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**NATURAL HAZARDS THAT MAY TRIGGER
A RADIOLOGICAL RELEASE
FROM A PLUTONIUM PROCESSING FACILITY**

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MASTER

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
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SUBJECT DESCRIPTORS

Accidents
Contamination
Hazards
Plutonium
Probability

**ROCKWELL INTERNATIONAL
ATOMICS INTERNATIONAL DIVISION
ROCKY FLATS PLANT
P.O. BOX 464
GOLDEN, COLORADO 80401**

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NATURAL HAZARDS THAT MAY TRIGGER A RADIOLOGICAL RELEASE FROM A PLUTONIUM PROCESSING FACILITY

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Abstract. Calculations show the probability of a tornado striking a plutonium area at Rocky Flats is 2.2×10^{-4} per year. The source term (expected value of plutonium release) should such an event occur is calculated at 3.3×10^{-7} grams. The source term for high-velocity, downslope winds is higher— 2.2×10^{-3} grams. The probability of a meteorite that weighs one or more pounds (453 grams) striking a plutonium area is estimated at 8.88×10^{-7} per year. Because of this small probability and the remote chance that a plutonium release would occur even if a meteorite hit occurred, the hazard from meteorite impact is considered negligible. Conservative assumptions result in all calculated frequencies being almost certainly too high. Empirical observations have indicated lower frequencies than those calculated.

INTRODUCTION

Natural events that may cause damage leading to the release of radioactive material at Rocky Flats are tornadoes, downslope windstorms, earthquakes, and impact by meteorites. Floods, tidal waves, cyclones, hurricanes, and volcanoes are not considered to be hazards at the Rocky Flats site. For each of the natural hazards of interest, the probabilities are greater than about 10^{-8} per year. The damage that could result from the event and the subsequent radiological release should be assessed.

In this report, the probability of occurrence is computed for severe downslope windstorms and tornadoes. The possible damage and associated release of plutonium are also estimated as are the hazards from possible meteorite impact. The probabilities and possible release for earthquakes are still under study.

PROBABILITIES FOR DOWNSLOPE WINDSTORMS

The Front Range area of the State of Colorado from Colorado Springs to Fort Collins is subject to occasional, severe, downslope windstorms occurring in the lee of the Rocky Mountains. These storms generally are strongest and cause the most damage in the city of Boulder, about 10 miles north of Rocky Flats. Figure 1 shows schematically the wave-like character of the winds.* Rocky Flats, which lies between Boulder and Jefferson County Airport, can be expected to experience high winds at about the same time and with comparable maximum-wind velocities as those occurring in Boulder. Several studies of Boulder windstorms have dealt with the characteristics of the winds (their gustiness and maximum speeds), the frequency of occurrence of the storms, and the wind damage produced.¹⁻³ This report treats the winds at Rocky Flats in a similar manner.

Windstorm Frequency

The frequency of occurrence of reported windstorms** in Boulder over the 104-year period from 1869 to 1972 ranges from 0 to 14 storms per year.*** The number reported is greatest during the latter part of that period because of the city's expansion into previously open areas, particularly the Table Mesa section of that city.

The average number of storms from 1960 to 1972 was 6.08 per year. The value of six storms per year

*Reference 1, Page 4.

** A windstorm for the Boulder and Rocky Flats area is defined as a period when all of the National Center for Atmospheric Research (NCAR) wind-measuring stations in Boulder reported winds of greater than 50 mph, and at least one station reported speeds greater than 75 mph (hurricane force).

***Reference 1, Page 12.

FIGURE 1. Cross Section of Potential Temperature ($^{\circ}\text{K}$) During a Windstorm at Boulder, Colorado. The short dashed lines are flight paths of the aircraft that conducted the potential temperature survey. Lines of constant potential temperature can be considered as streamlines of atmospheric flow. (See Reference 3.)

will be used in this study as an estimate of the frequency of windstorms at Rocky Flats.

Maximum Wind Speed

Wind gusts of over 100 mph have been measured during downslope windstorms in the Boulder and Rocky Flats areas. The statistical theory of extremes makes use of past data on maximum gusts to estimate the probability of occurrence of high winds during future storms.⁴ Following this theory, a particular probability distribution is fit to previously observed, maximum gusts and is projected to give the probability of high wind-speed values. In this study, the estimates are based on data collected during 32 recent storms representing a five-year period. The data are shown in Table 1.

Two distributions have been used here to fit these extreme wind values: the Fisher-Tippett Type I and the Fisher-Tippett Type II distributions.^{2, 4, 5} The first distribution is appropriate when data having extremes that are of interest follow an exponential type distribution—the second when the *logarithms* of the data have this form. When each of these models is fit by the method of order statistics to this sample of peak gusts recorded at Rocky Flats, the following extreme distributions are obtained:

Type I: Probability (gust $\geq x$ mph)

$$= 1 - \exp(-\exp(-(x - \alpha)/\beta))$$
 with $\alpha = 71.0337$ and $\beta = 12.1785$

Type II: Probability (gust $\geq x$ mph)

$$= 1 - \exp(-(x/\beta) - \gamma)$$
 with $\gamma = 6.27058$ and $\beta = 70.2809$

TABLE 1. Maximum gusts recorded at Rocky Flats

Year	Month	Day	Maximum Wind Speed (mph)
1969	1	7	98
	1	29	62
	1	31	100
	3	19	86
	4	7	71
1970	1	25	74
	2	3	97
	2	16	79
	11	21	62
	11	25	71
	11	28	62
	11	30	97
	12	31	67
1971	1	20	71
	1	23	66
	1	25	95
	1	29	76
	2	11	75
	3	4	71
	3	31	74
	12	20	62
1972	1	5	81
	1	9	56
	1	11	105
	1	21	68
	1	24	82
	1	28	91
	11	26	104
1973	12	1	68
	3	13	72
	11	1	70
	12	2	92

TABLE 2. Estimates of the Maximum Wind Speed Probabilities

Wind Speed (mph)	Probability Per Year that the Peak Gust Equals or Exceeds the Wind Speed Shown	
	Type I Distribution	Type II Distribution
100	5.3×10^{-1}	6.2×10^{-1}
150	9.0×10^{-3}	5.1×10^{-2}
200	1.5×10^{-4}	8.4×10^{-3}

details of the calculation of these probabilities; Appendix A also presents graphs showing the entire probability distributions (from which an intermediate value can be read).

Probabilities can be computed theoretically for wind speeds greater than 200 mph; however, it is estimated that from a practical viewpoint, down-slope winds cannot exceed 200 mph. Above 200 mph, a turbulent breakdown in the flow is expected, which would prevent a flow increase to greater speeds.⁶

FREQUENCY OF OCCURRENCE OF TORNADES

The probability of a tornado striking the Rocky Flats facility is estimated primarily from historical data giving the number and sizes of tornadoes reported locally during a 21-year period. The presence of the Rocky Mountains, with the foothills being only four miles west of the plant, influences the meteorological conditions in the area. In particular, theories of tornado formation predict that storms that are intense enough to generate tornadoes will rarely occur this close to the mountains—also that any tornadoes generated will be smaller and weaker than those occurring in the plains to the east.* A study of all reported tornadoes in the State of Colorado during 1959-1972, for which wind speeds were recorded or estimated, supports these theories.** Figure 2 shows the

*Reference 7, Pages 4-5.

**Reference 7, Page 11.

These formulae were used to compute the probability of attaining or exceeding a particular gust speed in a given storm. Multiplying that probability by the expected six storms per year gives the wind speed probabilities per year shown in Table 2.

As can be seen from Table 2, these probabilities differ depending on whether the Type I or Type II assumption is made. The Type II distribution has been used more often with wind data. Since it also gives larger probability values, the conservative assumption that the Type II model is the better one will be made in this study. Appendix A gives

FIGURE 2. Geographical Distribution of Tornadoes in the State of Colorado During 1959-1972. Encircled numbers correspond to Fujita Scale damage specifications explained in the text (see Reference 7).

geographical distribution of these tornadoes. Each circle in Figure 2 represents the location of a tornado, and the number inside each circle is a measure of the storm's intensity on the Fujita Scale.⁸ This scale is a way to correlate, approximately, wind speeds with reported damage. The scale is described more fully in the section of this report entitled Structural Damage to Rocky Flats Buildings.

Because of the dependence of tornado frequency and size on the proximity of the mountains, the tornado probability for Rocky Flats is assessed by means of a detailed study of the local area. The geographical area studied is a long, narrow, rectangular region approximately parallel to the

mountains and with the plant in the center of the western edge. The north-south dimension is approximately 41 miles, and the east-west dimension is approximately 10 miles, giving a total area of 429 square miles. The region was defined in terms of its longitudinal and latitudinal coordinates so as to conform to the format in which data on tornado locations are reported.

Specifically, the region is the area from the plant site (39° 54' north latitude, 105° 12' west longitude) plus 0° 18' to the north, minus 0° 18' to the south, and minus 0° 24' to the east. The area of interest therefore is bounded by 39° 36' and 40° 12' north latitude and 105° 12' and 104° 48' west longitude.

TABLE 3. Fujita Scale Damage Specifications (from Reference 15)

Fujita Scale	Wind Speed Range (mph)	Damage Classification	Damage Description
F0	40-72	Light	Some damage to chimneys and TV antennae; breaks twigs off trees; pushes over shallow rooted trees.
F1	73-112	Moderate	Peels surface off roofs; windows broken; light trailer houses pushed or overturned; some trees uprooted or snapped; moving automobiles pushed off the road. 73 mph is the beginning of hurricane wind speed.
F2	113-157	Considerable	Roofs torn off frame houses leaving strong upright walls; weak buildings in rural areas demolished; trailer houses destroyed; large trees snapped or uprooted; railroad boxcars pushed over; light object missiles generated; cars blown off highway.
F3	158-206	Severe	Roofs and some walls torn off frame houses; some rural buildings completely demolished; trains overturned; steel-framed hangar-warehouse type structures torn; cars lifted off the ground; most trees in a forest uprooted, snapped, or leveled.
F4	207-260	Devastating	Whole frame houses leveled, leaving piles of debris; steel structures badly damaged; trees debarked by small flying debris; cars and trains thrown some distances or rolled considerable distances; large missiles generated.

Information from The Severe Storms Forecast Center at Kansas City and from a survey of the Environmental Data Services' *Monthly Bulletin of Storm Data* shows that during the 21 years from 1954 through 1974, eighteen tornadoes were

FIGURE 3. Schematic Representation of Locations of Reported Tornadoes (1954-1974) by Geological Coordinates and in Relation to Rocky Flats. (Notice that scale in miles is different for vertical and horizontal axes.)

reported within the geographical area selected. The intensities were reported for 12 of these and are all either F0 or F1 on the Fujita Scale (see Table 3). The location of these 18 tornadoes by geological coordinates and relative to Rocky Flats is shown schematically in Figure 3.

Probability of a Tornado at Rocky Flats

The average number of tornadoes per year in the region studied is 0.86. Its area is 429 square miles, giving a probability of about 2.0×10^{-3} per year for the occurrence of a tornado per square mile. The probability per year of a tornado striking one or more of the plutonium areas at Rocky Flats is found by multiplying 2.0×10^{-3} by the size of the vulnerable area within the plant site and by taking into account the typical dimensions of the tornado reported in this area. The probability must also be increased somewhat to allow for the supposition that some tornadoes are unreported. Details of

this computation are shown in Appendix B. The probability value obtained is 2.2×10^{-4} per year.

Tornadic Wind Speed at Building Height

The wind speed within a tornado is believed to vary depending on its height above ground and the distance from the tornado center.⁹ Taking the height variation into account and assuming that the strongest tornado that could occur in this geographical location would be of strength F3 (see Table 3), the resulting wind speed at the heights of Rocky Flats' buildings would be in the range of 100 to 150 mph.

DAMAGE FROM DOWNSLOPE WINDS OR TORNADOES

Structural Failure

Information about high-wind damage to structures comes in part from reports of tornado damage and in part from theoretical wind-tunnel studies. For ordinary residential buildings, extensive failure of roofs, walls, and even foundations occur during wind speeds in the range of 150 and 200 mph.^{*} At these speeds, however, reinforced concrete buildings usually are not damaged, except for possible interior damage to areas where windows are broken.^{**} For example, when cyclone Tracy hit Darwin, Australia on Christmas, 1974, wind speeds of up to about 170 mph were measured. Descriptions of the damage included these observations: "Photographs show iron cladding stripped from steel frame hangers of the Air Force Base, and the unreinforced masonry buildings at the Naval Headquarters completely demolished as though they had been hit by an earthquake! On the other hand, concrete structures at the Travel Lodge Motel appear undamaged."¹² And "this

type of structure (reinforced concrete) appeared to perform adequately although the failure of reinforced concrete columns at the Community College in the northern suburbs was an exception. The major reinforced-concrete buildings in the commercial centre suffered damage to brick infill, roof membranes and glazing but apparently no structural damage."¹³

Concrete block and other masonry structures are often damaged by wind speeds above 100 mph. A report on a Dallas, Texas tornado in 1957 contrasts the damage experienced by frame houses and by masonry structures.

In studying damage to structures, two general modes of collapse, one typical for frame houses and the other for masonry structures could be distinguished. Masonry buildings responded to the internal force caused by the pressure reduction outside of the building, which pushed the walls outward and allowed the roof to fall in while frame houses with more ventilation and therefore more possibility for equalization of pressures showed rather the struggle to resist the sheer driving force of the wind. In the latter, the roofs were ripped off by wind motion, and the walls blown over and strewn along the tornado path. Masonry walls, exhibiting more rigidity, acted as a unit and were pushed over at once, while frame construction could give and therefore was not so frequently seriously damaged.*

The minimum wind speeds necessary to cause the collapse of masonry walls during this tornado were estimated at from 92 to 109 mph.^{**}

A general description of the damage resulting from winds of different speeds is found in the Fujita Scale mentioned earlier. This scale classifies storms into five types as shown in Table 3.

Structural Damage to Rocky Flats Buildings

Using the Fujita Scale to classify the winds and applying the descriptive information gathered to

*See Pages 232-252 of Reference 10 for wind-tunnel test results. See Pages 35-43 of Reference 10 for reports on damage from the Topeka tornado of June 8, 1966.

**Eagleman, et al, in discussing the Topeka tornado of June 8, 1966 states, "The large reinforced concrete structures withstood the tornadic winds, although the contents and internal partitions were severely damaged." (Reference 10, Page 27). Melarango (Reference 11) reports that modern reinforced concrete buildings have survived tornado hits with only minor damage.

*Reference 14, Page 167.

**Reference 14, Page 174.

the plutonium buildings at Rocky Flats, the following estimates of the effects on structure from high-speed winds are obtained.

Case A – Winds 125-157 Miles Per Hour

At this speed, buildings having metal or asbestos siding would be expected to suffer some structural damage. Sheets of metal siding might be ripped off. Holes in the wall would allow equipment and stored material to be blown around in the interior of the building. Some of the walls of concrete block buildings may collapse.

Holes might be made in the walls of Building 4, siding might be torn loose from Building 8, and walls of Building 5 and 7 may partially collapse. A speed of 125 mph is used as the lower limit for this case since that value is the design basis wind for Buildings 4, 7, and 8.

Case B – Winds 158-206 Miles Per Hour

Damage to metal or asbestos buildings would be more extensive than that described under Case A. Asbestos siding may shatter in places, and large portions of the walls of masonry (concrete block) buildings may collapse. Doors on concrete structures might be blown in or out allowing some interior wind damage to occur.

Damage from Wind- or Tornado-Borne Missiles

In addition to structural damage during a high wind, buildings may be damaged by loose objects or pieces of more fragile buildings that are picked up and carried along by the wind. The higher the wind speed, the more likely an object is to become airborne and the greater its force when it crashes into anything in its path. Objects that are heavy enough to be a serious source of damage, however, require very fast wind speeds before they become airborne; furthermore, because of air resistance, these airborne missiles travel at speeds less than that of the wind that carries them along. As an example, film analyses of a 1957 tornado in Dallas indicated that although wind speeds reached

172 mph, none of the speeds of 400 pieces of debris travelling over paths that were observed exceeded 125 mph.¹⁶ On the other hand, an example of an object unusual in that it is both heavy and yet “flies well” would be a steel reinforced beam attached to a carport roof that has been torn off its wall by the storm. During a 1973 tornado in Plainview, Texas, such a beam penetrated the exterior wall of a conventional brick-veneer residence and passed through several pieces of furniture inside the house.¹⁵

In safety studies for nuclear reactors, possible damage by missiles ranging from wooden planks to automobiles has been discussed.¹¹ The force with which a missile strikes a building depends on details of the physical characteristics of the object (its weight, size, and aerodynamic features), the speed of the wind, and the vertical and horizontal distances the object is carried. This information would be difficult to obtain for all likely objects and storms; furthermore, the theoretical formulae for penetration gives values that do not correspond closely to empirical data.¹⁷ For these reasons, the following assumptions about types of airborne missiles and their damage will be made.

<u>Missile Description</u>	<u>Damage Expected</u>
Large wooden plank, 12-foot long, weighing about 200 pounds.	Would penetrate the exterior wall (which is 0.5-inch asbestos board) of Building 4.
Steel pipe, 10-feet long weighing about 100 pounds.	Would penetrate the exterior wall of Building 4. Could penetrate the roof of Building 5. (Minimum roof thickness is 2 inches of concrete.)
Automobile, 3000 pounds, rolling into building.	Would make a hole in the wall of Buildings 4, 5, 7, and 8.

It is hypothesized that the wooden plank would become airborne during a windstorm or a tornado at wind speeds in the upper end of the F2 range (about 140-158 mph). It is assumed that a plank hits each of the plutonium buildings when winds

are in that range. For winds above 158 mph, the effect of the missile damage will be ignored because of the more serious structural damage expected, which results in a greater contribution to any radioactive release.

A steel pipe missile is assumed to become airborne during the sustained winds of a tornado (but not during the gusts of a windstorm) and to hit the roof of every plutonium building.

An automobile would become a rolling missile at wind speeds above about 200 mph; however, as was the case for wooden planks, structural damage or failure would be more important at these speeds. For this reason, automobile damage will be omitted.

The assumption that one plank or pipe hits each building under the conditions specified is a compromise between scenarios where no missiles are available and those where many missiles hit each building.

RADIOACTIVE RELEASE

Radioactive Release Resulting from Missiles

Although the three types of missiles discussed would damage the buildings, in most cases no radioactive release would be expected to occur. A missile penetrating a roof would have to hit and make a hole in a filter plenum or in duct work leading to the plenum to cause a release. Such a missile would probably remain lodged in the hole created. If not, the airflow would be into rather than out of the hole as long as the filter's air pump was operating. During a tornado, however, negative pressure for a few seconds outside the building would draw out unfiltered air. Negative pressure also may occur during high winds because of the Bernoulli effect. The amounts of release and their probabilities for each building have been assessed, taking into account the proportion of the second floor that contains ducts and filter plenums. Missiles penetrating the walls of Building 4 will be considered as possibly causing a release (with probability = 0.01) if the hole made is near a glove-box area. In this case, the containment of the box and its duct work could be breached, which would

allow the release of unfiltered air and chips of plutonium.

In the case of damage by missiles to buildings containing plutonium packaged for shipping, it is assumed that holes in the structure will not result in a plutonium release and that containers within the building that might be hit by missiles or blown around by the wind probably would not be broken open. Even if they were, no release of radioactivity from the building would be expected.

Radioactive Release Resulting from Structural Damage

Partial collapse of walls or the ripping off of metal siding from buildings containing packaged plutonium is not expected to lead to any release of radioactivity. For Building 4, the release from possible fracturing of the siding by winds that are in the F2 range of the Fujita Scale would be comparable to that occurring from missile damage. For F3 winds, damage to the walls will be assumed to occur in many locations.

SUMMARY OF HAZARDS

Probabilities

Tornado: The probability per year that a plutonium building will be hit by a tornado is found to be approximately 2.2×10^{-4} .

Maximum Downslope Wind: The probability that the maximum wind speed experienced during a storm will be any particular value is assumed to follow a Fisher-Tippet Type II (Frechet) distribution. The distribution was fit to maximum wind speed data collected at Rocky Flats during five years (32 wind storms). According to these data, the probabilities of high-speed wind gusts are as shown below.

Wind Speed (mph)	Probability (per year)	Return Period (years)
≥100	0.62	1.6
≥150	0.051	20
≥200	0.0084	120

TABLE 4. Summary of Probabilities of Release, Release Amounts, and Weighted Average of Release for Tornadoes

Release Amount (g Pu)	Total Probability (per year)	Weighted Average of Release (g Pu)
0.6	1.1638×10^{-9}	6.9828×10^{-10}
0.7	6.2646×10^{-8}	4.3852×10^{-8}
1	1.0105×10^{-7}	1.0105×10^{-7}
3	6.2646×10^{-8}	1.8794×10^{-7}
Total Tornado Weighted Average of Release (Source Term)		$\sim 3.3 \times 10^{-7}$

Grouping the wind speeds into ranges to correspond to the Fujita wind speed scale produces the following results:

Wind Speed Range (mph)	Fujita Scale Number	Probability (per year)	Return Period (years)
125 - 157	F2	0.16	6.3
158 - 206	F3	0.032	31

Weighted Average of the Release

The amounts of plutonium released, given that a building is damaged, and the probabilities of these releases are assessed by considering the strength of the wind, the amount of plutonium available in the buildings, the distance of the plutonium from exterior walls, the element's form and its containment. Tables 4 and 5 show the total probability, release amount, and wind speed category for tornado and downslope winds. The last column in Tables 4 and 5 is the weighted average of the release (release amount times the total probability). The overall, total, weighted average of the release caused by tornadoes is 3.3×10^{-7} grams plutonium. For high winds, it is found to be 2.2×10^{-3} grams of plutonium (this is also called the "expected value of the release" and the "source term"). These figures show that downslope winds make

TABLE 5. Summary of Probabilities of Release, Release Amounts, and Weighted Average of Release for Downslope Winds

Building	Wind Speed	Total Probability (per year)	Release (g Pu)	Weighted Average of Release (g Pu)
4	F2	1.7392×10^{-5}	0.7	1.2174×10^{-5}
		1.2215×10^{-4}	1	1.2215×10^{-4}
		1.7392×10^{-5}	3	5.2176×10^{-5}
	F2 Total (1.8650×10^{-4})			
	F3	9.1785×10^{-5}	2.1	1.9275×10^{-4}
		2.7219×10^{-4}	3	8.1657×10^{-4}
		9.1785×10^{-5}	9	8.2607×10^{-4}
	F3 Total (1.8354×10^{-3})			
5	F2	1.1842×10^{-5}	0.6	7.1053×10^{-6}
	F3	7.8342×10^{-5}	1.8	1.4101×10^{-4}
Total (5.5103×10^{-4})				
No release from other plutonium buildings		Grand Total Weighted Average of Release (Source Term)		2.1700×10^{-3}

the greatest contribution to the weighted average of releases.

Precision of Results

The computed weighted average of the release caused by high winds (2.2×10^{-3} grams) seems large. It is greater than that computed for aircraft crashes (3.7×10^{-4} grams) and tornadoes (3.3×10^{-7} grams). This value could be unrealistically high if the probabilities of the high winds are too large, if the postulated damage to the buildings is greater than would actually occur, if the assessment of the amount of plutonium released is too conservative, or if any combination of these is the case.

The wind probabilities are based on a well-known mathematical model; however, at some point this model will no longer apply since infinitely fast

winds do not occur. It is not known at what speeds true wind-speed probabilities begin to differ from theoretical ones, nor to what extent they differ. Computing the probabilities with several more years of data would be one way of improving the estimates.

The damage postulated to occur at various wind speeds is based on descriptions of what has happened to buildings of this general type under severe wind conditions. The Rocky Flats buildings may be stronger than the general class. This estimate of building strength could be improved by engineering tests.

Support for the argument that the probability or the damage estimates are too high comes from consideration of the "return period" for the F2 and F3 category winds. The F2 return period is estimated to be 6.3 years. This means that a wind gust in that range would be expected to occur about once every 6.3 years. Since measuring instruments used in the past at Rocky Flats were not designed to record values in excess of 100 mph, the frequency of F2-range winds cannot be verified. It is postulated that in such a wind, the exterior walls of Buildings 4 and 5 would be breached at some point, either by wind-borne missiles or because of structural failure. This damage has not been experienced since the buildings were constructed; consequently, it can be assumed that either the probabilities, the damage, or both are probably overestimated.

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APPENDIX A

DETAILS OF CALCULATIONS OF WIND-SPEED PROBABILITIES

This Appendix details the technique used to compute wind-speed probabilities of maximum gusts on the basis of sample data. The steps in the calculation are (1) The preparation of a probability graph of the data, (2) The fitting, by order statistics, of a straight line through the data. This is used in extrapolations to estimate probabilities for wind speeds greater than those observed in the sample, and (3) The determination of the confidence of probabilities estimated in Step (2). The theory behind these calculations is attributed mainly to Gumbel;⁴ the application of the theory, especially the order statistics calculation, follows the method clearly presented by Lieblein.¹⁸

The data are analyzed by the two distributions, Fisher-Tippett Type I and Fisher-Tippett Type II (also called the Frechet distribution). The second of these assumes that the logarithm of the variable (wind speed), of which the extreme values (maximum gusts) are being studied, follows an exponential type of distribution. This is a commonly made assumption; thus, the Type II distribution will be taken as the correct distribution from which to estimate the maximum wind-speed probabilities. The Type I distribution is shown simply for purposes of comparison and because it was the distribution applied by Amr.² Further data must be collected and work done before anything further can be said on the relative merits of these two distributions.

For the Type I distribution, the cumulative probability of x , $F(x)$, which is the probability of a value (in this example the wind speed) being less than or equal to x , is written as follows:

Type I:

$$P(\text{wind speed} \leq x) = F(x) \quad (1)$$

$$= \exp \left(-\exp \left(-\left(\frac{x-a}{\beta_1} \right) \right) \right)$$

where a and β_1 are constants. The Type II distribution can be found either by substituting $\ln x$ for x or by rewriting the distribution as

Type II:

$$P(\text{wind speed} \leq x) = F(x) \quad (2)$$

$$= \exp \left(-\left(\frac{x}{\beta_2} \right)^{-\gamma} \right)$$

The constants γ and β_2 can be expressed in terms of the Type I constants as

$$\gamma = \frac{1}{\beta_1} \text{ and } \beta_2 = \exp a.$$

The probability of a wind speed greater than the value x , in other words the probability of exceeding x , is equal to $1 - F(x)$ or,

Type I:

$$P(\text{wind speed} > x) = 1 - F(x) \quad (3)$$

$$= 1 - \exp \left(-\exp \left(-\left(\frac{x-a}{\beta_1} \right) \right) \right)$$

and

Type II:

$$P(\text{wind speed} > x) = 1 - F(x) \quad (4)$$

$$= 1 - \exp \left(-\left(\frac{x}{\beta_2} \right)^{-\gamma} \right)$$

For simplicity of notation, a transformation of x is made to y where $y = (x - a)/\beta$ so that, for example, the Type I distribution can be written

$$F(y) = \exp \left(-\exp (-y) \right).$$

TABLE A-1. Rocky Flats Wind Data Covering Five Years

Year	Date*		Data: Original Order, Maximum Wind Speed (mph)	Data: Ordered in Groups of Six Observations (mph)	Data: Ordered from Minimum to Maximum (mph)	Rank
	Month	Day				
1969	1	7	98	62	56	1
	1	29	62	71	62	2
	1	31	100	74	62	3
	3	19	86	86	62	4
	4	7	71	98	62	5
1970	1	25	74	100	66	6
	2	3	97	62	67	7
	2	16	79	62	68	8
	11	21	62	71	68	9
	11	25	71	79	70	10
	11	28	62	97	71	11
	11	30	97	97	71	12
	12	31	67	66	71	13
1971	1	20	71	67	71	14
	1	23	66	71	72	15
	1	25	95	75	74	16
	1	29	76	76	74	17
	2	11	75	95	75	18
	3	4	71	56	76	19
	3	31	74	62	79	20
	12	20	62	71	81	21
1972	1	5	81	74	82	22
	1	9	56	81	86	23
	1	11	105	105	91	24
	1	21	68	68	92	25
	1	24	82	68	95	26
	1	28	91	72	97	27
	11	26	104	83	97	28
	12	1	68	91	98	29
1973	3	13	72	104	100	30
	11	1	70	70	104	31
	12	2	92	92	105	32

*Dates correspond to Boulder-area wind storms.

This is analogous to the use of a standardized variate $t = (x - \mu) / \sigma$ in the normal distribution. This y is referred to as the "reduced variate."

Probability Graph

A probability graph is prepared from data that have been put in order from smallest to largest.

The rank of an observation is then taken as an estimate of its cumulative probability. For example, Table A-1 shows the observed, maximum, wind speed recorded in each of 32 storms. Column 2 lists the data according to original observations. In Column 4, the data have been reordered from smallest to largest. The rank order of each observation is shown in Column 5. The information to be plotted on the probability graph is the ordered

FIGURE A-1. Fitting the Data to a Fisher-Tippett Type I Distribution

FIGURE A-2. Fitting the Data to a Fisher-Tippett Type II Distribution

observations, x_i , $i = 1$ to n , versus their cumulative probability estimate taken to be $i/(n+1)$, where i is the rank and n the total number of observations (here $n = 32$). The x values are plotted on a uniform scale along the horizontal axis. The $i/(n+1)$ values are plotted on a distorted vertical axis, designed in such a manner that the extreme value distribution, $\exp(-\exp(-y))$ will plot as a straight line. To obtain this feature on ordinary graph paper, the value plotted along the vertical axis is

$$y = -\ln(-\ln(i/(n+1))).$$

Wind data graphed in this manner are presented in Figures A-1 and A-2. Two additional scales have been drawn in to permit one to read directly from the graphs the probability of exceeding any wind speed and the corresponding "return period" (the reciprocal of the probability, interpreted as the expected number of storms or years between the occurrence of winds this high or higher). For greater precision the probabilities should be computed from Equation 1 and 2 or Equation 3 and 4 using the constants developed in the next section.

Fitting a Line to the Data

Once the observations have been plotted on an extreme-value probability graph, as described above, a line can be fit by eye to the data. This will provide an approximate method for finding (by interpolation or extrapolation) the probabilities associated with wind speeds other than those observed in the sample. A better way to fit a line to the data, however, is mathematically by means of order statistic as described by Lieblein.¹⁸ The first step in the procedure is to order the data within groups of six observations (Column 3, Table A-1). For details of the rest of the method, see Reference 18. This method yields estimates of the constants in Equation 1 and 2 so that once a model for the process has been chosen (it is concluded here that Equation 2, the Type II model, is appropriate), the cumulative probability values for any x (wind speed) can be determined from the equation. For these data, the constants were computed to be:

$$\text{Equation 1} \quad a = 71.0337$$

$$\beta_1 = 12.1785$$

$$\text{Equation 2} \quad \gamma = 6.27058$$

$$\beta_2 = 70.2809$$

So, for example, applying the Type II distribution for a wind speed of 150 mph results in (from Equation 4)

$$\begin{aligned} P(\text{wind speed} > 150) &= 1 - F(x) \\ &= 1 - \exp\left(-\left(\frac{150}{70.2809}\right)^{-6.27058}\right) \\ &= 1 - \exp(-0.008618) \\ &= 1 - 0.99142 \\ &= 8.5806 \times 10^{-3} \\ &\sim 8.6 \times 10^{-3} \end{aligned}$$

This is the probability of a wind >150 mph *per storm*. To convert to probability per year, we multiply by 6, the estimated number of storms per year.

Confidence of the Estimates

When a line is fit statistically to data as described above and shown in the figures, it is possible to calculate the degree of confidence one should have in that line compared to an ideal line that would be obtained if an infinite amount of data were available. Uncertainty about the accuracy of the position of the fitted line—whether, for example,

its slope should be slightly steeper or less steep—will have a large effect upon values obtained by extrapolating the line far beyond the observed points. For example, using the Type II distribution in Figure A-2 and converting the probabilities to probabilities of occurrence per year, the maximum wind speed of 200 mph is found to have a probability of about 8.4×10^{-3} .

For that probability, however, the corresponding, maximum wind speed would be quite different if the slope of the line changed. It is possible to compute for each probability, the wind speed range about the line, which is plus or minus two standard deviations from the line position. For 200 mph and probability equaling 8.4×10^{-3} , the wind speed range is from about 140 mph to 290 mph. This means it might be correct to say the probability per year of a wind exceeding 140 mph is 8.4×10^{-3} (e.g., the line should be steeper and high value winds are less likely than implied by the present line) or, on the contrary, that the probability per year of a wind exceeding 290 mph is 8.4×10^{-3} (e.g., the line is less steep and higher speed winds are more likely than shown). Consequently, there is a great deal of uncertainty associated with these figures. Nevertheless, the lines as shown are the best estimates of the correspondence between maximum winds and probabilities that can be found from the available sample of 32 storms. There is no statistical reason to assume that the line should be in the steeper part of the range (implying a lessened wind hazard) rather than in the less steep part of the range.

APPENDIX B

DETAILS OF CALCULATIONS OF TORNADO PROBABILITY

Vulnerable Area

The size of the area vulnerable to tornado is taken to be 0.0884 square mile. This figure is computed by adding the "extended areas" of the plutonium buildings. These extended areas are increasing the building dimensions by 145 feet in every direction to account for the fact that the tornado, which is treated as a point in the probability calculation, actually has a width and length. This is the same as saying that if the center of the tornado passes within 145 feet of a building, the building will be assumed to be hit by the tornado. The value of 145 feet is an estimate of the tornado size, based on reported tornadoes in the area and allowing for the possible orientation of the tornado.

Unreported Tornadoes

It is estimated that 80 percent of the tornadoes occurring in this geographical area are reported.

An estimate of the actual tornado frequency, therefore, can be obtained by multiplying the observed frequency by 1.25.

Computation of Annual Probabilities per Square Mile

Nearby area = 429 square miles

Years of observation = 21

Tornadoes observed = 18

Tornadoes per square mile per year = $18/429/21$
 $\cong 2.0 \times 10^{-3}$

Factor to account for unreported tornadoes = ~ 1.25

Annual probability of a tornado, per square mile
 $= 2.0 \times 10^{-3} \times 1.25 = 2.4975 \times 10^{-3}$

At Rocky Flats' Plutonium Areas

2.4975×10^{-3} per square mile $\times$ 0.0884 miles of
vulnerable area = $2.2074 \times 10^{-4} \approx 2.2 \times 10^{-4}$ per year

APPENDIX C

TECHNICAL NOTE ON THE HAZARD AT ROCKY FLATS
FROM POSSIBLE METEORITE IMPACT

The probability per year of a meteorite striking a plutonium building at Rocky Flats is computed to be approximately 8.88×10^{-7} . This implies that such a meteorite impact would be expected less than once in a million years. Because of the small probability of this occurrence and the presumption that even if a meteorite were to hit a plutonium building, there is little chance that a release of plutonium would result, the hazard at Rocky Flats from meteorite impact is considered negligible.

The probability of meteorite impact was computed following the general method proposed by V. E. Blake.¹⁹ Only meteorites having a size greater than or equal to one pound are considered. It has been estimated that about 3,500 such meteorites strike the earth every year. It is assumed that they strike the earth at random; that is, that are equally likely to hit any part of the earth.

Details of the Calculation

The total surface of the earth is approximately equal to 1.97×10^8 square miles. The part of Rocky Flats composed of buildings containing plutonium has an area equal to 0.05 square miles; therefore, the fraction of the earth's surface occupied by these plutonium buildings at Rocky Flats is

$$\frac{0.05}{1.97 \times 10^8}$$

The proportion of the earth *not* occupied by those buildings is then

$$1 - \frac{0.05}{1.97 \times 10^8}$$

Since a meteorite is assumed to strike the earth at a random location, this proportion is also equal to the probability that any particular meteorite hits the earth elsewhere than at a Rocky Flats plutonium building. If there are 3,500 meteorites

equal to or larger than one pound striking the earth per year, the probability that *none* of them hits Rocky Flats is the product of all these probabilities or

$$\left(1 - \frac{0.05}{1.97 \times 10^8}\right)^{3,500}$$

Consequently, the probability that one or more of the meteorites hits Rocky Flats is equal to one minus the probability that none does, or,

$$1 - \left(1 - \frac{0.05}{1.97 \times 10^8}\right)^{3,500}$$

To solve for this quantity, we first find the probability that none strikes Rocky Flats, using the series expansion:

$$(1-a)^n = 1 - na + \frac{n(n-1)a^2}{2!} - \frac{n(n-1)(n-2)a^3}{3!} + \dots$$

or

$$\begin{aligned} \left(1 - \frac{0.05}{1.97 \times 10^8}\right)^{3,500} &= (1 - 2.54 \times 10^{-10})^{3,500} \\ &= 1 - 3,500 (2.54 \times 10^{-10}) \\ &\quad + \frac{3,500 (3,499) (2.54 \times 10^{-10})^2}{2!} - \dots \end{aligned}$$

$$= 1 - 8.88 \times 10^{-7} + 7.89 \times 10^{-13} - \dots$$

The terms in this expansion after the first two are negligible, so we have

$$1 - 8.88 \times 10^{-7}$$

for the probability per year of no meteorite impact at Rocky Flats. The probability per year of one or more such impacts then becomes

$$1 - (1 - 8.88 \times 10^{-7})$$

or

$$8.88 \times 10^{-7}$$