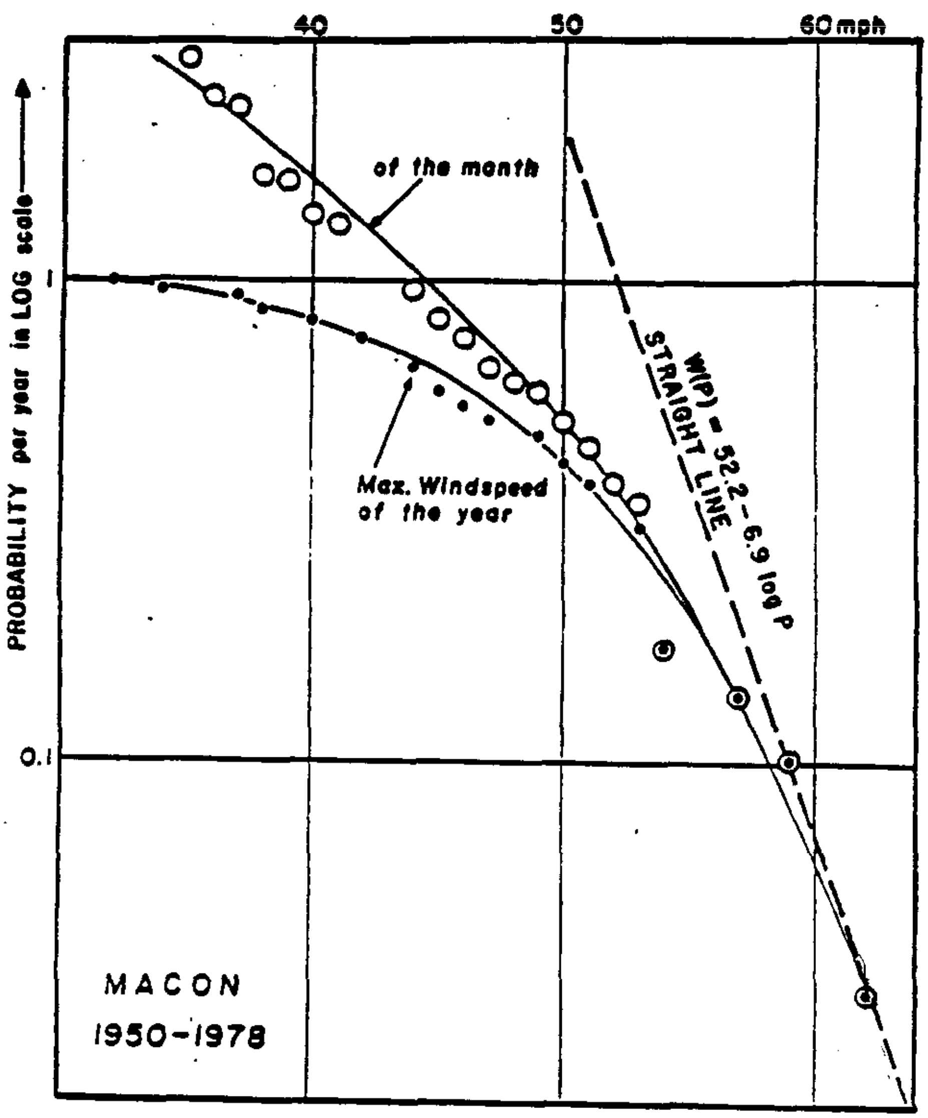

FIGURE A1. Determination of the Straight-Line Function on Log P vs. Windspeed Coordinates Applicable to the Savannah River Site

APPENDIX B

McDONALD'S COMPUTATION OF HIGH-WIND PROBABILITIES

The data used in McDonald's report are in the set of annual extreme fastest one-minute wind speeds recorded at Augusta, Georgia from 1950-1978. The probability model is derived in the following manner:

Let X be the maximum fastest one-minute wind speeds in a given year. The distribution of X can be reasonably modeled by a Type I extreme distribution:[10]

$$F(\chi) = \exp\left\{-\exp\left[-(\chi-\mu)/\sigma\right]\right\}, \qquad \text{(B1)}$$

where μ and σ are location and scale parameters, respectively. Using the method of moments, σ and μ can be estimated by

$\hat{\sigma} = \frac{\sqrt{6}}{\pi}\, s$ and $\hat{\mu} = \bar{X} - 0.5772\, \hat{\sigma}$, where $\bar{X}$ is the sample mean and s is the sample standard deviation. McDonald's data are shown in Table B1, and $\bar{X} = 45.0$, $s = 12.1$.

Let V_N be the extreme wind speed corresponding to a specific mean recurrence interval N. Then $P(X > V_N) = 1/N$, or $F(V_N) = P(X < V_N) = 1 - 1/N$. Replacing μ, σ and χ by $\hat{\mu}$, $\hat{\sigma}$, and V_N, respectively in Equation B1, V_N can be expressed as $V_N = \bar{X} + s\,(y - 0.5772)\,\frac{\sqrt{6}}{\pi}$, where $y = -\ln\left[-\ln\left(1 - \frac{1}{N}\right)\right]$. In addition, McDonald also calculated $(1 - \alpha)\,100$ percent confidence interval:

$$V_N \mp Z_{\alpha/2}\ SD\,(V_N),$$

where $SD\,(V_N)$ is the estimated standard deviation of V_N and is equal to $1.7519\left[\frac{\pi^2}{6} + 1.1396\,(y - 0.5772)\,\frac{\pi}{\sqrt{6}} + 1.1\,(y - 0.5772)^2\right]^{1/2}$.

To be consistent with the normally accepted convention (such as ANSI A58.1), McDonald converted the fastest one-minute wind speeds to the fastest-mile wind speeds by the following relation:

$$V_{(F-M)} = 1.17^{V(1-min)} - 10.34 \qquad \text{(B2)*}$$

Table B2 summarizes McDonald's straight high-wind probability results.

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* Equation B2 was shown in Reference 4. However, the tabulations in Table B2 furnished by McDonald do not match with his equation.

TABLE B1

Annual Extreme Fastest One-Minute Wind Speeds at Augusta, Georgia

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

* Wind speeds corrected to 10 m anemometer height.
** Wind speed occurred more than once during the year.

TABLE B2

Summary of Straight Wind Probabilities with 95% Confidence Limits

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

* Values in parentheses are fastest-mile wind speeds. See Equation (2) for relationship between fastest-mile wind speed and fastest one-minute wind speed.

APPENDIX C

FUJITA'S METHODOLOGY FOR TORNADO PROBABILITY COMPUTATION

The data set used by Fujita contains all the reported tornadoes within 100 miles of the SRP site from 1916-1978.

The basic formula in computing tornado probabilities is

$$P(F,V) = \frac{L_F \times \text{DAPPLE }(F,V)}{A \times Y},$$

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 is a function of the tornado's F-scale and specific windspeed V.

In order to evaluate the site-specific tornado probabilities, Fujita devised a weighting function which decreases gradually with the distance from the site. The distance function F(D) is defined as:

$$F(D) = \cos^m (0.9° \times D),$$

where D is the distance to the site (≤100 mi) and m is a constant. Fujita found the probabilities corresponding to m=1 and m=0 (no distance function) are essentially the same.

The details of Fujita's tornado probability calculations are described as follows:

1. Statistical year. Since the reported tornado frequencies in the early years are only about one-tenth of the current rate, Fujita adjusted the total number of observed years by a statistical year Y defined as:

$$\bar{Y} = (1978 - 1964) \times \frac{\sum_{n=1916}^{1978} N(n)}{\sum_{n=1965}^{1978} N(n)}$$

Where N(n) denotes the annual tornado frequencies in the year n. Table C1 shows the weighted statistical years in Fujita's study. As shown in Table C1, Fujita divided the classes of F-scale tornadoes into three categories: weak (F0+F1), strong (F2+F3), and violent (F4+F5).

2. Statistical area. The topography and water factors can make tornadoes unobservable. To account for this, Fujita designed an index function F_1, as:

$$F_1\ (TI,WI) = (1-0.1TI)(1-0.1WI),$$

where TI, WI are topograph and water indicies which are defined in Table C2. The study region is divided into 128 equal area sub-boxes with area A_s (249.4 mi^2). Then the statistical area is obtained by:

$$A = A_s \sum_{1}^{128} F(D)\ F_1\ (TI,WI).$$

Table C3 shows the values of $F(D)\ F_1(TI,WI)$ used in Fujita's analysis.

3. Path length of F-scale tornadoes, L_F. Tornadoes occurring in a forest or at the place far away from the road will likely be unreported. Therefore, Fujita designed an index function F_2 defined as

$$F_2\ (RI,FI) = (1+0.2RI)(1+0.1FI),$$

where RI,FE are road and forest indicies which are defined in Table C2. Then the total path length for a scale F tornado is

$$L_F = \Sigma L \times F(D) \times F_2(RI,FI),$$

where the L's are the observed path lengths and the summation is over all tornadoes of scale F. The values of $L \times F(D) \times F_2(RI,FI)$ are also shown in Table C3.

4. DAPPLE function: DAPPLE function has two variables: windspeed V and tornado categories (w, s, and v, all in terms of F-scale). Empirical results for this function are shown in Table C4.

The probability of all tornadoes affecting the site at a given windspeed can be computed as a sum,

$$P(V) = P(w,V) + P(s,V) + P(v,V).$$

Table C5 shows the final tabulation of P(V) for the SRP site.

TABLE C1

Weighted Statistical Years, $\bar{Y}$ for Risk Computations Based on Frequencies Between 1916 and 1978

Scale	Statistical Period (1916-1978)	(1965-1978)	Actual Years	Weighted Years (Y)
F0	5,718	3,260	63.0	24.6
F1	8,645	4,453	63.0	27.2
F2	7,102	2,762	63.0	36.0
F3	2,665	850	63.0	43.9
F4	673	209	63.0	45.1
F5	127	30	63.0	59.2
F0+F1 (w)	14,363	7,713	63.0	26.1
F2+F3 (s)	9,767	3,612	63.0	37.9
F4+F5 (v)	800	239	63.0	46.9

TABLE C2

Definitions for RI, FI, TI, and WI

Index	Value	Definition
	0	Town or city areas and their immediate vicinity
RI	1	Area of section-line roads of 1-mile grid
	n	Area of roads approximately n-miles apart
	10	Area of roads separated by 10 miles or further
	0	No forest in sub-box
FI	1	1/10 of a sub-box area is forest
	n	n/10 of a sub-box area is forest
	0	The ground within the circle of 1-mile radius is more or less flat
TI	1	Height difference within the circle is about 250 ft
	n	Height difference within the circle is about n x 250 ft
	10	Height difference within the circle is 2500 ft or larger
	0	No water area in a sub-box
	1	1/10 of a sub-box area is water
WI	n	n/10 of a sub-box area is water
	10	Entire area is water

TABLE C3

Tornado Parameters for Savannah River Plantsite (m = 1)

D...... Distance in miles
F(D)... Distance function
L...... Path length

L"..... L x F(D) x F_2 (RI,FI)

RI .... Road index
FI .... Forest index
TI .... Topography index
WI .... Water index
G .... F(D) x F_1 (TI,WI)

Sub-box	D	F(D)	RI	FI	L_w	L''_w	L_s	L''_s	L_v	L''_v	TI	WI	G
1	99	0.02	1	4	1	0.03	5	0.16	34	1.09	0	0	0.02
2	94	0.09	4	5	-	-	4	0.83	4	0.83	0	0	0.09
3	93	0.11	5	7	1	0.30	14	4.16	-	-	0	0	0.11
4	94	0.09	5	6	6	1.40	3	0.70	-	-	0	0	0.09
5	99	0.02	4	5	18	0.83	12	0.55	-	-	0	0	0.02
6	96	0.06	1	4	2	0.19	23	2.21	10	0.96	1	0	0.05
7	87	0.20	2	4	2	0.72	16	5.76	2	0.72	0	0	0.20
8	83	0.26	2	5	1	0.49	8	3.95	-	-	0	0	0.26
9	79	0.32	4	6	3	2.30	2	1.54	-	-	0	0	0.32
10	77	0.35	4	7	12	10.50	3	2.63	7	6.13	0	0	0.35
11	79	0.32	4	6	-	-	3	2.30	-	-	0	0	0.32
12	83	0.26	4	6	1	0.62	-	-	-	-	0	0	0.26
13	87	0.20	5	8	1	0.56	-	-	-	-	1	0	0.18
14	96	0.06	3	7	3	0.41	7	0.97	-	-	0	0	0.06
15	93	0.11	2	5	1	0.21	4	0.84	14	2.93	0	0	0.11
16	82	0.28	2	6	3	1.68	1	0.56	19	10.64	0	0	0.28
17	73	0.41	3	7	14	13.20	5	4.72	31	29.23	0	0	0.41
18	67	0.50	1	5	24	20.40	3	2.55	15	12.75	0	0	0.50
19	62	0.56	5	6	15	21.84	2	2.91	15	21.84	0	0	0.56
20	61	0.58	4	5	9	12.01	16	21.34	6	8.00	0	0	0.58
21	62	0.56	3	4	8	8.96	33	36.96	-	-	0	1	0.50
22	67	0.50	3	6	8	8.80	16	17.60	-	-	0	0	0.50
23	73	0.41	2	6	2	1.64	4	3.28	-	-	0	0	0.41
24	82	0.28	6	5	-	-	2	1.51	11	8.32	0	0	0.28
25	93	0.11	3	4	-	-	6	1.32	4	0.88	0	0	0.11
26	97	0.05	3	5	1	0.11	5	0.53	-	-	0	0	0.05
27	83	0.26	3	5	2	1.09	1	0.55	-	-	0	0	0.26
28	72	0.43	5	5	-	-	4	4.30	15	16.13	0	0	0.43
29	61	0.58	6	6	6	9.74	-	-	8	13.00	0	0	0.58
30	52	0.68	6	7	3	5.92	-	-	-	-	0	0	0.68
31	45	0.76	3	6	1	1.67	2	3.34	-	-	0	0	0.76
32	43	0.78	3	6	1	1.72	12	20.59	-	-	0	0	0.78
33	45	0.76	4	7	1	1.90	14	26.60	14	26.60	1	0	0.68
34	52	0.68	3	7	3	4.69	11	17.20	15	23.46	1	0	0.61
35	61	0.58	4	6	2	2.78	3	4.18	15	20.88	0	0	0.58
36	72	0.43	4	6	3	3.10	-	-	5	5.16	0	0	0.43
37	83	0.26	3	4	3	1.56	1	0.52	-	-	0	0	0.26
38	97	0.05	3	6	6	0.66	1	0.11	-	-	0	0	0.05
39	90	0.16	2	7	-	-	-	-	5	1.68	0	0	0.16

TABLE C3, Contd

Sub-box	D	F(D)	RI	FI	L_w	L''_w	L_s	L''_s	L_v	L''_v	TI	WI	G
40	75	0.38	3	7	-	-	4	3.50	1	0.87	0	0	0.38
41	62	0.56	5	7	-	-	2	3.02	-	-	0	0	0.56
42	51	0.70	5	7	1	1.89	3	5.67	-	-	0	0	0.70
43	39	0.82	4	8	3	6.40	-	-	-	-	0	0	0.82
44	30	0.89	5	7	16	38.45	6	14.42	-	-	1	0	0.89
45	27	0.91	4	6	8	17.47	12	26.21	7	15.29	0	0	0.91
46	30	0.89	3	5	2	2.74	15	28.04	3	5.61	0	0	0.89
47	39	0.82	3	4	5	8.20	34	55.76	-	-	0	0	0.82
48	51	0.70	3	5	20	29.40	10	14.70	-	-	0	0	0.70
49	62	0.56	3	4	20	22.40	-	-	-	-	0	0	0.56
50	75	0.38	3	3	3	2.17	14	10.11	-	-	0	0	0.38
51	90	0.16	4	7	4	1.60	7	2.80	-	-	0	0	0.16
52	87	0.20	3	8	-	-	5	2.40	2	0.96	0	0	0.20
53	73	0.41	3	6	1	0.90	-	-	-	-	0	0	0.41
54	58	0.61	2	5	2	2.32	11	12.75	-	-	0	0	0.61
55	44	0.77	2	5	1	1.46	19	27.80	-	-	0	0	0.77
56	30	0.89	3	5	1	1.87	7	13.08	4	7.48	0	0	0.89
57	16	0.97	5	5	5	12.13	2	4.85	-	-	0	0	0.97
58	9	0.99	4	5	4	9.11	-	-	-	-	0	0	0.99
59	16	0.97	2	3	5	8.25	4	6.60	-	-	0	0	0.97
60	30	0.89	3	4	12	21.36	15	26.70	-	-	0	0	0.89
61	44	0.77	3	6	22	37.27	1	1.69	-	-	0	0	0.77
62	58	0.61	3	6	7	9.39	2	2.68	-	-	0	0	0.61
63	73	0.41	5	6	4	4.26	5	5.33	-	-	0	1	0.37
64	87	0.20	6	8	8	4.80	1	0.60	-	-	0	3	0.14
65	87	0.20	2	7	1	0.42	11	4.62	-	-	0	0	0.20
66	73	0.41	3	6	5	4.51	-	-	-	-	0	0	0.41
67	58	0.61	3	6	-	-	10	13.42	-	-	0	0	0.61
68	44	0.77	3	4	2	3.08	16	24.64	-	-	0	0	0.77
69	30	0.89	3	3	-	-	14	23.67	-	-	0	0	0.89
70	16	0.97	5	4	-	-	3	6.98	-	-	0	0	0.97
71	9	0.99	4	5	-	-	1	2.28	-	-	0	0	0.99
72	16	0.97	3	4	2	3.88	1	1.94	-	-	0	0	0.97
73	30	0.89	3	5	-	-	-	-	-	-	0	0	0.89
74	44	0.77	3	6	-	-	1	1.69	3	5.08	0	0	0.77
75	58	0.61	3	7	1	1.40	-	-	-	-	0	0	0.61
76	73	0.41	4	8	1	1.07	-	-	-	-	0	0	0.41
77	87	0.20	5	8	7	3.92	-	-	-	-	0	0	0.20
78	90	0.16	4	7	-	-	1	0.40	-	-	1	0	0.14
79	76	0.37	2	6	-	-	19	14.06	-	-	1	0	0.33
80	63	0.55	2	5	-	-	9	9.41	-	-	0	0	0.55
81	51	0.70	3	5	-	-	2	2.94	-	-	0	0	0.70
82	39	0.82	3	5	1	1.72	13	22.39	-	-	0	0	0.82
83	30	0.89	3	5	3	5.61	13	24.30	-	-	0	0	0.89
84	27	0.91	3	4	-	-	7	12.74	-	-	0	0	0.91

TABLE C3, Contd

Sub-box	$\bar{D}$	F(D)	RI	FI	L_w	L_w''	L_s	L_s''	L_v	L_v''	TI	WI	G
85	30	0.89	4	6	-	-	-	-	-	-	0	0	0.89
86	39	0.82	3	6	11	19.84	9	16.24	-	-	0	0	0.82
87	51	0.70	3	8	7	11.76	-	-	-	-	0	0	0.70
88	63	0.55	3	8	4	5.28	1	1.32	-	-	0	0	0.55
89	76	0.37	3	9	9	8.33	-	-	-	-	0	0	0.37
90	90	0.16	3	7	15	5.52	-	-	-	-	0	0	0.16
91	97	0.05	3	6	2	0.22	2	0.22	-	-	0	0	0.05
92	83	0.26	2	5	1	0.49	13	6.42	-	-	0	0	0.26
93	73	0.41	2	6	1	0.82	26	21.32	2	1.64	0	0	0.41
94	63	0.55	2	6	1	1.10	15	16.50	-	-	0	0	0.55
95	52	0.68	2	5	-	-	3	3.88	-	-	0	0	0.68
96	45	0.76	2	5	-	-	-	-	2	2.89	0	0	0.76
97	43	0.78	2	5	3	4.45	-	-	-	-	0	0	0.78
98	45	0.76	5	8	-	-	2	4.26	-	-	0	0	0.76
99	52	0.68	4	7	-	-	1	1.77	-	-	0	0	0.68
100	63	0.55	5	7	-	-	-	-	-	-	0	0	0.55
101	73	0.41	5	4	-	-	-	-	-	-	0	0	0.41
102	83	0.26	6	3	1	0.65	-	-	-	-	0	0	0.26
103	97	0.05	3	4	-	-	-	-	-	-	0	0	0.05
104	93	0.11	2	6	-	-	1	0.22	1	0.22	0	0	0.11
105	83	0.26	2	6	5	2.60	-	-	-	-	0	0	0.26
106	73	0.41	3	6	-	-	1	0.90	-	-	0	0	0.41
107	67	0.50	3	5	-	-	1	1.05	4	4.20	0	0	0.50
108	63	0.55	2	4	-	-	3	2.97	15	14.85	0	0	0.55
109	61	0.58	3	7	4	5.34	6	8.00	-	-	0	0	0.58
110	63	0.55	4	8	11	15.73	4	5.72	-	-	0	0	0.55
111	67	0.50	5	9	-	-	-	-	-	-	0	0	0.50
112	73	0.41	5	7	1	1.11	-	-	-	-	0	0	0.41
113	83	0.26	3	2	8	3.74	-	-	-	-	0	1	0.24
114	93	0.11	3	2	-	-	-	-	-	-	0	8	0.02
115	97	0.05	3	6	-	-	4	0.44	-	-	0	0	0.05
116	88	0.18	1	5	1	0.31	4	1.22	-	-	0	0	0.18
117	83	0.26	3	6	2	1.14	7	4.00	-	-	0	0	0.26
118	79	0.32	2	8	7	4.93	-	-	-	-	0	0	0.32
119	77	0.35	3	9	-	-	-	-	-	-	0	0	0.35
120	79	0.32	3	9	-	-	-	-	-	-	0	0	0.32
121	83	0.26	2	4	6	2.81	6	2.81	-	-	0	0	0.26
122	88	0.18	5	4	1	0.43	1	0.43	-	-	0	0	0.18
123	97	0.05	2	7	2	0.21	1	0.11	-	-	0	0	0.05
124	98	0.03	5	7	-	-	1	0.08	-	-	0	0	0.03
125	94	0.09	4	8	1	0.23	2	0.47	-	-	0	0	0.09
126	93	0.11	4	9	1	0.30	4	1.19	-	-	0	0	0.11
127	94	0.09	4	8	1	0.23	-	-	-	-	0	0	0.09
128	98	0.03	7	4	1	0.08	-	-	-	-	0	2	0.02
		Total				509.13		733.00		270.32			58.31

TABLE C4

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
Violent							
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	5.35E-01*	1.71E-01	3.94E-02	6.92E-03	9.64E-04	1.09E-04	1.03E-05
Strong							
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	3.15E-01	5.36E-02	6.47E-03	6.02E-04	4.52E-05	2.82E-06	1.50E-07
Weak							
AF-75	0.074	0.0028	0.000052	-	-	-	-
DBT-78	0.076	0.0000	0.000000	-	-	-	-
Mean	0.075	0.0014	0.000026	-	-	-	-
Smoothed	6.54E-02	1.60E-03	2.40E-05	2.52E-07	1.99E-09	1.24E-11	6.30E-14

* 5.35E-01 = 5.35×10^{-1}

TABLE C5

Tornado Probabilities (per year) at the Savannah River Site Computed with Distance Function with m=1. Statistical Path Lengths are:

m=1	Windspeeds at 10 m AGL 50	100	150	200	250	300	350
Violent tornado	2.12E-04*	6.79E-05	1.56E-05	2.75E-06	3.83E-07	4.33E-08	4.09E-09
Strong tornado	4.19E-04	7.13E-05	8.61E-06	8.01E-07	6.01E-08	3.75E-09	2.00E-10
Weak tornado	8.77E-05	2.15E-06	3.22E-08	3.38E-10	2.67E-12	1.66E-14	8.45E-17
All tornadoes	7.19E-04	1.41E-04	2.42E-05	3.55E-06	4.43E-07	4.71E-08	4.29E-09

* 2.2E-04 = 2.12×10^{-4}

APPENDIX D

MCDONALD'S METHODOLOGY OF TORNADO PROBABILITIES

McDonald derived the area-intensity and occurrence-intensity relationships for the SRP site, and used those results to compute tornado probabilities. For establishing the area-intensity relationship, McDonald used the reported tornado data in the global region (see Figure D1) from 1971 to 1978; he used the data in the local region (see Figure D1) from 1950 to 1978 for developing the occurrence-intensity relationship.

1. Area-Intensity Relationship: The area-intensity data, taken from the DAPPLE tape (assembled by Fujita of University of Chicago) include all reported tornadoes in the area bounded by latitudes 31° to 36° and longitudes 79° to 84° from 1971 to 1978. The mean tornado damage path area for each F-scale classification were determined from a linear regression analysis using a log-log plot of area versus tornado windspeed:

   $$\text{Log } a = 3.0488 \text{ Log } V - 6.8595,$$

   where a is the damage area in square miles, and V is the windspeed in mph. Confidence intervals of the mean damage path area for each F-scale tornado are also calculated (see Table D1).

2. Occurrence-Intensity Relationship: The occurrence-intensity data, taken from the DAPPLE tape, include all reported tornadoes in the area bounded by latitudes 32° to 35° and longitudes 80° to 83° from 1950 to 1978. The number of unreported tornadoes is estimated based on the correlation between reported tornado frequencies and population densities. The expected number of tornadoes for each F-scale is the sum of the numbers of reported tornadoes and estimated unreported tornadoes. The occurrence-intensity relationship for the SRP site is shown in Table D2.

3. Tornado Probabilities: The probability of tornado windspeed in each F-scale windspeed interval V_j is calculated using the equation:

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

   where A = area of the region studied (34,453 mi^2),

   λ_i = the number of tornadoes per year in F-scale windspeed interval i (see Table D2),

   a_{ij} = the path area that is exposed to windspeed in the interval j of a tornado whose maximum windspeed is in the interval i (see Table D1).

The probability of tornado windspeed exceeding interval values in one year is then calculated by:

$$P\ (V > V_j) = \sum_{k=j}^{6} P\ (V = V_k).$$

Table D3 shows the results of exceedance probabilities with 95% confidence intervals.

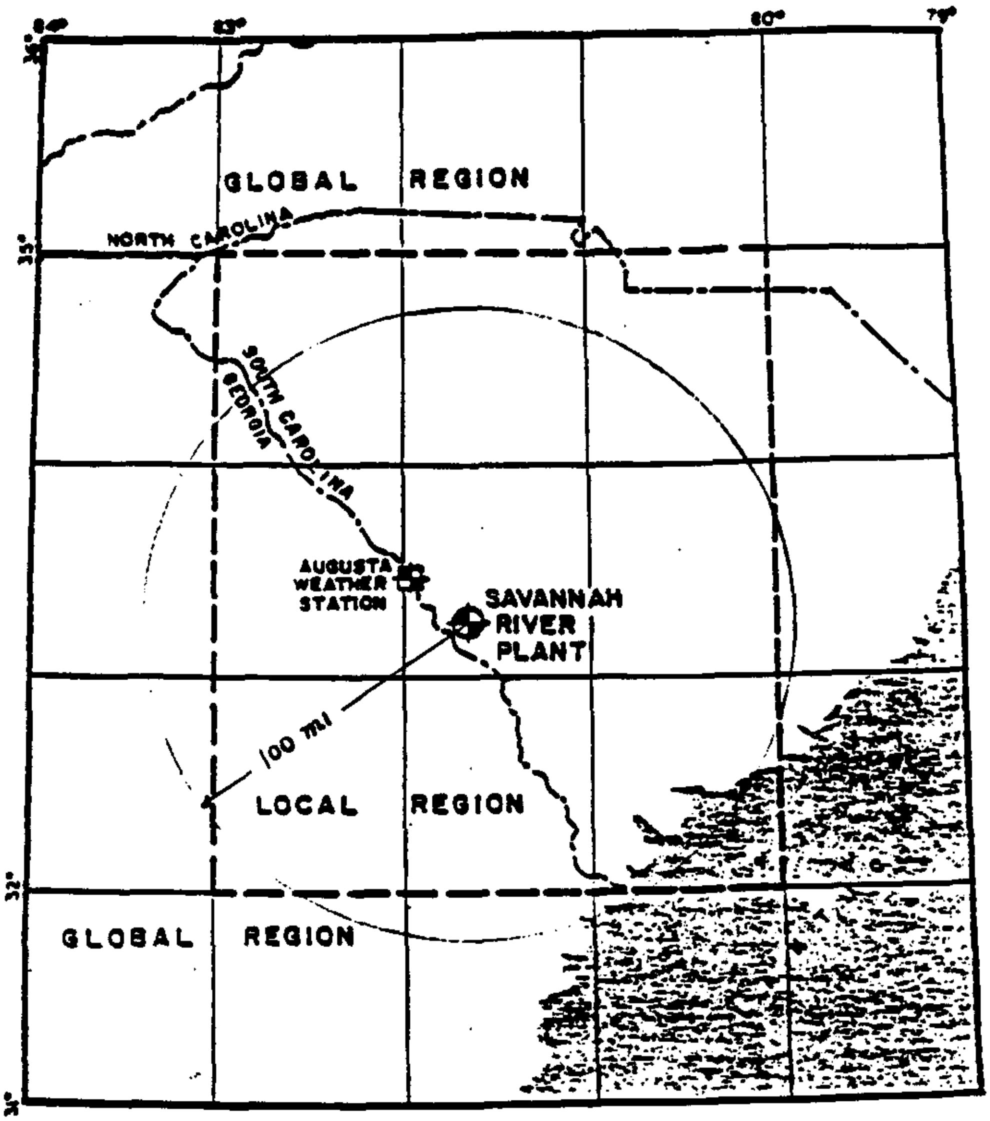

FIGURE D1. Local and Global Regions

TABLE D1

Area-Intensity Relationship

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

The quantity a_{ij} can be computed by: $a_{ij} = a_i K_{ij}$, where K_{ij} is the ith row and jth column element of the matrix used by McDonald.*

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* McDonald 1979 (see Reference 4)

TABLE D2

Occurrence-Intensity Relationship

	F0	F1	F2	F3	F4	F5
Total expected No. of tornadoes	75.30	143.18	81.65	17.84	3.40	0.62
Lower limit	60.41	125.70	66.35	9.80	-	-
Upper limit	90.19	160.66	96.95	25.89	6.99	2.17
Expected No. of tornadoes per year, λ_i	2.60	4.94	2.82	0.62	0.12	0.0214
Lower limit λ_i	2.08	4.33	2.29	0.34	-	-
Upper limit λ_i	3.11	5.54	3.34	0.89	0.24	0.07
Windspeed, mph	40	73	113	158	207	261

TABLE D3

Summary of McDonalds Tornado Probabilities

Windspeed (mph)	Exceedance Probability	95% Confidence Interval	
		Lower Bound	Upper Bound
73	6.46E-5*	3.13E-5	1.29E-4
113	2.41E-5	1.06E-5	5.22E-5
158	5.78E-6	1.87E-6	1.54E-5
207	1.01E-6	2.29E-7	3.57E-6
261	1.16E-7	2.68E-8	5.67E-7

* 6.46E-5 = 6.46×10^{-5}

APPENDIX E

MODIFIED McDONALD'S METHOD

For estimating unreported tornado frequencies, McDonald divided the local region into 144 equal area sub-boxes. The numbers of reported tornadoes were recorded and tabulated in descending order with respect to their population densities. The number of reported tornadoes is actually an increasing function of the population density (see Figure E1). The average number of tornadoes for the first n sub-boxes, n=1,2...,144, are computed. Among them, 2.24 is the average number of tornadoes for the sub-boxes with population density 74 (per mi^2) or more (74 is the same as the average population density for these 141* sub-boxes). McDonald used 144 x 2.24 minus the total number of reported tornadoes as an estimated number of unreported tornadoes. Since the population density is uncorrelated to the tornado (reported plus unreported) frequency, McDonald's estimation seems to be conceptually wrong. The mean number of tornadoes (reported plus unreported) in a sub-box should be close to the maximum of that increasing function (see Figure E1). Thus, McDonald's estimation method can be improved as follows: let $f(\chi)$ be the average number of tornadoes for a sub-box with population density χ or more. The bounded increasing function $f(\chi)$ can be modeled as:

$$f(\chi) = a - be^{-c\chi}.$$

The least squares estimate of a, b, and c from McDonald's data are $\hat{a} = 5.88$, $\hat{b} = 4.44$, and $\hat{c} = 0.0037$. In this fit, the mean squares for regression and residual, respectively, are 284.94 and 0.09. Figure E1 shows the fitted curve and several data points. The estimated maximum of this function is $\hat{a} = 5.88$. If we replace 2.24 by 5.88 as the mean number of tornadoes in a sub-box for McDonald's method, then the probabilities of exceeding threshold windspeed in one year can be obtained as:

Windspeed, mph	40	73	113	158	207	261
Probability	4.25×10^{-4}	1.70×10^{-4}	6.33×10^{-5}	1.52×10^{-5}	2.62×10^{-6}	3.05×10^{-7}

* Deleting three sub-boxes in the sea area

It is worth to mention that Fujita abandoned the use of correlation between population density and tornado frequency because he believed that this is biased by local population concentration. However, due to the absence of big cities in this region, the biases could be considered as the part of residual variability in the least squares fitting.

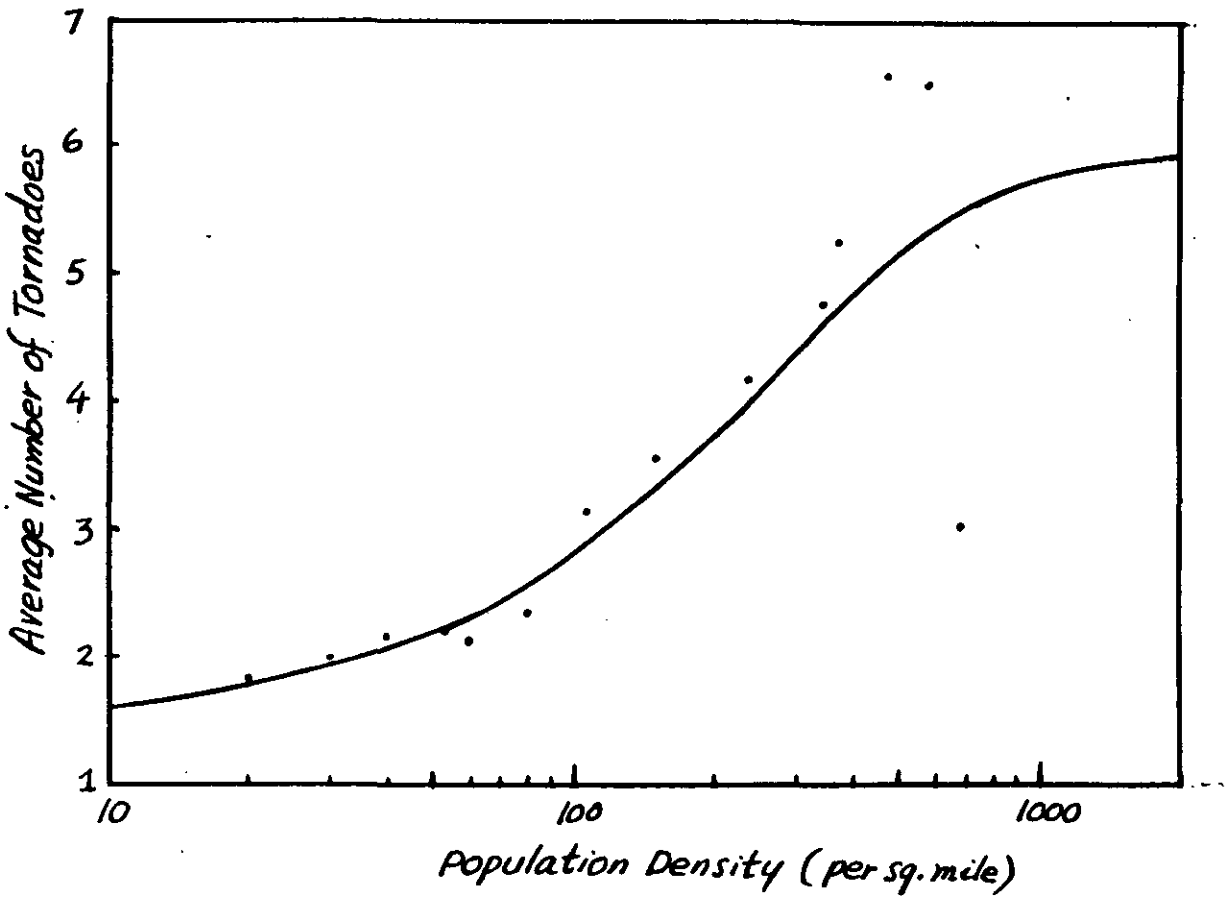


FIGURE E1. Correlation Between Tornado Frequency and Population Density

APPENDIX F

BLUME'S METHODOLOGY IN DERIVING EARTHQUAKE PROBABILITIES FOR THE SRP SITE

Blume modeled the geographic distribution of earthquakes in terms of three source regions: the Atlantic coastal plain and Appalachian Mountain tectonic provinces, and the Charleston seismic zone. For the Charleston seismic zone, two configurations were considered (see Figure F1). Blume's data base consists of all earthquakes with maximum epicentral intensity VII or greater (MMI scale) in these three regions from the past century.

The methodology used by Blume can be summarized as follows:

(1) The earthquake occurrence rate is determined by using the relationship:

$$\log N = a - b\ I_o, \qquad \text{(F1)}$$

where N is the number of events of epicentral intensity I_o or greater per year in an area of 1,000 km^2. The parameter b was empirically determined to be 0.54 by Bollinger[5] for the whole eastern and southeastern United States. The values of a for three regions were determined using the appropriate recorded earthquake data. The results of a and b values are shown in Table F1.

(2) The attenuation of earthquake intensity was obtained using the Bollinger's equation:[5]

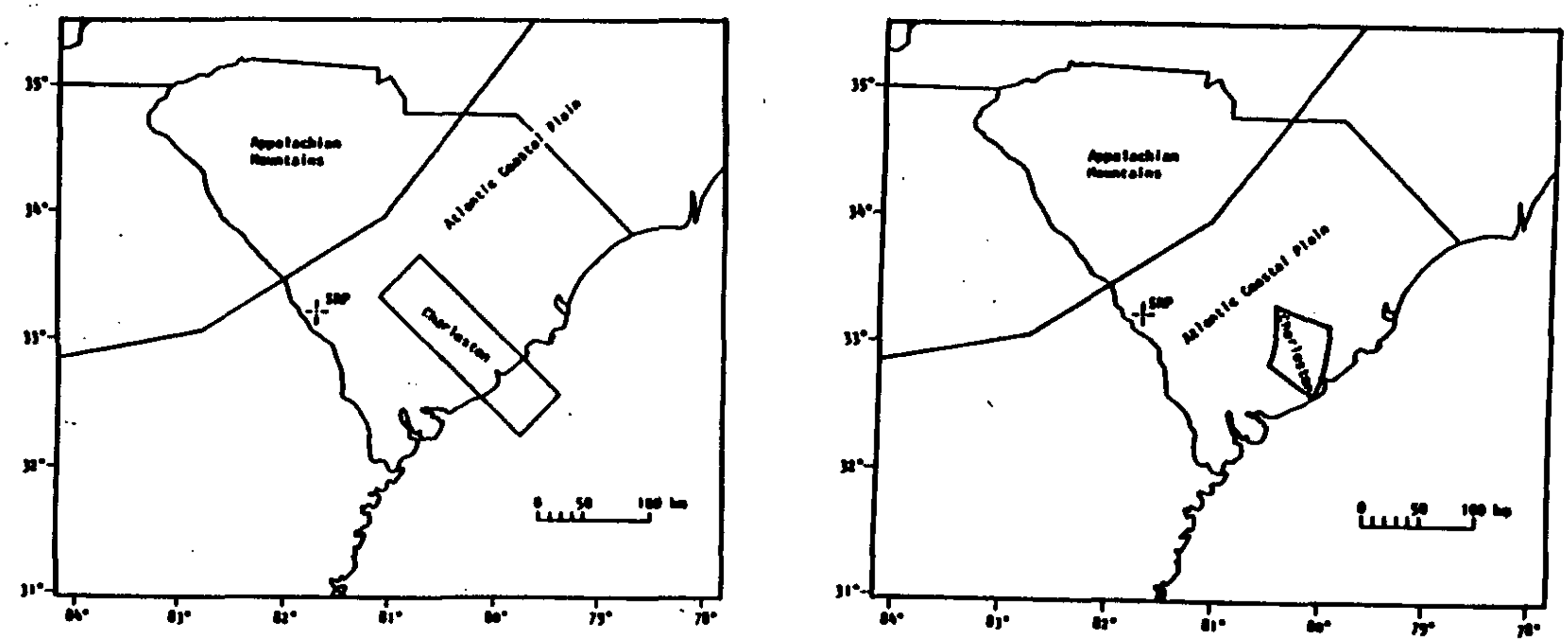
$$I = \begin{cases} I_o + 2.87 - 0.00052R - 2.88 \log R & \text{if } R > 10 \text{ km} \\ I_o & \text{if } R < 10 \text{ km,} \end{cases} \qquad \text{(F2)}$$

where I_o and I, respectively, are the earthquake intensities (MMI scale) at the epicenter and at distance R (in km) from the epicenter.

(3) The probability of exceeding a given site acceleration for an earthquake of given epicentral intensity and epicentral distance is calculated by assuming the peak ground acceleration (PGA) is lognormally distributed.* This probability was integrated over the area of source region, yielding the probability that the given site acceleration will be exceeded

* Murphy and O'Brien showed that PGA is approximately distributed as lognormal with standard deviation 0.36 and mean derived from: $\log A = 0.25 + 0.25I$, where A is the mean PGA in cm/sec^2.

should the earthquake occur in the source region. This set of probabilities was then multiplied by the occurrence rates derived from Equation F1, and the results were integrated with respect to epicentral intensity to obtain the total probability of exceeding a given site acceleration due to the occurrence of all earthquakes in a source region. Results for three source regions were summed to yield the total probability of exceeding a given site acceleration. The result of exceedance probability as a function of PGA at the SRP site is shown in Table F2.



SOURCE CONFIGURATION 2

SOURCE CONFIGURATION 1

FIGURE F1. Source Configurations

TABLE F1

Earthquake Recurrence Parameters

Parameter	Tectonic Province: Atlantic Coastal Plain	Appalachian Mountains	Charleston Seismic Zone
Area (x 1,000 km^2)	300	350	3.0,* 8.5**
Number of events per century, I_o >VII	3	10	1
Parameter a†	−0.22	0.24	1.3,* 0.85**
Parameter b†	0.54	0.54	0.54

* Source configuration 1.

** Source configuration 2.

† $\log N(I_o) = a - bI_o$, where a and b are determined empirically; $N(I_o)$ = number of earthquake events with epicentral intensity $>I_o$ per 1,000 km^2 per year.

TABLE F2

Mean Annual Ground Motion Exceedance Probabilities

Source Region	Exceedance Probabilities* by PGA (cm/sec^2, g) and Approximate MMI — cm/sec^2: 20; g: 0.02; MMI: IV	cm/sec^2: 100; g: 0.10; MMI: VII	cm/sec^2: 200; g: 0.20; MMI: VIII
Atlantic coastal plain	3.65E-2**	6.87E-4	7.41E-5
Appalachian mountains	5.16E-2	5.23E-4	3.19E-5
Charleston (configuration 1)	2.12E-2	5.29E-4	7.84E-5
Charleston (configuration 2)	2.47E-2	6.36E-4	1.00E-4
Total (configuration 1)	1.09E-1	1.74E-3	1.84E-4
Total (configuration 2)	1.13E-1	1.85E-3	2.06E-4

* Probabilities of exceedance are given to a uniform precision of three significant figures; however, the accuracy of these values is about ±5% with respect to the given seismicity model.

** Entry 3.65E-2 is read as 3.65×10^{-2}, etc.

APPENDIX G

THE DERIVATION OF POINT PROBABILITIES FOR THE STRIKE OF A METEORITE

The point probability of a meteorite strike can be conservatively derived by assuming that the cross section area of a meteorite (before entering the earth's atmosphere) is one-one hundredth of its crater area (see Table G1).

Define:

n = the number of meteorites with mass greater than or equal to m (before entering) falling on the earth yearly,

a = cross section area of the meteorite

b = lethal area of the meteorite

A = area of the earth surface = 5.48×10^{15} ft^2.

Several immediate relations are:

$$m = c_1 a^{3/2}$$

$$b = c_2 a^*$$

$$n = c_3 N$$

for some constants c_1, c_2, and c_3. Using the relations above in the equation $\log_{10} N = -5.61 - 0.7 \log_{10} m$, we obtain

$$n = c\ (b^{3/2})^{-0.7} = cb^{-1.05}$$

for some constant c, and c is found approximately to be 10^5 (if the unit of b is ft^2) by large values of m in Table G1. Taking the derivative of n with respect to b, one obtains $-\frac{dn}{db} = -1.05 \times 10^5\ b^{-2.05}$. Let Δ b the small change of b and $\ell = -\left(\frac{dn}{db}\right) \Delta b$. The probability that a meteorite with lethal area greater than a_o ($a_o < A$) is at most

$$\lim_{\Delta b \to o} \sum \left[1 - \left(1 - \frac{b}{A}\right)^{\ell}\right] + \int_A^{\infty} \left(-\frac{dn}{db}\right) db \qquad (G1)$$

where Σ is the sum over bs which are between a_o and A. The second term of the expression G1 is the point probability of the meteorite with lethal area greater than A; the first term of the expression G1 denoted by Q, is for lethal area between a_o and A, and can be rewritten as:

* Blake used $c_2 = 16$

$$Q = \lim_{\Delta b \to o} \sum \left[\sum_{k=1}^{\infty} \frac{\ell\,(\ell-1)\ldots(\ell-k+1)}{k!} \left(\frac{b}{A}\right)^k \right]$$

$$= \sum_{k=1}^{\infty} \frac{1}{k} \lim_{\Delta b \to o} \left[\sum \left(\frac{b}{A}\right)^k \left(-\frac{dn}{db}\right) \Delta b \right]$$

$$= \sum_{k=1}^{\infty} \frac{1}{k} \int_{a_o}^{A} \left(\frac{b}{A}\right)^k 1.05 \times 10^5\, b^{-2.05}\, db$$

$$= 1.05 \times 10^5 \sum_{k=1}^{\infty} \frac{1}{k\,(k-1.05)} \cdot \frac{\left(A^{k-1.05} - a_o{}^{k-1.05}\right)}{A^k}$$

Apparently, there is no closed form for the above expression. However, the value Q is dominated by the term k=1 when a_o/A is small. The sum of the terms with $k \geq 2$ in Q is bounded above by $(0.95\ A^{1.05})^{-1}$, because:

$$\sum_{k=2}^{\infty} \frac{1}{k(k-1.05)} \times \frac{\left(A^{k-1.05} - a_o{}^{k-1.05}\right)}{A^k}$$

$$< \frac{1}{0.95\ A^{1.05}} \sum_{k=2}^{\infty} \frac{1}{k\,(k-1)}$$

$$= \left(0.95\ A^{1.05}\right)^{-1}.$$

Therefore, the expression G1 is bounded above by

$$1.05 \times 10^5 \left[-\frac{\left(A^{-0.05} - a_o{}^{-0.05}\right)}{0.05\ A} + \frac{A^{-1.05}}{0.95} \right] + \int_A^{\infty} \left(-\frac{dn}{db}\right) db$$

$$= \left(3.83\ a_o{}^{-0.05} - 0.56\right) \times 10^{-10}$$

$$= \left(2.50\ m^{-1/30} - 0.56\right) \times 10^{-10} \qquad \text{(G2)}$$

where m is the mass (in tons) of the meteorite before entering the earth's atmosphere. On the other hand,

$$Q > 1.05 \times 10^5 \times \frac{1}{1 \times (1-1.05)} \times \frac{\left(A^{-0.05} - a_o^{-0.05}\right)}{A}$$

$$= \left(3.83\ a_o^{-0.05} - 0.63\right) \times 10^{-10}$$

Therefore, the expression G1 is bounded below by

$$\left(3.83\ a_o^{-0.05} - 0.63\right) \times 10^{-10} + \int_A^{\infty} \left(- \frac{dn}{db}\right) db$$

$$= \left(3.83\ a_o^{-0.05} - 0.60\right) \times 10^{-10}$$

Since the difference of this value and that from the expression G2 is 4×10^{-12}, hence the latter is greater that from the expression G1 by at most 4×10^{-12}.

TABLE G1

Relations Among Iron Meteorite Weights, Crater Radius and Lethal Areas

Meteorite Weight (tons)	Cross Section Radius (ft)	Impact Weight (lb)	Crater Radius (ft)	Lethal Area (ft^2)	** (ft^2)
10^0	9.9E-1*	2.4E+2	9.9E-1	5.02E+1	5.02E+3
10^1	2.1E+0	9.0E+3	8.3E+0	3.62E+3	2.31E+4
10^2	4.6E+0	1.4E+5	2.8E+1	3.90E+4	1.09E+5
10^3	9.9E+0	1.7E+6	7.8E+1	3.07E+5	5.02E+5
10^4	2.1E+1	1.9E+7	1.9E+2	1.87E+6	2.31E+6
10^5	4.6E+1	1.9E+8	4.4E+2	9.76E+6	1.09E+7
10^6	9.9E+1	2.0E+9	9.8E+2	4.74E+7	5.02E+7
10^7	2.1E+2	2.0E+10	2.1E+3	2.26E+8	2.31E+8
10^8	4.6E+2	2.0E+11	4.6E+3	1.09E+9	1.09E+9
10^9	9.9E+2	2.0E+12	1.0E+4	5.02E+9	5.02E+9
10^{10}	2.1E+3	2.0E+13	2.3E+4	2.31E+10	2.31E+10
10^{11}	4.6E+3	2.0E+14	4.6E+4	1.09E+11	1.09E+11
10^{12}	9.9E+3	2.0E+15	1.0E+5	5.02E+11	5.02E+11
10^{13}	2.1E+4	2.0E+16	2.2E+5	2.31E+12	2.31E+12

* 9.9E-1 = 9.9×10^{-1}

** Lethal areas used in the conservative computations of the point probabilities

APPENDIX H

THE DERIVATION OF THE PROBABILITY OF METEORITE IMPACT ON A STRUCTURE WITH AREA S

To find the probabilities that a building with certain area S will be damaged by a meteorite per year, Equation (G1) should be replaced by

$$\lim_{\Delta b \to o} \sum \left[1 - \left(1 - \frac{(\sqrt{b} + \sqrt{S})^2}{A} \right)^{\ell} \right] + \int_{(\sqrt{A} - \sqrt{S})^2}^{\infty} \left(- \frac{dn}{db} \right) db. \qquad (H1)$$

The first term of (H1) can be shown to be

$$1.05 \times 10^5 \sum_{k=1}^{\infty} \frac{1}{k} \int_{a_o}^{(\sqrt{A} - \sqrt{S})^2} \left[\frac{(\sqrt{b} + \sqrt{S})^2}{A} \right]^k b^{-2.05} \, db \qquad (H2)$$

The value of (H2) is dominated by the first term k=1. For k = 1,

$$1.05 \times 10^5 \int_{a_o}^{(\sqrt{A} - \sqrt{S})^2} \frac{(\sqrt{b} + \sqrt{S})^2}{A} b^{-2.05} \, db$$

$$\approx \frac{1.05 \times 10^5}{A} \left[\int_{a_o}^{(\sqrt{A} - \sqrt{S})^2} b^{-1.05} \, db + 2\sqrt{S} \int_{a_o}^{(\sqrt{A} - \sqrt{S})^2} b^{-1.55} \, db \right]$$

$$\approx \left(3.83 \, a_o^{-0.05} + 0.70 \sqrt{S} \, a_o^{-0.55} - 0.63 \right) 10^{-10}$$

The rest of the term, denoted by R, can be discussed in two cases:

Case I. $a_o > S$: changing variable b to u by the relation $(\sqrt{b} + \sqrt{S})^2 = u$, we obtain

$$R = 1.05 \times 10^5 \sum_{k=2}^{\infty} \frac{1}{k} \int_{(\sqrt{a_o} + \sqrt{S})^2}^{A} \frac{u^{k-0.5}}{A^k} \left(\sqrt{u} - \sqrt{S} \right)^{-3.1} du \quad (H3)$$

Since $(\sqrt{u} - \sqrt{S})^{-3.1} = \left(\frac{\sqrt{u} - \sqrt{S}}{\sqrt{u}}\right)^{-3.1} (\sqrt{u})^{-3.1}$

$$= \left(\frac{\sqrt{u}}{\sqrt{u} - \sqrt{S}}\right)^{3.1} u^{-1.55}$$

$$< \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1} u^{-1.55}$$

Therefore,

$$R < 1.05 \times 10^5 \sum_{k=2}^{\infty} \frac{1}{k} \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1} \int_{(\sqrt{a_o} + \sqrt{S})^2}^{A} \frac{u^{k-2.05}}{A^k} du$$

$$< \frac{1.05 \times 10^5}{A^{1.05}} \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1} \sum_{k=2}^{\infty} \frac{1}{k\ (k-1.05)} \left[1 - \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{A}}\right)^{2k-2.1}\right]$$

$$< \frac{1.05 \times 10^5}{A^{1.05} \times 0.95} \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1}$$

$$= 0.03294 \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1} \times 10^{-10}$$

Case II. $A_o < S$: From Equation H3, R can be rewritten as

$$R = 1.05 \times 10^5 \left[\sum_{k=2}^{\infty} \frac{1}{k} \int_{(\sqrt{a_o} + \sqrt{S})^2}^{4S} \frac{u^{k-0.5}}{A^k} (\sqrt{u} - \sqrt{S})^{-3.1} du \right.$$

$$\left. + \sum_{k=2}^{\infty} \frac{1}{k} \int_{4S}^{A} \frac{u^{k-0.5}}{A^k} (\sqrt{u} - \sqrt{S})^{-3.1} du \right]$$

The second term is bounded above by 0.28×10^{-10} from the Case I. The first term is bounded above by

$$1.05 \times 10^5 \sum_{k=2}^{\infty} \frac{1}{2k} \left(\frac{4S}{A}\right)^k (\sqrt{S})^{-4.1}$$

$$= 0.525 \times 10^5 (\sqrt{S})^{-4.1} \left(\frac{4S}{A}\right)^2 1\left(- \frac{4S}{A}\right)^{-1},$$

which is negligible in comparing with 10^{-10}.

Combining both cases, we conclude that expression H1 is bounded above by:

$$\begin{cases} (q - 0.32) \times 10^{-10} & \text{if } S > a_o \\ (q + 0.03294\ t - 0.60) \times 10^{-10} & \text{if } S < a_o \end{cases} \qquad \text{(H4)}$$

where $q = 3.83\ a_o^{-0.05} + 0.70 \sqrt{S}\ a_o^{-0.55} = 2.50\ m^{-1/30} + 6.48\ m^{-11/30}$

and $t = \left(\frac{\sqrt{a_o} + \sqrt{S}}{\sqrt{a_o}}\right)^{3.1} = \left(\frac{70.546\ m^{1/3} + \sqrt{S}}{70.546\ m^{1/3}}\right)^{3.1}.$

This upper bound (H4) is greater than (H1) by at most 2.8×10^{-11}, because $R < 2.8 \times 10^{-11}$ from Case I and II.

According to the expression H4, the probability for a structure of area 10^6 ft^2 to be struck by a meteorite with earth surface impact weight 240 lb or greater is no more than 8.63×10^{-10} per year. The comparison of the expression H4 and Poe's finding are shown in Figure H1.

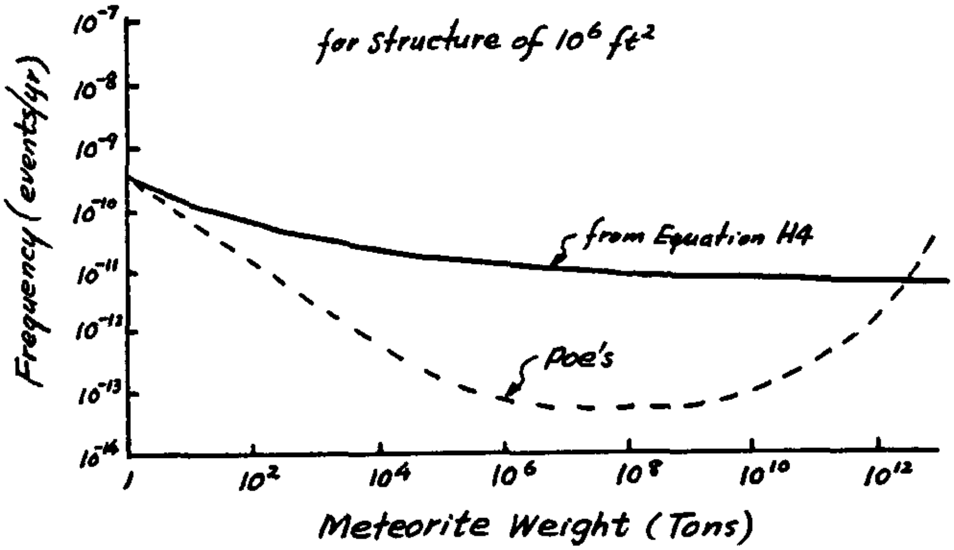


FIGURE H1. Meteorite Impact Frequency

OSR 25-5
(REV 3-83)

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CC: J. W. Hayes

August 2, 1985

Mr. A. F. Westerdahl, Chief
Patent Branch
U. S. Department of Energy
Aiken, South Carolina 29808

Dear Mr. Westerdahl:

REQUEST FOR PATENT REVIEW

Please review for patent matter:

DPST-84-718, "PROBABILITIES OF NATURAL EVENTS OCCURRING AT SAVANNAH RIVER PLANT", by J. C. Haung and Y. S. Hsu

If any technical clarification is needed please call C. J. Banick whose Document Review is attached.

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If you decide to pursue a patent on any development covered, I shall be happy to supply additional information required such as appropriate references and the names of persons responsible for the development.

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Records Management

The above item is approved for release.

A. F. Westerdahl
Chief Patent Branch
DOE-SR

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CC: A. F. Westerdahl, DOE-SR

August 2, 1985

TO: J. W. HAYES

FROM: C. J. BANICK

DOCUMENT REVIEW

Document DPST-84-718

Title: PROBABILITIES OF NATURAL EVENTS OCCURRING AT SAVANNAH RIVER PLANT

Author(s) J. C. Huang - Y. S. Hsu

Contractual Origin: DE-AC09-76SR00001

Present Classification: Unclassified Paper

References:

No items were noted that, in my opinion, should be called to the attention of the DOE for patent consideration.

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TECHNICAL DIVISION
SAVANNAH RIVER LABORATORY

November 19, 1985

TO: DISTRIBUTION

FROM: J. C. HUANG

NATURAL EVENT PROBABILITIES IN TABULATED FORMS

Ref: Supplement to "Probablities of Natural Events Occurring at Savannah River Plant", DPST-84-718, by J. C. Huang et at, dated January 21, 1985.

For technical consistency and quality assurance of SAR natural phenomena risk assessments, the Environmental Technology Division has developed a standard set of occurence probabilities for natural events (straight winds, tornadoes, earthquakes, and meteorites). Because these probabilities are represented by curves plotted on logarithmic scales, you may encounter difficulties of reading the numbers. Therefore, it has been suggested that these probability curves be tabulated for your convenience.

The tabulated probabilities in the attached sheets are prepared either by direct reading from the curves or by calculation from appropriate formulas as described in the referenced document. Table S-1 shows the probabilities of high-velocity straight winds as a function of wind speed. The point probabilities of tornadoes as a function of wind speed are shown in Table S-2. Table S-3 shows the probabilities of earthquakes in terms of peak ground acceleration (PGA). The probabilities of meteorite impact from various sizes are shown in Table S-4.

JCH/jfp

TABLE S-1 PROBABILITIES OF HIGH-VELOCITY STRAIGHT WINDS

Wind Speed (mph)	Occurrence Probability (per year)
50	2.4×10^{-1}
60	1.1×10^{-1}
70	4.5×10^{-2}
80	1.8×10^{-2}
90	7.4×10^{-3}
100	3.0×10^{-3}
110	1.2×10^{-3}
120	4.9×10^{-4}
130	2.0×10^{-4}
140	8.1×10^{-5}
150	3.3×10^{-5}
160	1.3×10^{-5}
170	5.3×10^{-6}
180	2.2×10^{-6}
190	8.7×10^{-7}
200	3.5×10^{-7}
210	1.4×10^{-7}
220	5.7×10^{-8}
230	2.3×10^{-8}
240	9.4×10^{-9}
250	3.8×10^{-9}
260	1.5×10^{-9}
270	6.2×10^{-10}
280	2.5×10^{-10}
290	1.0×10^{-10}
300	4.0×10^{-11}

TABLE S-2 POINT PROBABILITIES OF TORNADOES

Wind Speed (mph)	Occurrence Probability (per year)
50	7.2×10^{-4}
60	5.2×10^{-4}
70	4.0×10^{-4}
80	3.0×10^{-4}
90	2.1×10^{-4}
100	1.5×10^{-4}
110	1.0×10^{-4}
120	6.8×10^{-5}
130	5.0×10^{-5}
140	3.8×10^{-5}
150	2.6×10^{-5}
160	1.6×10^{-5}
170	1.2×10^{-5}
180	8.0×10^{-6}
190	5.0×10^{-6}
200	4.1×10^{-6}
210	2.2×10^{-6}
220	1.5×10^{-6}
230	1.0×10^{-6}
240	7.2×10^{-7}
250	4.6×10^{-7}
260	3.0×10^{-7}
270	2.0×10^{-7}
280	1.2×10^{-7}
290	7.8×10^{-8}
300	5.6×10^{-8}

TABLE S-3 PROBABILITIES OF EARTHQUAKES

PGA (g)	Occurrence Probability (per year)
0.03	5.0×10^{-2}
0.04	2.3×10^{-2}
0.05	1.2×10^{-2}
0.06	8.8×10^{-3}
0.07	5.4×10^{-3}
0.08	3.7×10^{-3}
0.09	2.7×10^{-3}
0.10	2.0×10^{-3}
0.11	1.5×10^{-3}
0.12	1.1×10^{-3}
0.13	8.0×10^{-4}
0.14	6.0×10^{-4}
0.15	5.2×10^{-4}
0.16	4.2×10^{-4}
0.17	3.5×10^{-4}
0.18	2.8×10^{-4}
0.19	2.4×10^{-4}
0.20	2.0×10^{-4}
0.21	1.8×10^{-4}
0.22	1.5×10^{-4}
0.23	1.3×10^{-4}
0.24	1.1×10^{-4}
0.25	9.0×10^{-5}
0.26	8.0×10^{-5}
0.27	7.0×10^{-5}
0.28	6.0×10^{-5}
0.29	5.2×10^{-5}
0.30	4.8×10^{-5}

TABLE S-4 PROBABILITIES OF METEORITES

Weight (tons)	Occurrence Probability (per year)
1×10^{-1}	2.1×10^{-10}
1×10^{0}	1.9×10^{-10}
1×10^{1}	1.8×10^{-10}
1×10^{2}	1.6×10^{-10}
1×10^{3}	1.4×10^{-10}
1×10^{4}	1.3×10^{-10}
1×10^{5}	1.1×10^{-10}
1×10^{6}	1.0×10^{-10}
1×10^{7}	9.0×10^{-11}
1×10^{8}	8.0×10^{-11}
1×10^{9}	7.0×10^{-11}
1×10^{10}	6.0×10^{-11}
1×10^{11}	5.0×10^{-11}
1×10^{12}	4.5×10^{-11}
1×10^{13}	3.5×10^{-11}