Rainfall Rates and Drop-Size Distributions for Environmental Testing

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Rainfall Rates and Drop-Size Distributions for Environmental Testing

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Abstract

Rainfall rates and associated drop-size distributions are important considerations in the design and testing of most items that must operate in and withstand the effects of weather. Erosion of aerospace vehicles, triggering of impact fuses and leakage into sealed components are some examples of the many ways that rain can impact different types of hardware. To properly design and test systems and equipment for rain, appropriate intensities and associated drop-size distributions need to be determined. This paper discusses the pertinent climatic data available on rain, how they were used to derive the design values presented in MIL-STD-210C, and how to determine the appropriate intensity values for each system's intended life cycle.

1. Background

Records of rainfall amounts are available for thousands of locations worldwide for more than 100 years in many instances. However, data collection was oriented toward agricultural and hydrological purposes for which monthly, daily, and less commonly, 3 and 6 h totals were collected. Precipitation amounts for intervals of 3 h down to 5 min are available for many locations in the United States, but for few locations in other parts of the world. For most design considerations instantaneous rainfall rates would be more appropriate, but 1-min rates are generally considered the most practical. Much of the meager amount of data on 1-min rates was collected during special field programs conducted for limited time periods (e.g., 1-3 years). This has prompted the development of numerous models to estimate 1-min rates.

Tattelman and Grantham (1985) discuss sources of one minute data and present a survey and comparison of models for estimating one minute rates. They found six models that estimate rainfall-rate distributions, but only one that estimates rates on a monthly basis. Due to the importance of worst-month considerations for design and operation problems, the monthly model developed by Tattelman and Scharr (1983) was used to derive atlases of 1-min rates (Tattelman and Grantham, 1983a, 1983b).

2. Frequencies of Extreme Rainfall Rates

a. The Tattelman-Scharr Model

The T-S model is made up of six regression equations to estimate rates that are equaled or exceeded for exceedance levels \( p = 0.01, 0.05, 0.10, 0.50, 1.0, \) and 2.0 percent of time during a month (approximately 4.4 min, 22 min, 44 min, 3.6 hr 7.3 hr, and 14.6 hr, respectively). Information required to make the estimates for each of the six exceedance levels \( p \) consists of monthly mean temperature, monthly mean precipitation, number of days in the month with precipitation (based on any of three threshold values that define a rainy day), and latitude. The minimum threshold amount of precipitation to define a rainy day varies with country. Three of the most common threshold values used worldwide to define a rainy day are 0.25, 1, and 2.54 mm. The number of rainy days during the month based on each of these threshold amounts, as well as monthly precipitation and monthly mean temperature, were observed coincident with the rain-rate frequencies. The number of days per month with another frequently used threshold called a "trace" differed only slightly with the number of days equal to greater than 0.25 mm, and was not used.

The basic form of the model equation is expressed by

\[
R_p = A_p + B_p T + C_p I + D_p f(L,T)  
\]

where \( R_p \) is the estimated precipitation rate (mm/min) for exceedance level \( p \), \( T \) is the monthly mean temperature (°F or 1.8 \( \times \) \( 23 \)) °C), \( I \) is a precipitation index (monthly mean precipitation divided by the monthly mean number of days with precipitation) and \( f(L,T) \) is a latitude-temperature term. \( A_p \) is the constant for exceedance level \( p \) and \( B_p, C_p, \) and \( D_p \) are multiple.
where \( L \) is the latitude (degrees and tenths) of the location of interest. This term accounts for the increasing importance of temperature for estimating precipitation rates at higher latitudes.

b. Rain-Rate Atlases

During the preparation of MIL-STD-210B, the Office of the Assistant Secretary of Defense specified that the frequency of occurrence during the worst month in the severest part of the world for a climatic element should be the basis for values presented in the Standard. For rainfall and associated vertical profiles, rates occurring 0.5 percent of the time are recommended for initial design consideration in MIL-STD-210C. Rainfall rates associated with lower frequencies-of-occurrence are also provided in the standard. Rainfall rates are presented for lower frequencies than other climatic elements because high rates are quite extensive in the tropics and can be a problem in many months of the year.

Atlases of 1-min rates based on the new model were used to determine the areas in the world with the highest rainfall rates occurring 0.5, 0.1, and 0.01 percent of the time during the worst month. Although rates are generally highest in the northern hemisphere tropics, the estimated rates for two locations in northeast Brazil, Barro Do Corda and Teresina, are about the same as the rates estimated for Cherrapunji for all three frequencies. The rates for this area in northeast Brazil are 0.6 mm/min (36 mm/hr), 1.4 mm/min (84 mm/hr), and 2.8 mm/min (168 mm/hr) for 0.5, 0.1, and 0.01 percent of the worst month, respectively.

Elsewhere, values in the Northern Hemisphere tropics exceed 0.4, 1.2, and 2.4 mm/min during 0.5, 0.1, and 0.01 percent of the most severe month in many areas, especially in southeast Asia. Since these rates occur over large areas in the tropics, the slightly higher rates in northeastern Brazil were used to represent the worst month/area rates in MIL-STD-210C.

3. Drop-Size Distributions

The drop-size distributions presented in MIL-STD-210B were based upon an exponential model of drop number concentrations. Numerous investigators have pointed out the inadequacy of the exponential distribution in describing observed drop-size distributions, particularly for high-intensity convective rains. Tattelman and Willis (1985) analyzed a large sample of drop-size distributions during intense rainfall collected from reconnaissance of Atlantic hurricanes/tropical storms. The data set was normalized and fit by a gamma distribution to provide a better model to determine drop-size distributions for MIL-STD-210C.

The gamma distribution function, of which the exponential is a special case, fits tropical convective rain distributions particularly well (Willis, 1984). Most functional descriptions of the size distributions of raindrops are encompassed by the following expression:

\[
N(D) = \frac{a D^b \exp(-AD)}{\Gamma(b)}
\]

where \( a \) is the shape parameter of the distribution, \( b \) is the scale parameter, \( D \) is the drop diameter, and \( \Gamma \) is the gamma function.

It can be shown that \( D_o \), the median volume diameter of a distribution, is given by the approximate expression:

\[
D_o = 3.67 + \frac{a}{A}
\]

as long as \( a > -2 \), and if \( D_{max}/D_o > 2.5 \).

The model is applied as follows: If a drop-size distribution is desired for a given liquid water content \((q/w)\), first compute the median volume diameter from

\[
D_o = 0.1571 \left( \frac{q}{w} \right)^{0.1641}
\]

where \( D_o \) is in cm. If the rainfall rate, \( R(\text{mm/hr}) \) is specified, compute \( N \) from

\[
N = 0.062 \left( \frac{R}{q/w} \right)^{0.913}
\]

Then the three parameters of the gamma distribution, \( A, b \), and \( N \), are computed:

\[
A = 5.5880/D_o
\]

\[
b = 2.160
(8)
\]

\[
N = \frac{512.85R^{10^{-6}}}{D_o^{3.166}}
(9)
\]

As an example, the equations for the drop size distributions for the three rainfall rates discussed in section 2 are:

\[
R = 36 \text{ mm/hr} \quad N(D) = 45.08D^{0.166} \exp[-32.75D]
(10)
\]

\[
R = 84 \text{ mm/hr} \quad N(D) = 43.86D^{0.166} \exp[-28.76D]
(11)
\]

\[
R = 168 \text{ mm/hr} \quad N(D) = 42.88D^{0.166} \exp[-25.86D]
(12)
\]

where \( N(D) \) is in \( \text{cm}^3 \), and \( q/w \) is in \( \text{g/cm}^3 \). Thus, to find the concentrations per \( m^3 \) in a 0.1 mm diameter size interval, \( N(D) \) in \( \text{cm}^3 \) must be multiplied by 1000.

Greater detail on the model is provided in Tattelman and Willis (1985). This report also provides vertical profiles of
rainfall rate, drop-size distribution and liquid water content up to 20 km.

4. Establishing Design and Test Requirements

The appropriate values of climatic elements specified for design of equipment depend upon:

a. Areas of Exposure. This includes:

1. Geographical locations through which it may be transported.
2. Where it may be stored.
3. Where it may be deployed.
4. How it will be transported.
5. Circumstances when it will be protected from the environment.

b. Operational Requirements

It is ordinarily costly or technologically impossible to design equipment to operate under the most extreme conceivable conditions. Therefore, military planners accept equipment designed to operate for all but a certain small percentage of the time. The procuring agency is responsible for determining the operational requirements of the item or system. These requirements should then be used to determine the acceptable frequency of occurrence of a climatic element.

For rainfall MIL-STD-210C recommends that rates associated with a frequency of occurrence of 0.5% of the time during the worst month (about 3.5 hrs) be initially considered for design. In the case of rainfall, extreme conditions are so widespread in the rainy tropics that less extreme values associated with higher frequencies are not provided.

c. Safety and Equipment survivability

For some material, one-time exposure to a climatic extreme can render it permanently inoperable or dangerous. For such material, long-term climatic extremes would be more appropriate for design of equipment that is not protected from the environment. Depending on the degree of the hazard, the use of the most extreme recorded value may be required. The use of these more extreme values, instead of those occurring for a percent of the time during the most severe month each year, shall be determined by the agency or department responsible for development.

5. Other Considerations

The climatic values in 210C represent free air (ambient) conditions. The conditions that an item will see depend on how the natural environment is modified by the platform on which the item is expected to function. Design requirements and test procedures can be established only after the platform characteristics are identified and the platform environment is defined.

Once the platform environment(s) is(are) defined, problems in designing for any of the climatic conditions will surface if they have not already done so. If design to one or more of the initially derived extreme climatic conditions proves unacceptable due to technical or cost considerations, alternatives need to be considered. Although the procuring agency establishes the requirements, the ramifications as to cost or achievability can only be evaluated after they have been factored into the design by the contractor. The procuring agency should be made aware of the problems and potential solutions. The use of alternatives, such as less extreme values associated with higher frequencies of occurrence (and reduced operational capability), must be weighed by the procuring agency.

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References


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