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SECTION 7

PRECIPITATION, FOG, AND ICING

7.1 Introduction. Precipitation, fog, and icing are atmospheric phenomena of interest to the design, fabrication, and flight of aerospace vehicles. In some arid areas of the world, however, precipitation does not occur for several years. Likewise, in areas of moderate to heavy rainfall, there are periods of time without rain. Because precipitation does occur in discrete events, statistical representation may be misleading; therefore, caution must be taken to ensure that data relative to the desired location are used. Definitions used in this section are given in the following paragraphs. For definition of size ranges see reference 7.21.

7.2 Definitions.

Precipitation: Precipitation is usually defined as all forms of hydrometeors, liquid or solid, which are free in the atmosphere and reach the ground. In this report, the definition is extended to those hydrometeors which do not reach the ground but impinge on a flying surface, such as space vehicles. Accumulation is reported in depth over a horizontal surface, i.e., millimeters or inches for liquid phase, and in depth or depth-of-water equivalent for the frozen phase.

Icing: In general, any deposit or coating of ice on an object, caused by the impingement and freezing of liquid hydrometers. Aircraft “icing” forms by the freezing of supercooled cloud drops and is always determined by aerodynamical considerations.

Mist: Mist is composed of a suspension of very small (from submicrometer to ~20 μm in diameter) water droplets in the air. Mist reduces the horizontal visibility at the Earth's surface, as does fog, rain, snow, and other hydrospheric and lithospheric substances.

Drizzle: Drizzle consists of droplets which are so small that they make no precipitable impact on surfaces. If individual droplets make a distinct splash on striking the ground or a water surface, they should be recorded as rain (ref. 7.1).

Glaze: A coating of ice, generally clear and smooth but usually containing some air pockets, formed on exposed objects by the freezing of a film of supercooled water deposited by rain, drizzle, fog, or possibly condensed from supercooled water vapor.

Rain: There is no universal agreement on the precise dividing line between drizzle and rain. However, many texts suggest diameters near 0.5 mm or larger. Regardless, most observers can easily determine when moisture begins to fall as visibly separate drops, which then becomes the practical differentiation between the two terms.

Freezing Rain: Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground or exposed objects.

Fog: A visible mist.

Hail: Precipitation in the form of balls or irregular lumps of ice and is always produced by convective clouds. Through established convention, to be classified as hail the diameter of the ice must be 5 mm or more and the specific gravity must be between 0.60 and 0.92.

Rime: A white or milky and opaque granular deposit of ice formed by the rapid freezing of super cooled water drops as they impinge upon an exposed object.

Sleet: A mixture of rain and snow, or partially melted snow.

Small Hail: Precipitation in the form of semitransparent round or conical grains of frozen water under 5 mm in diameter. Each grain consists of a nucleus of soft hail (ball of snow) surrounded by a very thin ice layer. The grains are not crisp and do not usually rebound when striking a hard surface.

Snow: All forms of frozen precipitation except large hail. It encompasses snow pellets, snow grains, ice crystals, ice pellets, and small hail.

The previously described precipitation forms are sufficiently different that each must be considered separately in design problems.

7.3 Rainfall. There are four major rainfall-producing atmospheric conditions: (1) the monsoon, which produces the heaviest precipitation over long periods (most world records of rainfall rates for periods greater than 12 hours are a result of monsoons); (2) thunderstorms, which generate high rates of precipitation for short periods; (3) cold and warm frontal systems, frequently accompanied by bands of steady light rain. Frontal-produced rain can persist for several days depending upon the movement of synoptic scale weather systems (thunderstorms may occur with frontal systems to give heavier rain), and (4) hurricanes, which produce heavy rain associated with winds. These four rainfall types are defined in the following paragraphs.

Monsoon: The monsoon is a seasonal wind which blows for long periods of time, usually several months from one direction. When these winds blow from the water to land with increasing elevation from the water, the orographic lifting of the moisture-laden air releases precipitation in heavy amounts. In Cherrapunji, India, 9,144 mm (360 in) of rain has fallen in a 1-month period from monsoon rains. The amount of rain from monsoons at low elevations is considerably less than at higher elevations.

Thunderstorm: In general, the thunderstorm (local storm) is produced either by lifting of unstable moist air, heating of the land mass, lifting by frontal systems, or a combination of these conditions. Cumulonimbus clouds, which are produced by these storms, are always accompanied by lightning and thunder. The thunderstorm is a consequence of atmospheric instability and is defined loosely as an overturning of air layers in order to achieve a stable condition. Strong wind gusts, heavy rain, severe electrical discharges, and sometimes hail occur with the thunderstorm, with the most frequent and severe occurrences in the late afternoons and evenings.

Rain shower: Precipitation from a convective cloud. Showers are characterized by the suddenness with which they start and stop, by the rapid changes of intensity, and usually by rapid changes in the appearance of the sky.

Cold and warm front precipitation: When two masses of air meet-one more dense than the other-the lighter air mass (warm) will slide up over the more dense air mass (cold). If sufficient moisture is in the air mass being lifted, then the moisture will be condensed out and fall as precipitation, either rain or snow, depending on the temperature of air masses.

Hurricanes: A hurricane is a severe “tropical storm” which forms over the various oceans and seas, nearly always in tropical latitudes. At maturity the tropical cyclone (storm) is one of the most intense and feared storms in the world: Winds exceeding 90 m/s (175 km) have been measured, and rainfall can be torrential. The wind speed must exceed 33 m/s (64 km) for the storm to be classified as a hurricane.

Orographic effects should not be overlooked in a discussion of rainfall. Islands located in persistent moist air flow receive extreme rainfall as a result of the moist air being lifted to the condensation level (frequently over 2,000 to 5,000 ft altitude), with resulting persistent rain. This phenomenon accounts for wide variations in precipitation amounts between locations in close proximity in mountainous areas.

7.3.1 Record Rainfall. In design analysis, the maximum amounts of rainfall for various periods need to be considered. These extreme values vary considerably in different areas of the world, but in areas of similar climatic conditions the extreme values are similar.

7.3.1.1 World Record Rainfall. To best study the maximum amounts of rainfall that have occurred worldwide for different periods, log-log graph paper is used. Figure 7.1 shows these worldwide values and the envelope of these values as a straight line with the equation

$$R = 363.0\sqrt{D_h}\ (\text{mm}) \qquad \text{or} \qquad R = 14.3\sqrt{D_h}\ (\text{in}) \tag{7.1}$$

where R is the depth or rainfall in millimeters for period D, and D_h is the duration of rainfall in hours. Due to the lack of sufficient objective data at less than about 20 min duration, much greater scatter in individual measurements is observed, which reduced the reliability of the straight line graph in this region.

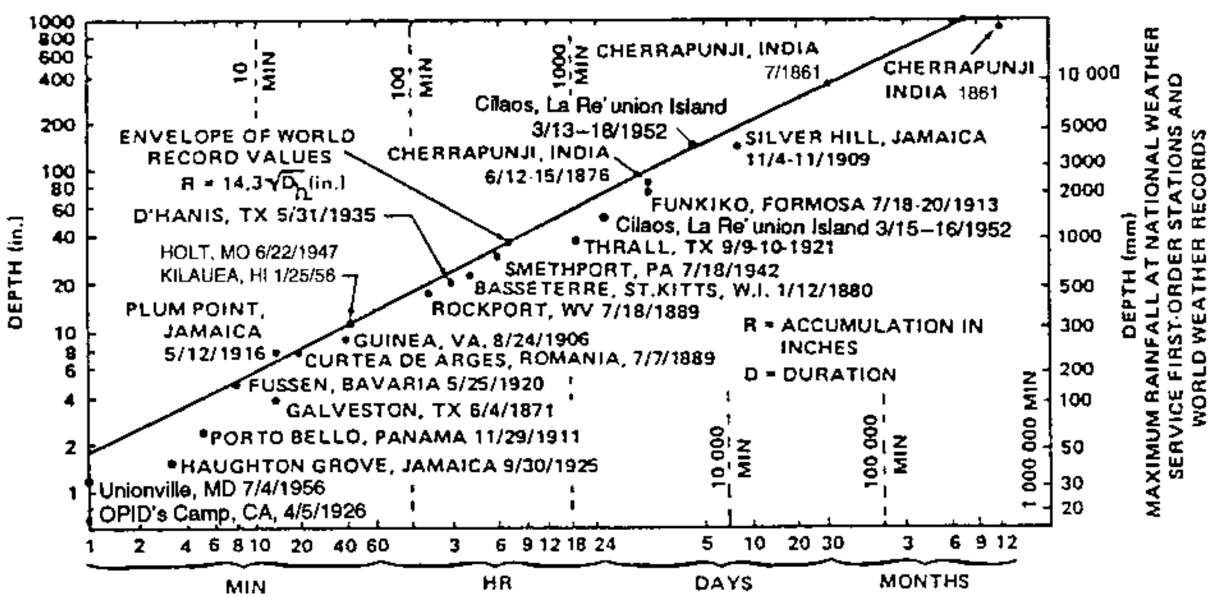


FIGURE 7.1 World Record Rainfalls and an Envelope of World Record Values (after R.D. Fletcher and S. Sartos, Air Weather Service Tech. Report No. 105-81, 1951 and Ref. 7.2).

7.3.1.2 Design Rainfall Rates. For design and testing, the rate of rainfall per unit time is more useful than the total depth of rainfall. The normal rates used are shown in millimeters per hour or inches per hour. Figure 7.2 shows the envelope of world record values plotted as the rate per hour (inches and millimeters) versus duration.

The Kennedy Space Center and Vandenberg AFB design rainfall rate curves are also shown in figure 7.2 with the 5-year and 100-year return periods for a few select stations. The 5-year and 100-year return period data were taken from rainfall intensity-duration-frequency curves published by the U.S. Department of Commerce, Weather Bureau (Ref. 7.3). These data were analyzed by the extreme value method of Gumble (Ref. 7.4).

The term "return period" is a measure of the average time interval between occurrences of a specific event. For example, the 99th percentile rainfall rate for Tampa, Florida, is approximately 10 in/hr for a duration of 6 min (from fig. 7.2 and table 7.1). On the average this rainfall rate can be expected to return in 100 years at Tampa. Return periods can be expressed as probabilities, as shown in table 7.1.

Values of design rainfall for various locations and worldwide extremes of rainfall are given in tables 7.2, 7.3, 7.4, and 7.5 with values of the corresponding drop size. The worldwide extremes would not normally be used for design of space vehicles but may be needed for facility design, tracking stations, etc. The values of rainfall rates are represented with the following equation:

$$r = \frac{C\sqrt{D_m}}{D_m} = \frac{C}{\sqrt{D_m}} , \tag{7.2}$$

where

r = rate in inches per hour or mm per hour

D_m = time in minutes

C = constants for locations are given in table 7.6.

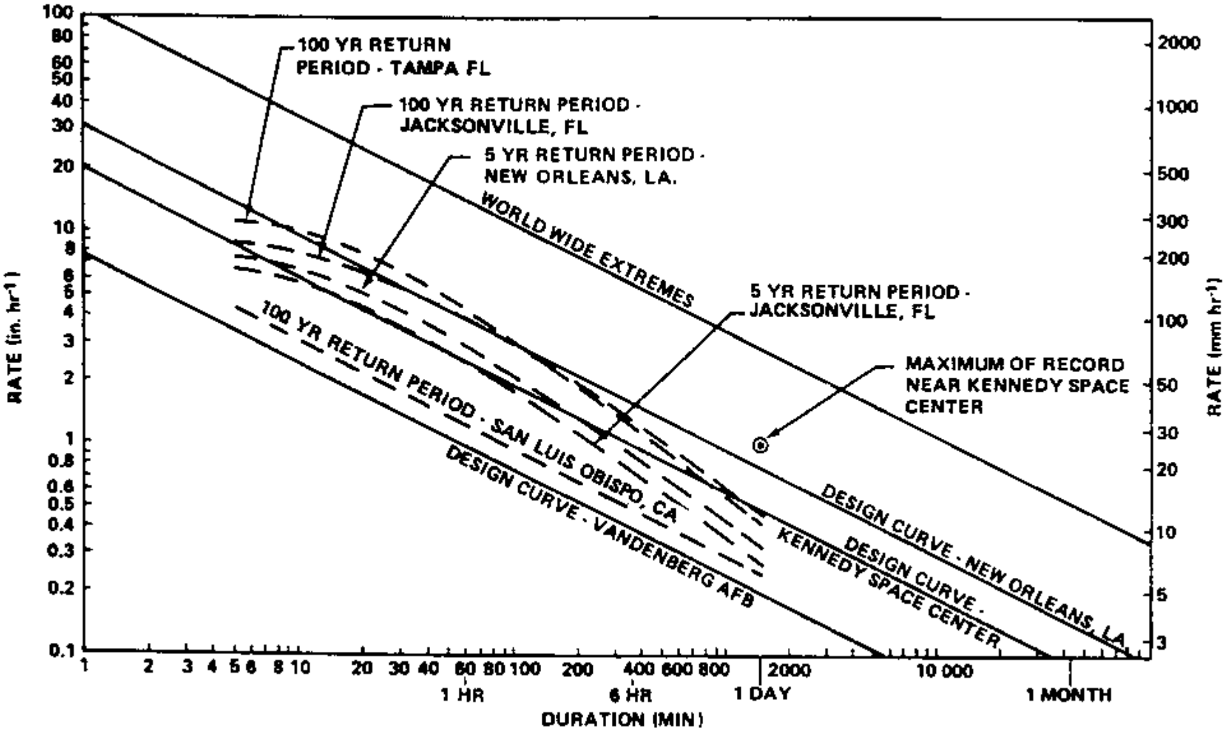


FIGURE 7.2 Design Rainfall Rates.

TABLE 7.1 Relationship of Return Periods to Probabilities.

Return Period	Percentile	Return Period	Percentile
(year)	(%)	(year)	(%)
2	50	50	98
5	80	100	99
10	90	1,000	99.9

TABLE 7.2 Design Rainfall, Kennedy Space Center, FL, and Huntsville, AL, Based on Yearly Largest Rate for Stated Time Periods.*

TimePeriod	Rainfall Rate (*r*)		Rainfall Total Accumulation		Raindrop Size Average	Raindrop Size Largest
	mm h^{-1}	in h^{-1}	mm	in	mm	mm
1 min	492	19.4	8	0.3	2.0	6.0
5 min	220	8.7	18	0.7	2.0	5.8
15 min	127	5.0	32	1.25	2.0	5.7
1 h	64	2.5	64	2.5	2.0	5.0
6 h	26	1.0	156	6.1	1.8	5.0
12 h	18	0.7	220	8.7	1.6	4.5
24 h	13	0.5	311	12.2	1.5	4.5

*Use average rate of fall for raindrops of 6.5 m/s for all time periods.

TABLE 7.3 Design Rainfall, New Orleans, LA, Based on Yearly Largest Rate for Stated Time Periods.*

Time Period	Rainfall Rate (r)		Rainfall Total Accumulation		Raindrop Size Average	Raindrop Size Largest
	mm h^{-1}	in h^{-1}	mm	in	mm	mm
1 min	787	31.0	13	0.5	2.1	6.0
5 min	352	13.9	29	1.2	2.0	6.0
15 min	203	8.0	51	2.0	2.0	5.7
1 h	102	4.0	102	4.0	2.0	5.5
6 h	41	1.6	249	9.8	1.9	5.0
12 h	29	1.2	352	13.9	1.8	5.0
24 h	21	0.8	498	19.6	1.6	5.0

*Use average rate of fall for raindrops of 6.5 m/s for all time periods.

TABLE 7.4 Design Rainfall, Vandenberg AFB, CA, Edwards AFB, CA, and White Sands Missile Range, NM, Based on Yearly Largest Rate for Stated Time Periods*.

Time Period	Rainfall Rate (r)		Rainfall Total Accumulation		Raindrop Size Average	Raindrop Size Largest
	mm h^{-1}	in h^{-1}	mm	in	mm	mm
1 min	197	7.7	3	0.1	2.0	5.6
5 min	88	3.5	7	0.3	2.0	5.3
15 min	51	2.0	13	0.5	2.0	5.0
1 h	25	1.0	25	1.0	1.8	5.0
6 h	10	0.4	62	2.4	1.5	4.6
12 h	7	0.3	88	3.5	1.3	4.3
24 h	5	0.2	124	4.9	1.3	4.0

*Use average rate of fall for raindrops of 6.5 m/s for all time periods; except use 6.0, 5.8, and 5.5 m/s for 6, 12, and 24 h, respectively.

TABLE 7.5 Design Rainfall, Worldwide Extremes, Based on Yearly Largest Rate for Stated Time Periods.*

Time Period	Rainfall Rate (r)		Rainfall Total Accumulation		Raindrop Size Average	Raindrop Size Largest
	mm h^{-1}	in h^{-1}	mm	in	mm	mm
1 min	2,813	110.8	47	1.8	2.5	8.0
5 min	1,258	49.5	105	4.1	2.2	8.0
15 min	726	28.6	182	7.1	2.1	8.0
1 h	363	14.3	363	14.3	2.0	8.0
6 h	148	5.8	890	35.3	2.0	5.8
12 h	105	4.1	1,258	49.5	2.0	5.5
24 h	74	2.9	1,779	70.1	2.0	5.2

*Use average rate of fall for raindrops of 6.5 m/s for all time periods.

TABLE 7.6 Constants to Use With Equation (7.2) for Rainfall Rates.

	Kennedy Space Center, Huntsville	New Orleans	Vandenberg AFB, Edwards AFB, White Sands Missile Range	World Extremes
in h^{-1} mm h^{-1}	19.365 491.87	30.984 786.99	7.746 196.75	110.767 2,813.48
Values of *r* given in Table No.	7.2	7.3	7.4	7.5

7.3.2 Raindrop Size. A knowledge of raindrop sizes is required to (1) simulate rainfall tests in the laboratory, (2) know the rate of fall of the raindrops and impact energy, and (3) use in erosion tests of materials.

At the surface, the size of the raindrops varies with the rate of rainfall per unit time; the heavier the rainfall, the larger the drops. Any one rainstorm will contain a variety of sizes of raindrops ranging from less than 0.5 mm (the lower limit of size measurement) to greater than 4.0 mm. The more intense the storm (the higher the rate of rainfall), the larger some of the drops will be. Reference 7.5 shows data on probability of occurrence of various raindrop sizes with relation to types of rain-producing storms: (1) thunderstorms, (2) rain showers, and (3) continuous rain. Thunderstorms have the greatest occurrence of the larger drops (over 2 mm). Rain showers have the next greatest occurrence, while the continuous rain produces the lowest occurrence of the larger drops. Rain drop sizes below 2 mm in diameter occur with near equal probability from all types of storms. In comparing drop sizes with various rainfall rates, the larger drops occurred with the highest probability from the highest rainfall rates. Raindrops over 8 mm in diameter are not expected to occur frequently because the rate of fall breaks these large drops into smaller ones (Ref. 7.6).

The raindrop size distribution depends critically on the origin of the rain. In particular, very large drops can exist when they are stabilized by a little unmelted ice as from a thunderstorm soft hail shower.

7.3.3 Statistics of Rainfall Occurrences. One set of statistical data on precipitation will not be satisfactory for all needs in design; therefore, several sets of statistical data are presented in this section as follows.

7.3.3.1 Design Rainfall Rates. The design rainfall rates in figure 7.2 and tables 7.2, 7.3, 7.4, and 7.5 are based on precipitation occurrences; i.e., if precipitation is occurring, what is the probability of exceeding a given rate? These data are based on occurrences over a year and would be used in design of items continuously exposed, such as launch facilities.

7.3.3.2 Probability That Precipitation Will Not Exceed a Specific Amount in Any One Day. Values for each month with the probability that precipitation will not exceed a specified amount in any one day are given for several selected sites of aerospace vehicle design interest—Kennedy Space Center, FL; Edwards AFB, and Vandenberg AFB, CA, and New Orleans, LA—in tables 7.7 through 7.10, respectively. The values in the tables should not be interpreted to mean that the amount of precipitation occurs uniformly over the 24-h period, since it is more likely that most or all of the amounts occurred in a short period of the day.

7.3.3.3 Rainfall Rates Versus Duration for 50th, 95th, and 99th Percentile, Given a Day With Rain for the Highest Rain Month, KSC, FL. Rainfall rates for various durations for the 50th, 95th, and 99th percentile, given a day with rain in the highest rain month, are given in table 7.11 for the Kennedy Space Center, FL. The precipitation amounts should not be interpreted to mean that the rain fell uniformly for a brief period for the referenced time periods with no rain the remainder of the time period. As an example, the 99th percentile total of 49 mm (1.93 in) (i.e., left column, 99th percentile, 1-h duration as shown on table 7.11) could have occurred as follows: 25 mm (0.98 in) could have fallen during a 5-min period within a particular hour, with an additional 24 mm (0.95 in) of rainfall for another 5-min period, making a total of 49 mm (1.93 in) for a total of about 10 min. Subsequently, no rain would have fallen for 50 min of the hypothetical 1-h period. The 99th percentile rainfall data are referenced in that such extremes are important to consider in vehicle and facility design studies. Table 7.2 has rainfall rates listed as well as total accumulation, raindrop size, etc., for various periods for Kennedy Space Center and Huntsville, which are also valuable data to use as vehicle criteria.

7.3.4 Distribution of Rainfall Rates With Altitude. Rainfall rates normally decrease with altitude when rain is striking the ground. The rainfall rates at various altitudes in percent of the surface rates are given in table 7.12 for all areas (Ref. 7.7). Table 7.12 values are representative of summer rain rates (from 2.8 through 10.3 mm/h) in temperate latitudes for updrafts from 0.1 to 0.4 m/s.

Tattelman (Ref. 7.5) models the mil-standard, world-wide, extreme rainfall rates with height based on estimates of surface rates occurring 0.5, 0.1, and 0.01 percent of the time for the worst month in the severest rain areas of the world, also for the 42- and 1-min world record rainfalls. These five extreme cases are representative of surface rainfall rates of 36 to 1,872 mm/h.

Precipitation above the ground is generally colder than at the ground and frequently occurs as super-cooled drops which may cause icing on objects moving through the drops. Such icing can be expected to occur when the air temperature is about -2.2 °C (28 °F). The major factors that influence the rate of ice formation are (1) the amount of liquid water, (2) the droplet size, (3) air speed, and (4) the size and shape of the airfoil (Ref. 7.8). Terminal fall velocities for various raindrops with diameters from 0.05 to 0.70 cm are given in table 7.18.

7.3.5 Types of Ice Formation. The type of ice which will form on the outside exposed surfaces of cryogenic tanks is related to the temperature of the tank surface, the precipitation rate, drop size, and wind velocity (or tank velocity). In general, the larger the drop size and the higher the temperature, precipitation rate, and wind speed, the denser the ice will form until a condition is reached where surface temperatures are too high for ice formation. If the precipitation is at too high a temperature at relatively high precipitation rates and wind speed, it may warm the tank sufficiently to melt ice which formed previously.

Table 7.13 summarizes ice types for various tank wall temperatures with moderate precipitation (over 10 mm h^{-1}).

TABLE 7.7 Probability that Precipitation Will Not Exceed a Specific Amount in Any One Day, Kennedy Space Center, FL.

Amount		Jan.	Feb.	March	Apr.	May	June
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	68.1	60.8	62.2	70.6	64.2	54.7
Trace	Trace	77.1	71.4	71.3	80.0	76.2	65.7
0.01	0.25	79.0	74.3	72.5	82.7	79.4	68.4
0.05	1.27	84.8	79.4	77.5	86.6	84.7	74.1
0.10	2.54	87.1	82.3	81.6	89.3	89.4	75.8
0.25	6.35	90.0	85.8	87.8	93.5	92.9	82.8
0.50	12.70	93.9	91.6	91.6	95.9	96.4	90.8
1.00	25.40	97.1	96.1	96.3	98.0	99.3	97.1
2.50	63.50	99.4	100.0	99.5	99.5	100.0	99.8
5.00	127.00	100.0	100.0	99.8	99.8	100.0	100.0
Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	56.8	52.6	40.0	47.4	62.1	64.2
Trace	Trace	65.8	63.9	53.9	61.6	74.2	78.1
0.01	0.25	68.4	66.2	57.5	63.9	77.2	81.0
0.05	1.27	73.2	69.4	62.7	72.0	83.9	86.8
0.10	2.54	75.8	74.9	67.9	76.8	86.9	89.4
0.25	6.35	83.5	80.7	75.8	85.5	90.8	93.3
0.50	12.70	88.3	88.4	83.7	91.3	92.6	96.5
1.00	25.40	93.8	93.6	92.2	95.5	96.2	99.1
2.50	63.50	99.6	99.7	97.4	99.4	99.2	100.0
5.00	127.00	99.6	100.0	99.8	99.7	99.5	100.0

The 100 percent values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months, however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

TABLE 7.8 Probability that Precipitation Will Not Exceed a Specified Amount in Any One Day, Edwards AFB, CA.

Amount		Jan.	Feb.	March	Apr.	May	June
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	81.7	81.8	82.6	86.7	95.1	98.8
Trace	Trace	88.0	88.9	89.6	93.8	98.6	99.5
0.01	0.25	88.9	89.5	91.3	94.8	99.0	99.5
0.05	1.27	91.7	92.1	93.8	96.4	99.1	99.5
0.10	2.54	93.5	93.5	95.5	97.6	99.4	99.5
0.25	6.35	96.9	95.6	98.0	99.0	100.0	99.9
0.50	12.70	98.8	98.3	99.1	99.6	100.0	100.0
1.00	25.40	99.8	99.6	99.8	100.0	100.0	100.0
2.50	63.50	100.0	100.0	99.9	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0
Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	94.7	95.2	94.6	93.0	89.8	85.2
Trace	Trace	99.0	98.1	97.8	95.8	94.2	90.8
0.01	0.25	99.3	98.1	98.2	96.1	94.4	91.4
0.05	1.27	99.7	98.9	98.9	97.2	96.4	93.7
0.10	2.54	99.7	99.3	98.9	98.2	97.0	94.9
0.25	6.35	100.0	99.6	99.2	99.2	98.4	96.7
0.50	12.70	100.0	99.9	99.8	99.6	99.3	99.0
1.00	25.40	100.0	100.0	99.9	99.7	100.0	99.9
2.50	63.50	100.0	100.0	100.0	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

The 100 percent values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months, however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

TABLE 7.9 Probability that Precipitation Will Not Exceed a Specific Amount in Any One Day, Vandenberg AFB, CA.

Amount (in)	Amount (mm)	Jan. %	Feb. %	March %	Apr. %	May %	June %
0.00	0.00	69.4	70.4	61.7	70.4	71.8	70.0
Trace	Trace	79.1	75.9	72.2	80.4	94.0	94.8
0.01	0.25	81.1	76.9	74.6	82.5	96.8	97.7
0.05	1.27	83.5	81.4	83.9	87.9	98.0	100.0
0.10	2.54	88.3	84.4	85.9	90.8	98.8	100.0
0.25	6.35	91.5	90.4	91.5	95.4	99.6	100.0
0.50	12.70	95.1	94.4	96.3	97.5	100.0	100.0
1.00	25.40	98.3	96.9	98.7	99.2	100.0	100.0
2.50	63.50	99.9	99.9	99.5	100.0	100.0	100.0
5.00	127.00	100.0	100.0	99.9	100.0	100.0	100.0
Amount (in)	**Amount (mm)**	**July %**	**Aug. %**	**Sept. %**	**Oct. %**	**Nov. %**	**Dec. %**
0.00	0.00	62.4	63.4	77.9	79.4	73.3	73.8
Trace	Trace	98.2	94.9	95.4	95.1	82.6	80.6
0.01	0.25	98.9	98.1	95.8	95.5	83.3	83.1
0.05	1.27	100.0	98.8	97.5	95.9	85.9	87.4
0.10	2.54	100.0	99.5	97.9	96.7	87.4	89.2
0.25	6.35	100.0	99.9	98.7	97.5	90.0	93.5
0.50	12.70	100.0	100.0	99.9	98.7	94.4	97.1
1.00	25.40	100.0	100.0	100.0	99.5	98.8	99.6
2.50	63.50	100.0	100.0	100.0	99.9	99.9	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

The 100 percent values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months, however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

TABLE 7.10 Probability that Precipitation Will Not Exceed a Specific Amount in Any One Day, New Orleans, LA.

Amount		Jan.	Feb.	March	Apr.	May	June
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	77.1	70.2	73.6	79.7	75.9	72.2
0.01	0.25	77.7	71.1	74.1	79.9	76.4	72.6
0.05	1.27	80.9	74.5	78.1	81.9	78.0	77.7
0.10	2.54	85.7	76.4	81.0	83.6	82.9	82.3
0.20	5.08	89.1	80.4	82.8	87.0	86.5	85.3
0.50	12.70	94.0	88.8	88.6	91.2	92.2	90.3
1.00	25.40	97.4	93.8	92.9	95.3	95.6	93.8
2.00	50.80	98.9	97.8	97.9	97.8	99.0	98.8
5.00	127.00	99.7	99.7	99.7	100.0	100.0	100.0
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0
Amount		July	Aug.	Sept.	Oct.	Nov.	Dec.
(in)	(mm)	%	%	%	%	%	%
0.00	0.00	54.5	70.1	69.2	84.4	83.4	77.6
0.01	0.25	55.8	71.3	71.1	85.6	84.7	78.2
0.05	1.27	61.4	74.4	76.3	88.2	85.7	80.7
0.10	2.54	67.4	79.3	79.2	90.5	87.4	83.2
0.20	5.08	73.3	83.5	84.4	93.4	89.4	85.2
0.50	12.70	81.5	92.4	90.3	96.0	94.0	91.9
1.00	25.40	91.5	95.7	94.5	98.0	97.3	95.2
2.00	50.80	96.7	98.2	98.0	99.7	98.3	99.4
5.00	127.00	100.0	100.0	99.0	100.0	99.7	99.7
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0

The 100 percent values in the table indicate no chance of exceeding certain amounts of precipitation during most of the months, however, it should be realized that the length of available data records is not long and that there is always a chance of any meteorological extreme of record being exceeded.

TABLE 7.11 Highest rainfall rate versus duration for various probabilities, given a day with rain for the highest rain month, Kennedy Space Center, FL.

	Percentile											
	50				95				99			
Duration	(in)	(mm)	in h^{-1}	mm h^{-1}	(in)	(mm)	in h^{-1}	mm h^{-1}	(in)	(mm)	in h^{-1}	mm h^{-1}
5 min	0.22	5.6	2.6	66.0	0.72	18.0	8.7	221.0	1.00	25.0	12.0	305.0
15 min	0.23	5.8	0.93	24.0	0.88	22.0	3.5	89.0	1.30	33.0	5.2	132.0
1 h	0.25	6.4	0.25	6.4	1.17	30.0	1.17	30.0	1.93	49.0	1.93	49.0
6 h	0.28	7.1	0.05	1.3	1.55	39.0	0.26	6.6	3.18	81.0	0.53	13.0
24 h	0.43	10.9	0.02	0.5	2.62	67.0	0.11	2.8	5.00	127.0	0.21	5.3

TABLE 7.12 Distribution of Rainfall Rates With Height.

For All Four Locations*		For World Extremes†	
Height (Geometric) Above Surface (km)	Percent Surface Rate	Height Above Surface (km)	Percent Surface Rate
SFC	100	SFC	100
1	90	2	100
2	75	4	100
3	57	6	100
4	34	8	74
5	15	10	51
6	7	12	35
7	2	14	22
8	1	16	11
9	0.1	18	8
10 and over	<0.1	20	0

*Summer type rainfall in temperate latitudes representing 2.8 through 10.3 mm/h rain rates (Ref. 7.7).
†Mil-Std: For worst month, in severest rain area, representing 36 through 1,872 mm/h rain rates (Ref. 7.5).

TABLE 7.13 Ice Types as a Function of Tank Wall Temperatures.

Temperature of Tank Wall		Type of Ice	Density Range		Remarks
°F	°C		lb ft^{-3}	g cm^{-3}	
23 to 32	–5 to 0	clear ice	60	0.69	hard dense ice
15 to 23	–9 to –5	milky ice or clear ice with air bubbles	43 to 53	0.69 to 0.85	
below 15	below –9	rime ice	18 to 25	0.29 to 0.40	crumbly

Table 7.14 Summary of hydrometeor characteristics (ref. 7.9).

Type of Hydrometeor	Altitude (km)	Drop Diameter (μm)		Concentration per Unit Volume (cm^3)		Liquid Water Content Per Unit Volume ($g\ m^{-3}$)		Ambient Temperature (°C)
	Range	Range	Rep.[1]	Range	Rep.	Range	Rep.	Range≈
Layer Clouds	sfc–1.5	<1–40	11	<10–10,000	500	<0.1–1	0.2	+30 to –15
Layer Clouds	2.5–7.5	<1–50	12	<20–1,000	100	<0.1–1	0.2	+20 to –25
Layer Clouds (ice crystals)	7.5–15.0	<10–10,000	100	<0.1–10	0.2	<0.01–0.1	0.02	–10 to –55
Convective Clouds								
Fair Weather Cumulus	0.5–8.0	<1–75	12	<10–10,000	300	<0.1–1	0.5	+20 to –30
Cumulus Congestus	0.5–13.0	<1–200	25	<10–10,000	150	<1–10	4.0	+20 to –55
Continuous Type Rain	sfc–6.0	<500–3,000	1,000	<50–3,000*	500*	<0.05–0.7	0.1	+30 to –15
Shower Type Rain	sfc–13.0	<500–7,000	2,000	<10–3,000*	500*	<0.1–30	1.0	+30 to –55
Coalescence (Warm) Rain	sfc–5.0	<100–1,000	500	<500–50,000*	3,000*	<0.05–0.1	0.1	+30 to 0
Hail	sfc–13.0	<0.01–13 cm	0.8 cm	<0.5–1,000*	50*	<0.1–0.9**	0.8**	+30 to –55
Ice and Snow Crystals	sfc–13.0	<100–20,000	5,000	<1–1,000*	100*	<0.001–0.7***	0.07***	+5 to –55

1. Rep.: Representative value or value most frequently encountered.
* Per m^3
** Density of particles ($g\ cm^{-3}$)
*** Mass of crystals (mg)

7.3.6 Hydrometeor Characteristics With Altitude. Raindrops falling on the surface may originate at a higher altitude as some other form of hydrometeor, such as ice or snow. The liquid water content of these hydrometeors per unit volume would have a distribution similar to that given in table 7.14 for rainfall. A summary of the hydrometeor characteristics from reference 7.9 is given in table 7.14.

7.4 Snow. The accumulation of snow on a surface produces stress. For a flat horizontal surface, the stress is proportional to the weight of the snow directly above the surface. For long narrow objects, such as pipes or wires lying horizontally above a flat surface (which can accumulate the snow), the stress can be figured as approximately equal to the weight of the wedge of snow with the sharp edge along the object and extending above the object in both directions at approximately 45° to the vertical. (In such cases, the snow load would be computed for the weight of the snow wedge above the object and not the total snow depth on the ground). The weight of new-fallen snow on a surface varies between 0.5 kg m^{-2} per cm of depth (0.25 lb ft^{-2} in^{-1}) and 2.0 kg m^{-2} per cm of depth (1.04 lb ft^{-2} in^{-1}), depending on the atmospheric conditions at the time of the snowfall. Snow near 0 °C (wet snow) can build up on power lines to >10 times line diameter and lead to failure. Wind can cause galloping (wind induced oscillations) which enhance failure.

7.4.1 Snow Loads at Surface. Maximum snow loads of the following areas are:

a. Huntsville and Edwards AFB. For horizontal surfaces a snow load of 25 kg m^{-2} (5.1 lb ft^{-2}) per 24-h period (equivalent to a 10-in snowfall) to a maximum of 50 kg m^{-2} (10.2 lb ft^{-2}) in a 72-h period, provided none of the snow is removed from the surface during that time, should be considered for design purposes.

b. Vandenberg AFB and White Sands Missile Range. For horizontal surfaces, a maximum snow load of 10 kg m^{-2} (2.0 lb ft^{-2}) per one 24-h period (equivalent to a 4-in snowfall) should be considered for design purposes.

c. Kennedy Space Center and New Orleans area snow loads need not be considered.

7.4.2 Snow Particle Size. Snow particles may penetrate openings (often openings of minute size) in equipment and cause a malfunction of mechanical or electrical components, either before or after melting. Particle size, associated wind speed, and air temperature to be considered are as follows:

a. Huntsville and Edwards AFB. Snow particles 0.1-mm (0.0039-in) to 5-mm (0.20-in) diameter; wind speed 10 m s^{-1} (19 kn); air temperature -17.8 °C (0 °F).

b. Vandenberg AFB and White Sands Missile Range. Snow particles 0.5-mm (0.020-in) to 5-mm (0.20-in) diameter; wind speed 10 m s^{-1} (19 knots); air temperature -5.0 °C (24 °F).

7.5 Hail*. Hail is precipitation in the form of balls or irregular lumps of ice and is always produced by convective clouds. By definition, hail has a diameter of 5 mm (0.2 in) or more. Hailfalls are small-scale areal phenomena, with a relatively infrequent occurrence rate at any given geographical point. The resulting time and space variability of hail is its prime characteristic.

There are two areas of confusion regarding hail: (1) definition and (2) assessment of damage due to hail. First is the question of whether snow or ice pellets (often called "small hail") are hailstones. Sleet has also been confused with small hail, but convective cloud origin and size of stone are two factors which separate hail from any other form of frozen hydrometeors. The second area of confusion associated with hail concerns delineating crop loss due to hail. This type of loss often includes damage by wind, either that with the hail or that before or after the hail. The wind-induced damage can easily be mistaken as damage due to hail.

While North American hail data and information are generally sparse, there is much more information available than for any other location. In North America, very extensive hail data information are available for Alberta, Canada, and Illinois and Colorado in the United States. Hail phenomena studies have generally centered on hailstones, point hailfalls, hailstreaks, hailstorms, hailswaths, and hail days over areas of various sizes.

The principal hail area on the North American continent is located on the lee side of the Rocky Mountains where frequent and intense hail causes great damage over the Great Plains region. Another high-frequency hail area, related to spring storms, extends from Michigan to Texas. However, less crop damage is observed here because hail activity largely precedes the crop season.

The worldwide hail occurrence pattern is characterized by a greater hail frequency in continental interiors of mid-latitudes, with decreasing frequencies seaward, poleward, and equatorward. Most all hail is either orographically or frontally induced, although the Great Lakes affect the frequency close to that region. There are very few local-type hailstorms away from the mountains. The United States hail-days pattern is shown in figure 7.3.

Four key hail characteristics (average frequency, primary cause of hail, peak hail season, and hail intensity) were analyzed in order to delineate hail regions within the United States. Figure 7.4 indicates that 14 hail regions exist across the United States, with a marine-effect influence on the West Coast and in the lee of the Great Lakes.

Although most hail is produced by thunderstorms, the special climatologies of these two phenomena differ in some respects. The main difference is that thunderstorms generally exhibit a latitudinal distribution across North America, whereas hail has an inner-continental maxima with frequency decreasing outward in all directions, as mentioned previously.

The “intensity” of hail produces the damage. Intensity is a direct function of the number of stones, their size, and the wind. A hail intensity pattern has been developed specifically for potential property loss. The development of this pattern incorporated insurance data, stone size data, and extreme wind frequency data. The hail intensity pattern is shown in figure 7.5, which indicates a north-south oriented maximum located in the Great Plains region. This is the region of the continental United States in which large hailstones (the major factor in property loss) are most frequent and high winds occur most often.

An important difference between soft hail and hailstones (in the conventional sense) is the density - hailstones are close to ice (0.92 g cm^{-3}). The damage can be computed from the stone’s kinetic energy (KE) = $\frac{1}{2} mV^2$.

$$\left.\begin{array}{c} m \propto r^3 \\ V_{\text{terminal}} \propto \sqrt{r} \end{array}\right] KE \propto r^{\frac{7}{2}} \qquad (7.3)$$

This needs to be integrated over a size distribution to assess the overall effect. Also a specific critical size may exist for damage to specific surfaces.

*Subsection 7.5 contains figures and information from reference 7.10.

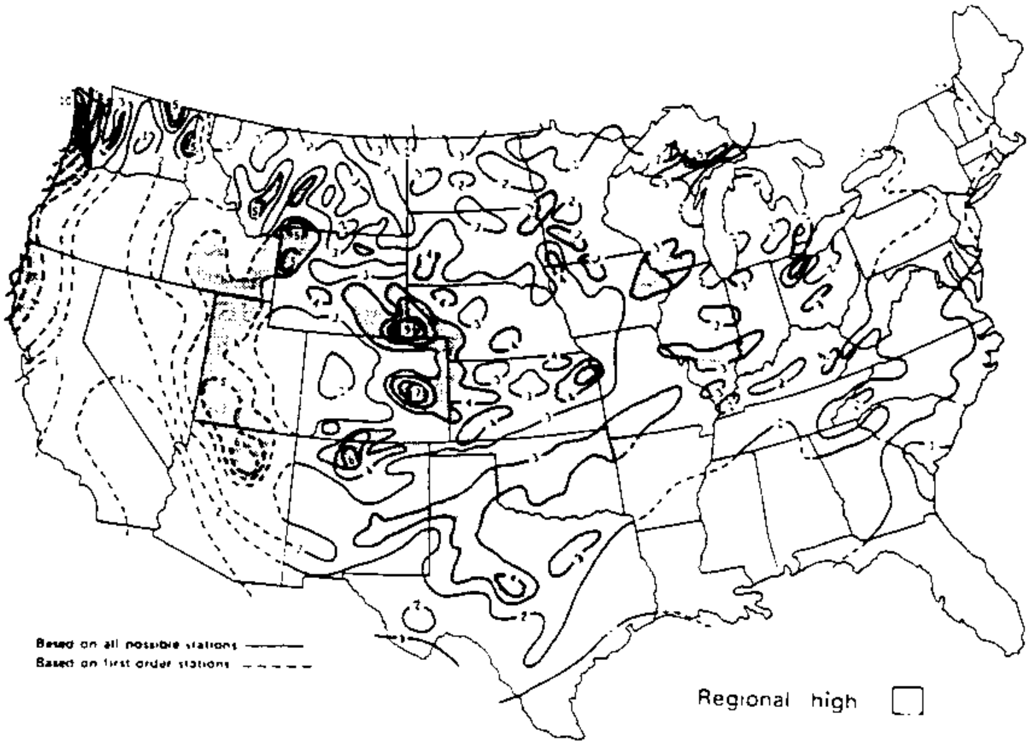
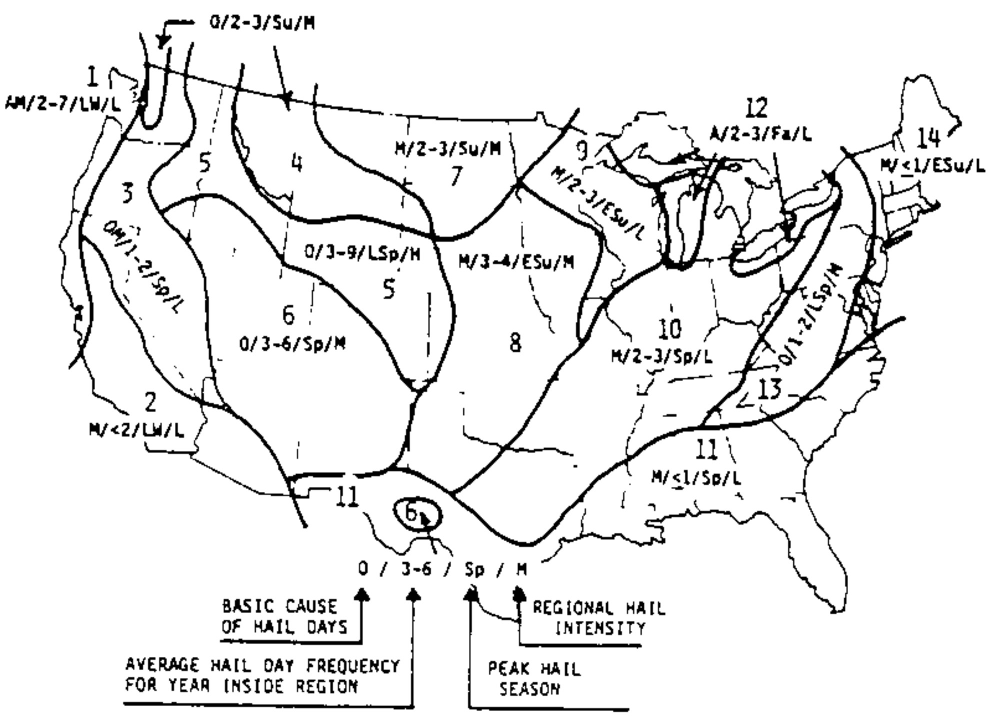


FIGURE 7.3 Average Number of Hail Days Based on Point Frequencies.



A = Marine, M = Macroscale, O = Organic
E = Early, L = Late, Fa = Fall, Su = Summer, Sp = Spring, W = Winter
L = Light, M = Moderate, H = Heavy

FIGURE 7.4 Hail Regions of the United States.

Since hailstone sizes as well as the number of stones are important to intensity, size distributions help account for regional differences. Hailstone sizes have not been systematically measured throughout the United States, but small-area studies have provided some information. Figure 7.6 indicates that the greatest frequency of large stones is found in the lee of mountain localities like Colorado. Small hailstones dominate in Illinois, New England, and mountain-top areas of Arizona. An Illinois hailfall averages 24 stones per hailpad (1 ft^2 or 930 cm^2), and only approximately 2 percent of these are more than 1.3 cm in diameter. In northeast Colorado, a hailfall averages 202 stones/ft^2, and more than half (51 percent) of these are larger than 1.3 cm.

The season of high hail activity varies across the country. East of the Great Plains, maximum hail activity occurs in the spring months, starting in March in the far south and in May in the northern states. In the lee-of-the-mountain states, maximum hail activity occurs in the summer months. The Great Lakes area is the only place in North America where maximum hail occurs in fall months. Along the West Coast certain areas have maximum hail in late winter or spring.

The duration of hailstorms is also variable. The average duration of hail near the mountains is 10 to 15 min, while in the Midwest it is 3 to 6 min. Hailstreaks, which have a median size of 20.7 km^2 (8 square miles), last an average of 10 min. A hailstreak is an area hit by a single volume of hail produced in a storm. A single storm may produce one or many hailstreaks.

In large areas, such as Iowa, Illinois, or Colorado, hail occurs on approximately 70 percent of all days with thunderstorms. In the Midwest, 50 percent of all thunderstorms connected with warm fronts and low pressure centers produce hail, but 75 percent of the thunderstorm days associated with cold fronts or stationary fronts are hail days.

Hail may also be accompanied by moderate to heavy rainfall, tornadoes, or wind. Crop-damaging hailstorms in Nebraska, Colorado, and Kansas are generally associated with moderate rains of 0.2 to 1.0 in, and 25 percent of the rain through the entire crop season falls with damaging hail. Hail days in Illinois typically have rainfall so heavy it averages nearly half (48 percent) of the monthly average. There have been cases where hailstones, falling at the same time or immediately before heavy rains, have blocked drains and downspouts, preventing much of the rain runoff from flat roofs and thereby causing roof collapse from the weight of the rainfall (ref. 7.11).

A study of tornadoes in Illinois shows that major large tornadoes - those having tracks longer than 40 km (>25 mi) - always have hailfalls somewhere near their track. During 1951 to 1960, nearly 96 percent of the 103 tornado days in Illinois were also hail days, and 12 percent of all hail days in Illinois were tornado days as well.

Wind with hail is another critical factor in crop loss, and the Illinois studies show that windblown hailstones occurred in 60 percent of all hailfalls. Whenever this happens, an average of 66 percent of the hailstones at any one point are windblown.

7.5.1 Hail at Surface. An estimate has been made of hail characteristics at selected space vehicle development and test locations. Figures 7.7, 7.8, 7.9, and table 7.15 give estimated hail characteristics for Kennedy Space Center, Vandenberg AFB, Edwards AFB, White Sands Missile Range, Northrup Strip, Marshall Space Flight Center, and Stennis Space Center. Since no direct measurements, except for the number of hail days, exist for these locations, all other items were estimated from Illinois hailpad measurements reported by Changnon (7.8). Hail characteristics estimated for use in evaluating hail protection needs and requirements are:

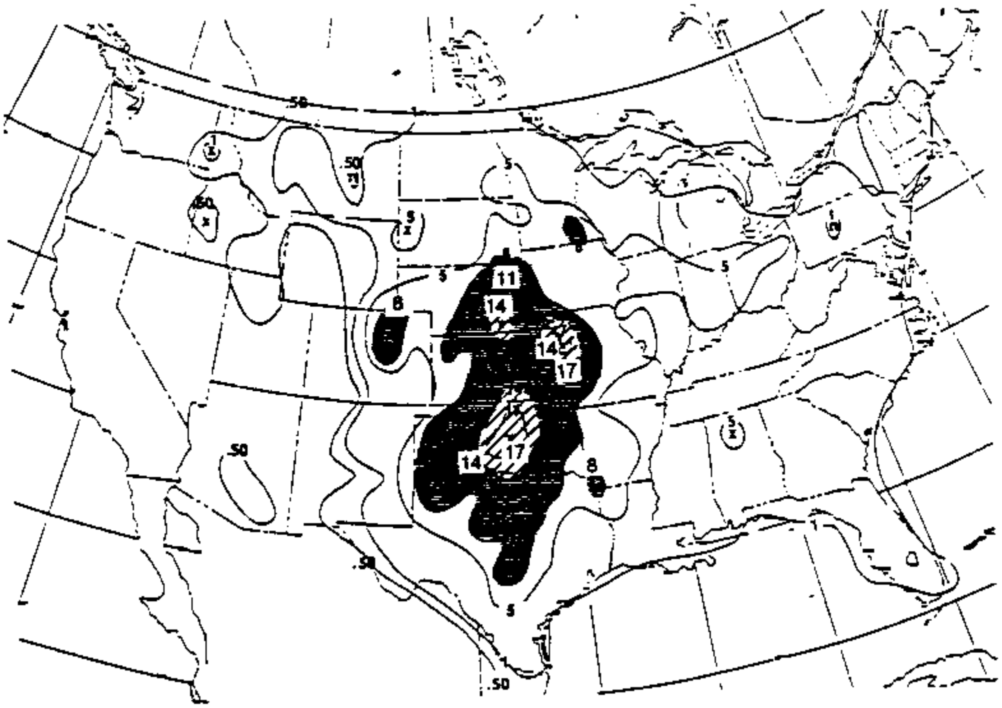


FIGURE 7.5 Frequency (Number of Reports) of Hail Greater than 1.9 cm Diameter per 26,000 km^2 Per Year (Ref. 7.11)

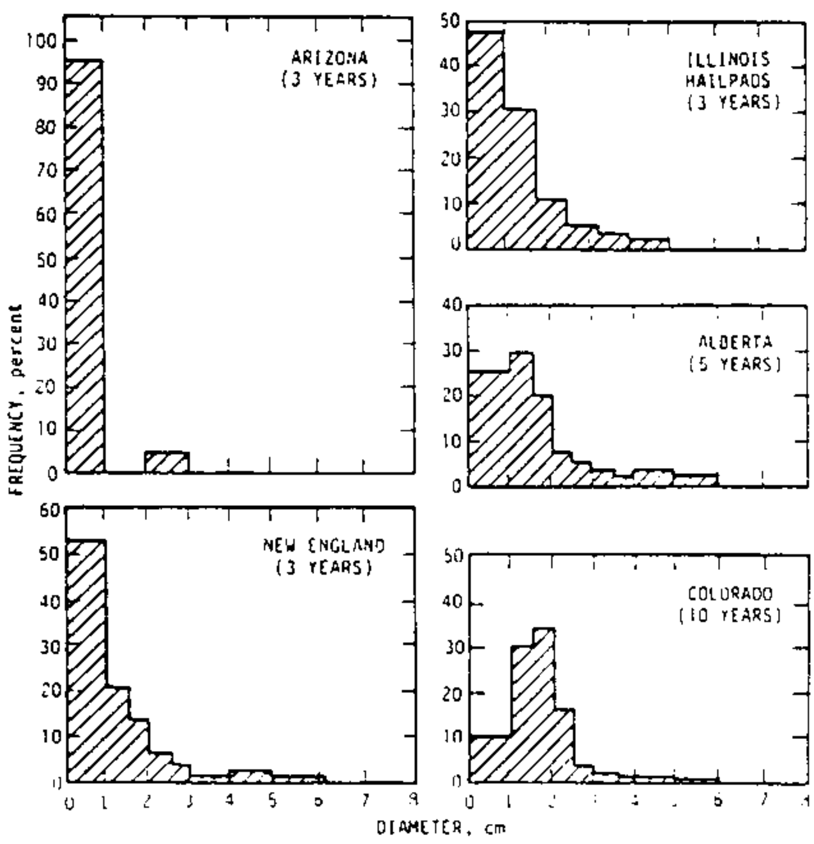


FIGURE 7.6 Frequency Distributions of Maximum Hailstone Sizes Reported From Many Hailfalls at Different Locales.

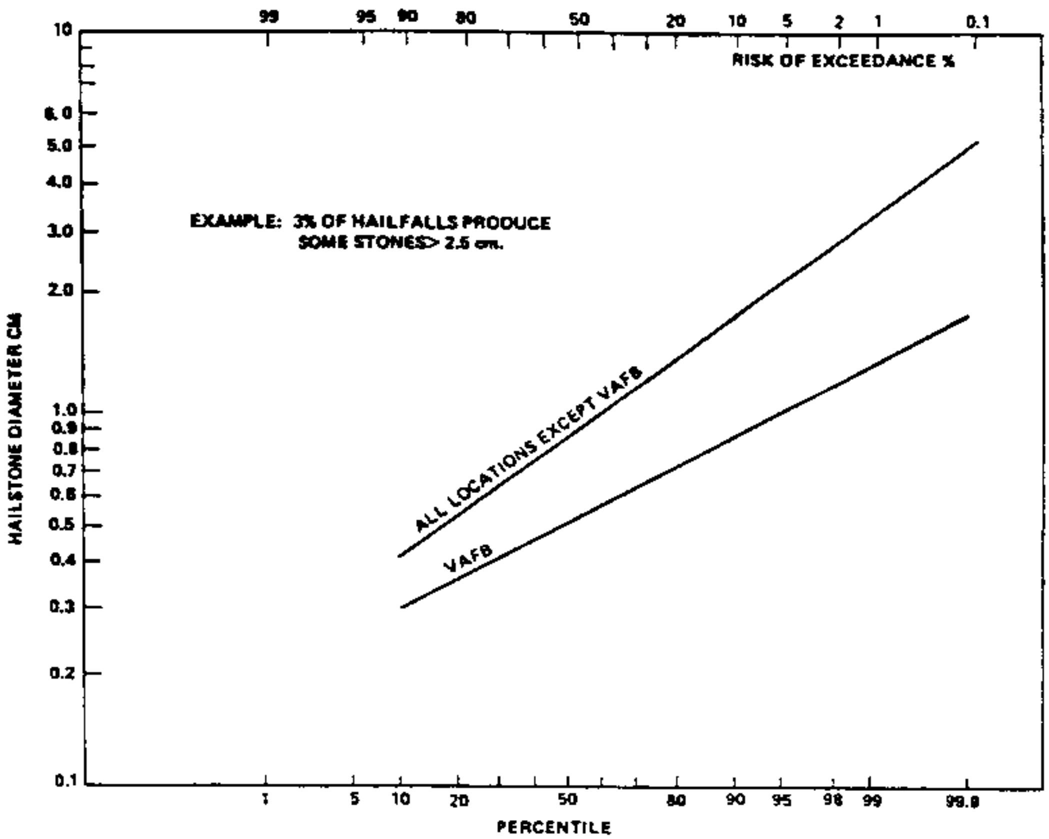


FIGURE 7.7 Maximum Hailstone Size Per Point Hailfall.

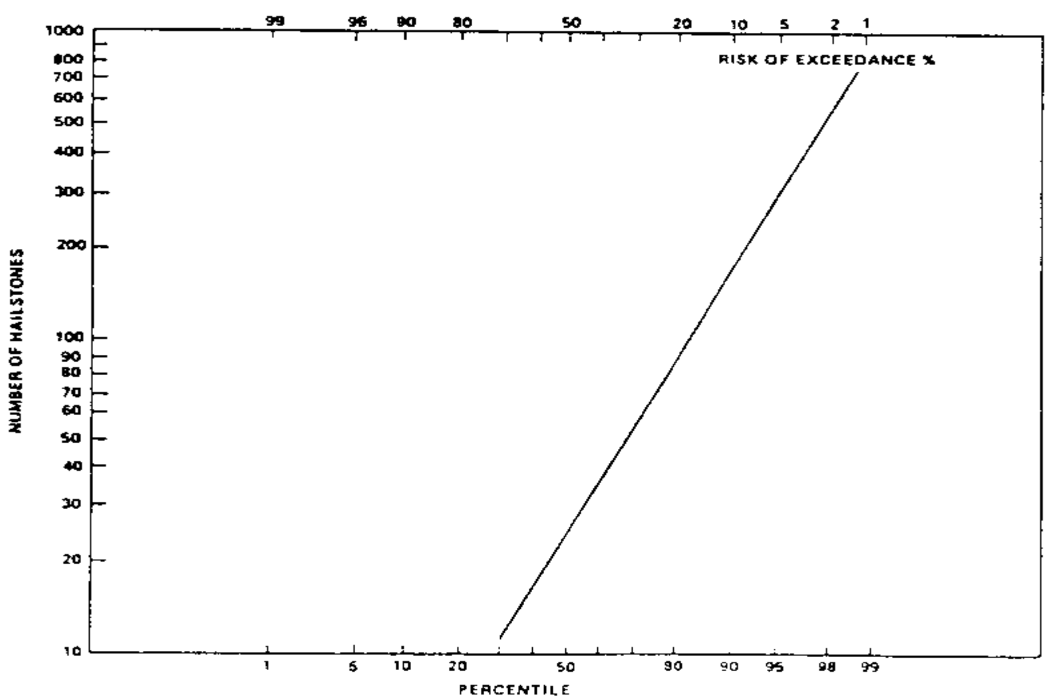


FIGURE 7.8 Probability (Percent) of Number of Stones Per Hailfall on Hailpad of 930 cm^2 (1 ft^2).

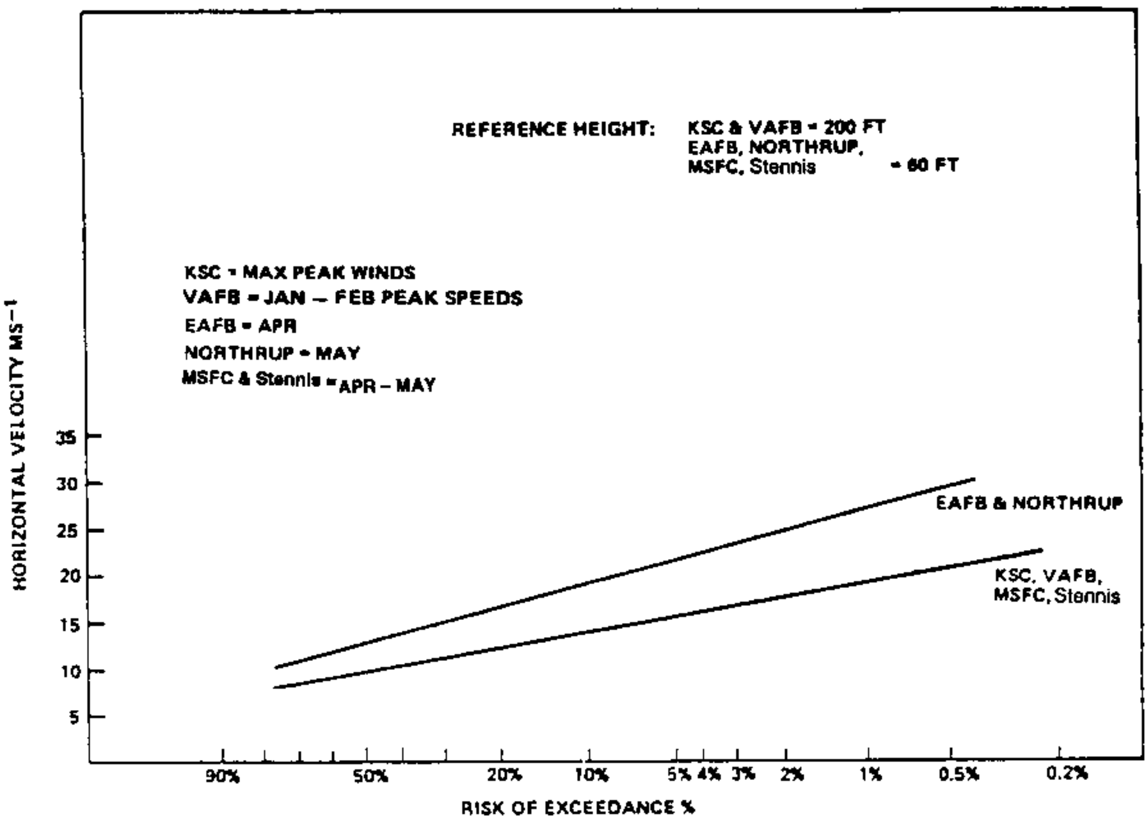


FIGURE 7.9 Horizontal Hailstone Velocity.

TABLE 7.15 Estimated Hail Characteristics at Selected Space Vehicle Locations.

Estimated Hail Characteristics	KSC	VAFB	EAFB	Northrup	MSFC	Stennis
Exposure Time Risk (%)						
Worst Month Reference Period	1	8	5	12	17	3
Worst 6 Months Reference Period	7	41	25	53	67	18
Mean Number of Hailstorm Days Per Year	0.1	1.1	0.6	1.5	2.2	0.4
Average Point of Duration of Hailfall (min)	5	5	5	5	5	5
Average Number of Hailstones Per 930 cm^2(1 ft^2)	24	24	24	24	24	24
Density of Hailstones (g/cm^3)	0.9	0.9	0.9	0.9	0.9	0.9
Size-diameter (cm) and Terminal Velocity (m/s)						
Representative Size (50-percent Risk)	0.9	0.5	0.9	0.9	0.9	0.9
Terminal Velocity	11	8	11	11	11	11
Large Size (5-percent Risk)	2.2	1.0	2.2	2.2	2.2	2.2
Terminal Velocity	17	11.5	17	17	17	17
Horizontal Velocity (m/s)—All Directions*						
Mean Speed	9	9	13	13	9	9
5-percent Risk Speed	15	15	22	22	15	15
Months of Max Frequency	May	Jan–Feb	Feb–Apr	May–July	April	Apr–May
Period of Record—Years	22	20	28	30	9	28

*KSC and VAFB reference height = 61 m (200 ft). All others = 18 m (60 ft).

a. Hailstone Size. Figure 7.7 gives the risk in percent of a point hailfall producing stones larger than indicated sizes. For example, only 3 percent of the hailfalls at Kennedy Space Center will produce stones larger than 2.5 cm, while 50 percent will produce some stones larger than 0.9 cm.

b. Terminal Velocity. The general expression for the terminal velocity of a sphere is given in ref. 7.2. However, for quick calculations, the best estimate of hailstone terminal velocity, as reported by several investigators, is given by the expression:

$$W = K\sqrt{D} \ , \qquad (7.4)$$

where

W = terminal velocity in m s^{-1}

D = hailstone diameter in cm

K = 11.5 .

c. Number of Hailstones Per Hailfall. Values used for space vehicle locations were taken from Illinois measurements which showed that point hailfalls average 24 stones and that only 5 percent of the storms produced more than 300 stones per hailpad of 930 cm^2 (1 ft^2). These numbers were used to prepare figure 7.8.

d. Horizontal Velocity of Hailstones. These values (fig. 7.9) were derived from peak wind speed distributions for each space vehicle location. These wind speeds may be different from other shuttle design values because only hail season winds were used rather than the windiest period concept.

The reference height at Kennedy Space Center and Vandenberg AFB is 61 m (200 ft). At all other locations it is 18.3 m (60 ft).

e. Density of Hailstones. A generally accepted value for the density of hail at all locations is 0.89 g cm^{-3} (56 lb ft^{-3}).

f. Recommended Procedures for Evaluating Protection Requirements.

(1) Use 50 percent values for stone size and number of stones.

(2) Use 5 percent risk horizontal wind speeds.

(3) Calculate risk of experiencing a hailfall during a specified continuous exposure period from:

$$\text{Risk} = 1 - e^{-lt} \qquad (7.5)$$

where

l = mean number of independent hailstorm days per year

t = exposure time in years

7.5.2 Distribution of Hail With Altitude. Although it is not the current practice to design space vehicles for flight in thunderstorms, data on distribution with altitude are presented as an item of importance. In general, the probability of hail increases with altitude from the surface to about 5 km and then decreases rapidly with increasing height. Above about 9 km, infrequent hail encounters have occurred, but cannot be completely discounted. Data on hailstone size versus altitude, with a 0.1-percent encounter probability while enroute aloft for 200 miles (322 km), in the worst month, worst area, are given in table 7.16. When including thunderstorm data from several areas, investigators have estimated probabilities of encountering hail versus altitude, as presented in table 7.17 (ref. 7.14). This supports the general shape of the vertical distribution. Further, it appears expedient to assume that any level between 3 and 6 km can become one of maximum hail concentration at any one time.

TABLE 7.16 Estimate of Hailstone Size Equaled or Exceeded, with a 0.1-Percent Probability of Encounter While Enroute Aloft for 200 Miles (322 km), in Most Severe Month and Area (Ref. 7.13).

Altitude (km)	Estimate of Hailstone Size (inch)	(cm)
1.5	1.2	3.1
3.0	2.4	6.1
6.1	2.4	6.1
7.6	1.9	4.8
9.1	1.7	4.3
10.7	1.5	3.8
12.1	1.1	2.8
13.7	0	0

TABLE 7.17 Estimates of the Probability of Encountering Hail of Any Size at a Single-Point Location by Altitude (Ref. 7.14).

Altitude (km)	Probability
Ground Level	0.000448
1.5	0.000448
3.0	0.00314
4.6	0.00314
6.1	0.00314
7.6	0.00134
9.1	0.00100
10.7	0.00067
12.2	0.00034
13.7	0.000

7.6 Laboratory Test Simulation. In the laboratory, simulated rain droplets are usually produced by use of a single orifice, mounted above the equipment being tested. Such a test will not necessarily duplicate the natural occurrence of precipitation and may or may not reflect the true effect of natural precipitation on the equipment since a single orifice produces drops all nearly the same size.

Each test should be evaluated to determine if the following factors which occur in natural precipitation are important in the test.

7.6.1 Rate of Fall of Rain Droplets. Natural rain droplets will have usually fallen a sufficient distance to reach their terminal velocity (maximum rates of fall). Simulation of such rates of fall in the laboratory requires the droplets to fall a suitable distance. Large droplets (4-mm diameter and greater) will require approximately 12 m (39 ft) to reach terminal velocity.

Values of terminal velocities of water droplets were measured by Gunn and Kinzer (ref. 7.15). Their results gave the values in table 7.18. Reference 7.15 should be consulted for more detailed information. Gunn and Kinzer found that water droplets greater than 5.8 mm would usually break up before the terminal velocity was reached.

TABLE 7.18 Values of Terminal Velocities of Raindrops (Ref. 7.15).

Drop Diameter (mm)	Terminal Velocity ($m\ s^{-1}$)
1	4.0
2	6.5
3	8.1
4	8.8
5	9.1
6	9.1
7	9.1

7.6.2 Raindrop Size and Distribution. Normal rainfall has a variety of drop sizes with a distribution as shown in figure 7.10 (ref. 7.15), which illustrates the wider distribution of droplet sizes in the heavier rain which has the larger droplets. The maximum drop diameter distribution could be adequately simulated by a number of orifices, all at the same water pressure, to produce droplets of approximately 1-, 2-, 3-, and 4- and 5-mm diameter. For the median drop diameter, the use of a single orifice to produce 1-mm droplets would be suitable.

7.6.3 Wind Speed. In most cases of natural rain there will be wind blowing near horizontal. This wind will modify the droplet paths from a vertical path to a path at some angle to the vertical, thus causing the rain droplets to strike at an angle. In addition, unless the equipment is streamlined in the direction of the wind, small vortices may develop at the surface of the equipment. These vortices may cause a considerable amount of the precipitation to flow in a variety of directions, including upward against the bottom of the equipment.

Studies of thunderstorms with rainfall rates from 12.7 to 76.2 mm h^{-1} (0.5 to 3.0 in h^{-1}) with relationship to wind speeds occurring at the same time have shown an average mean wind speed of 5 m s^{-1} for all storms combined. Peak winds were as high as 16 m s^{-1}. All storms, except one with rates exceeding 25 mm h^{-1}, had peak winds at least 5 m s^{-1} greater than the mean wind for the same storm.

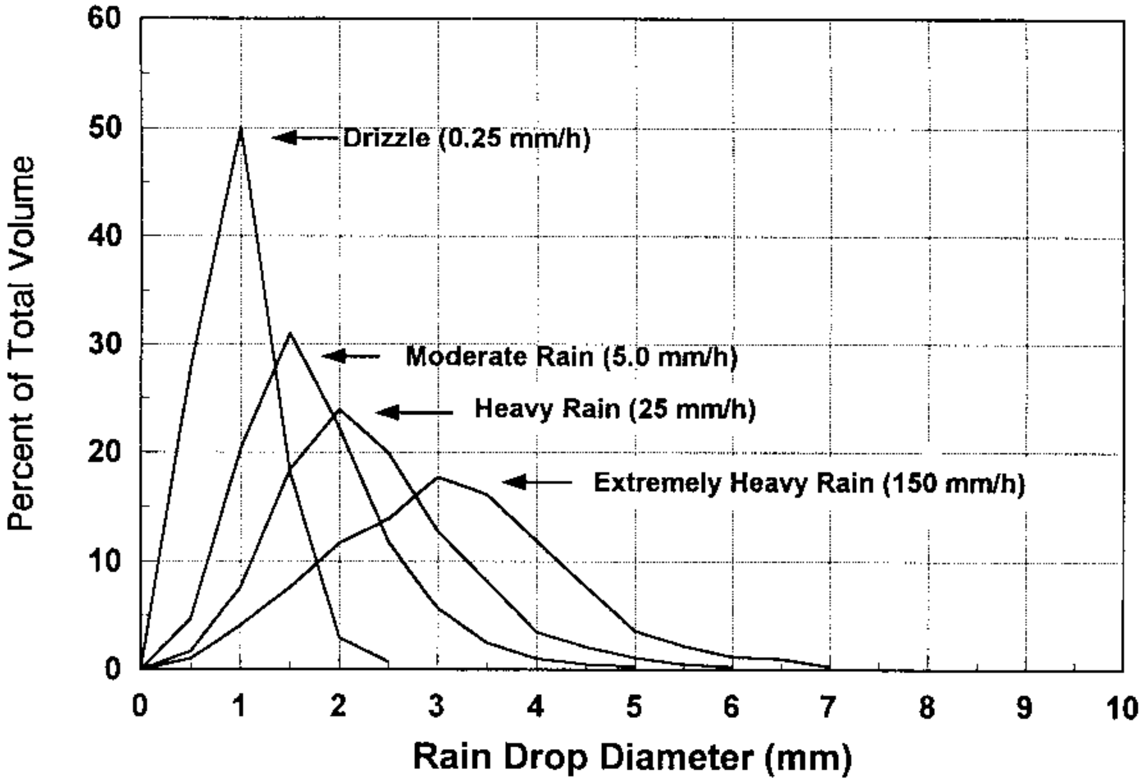


FIGURE 7.10 Distribution of Drop Sizes of Rain (Ref. 7.15).

7.6.4 Temperatures. The air temperature at the ground usually decreases several degrees at the start of rainfall. The amount of the temperature decrease is greatest in the summer, about 8 °C (14°F), when the temperature is high (greater than 32 °C (90 °F), with the final temperature approximately 24 °C (75 °F). In the winter the temperature decrease is usually about 2.8 °C (5 °F). At the end of the rainfall the summer temperature will increase again to nearly the same values as before the storm, but in the winter there is no general pattern of warming. This decrease in temperature is caused by the water droplets being colder than the surface air temperature.

7.6.5 Recommended Items to Include in Laboratory Rainfall Tests. The following items need to be considered in rainfall tests in the laboratory:

a. Raindrop size distribution.

Rates less than 25 mm h^{-1}, drop size of 1 mm.

Rates greater than 25 mm h^{-1}, drop size from 1 to 5 mm.

b. Rate of fall of drops. Drops should fall at least 12 m to obtain terminal velocity.

c. Wind Speed. A mean wind of 5 m s^{-1} with gusts of 15 m s^{-1} of 30-s duration at least once in each 15-min period.

d. Temperature. The temperature in the chamber should decrease from 32 ºC (90 ºF) to 24 ºC (75 ºF) at the start of rainfall for representative summer tests and should be maintained at 10 ºC (50 ºF) for winter tests. The decrease in air temperature may be obtained by using water at, or slightly below 24 ºC for the summer tests.

7.6.5.1 Idealized Rain Cycle, KSC, FL. For some studies and laboratory tests, it may be desirable to use an extreme rain cycle with associated drop sizes, wind speeds, and temperatures. The values from table 7.11 can be used in any combination of rainfall rate and duration such that the total accumulation does not exceed the table 7.11 value for the selected time period and percentile level. The percentile level should be compatible with the risk the operator is willing to accept. The 95 percentile values have a 5 percent risk of being exceeded— the 99 percentile values only a 1-percent risk.

If wind speed, temperature, and raindrop size are to be included in the test, the following values may be used with both 95- and 99-percentile rain rates:

Wind speed: 5.1 m s^{-1}, gusts to 15.4 m s^{-1}
10 knots, gusts to 30 knots
guat lasting 2 min applied every 15 min.

	Summer		Winter	
	Before	During	Before	During
Temperature:	32 ºC (90 ºF)	24 ºC (75 ºF)	13 ºC (55 ºF)	10 ºC (50 ºF)

Drop size: Average = 2 mm
Largest 1% = 5.9 mm

The following are some rain cycle examples using 95-percentile values from table 7.11:

Period of Rainfall		Rate (in/h)	Total Accumulation (in)
1 hr		1.17	1.17
3 hr		0.47	1.41
(1 h)	10 min	0.5	1.17
	3 min	8.7	
	5 min	3.5	
	42 min	0.51	
(3 h)	15 min	0.2	1.41
	30 min	0.5	
	5 min	3.5	
	25 min	0.5	
	105 min	0.35	

7.7 Rain Erosion

7.7.1 Introduction. Rain erosion is caused by the stress resulting from liquid droplets impinging a solid surface. This stress may dent or crack the surface or result in a mass loss (ref. 7.15). Multiple impacts can cause three times the damage of a single impact (ref. 7.16). With the advent of high-speed aircraft, careful consideration must be given in selecting materials to prevent erosion of paint coatings, structural plastics, and metallic parts.

7.7.2 Rain Erosion Criteria. The magnitude of rain erosion may be influenced by many parameters, such as impact velocity, drop size, density, viscosity, and surface tension. Different techniques have been applied to determine the effects of impact velocities on erosion. Tables listing erosion rates for various materials at specific velocities are found in references 7.17 and 7.18.

Tests by A. A. Fyall at the Royal Aircraft Establishment (ref. 7.19) on single rain droplets have shown that the rain erosion rate may increase considerably with lower air pressure (higher altitude) because of the lower cushioning effect of the air on the droplets at impact.

7.8 Fogs. Fogs are classified as either warm or supercooled fog, depending upon whether the ambient temperature is above or below 0 °C. In either case, fog consists of a considerable number of minute water drops suspended in the atmosphere near the Earth's surface and which reduce visibility to less than 1 km (American Meteorological Society's Glossary of Meteorology—Definitions).

The conditions most favorable for the formation of fog are high relative humidity, light surface winds, no overcast so that radiative cooling is most effective, and an abundance of condensation nuclei. Fog occurs more frequently in coastal areas than in inland areas since there is an abundance of water vapor.

Fogs are formed either by cooling the air until the water vapor condenses or by the evaporation of additional water vapor into the air. Common types are (1) radiation fogs, (2) advection fogs, (3) up-slope fogs, (4) frontal fogs, and (5) steam fogs. A brief description of each fog type follows:

Radiation fog forms on clear nights when the Earth loses heat very rapidly to the atmosphere. When humidity is high and cooling takes place rapidly, condensation occurs. If there are no winds, the fog will be very shallow or will be reduced to a dew or frost deposit. If winds are present (about 5 kn), then the fog will thicken and deepen. These fogs do not occur at sea since the sea surface does not cool as the land does.

Advection fog forms as warm, moist air moves over a colder surface. These fogs occur in coastal areas because the moist air moves inland by breezes over the colder land in the winter. In summer the warm, moist air is carried out to sea, where it forms a fog over the cool water and then the sea breezes advect the fog inland. These fogs are common along the coast of California in the summer.

Up-slope fog forms when stable, moist air moves up sloping terrain and is cooled by expansion. This cooling produces condensation, and fog forms. An up-slope wind is necessary for the formation and maintenance of this type of fog. Usually these fogs produce low stratus-type clouds.

Frontal fog forms in the cold air mass of the frontal system. The precipitation from the warm air mass, overrunning the cold air mass, evaporates as it falls through and saturates the cold air, thus producing the frontal-type fog. These fogs form rapidly, cover large areas, occur frequently in winter, and are associated with slow-moving or stationary fronts.

Steam fog forms by the movement of cold air over a warmer water surface. Steam fog rises from the surface of lakes, rivers, and oceans.

Although not classified as a common-type fog, there is a fog type called the ice (crystal) fog which is of interest. This fog occurs when the air temperature is approximately -34 °C, and as water vapor from the exhaust of aircraft engines, automobiles, etc., is produced, the vapor changes directly to ice crystals instead of condensing directly to liquid drops. The suspension of the ice crystals in the atmosphere produces the ice fog. These fogs can persist from a few minutes to several days and are quite a problem in arctic or polar regions. Salt fog, which develops along a coastal area, is presented in subsection 10.3.2.1.

Some typical microphysical characteristics of both radiation and advection types of fogs are as follows:

a. Radiation Fog (Inland)

(1) Diameter of drops (av)—10 µm

(2) Typical drop size—5 to 35 µm

(3) Liquid water content—110 mg/m^3

(4) Droplet concentration—200 cm^{-3}

(5) Vertical depth

(a) Typical—100 m

(b) Severe—300 m

(6) Horizontal visibility—100 m

b. Advection Fog (Coastal)

(1) Diameter of drops (av)—20 µm

(2) Typical drop size—7 to 65 µm

(3) Liquid water content—170 mg/m^3

(4) Droplet concentration—40 cm^{-3}

(5) Vertical depth

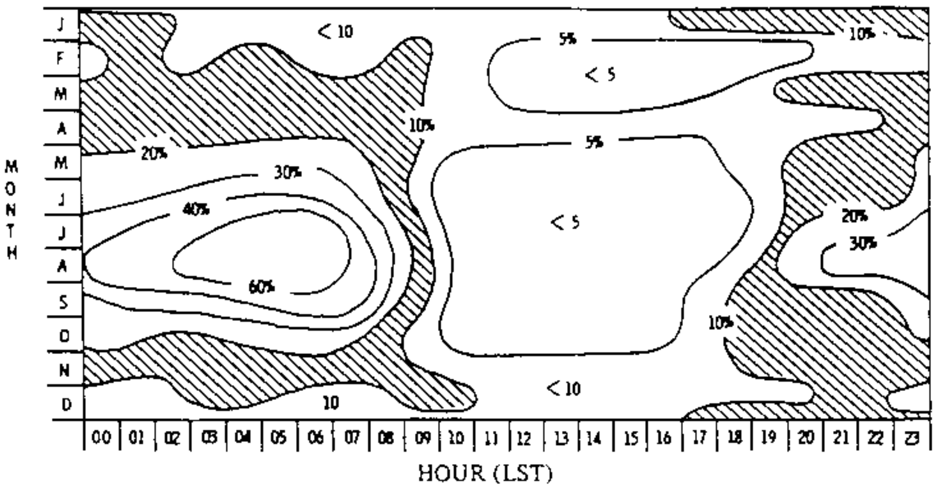
(a) Typical—200 m

(b) Severe—600 m

(6) Horizontal visibility—300 m.

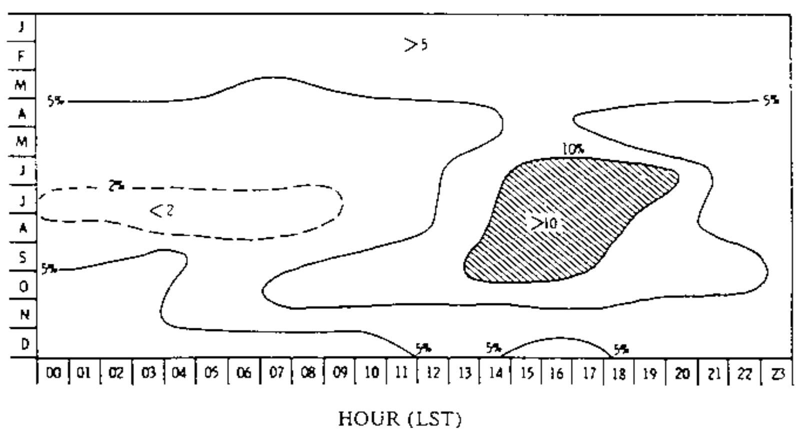
7.9 Precipitation or Fog (VAFB and KSC). Figures 7.11 and 7.12, showing the percentage frequency of precipitation or fog with visibility ≤0.8 km (0.5 mi) at Vandenberg AFB and Kennedy Space Center, were developed from historical records of hourly observations. Certain Vandenberg and Kennedy Space Center climatic characteristics that may be of significance to aerospace mission planning and operations are immediately apparent. That is, potentially unfavorable climatic conditions occur mainly during summer night and early morning hours at Vandenberg AFB but during summer afternoons at Kennedy Space Center. This, of course, is due to the high frequency of fog at Vandenberg AFB and summer afternoon showers in central Florida.

For climatological studies useful in operational design data for spacecraft and aircraft operations, the Department of Transportation-Federal Aviation Administration has produced a tabulation of ceilings, visibilities, wind, and weather data by various periods of the day and by various temperature and wind categories for 41 airports (Ref. 7.20).



VANDENBERG AFB

FIGURE 7.11 Probability of Precipitation or Fog with Visibility ≤ 0.8 km (0.5 mi).



KENNEDY SPACE CENTER (KSC)

FIGURE 7.12 Probability of Precipitation or Fog with Visibility ≤ 0.8 km (0.5 mi).

SECTION 7

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