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Report R-1993

CALIBRATION AND COMPARISON
OF
SIMULATED RAIN FIELDS WITH NATURAL RAINS

by

EUGENE A. MUELLER
ARTHUR L. SIMS

ILLINOIS STATE WATER SURVEY
at the
University of Illinois

for

U.S. Army
FRANKFORD ARSENAL
Philadelphia, Pennsylvania

Final Report
on
U. S. Army Contract DAAG 11-69-C-0748

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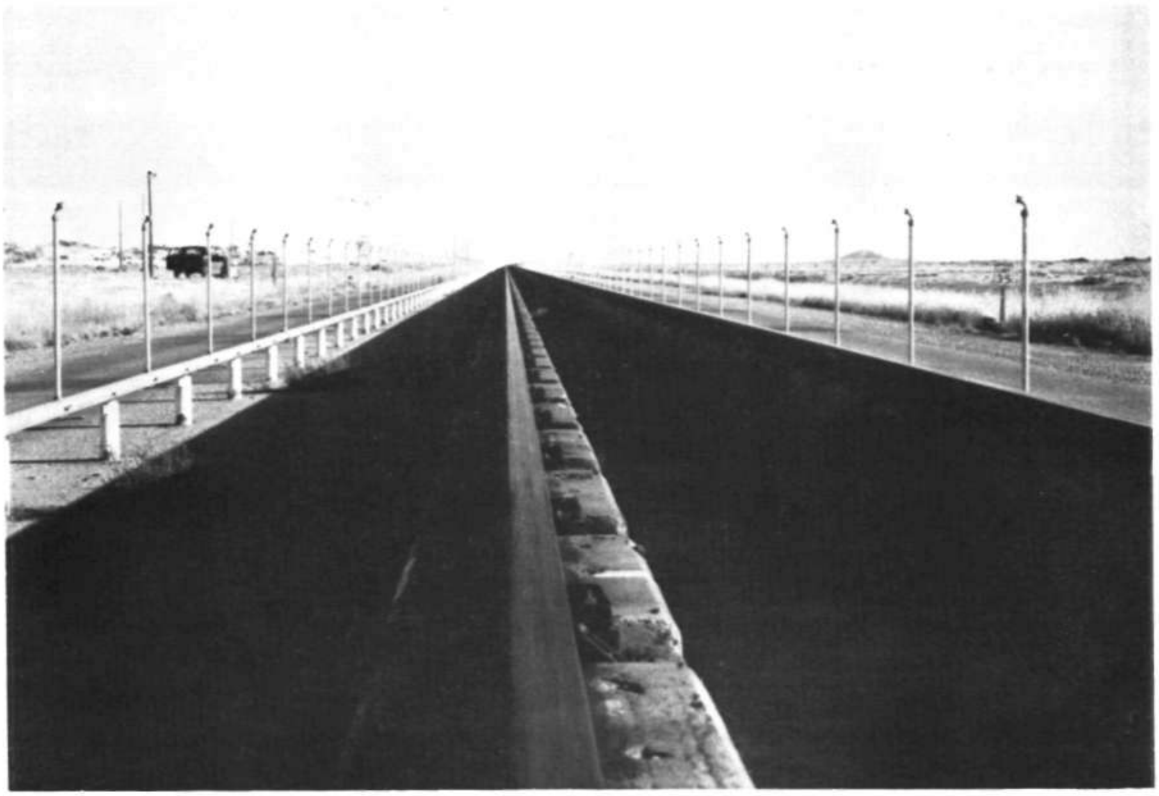
February 1971

DEPARTMENT OF THE ARMY
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

ARTILLERY RANGE WITH RAINFIELD



ROCKET TEST TRACK WITH RAINFIELD

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Ammunition Develop. 6 Engineering Labs
and
Quality Assurance Directorate
FRANKFORD ARSENAL
Philadelphia, Pa. 19137

February 1971

ABSTRACT

Drop-size measurements of the simulated rain fields at Holloman Air Force Base are reported. These measurements are compared with drop-size spectra from natural rains in various climatic regions. Average drop-size spectra for tropical, temperate, and arctic climatic regions are presented for rainfall rates of 1, 0.5, 0.1, 0.01 percent of total time. In general, there are too many drops in the simulated fields in comparison to natural rains. Particularly apparent are the large numbers of small drops in the range less than 1.0 mm. Even under accelerated test criteria the small drops occur too frequently. In general the simulated field using the H-1/2 U 80200 nozzle (artillery field nozzle) represents a drop density of about 9 times as heavy as natural tropical rain of 132 mm/hr. At drop diameters larger than 2.6 mm, the natural distribution lies between the two simulated distributions. It would appear that realistic testing requires a combination of the simulated rain fields.

Recommendations are made for utilizing the simulated fields in such a way as to make them more nearly simulate natural rains.

FOREWORD

This report summarizes work performed at the Holloman Air Force Base, N. M. by Dr. E. A. Mueller and A. L. Sims of the Illinois State Water Survey at the University of Illinois, for the U. S. Army Frankford Arsenal under Contract No. DAAAG 11-69-C-0748. This work was under the technical surveillance of Messrs. David Askin and John Sikra, of Frankford Arsenal, whose technical aid is greatfully acknowledged.

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INTRODUCTION

Frankford Arsenal personnel have made tests of the sensitivity of artillery fuzes to rain using the rocket test track facility at Holloman Air Force Base. Gun-fired tests have also been made through the Army's artillery rain field adjacent to the rocket test track at Holloman. While these tests have been quite useful in making fuze improvements, the exact characteristics of the simulated rains at Holloman were not known, and no correlation of these rains to natural rainfall had been made. The primary purpose of the work has been to provide information to allow meaningful correlation of results obtained in the simulated rain field with natural rainfall.

In July 1969 measurements of the drop-size spectra were made in the Holloman aritllery rain field. Similar measurements were also made on the rocket test track rain field for the Air Force Cambridge Research Laboratories (Contract F19628-69-C-0206), and some of the results of those measurements, as they relate to the Army's interests, will be reported here.

Natural raindrop size spectra collected previously by the Illinois State Water Survey have been used to aid in the comparison with the Holloman simulated rainfalls. Finally, recommendations are offered as to how the rain field data can be translated and effectively employed in future testing to better simulate natural rain.

MEASUREMENTS OF ARTILLERY RAIN FIELD

Instrumentation

Raindrop camera measurements of natural raindrop spectra by the University of Illinois have been made in nine different world-wide locations. Over 24,000 samples of one m^3 each of rain data have been collected since 1957. These data were collected using a camera system consisting of a 29-inch diameter parabolic mirror and an electrically operated 70-mm camera fixed in place. Four FT-503 flash tubes were used to illuminate the sampling volume.

For movable operation in the artificial rain field, it was decided that a smaller photographic system would be necessary. The same 70-mm camera was used, but a paraboloic mirror of 12-1/2-inch diameter was purchased. This mirror had a focal length of 100 inches instead of the 160 inches of the 29-inch mirror, producing a larger magnification of the film. A single FT-503 flash tube was found sufficient to light the smaller sample volume. The sample volume photographed on a single frame of film was 726 inches^3, or 0.0119 m^3. The larger drop camera used previously had a sample volume of 0.1M-3 m^3 per frame. The smaller sampling volume was a necessary consequence of having a movable system and of the requirement of measuring close to the rocket test track. This smaller volume was considered acceptable due to the much higher average concentration of raindrops expected in the artificial rain field than in natural rain.

The optical configuration for the drop camera, as used in these measurements, is shown in Figure 1. The 12-1/2-inch mirror is the first element of a Newtonian telescope. The camera lens aperture is located at the focal point of the mirror, producing a telecentric system which elminates most of the perspective effects. The volume of rain space photographed is a right circular cylinder that has a 12-1/2-inch diameter and a 6-inch depth. A small portion of this volume is eliminated by the obstructions of the diagonal flat mirror and its support.

After the film is processed, it is projected so that the drop images are three times the size of the original drops. Measurements of the horizontal and vertical sizes of the drops are then obtained using semiautomatic calipers. The measurements entered in punch cards are averaged in a computer to obtain the best estimate of the diameter of the drop. At the same time, the computer obtains a volume drop-size spectrum and computes rainfall parameters.

In the artillery range the nozzle H-1/2 U 80200 (manufactured by Spraying Systems Company) is generally used. This nozzle is frequently referred to

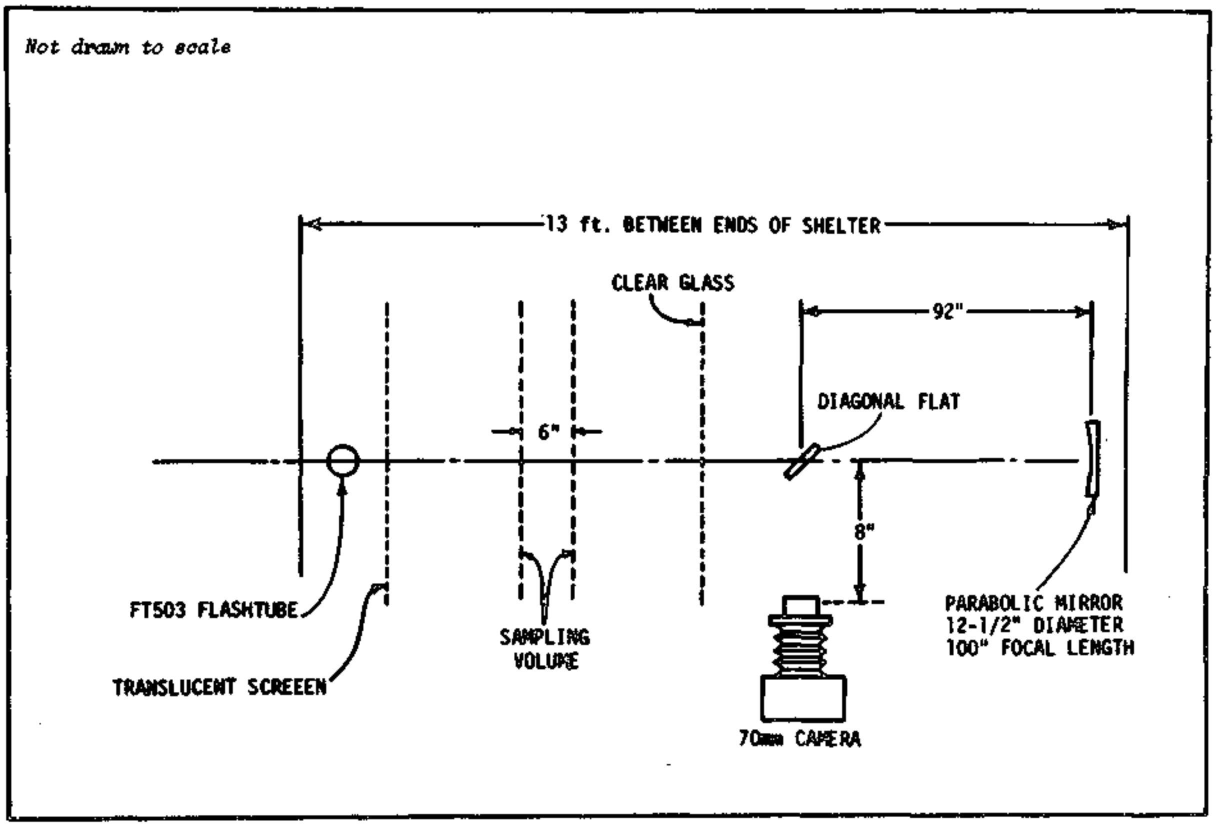

Figure 1. Optical configuration of the drop camera

as the deluge nozzle due to the extremely high concentration of drops which it produces, and in this paper it is referred to as the artillery field nozzle. This nozzle normally is operated at 3-1/2 psig.

The pressure is measured with the height reference of the gage at the top of the nozzle. However, the tap for the gage is in a reducer in the riser pipe. Turbulent fluctuations of +1/4 psi and uncertainties of the dynamic pressure in the reducing section restrict the use of this pressure to a means of resetting a condition in the field.

Data Collection

For the tests of the artillery rain field, the drop camera was mounted on a flatbed truck. It was positioned in such a way that the sampling volume end of the drop camera shelter protruded over the back of the truck bed. This allowed the water to fall through to the ground, rather than splash back into the sampling volume. By raising the camera on a framework about a foot above the truck bed, the lower edge of the 12-1/2-inch diameter sampling volume was located 5 feet 2 inches above the road. This placed the sampling volume at the height of the trajectory of the projectiles used in fuze testing. A generator to provide power to the camera was also mounted on the truck bed just behind the cab.

After a section of the rain field was turned on and adjusted to the proper pressure, the truck was slowly driven through the simulated rain. For the five runs reported here, the average speed was 104 ft/min or 1.2 mph, which was as slow as the truck could be driven smoothly. At the 28 frames/min rate of operating the camera, photographs were taken at intervals of about 3.7 ft.

A test run is defined in this report as a single pass of the truck mounted equipment through a 400-ft section of the artillery rain field. A total of 18 of these test runs was made. Of these test runs, five were made on the section nearest the impact area, seven were made on the second section from the impact area, and six on the third section. Since the measurement of the drop sizes from the film is very slow for the extremely high drop concentrations of the artillery rain field, only five test runs were measured. The correlation of the results of test runs on the same section of the rain field was excellent, so it was concluded that further measurements of the film would not be worth the considerable added effort.

RAIN FIELD OF THE ARTILLERY RANGE

Average Spectra

The average drop spectra for test runs 10, 11, 12, 15, and 16 are shown on Figures 2 - 6 , respectively. Runs 10 and 11 were made on the third section from the impact area, run 12 is of the second section, and runs 15 and 16 were made on the section nearest the impact area.

The total drop concentration shown on these figures is the total number of drops per m^3 in the spectra. The equivalent rainfall rate is defined as the rainfall rate which would be obtained if the drops of the measured spectrum were traveling at their terminal velocity. Much confusion has resulted in the past from the characterization of the artificial rain field by placing raingages in the artificial field and measuring the flux of water entering the gage. This parameter is misleading if directly applied to natural rain. Since the water drops in the artificial field are traveling slower than in natural rain, there is a higher concentration of drops for the same water flux rate. The rate of water flux transport in the artificial field is referred to as the accumulation rate. The equivalent rate is always greater than the "accumulation" rate, that is, the rate measured by a raingage placed in the artificial rain field, since the artificial field raindrops are traveling at less than terminal velocity. The liquid water content is the summation of the masses of the drops in a cubic meter of space.

There is considerable similarity between the results of the test runs made on the same sections of the rain field. Values from runs 15 and 16 (Figs. 5 and 6) are nearly identical, and runs 10 and 11 both have the same straight line appearance on the semi-logarithmic plots, although the numbers of drops in each size classes are a bit different. There are significant

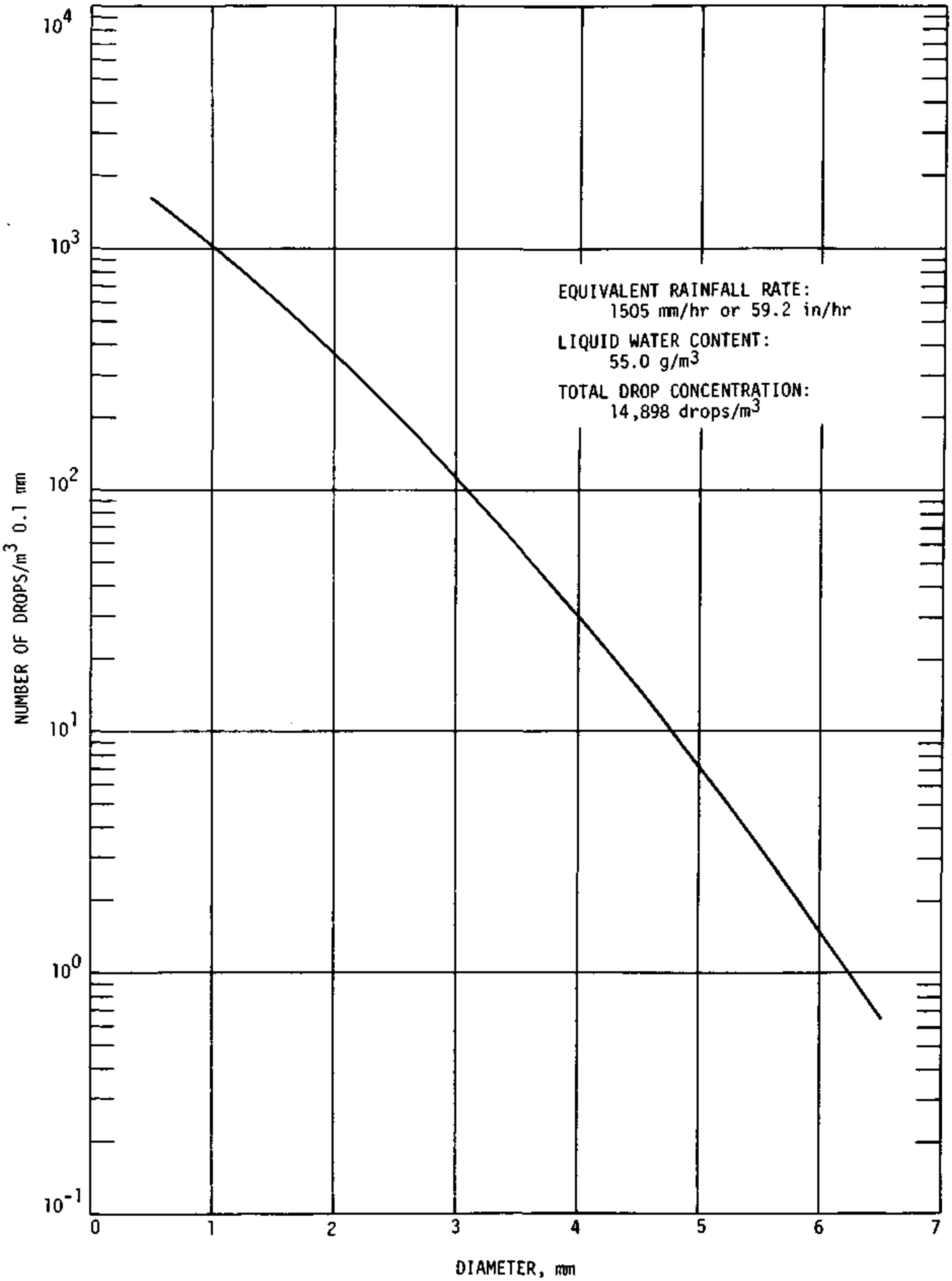

Figure 2. Drop-size spectrum from run no. 10 of the artillery rainfield

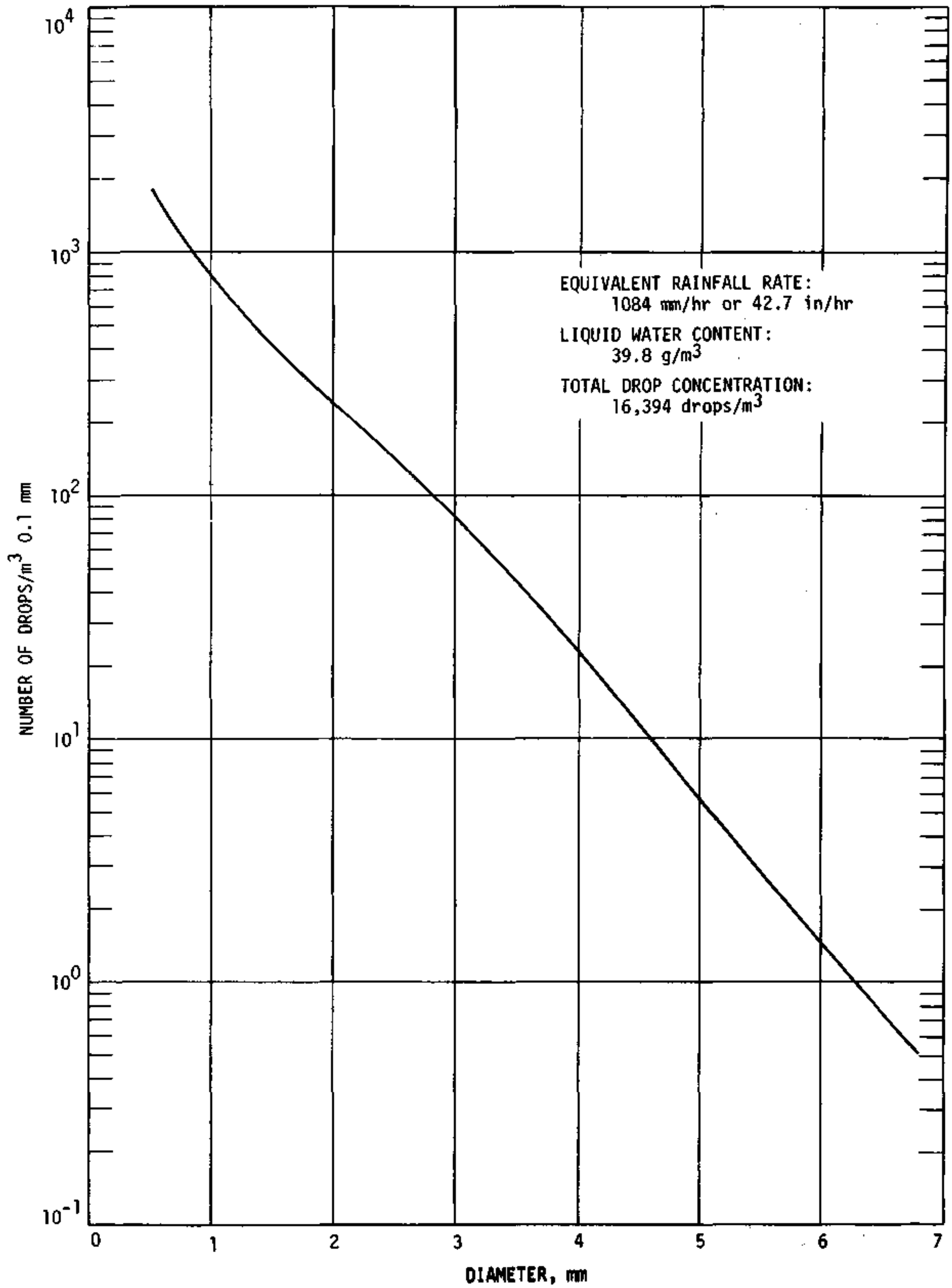

Figure 3. Drop-size spectrum from run no. 11 of the artillery rainfield

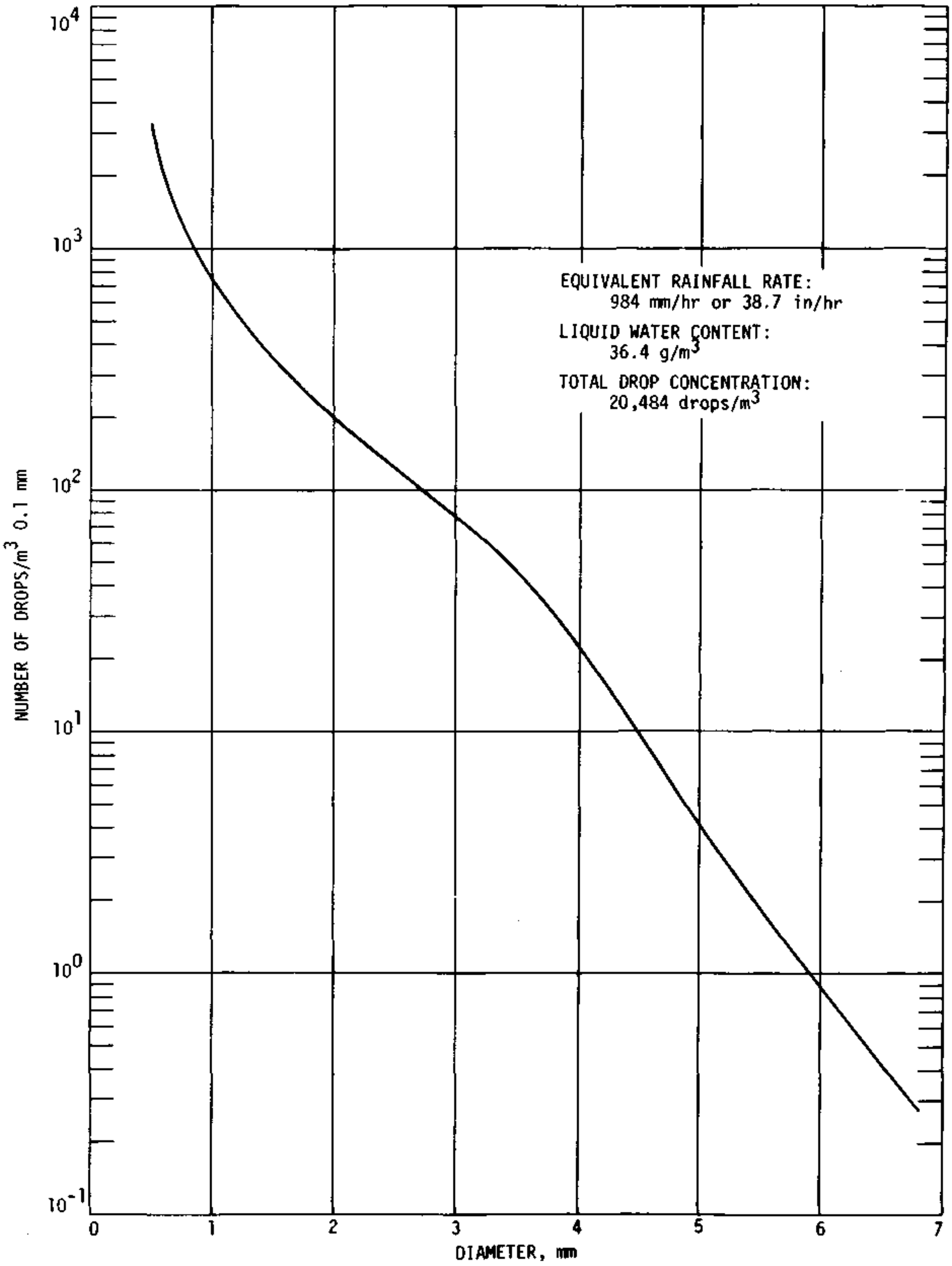

Figure 4. Drop-size spectrum from run no. 12 of the artillery rainfield

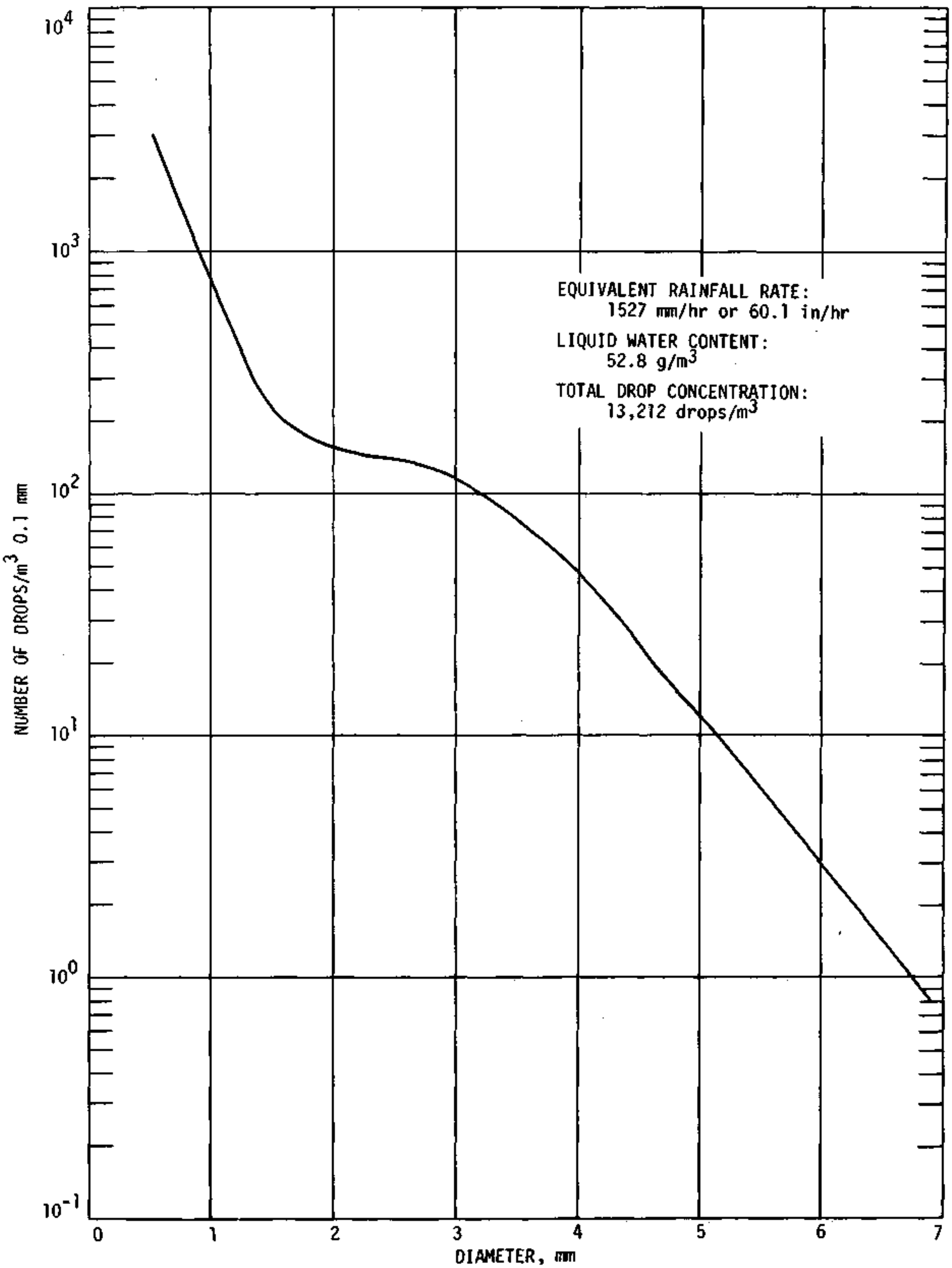

Figure 5. Drop-size spectrum from run no. 15 of the artillery rainfield

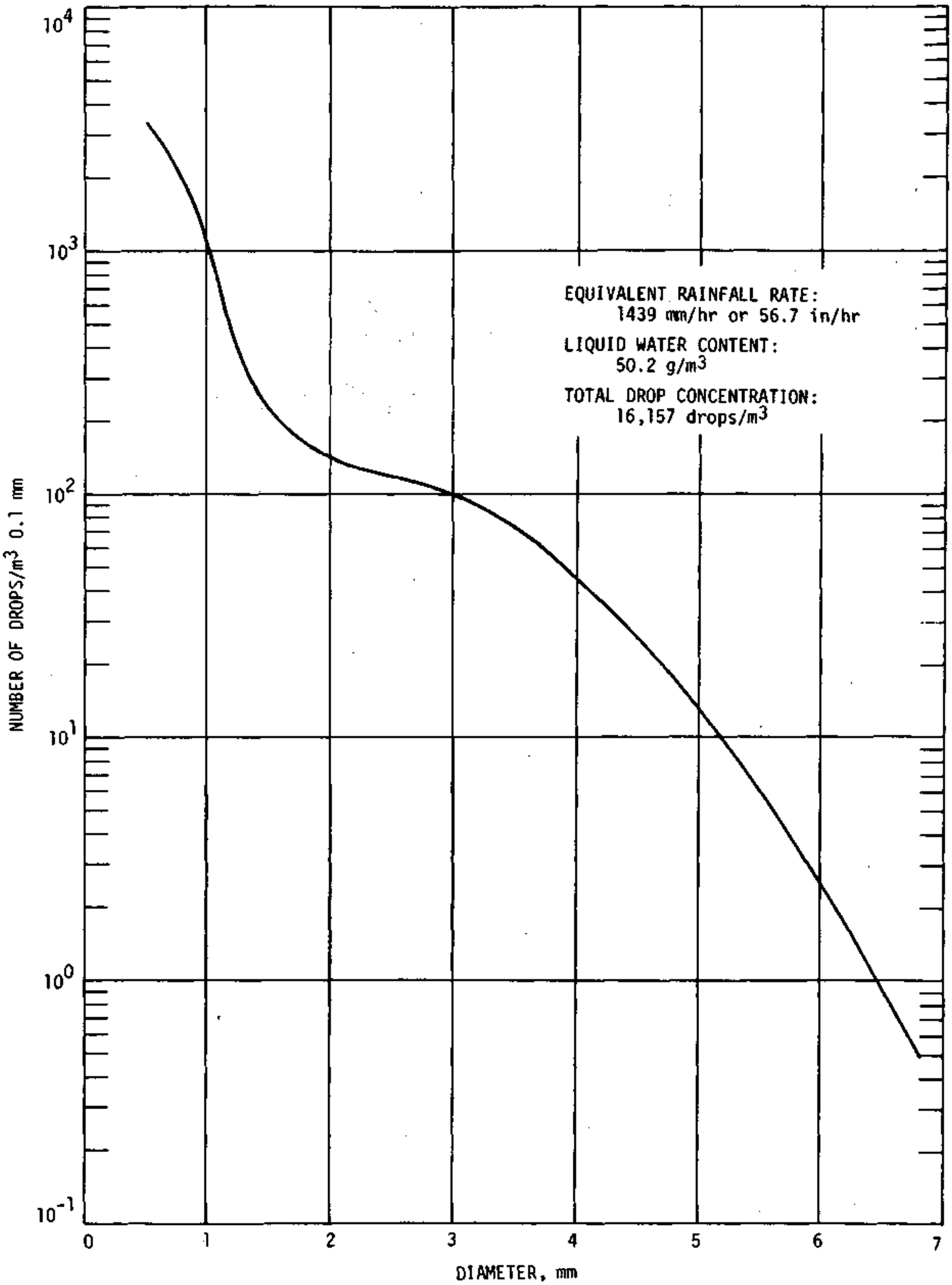

Figure 6. Drop-size spectrum from run no. 16 of the artillery rainfield

differences in the measurements on the three sections of the rain field. The explanation for these differences is not known, but it is suspected that some real difference existed in the alignment of the nozzles, or perhaps some nozzles were clogged with debris in such a way as to alter the distribution of drops produced. Before the runs were made, the nozzles were aligned in the routine manner, but no special alignment was performed.

The data from all three sections of the rain field were averaged. This average spectrum is plotted on Figure 7. This average curve would normally be experienced during artillery tests. Table I provides some of the statistics of this average spectrum. In this table the mean volume diameter is the diameter of the drop which has a volume equal to the total liquid water content divided by the number of drops. The median volume diameter is the diameter of the drop for which half of the liquid water content is above this diameter and one half below. In comparison with natural rains, the values of these parameters are between 1.4 and 2.1 for mean volume diameters and 1.2 and 2.0 for median volume diameters.

Variation of Drop Size Spectra with Height

All measurements in the artillery field were obtained at a height between 5 feet 2 inches to 6 feet 2 inches above the ground. However, there were measurements of drops from the same nozzles made on the fitting track. These fitting track data were obtained for effective heights of 5 feet 6 inches up to 7 feet 6 inches, as referred to the artillery range. The data from the fitting track along with the average spectrum from the artillery field were used to obtain the curves on Figure 8. In this figure it can be noted that the total concentration of drops is reasonably constant (±5%) over heights of 5 to 6.75 feet above the ground. Around 7 feet from the ground the total concentration decreases considerably. Most of this reduction is due to a reduction of the small drops, as shown by the curve for ≤1.0 mm drops. In fact at 7.5 feet (highest measured) the number of drops larger than 4.0 mm reduces only 30%, while the total number of drops is reduced by 75%.

In the spray of water produced in the artillery field there is apparently

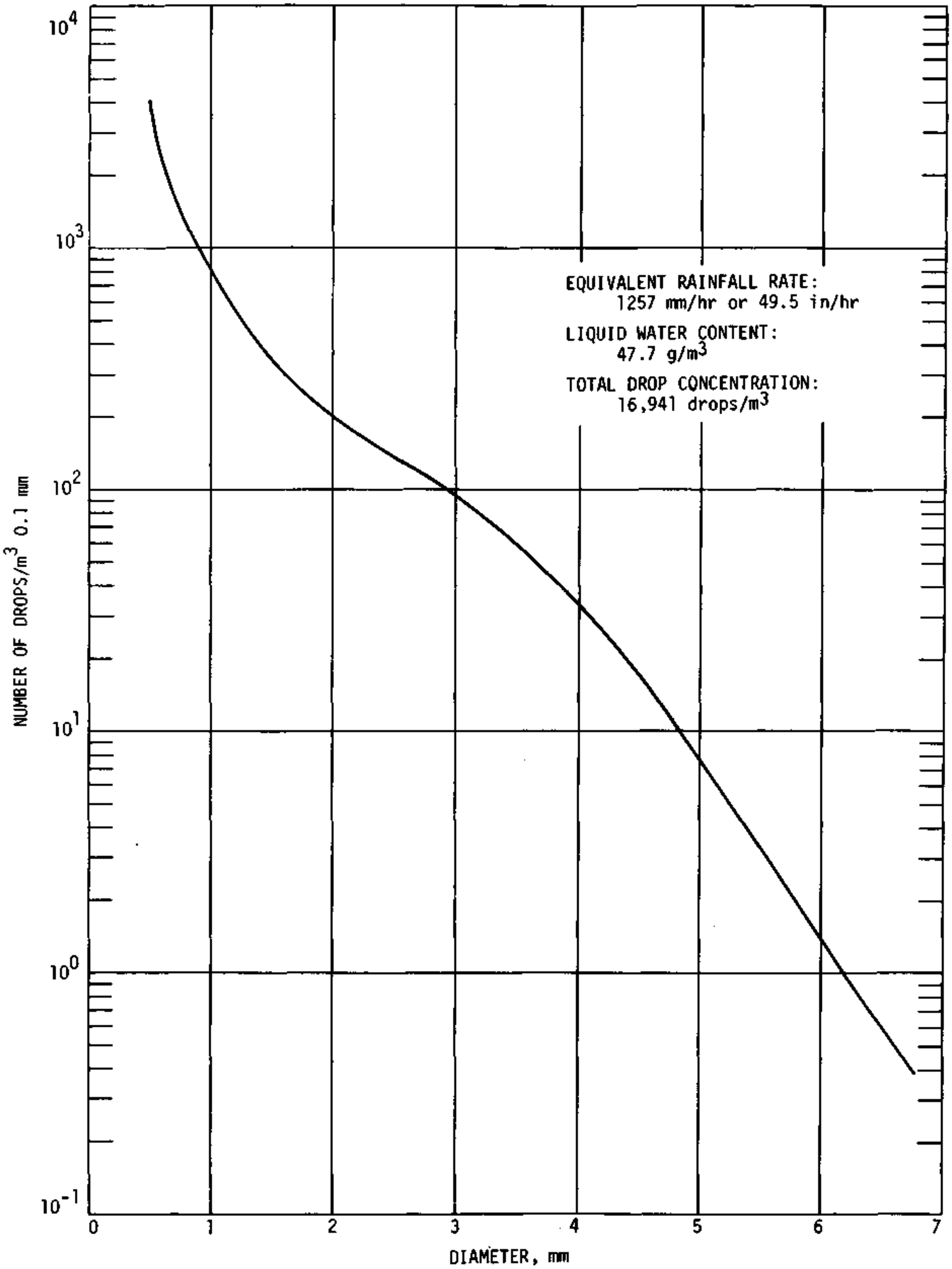

Figure 7. The average drop-size spectrum for the artillery rainfield (This is an average of runs 10, 11, 12, 15, and 16.)

a tendency for the large drops to be propelled with larger velocities so that large drops are prevalent as high as 7.5 feet from the ground. On the other hand, the number of large drops reduces more rapidly near 5 feet, so that testing which takes place below 5 feet will not be subject to nearly as many large drops. Unfortunately, no data were obtained at lower heights than the 5-foot level. All fitting track drop size data were at higher effective levels with respect to the nozzles because it was impossible to get the equipment positioned lower.

Table I. Characteristics of the average drop size spectrum from the artificial rain field on the artillery range.

Drop Diameter (D)	No/m^3 0.1 mm	No. Drops/m^3 $\leq$ D	Fraction of Drop $\leq$ D	Liquid Water in Drops $\leq$ D (g/m^3)	Fraction of Liquid Water in Drops $\leq$ D
0.5	4059	4059	0.24	0.36	0.0076
0.7	1650	7584	0.45	0.98	0.021
1.0	820	11089	0.66	2.51	0.053
1.5	340	13463	0.80	5.49	0.12
2.0	210	14743	0.87	9.70	0.20
2.5	140	15573	0.919	15.28	0.32
3.0	96	16150	0.953	22.18	0.47
3.5	60	16517	0.975	29.32	0.61
4.0	33	16726	0.987	35.47	0.74
4.5	17	16840	0.9940	40.29	0.85
5.0	7.9	16897	0.9974	43.68	0.916
5.5	2.4	16922	0.9989	45.60	0.956
6.0	1.4	16932	0.99947	46.65	0.978
6.5	0.5	16936	0.99971	47.12	0.988
All Sizes		16941	1.0	47.68	1.0

Other Miscellaneous Parameters

Equivalent rainfall rate = 1257 mm/hr or 49.5 in./hr
Liquid water content = 47.7 g/m^3
Total drop concentration = 16941 drops/m^3
Mean volume diameter = 1.75 mm
Median volume diameter = 3.21 mm

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* This represents the number of drops in one cubic meter of airspace in an interval of 0.1 mm centered on the specified diameter.

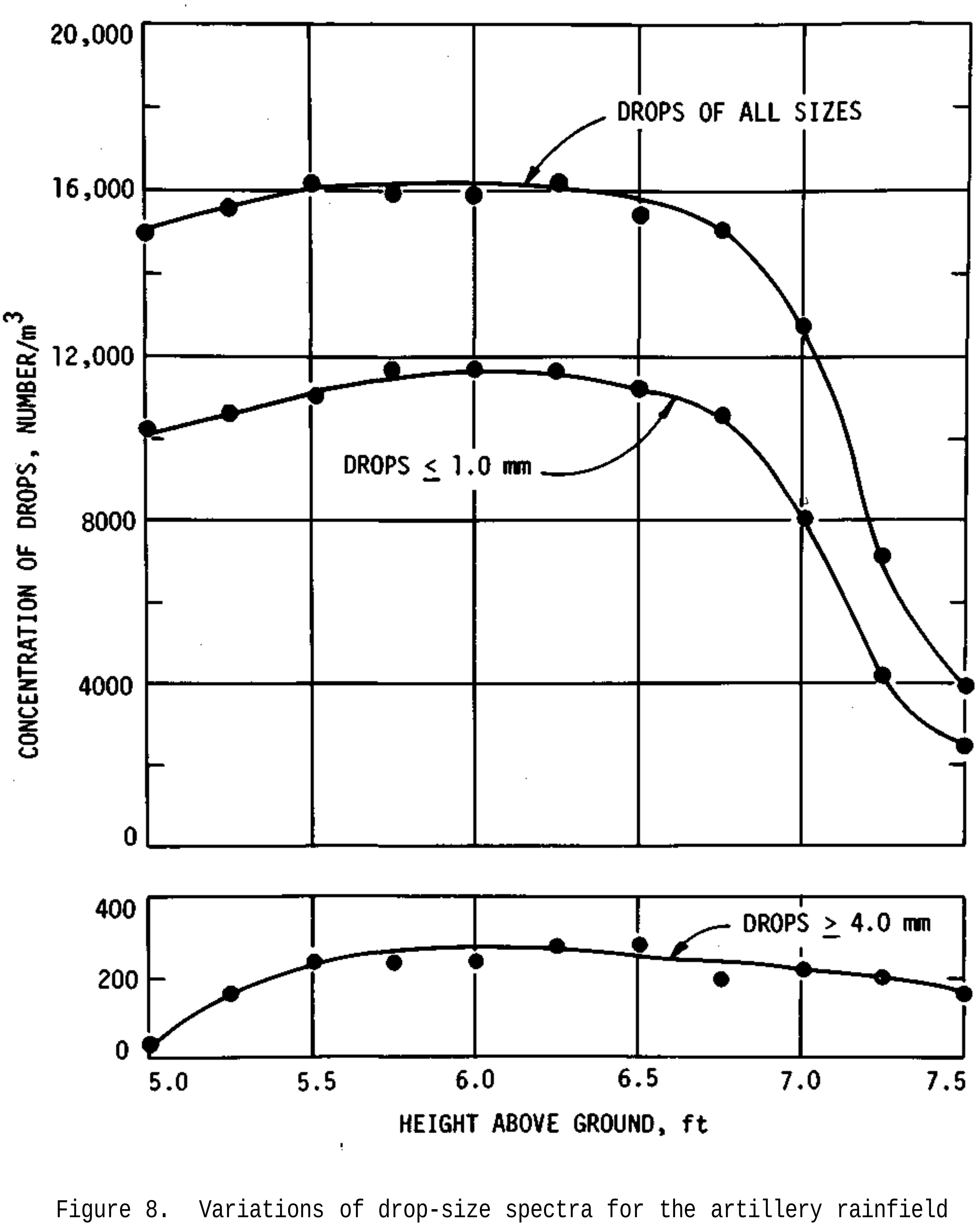

Figure 8. Variations of drop-size spectra for the artillery rainfield (H-1/2U 80200) as a function of height above ground

Within the level of 5 to 7 feet, the average sprectra of Table I is recommended as the most probable spectra. This spectrum is the one seen by the test item in transversing the range and is most appropriate to use in assessing the test environment.

Lateral Displacement Effects

With respect to left-right offset effects on the spectra within the rain field, very little can be definitively stated. The measurements for a truck driven through the rain field showed no variations within the 1-foot wide sample when the average spectra for a 400-foot section was used. This is at least in part due to the inability of the driver to maintain his position in the center of the field to within a few inches. Short sections of 40 feet were analyzed in an attempt to obtain some crude estimate of lateral variability. These estimates varied widely, and most probably are a result of the small sample size as well as the lateral variability. In addition, there was no way in which to ascertain the lateral displacement of the truck. Apparently, the spectra from the deluge nozzles are somewhat less affected by lateral displacement than the standard nozzles where an average reduction of 30% in effective rainfall rate was obtained 18 inches off the center line. Visual inspection of the vertical fans of water produced by these different nozzles would support these observations of smaller lateral variability than vertical variability.

Pressure Variation Effects

It was anticipated that as the nozzle pressures are increased the average drop sizes should decrease. Unfortunately, there is not the capability at Holloman Air Force Base for varying the pressure delivered to these nozzles over much range. The hydraulic system used will not permit operating at much higher pressures because of the capacity of the pump and delivery manifolds. Lower pressures fail to propel the drops with sufficient velocity to allow them to reach the sampling area.

Each of the H-l/2 U 80200 nozzles discharges 5.9 gallons per minute at

3-1/2 psig. Each manifold contains 50 nozzles. Thus, a rate of 245 gallons per minute is required for each manifold system. This rate of flow taxes the system so that only 2000 feet of the large nozzles may be employed at any one time. An even shorter length would be required at higher delivery rates.

Data at an indicated pressure of 3 and 4 psi was obtained on the fitting track. The actual meaning of this pressure is difficult to ascertain. The pressure gage is attached by a tapped fitting in a reducing section of pipe. The water flow in this region is turbulent as is indicated by continual fluctuation of the pressure gage. Since the flow is turbulent and is in a region where the average velocities are varying due to the diameter of the pipe changing, the actual pressure at the nozzle is difficult to assess. However, this measurement is sufficient to provide resetability from day to day.

At both pressures no significant differences in the spectra were observed, as shown in Figure 9. If the hydraulic limitations would permit higher pressures , changes in the spectra could be expected.

Angle Variation Effects

One part of this investigation was to determine whether change of the angle of the nozzles would produce a more natural drop size spectra. No direct measurements of the drop size spectra with respect to changes in the vertical angle of the nozzle were made on either the sled truck or the artillery rainfields. On the test track, changes of the angular position were made and it was apparent that no gain would accrue.

Using the standard pressure of 3-1/2 psig, if the nozzle is directed downward, the fan of water falls below the area of interest over the track. This loss of water can be noted in the calibration of the present field where at a height of 2 feet above the track a large loss of the small and medium drops occurs. Although the loss of small drops (less than 1 mm) may be beneficial to the simulation of the spectrum to that of natural rains, the relative proportion of medium sized drops (1 to 2.5 mm) to large drops becomes inappropriate when the sample is taken more than 2 feet above the track. There is also inefficient usage of water when sampling above 2 feet over the

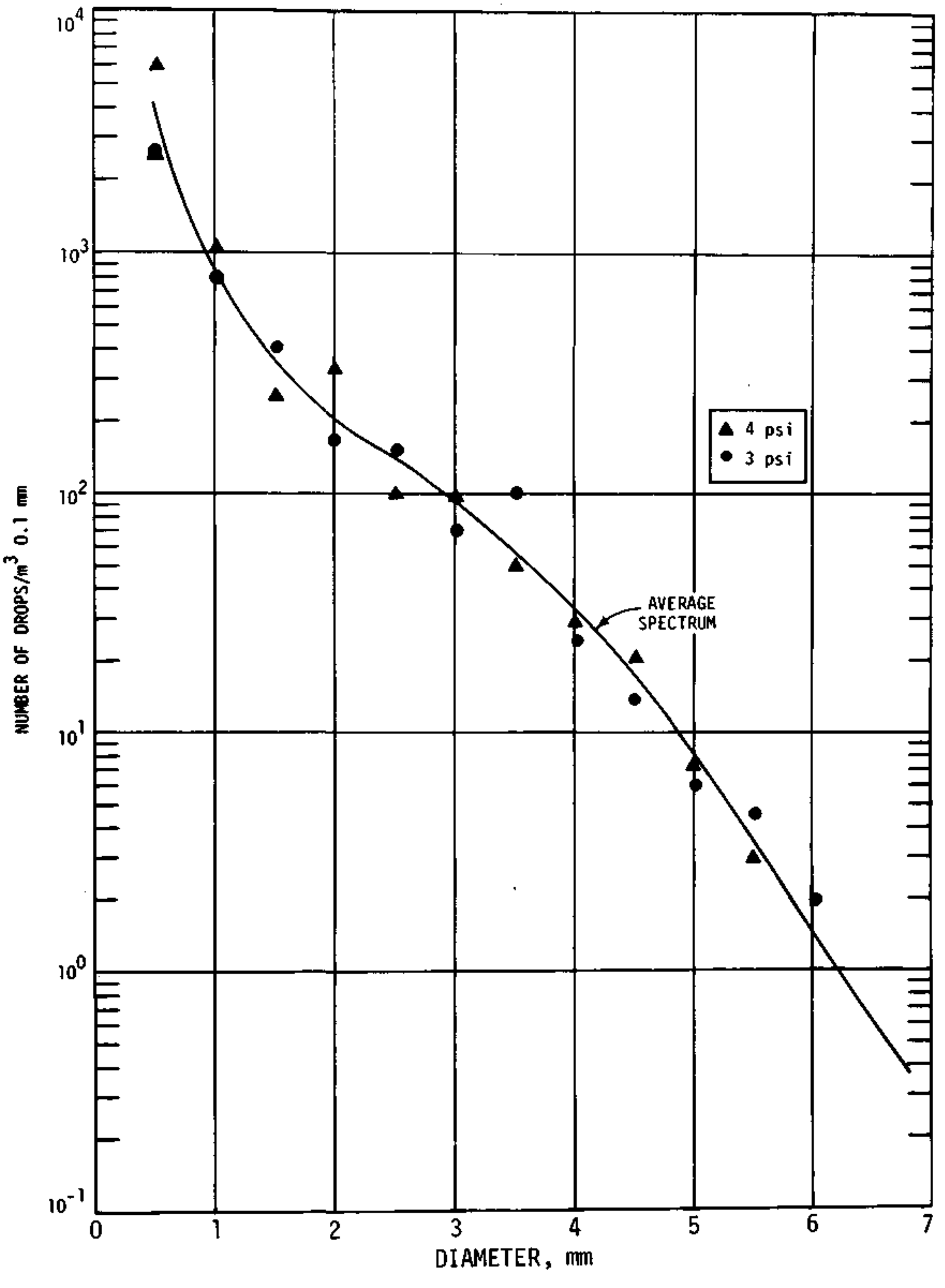

Figure 9. Effect of nozzle pressure on drop spectra

track.

If the nozzle is directed at a higher angle and if the pressure is maintained at 3-1/2 psi, the fan of water does not reach the track. Conceivably, the pressure could be increased to compensate for this underthrow, but the higher pressures cannot be maintained with the present water system. Another alternative would be to move the risers nearer to the point of interest. This is a possible solution for the artillery field, but is not possible along the rocket track. Furthermore, it is doubtful that any great advantage would be obtained. The only advantage may be in giving the large ill-defined masses of water* sufficient time to break up into more reasonably sized drops.

Since the water pressure at the discharge nozzle and the distance from the nozzle area to the sampling area are essentially fixed on the sled track, little benefit can be obtained by changing pressures and vertical angles using the H-1/2 U 80200 nozzles.

RAIN FIELD OF THE ROCKET TEST TRACK

Data Collection

For measurements on the rocket test track facility, the drop camera was mounted on a three-wheeled carriage provided by Holloman Air Force Base. Measurements of the rain field on the main track were obtained by pulling this carriage through the rain at about 30 ft/min. This same carriage was used on a separate section of track referred to as the "fitting track." This section of track was furnished with an identical section of rain field as the main track, but with only four nozzles on each side. It possessed the great advantage of permitting easy access to the artificial rain without interfering with rocket firings or schedules. Drop size spectra obtained from the fitting track were found to be identical to the main track.

Average Spectrum

For testing along the rocket test track, the standard nozzle is the H-1/4 U 8070. This nozzle provides a lower total concentration of drops than

*See Appendix

does the H-l/2 U 80200 nozzle. The standard nozzle is deficient in large size drops and thus for purposes where the larger sizes are important is not adequate. A more complete discussion of the calibration of this nozzle can be found in the final report, AFCRL-70-0282 on AFCRL Contract Number F19628-69-0206. The final average spectrum for the rocket track field with the standard nozzle is shown in Table II and Figure 10.

Table II. Parameters of the mean distribution under calm wind conditions for standard nozzle conditions on rocket test track.*

Drop Diameter (D) (mm)	No. Drops/m^3 $\leq$ D	Fraction of Drops $\leq$ D	Liquid Water in Drops $\leq$ D (gm/m^3)	Fraction of Liquid Water in Drops $\leq$ D
0.75	1450	0.29	0.209	0.026
1.25	3110	0.61	1.256	0.16
1.75	4345	0.86	3.617	0.45
2.25	4882	0.961	5.938	0.75
2.75	5032	0.9907	7.165	0.900
3.25	5068.9	0.9980	7.687	0.966
3.75	5076.6	0.99948	7.860	0.988
4.25	5078.6	0.99987	7.927	0.9961
4.75	5079.2	1.00	7.958	1.00

Other Miscellaneous Parameters

Equivalent rainfall rate = 158.7 mm/hr
Liquid water content = 7.96 gm/m^3
Total drop concentration = 5079 $drops/m^3$
Mean volume diameter = 1.44 mm
Median volume diameter = 1.80 mm

* This table is based on drops larger than 0.5 mm in diameter.

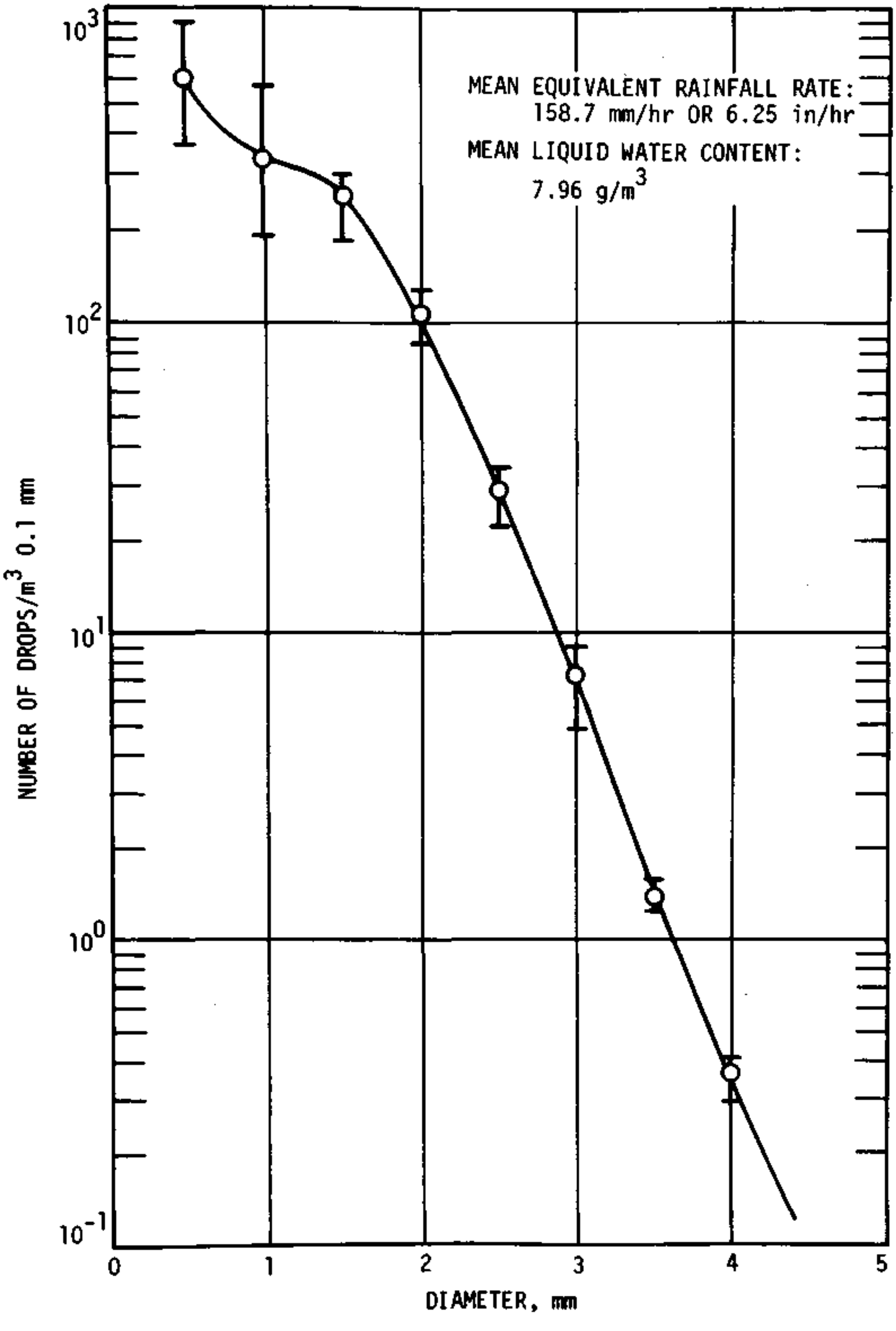

Figure 10. The average spectrum for the standard rocket test track rainfield based on four no-wind test runs (The vertical bars show the range of measurements from the four runs.)

NOZZLE MODIFICATIONS

Nozzle Spacing

Studies were conducted of the variability of drop concentration and liquid water content with position along the rain field. Since the nozzles are 8 feet apart on each side of the track, a cyclic repetition of these variables in multiples of 8 feet wavelength was expected. Actually, the nozzles on each side are offset by 4 feet from each other so that if there is no wind one expects a 4-foot repetition. Power spectra of the spatial samples were obtained and there was no evidence whatsoever of any tendency to be cyclic on 4 feet or multiples thereof. It may be that the statistical noise due to the small size obtained at each point may mask any effect that is in existence, and this may be quite valid. However, a test item would sample an even smaller area than the camera and thus is not subjected to cyclic damage.

It is concluded that the spacing of the nozzles is adequate as presently installed.

New Nozzles

Spraying Systems Co. makes other nozzles in the same series as are presently being used. Data furnished by the manufacturer of the size distributions of the drops produced by these nozzles have been examined to determine whether better nozzles might be used. The calibrations furnished by the manufacturer are not the same as actually obtained in a volume in space since their calibration is related to the total amount of water delivered. Nonetheless, a reasonable estimate may be made as to usefulness of other nozzles. Figure 11 shows spectra for the H-l/4 U 8070 nozzle, the measured spectrum from the track, and the spectrum from the flat spray nozzle 6570. This nozzle would be an intermediate nozzle to the two presently used.

As can be noted on Figure II, a fair agreement between the manufacturers spectrum and the measured spectrum was obtained for the H-l/4 U 8070 nozzle.

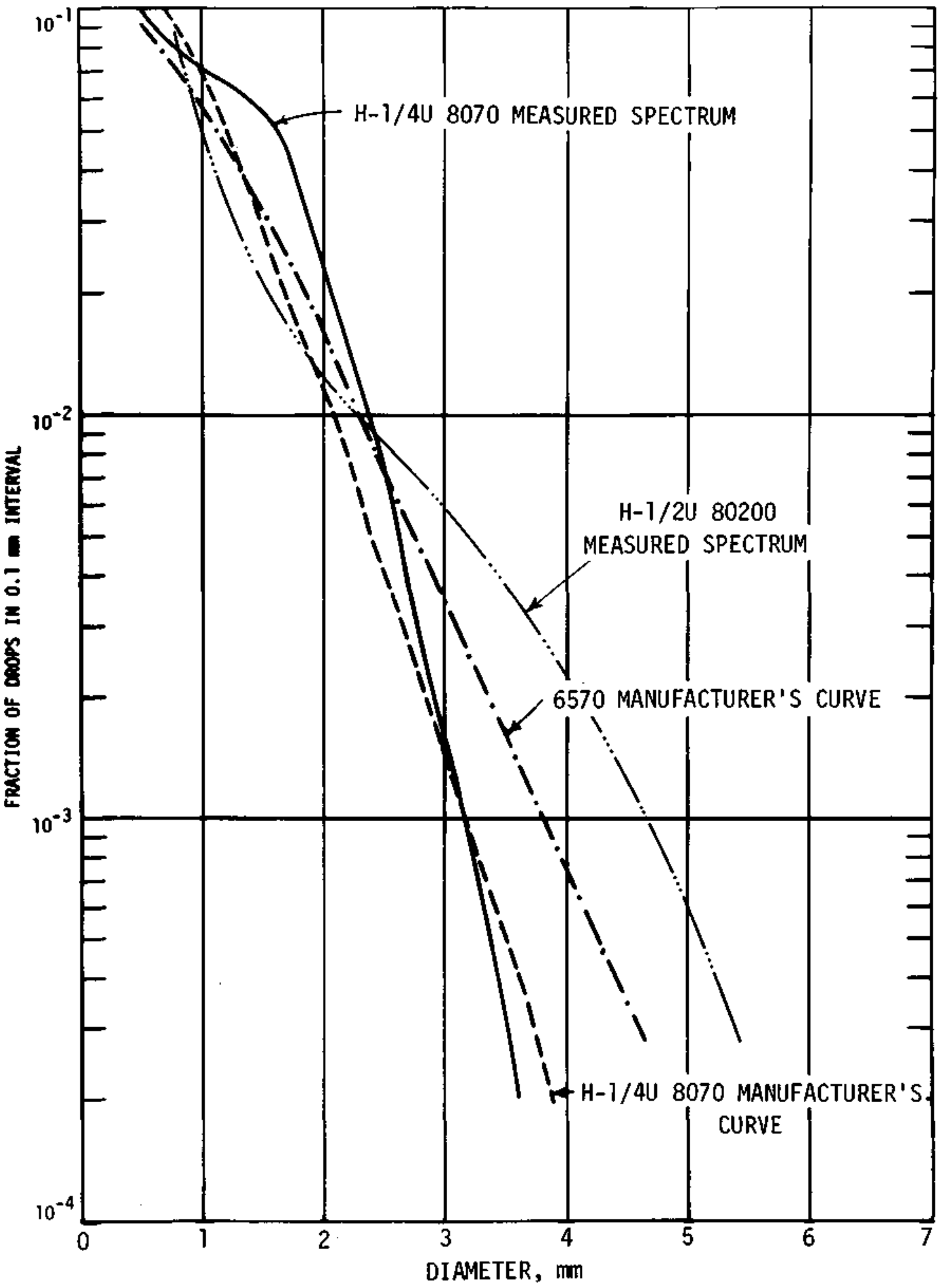

Figure 11. Comparison of drop spectra for different nozzles

The manufacturer did not furnish data for the H-l/2 U 80200 nozzle, but the measured distribution is plotted in Figure 11. The 6570 nozzle is intermediate to the 8070 and 80200 nozzle, however, it may require modifications of the water supply system. The first two digits of the nozzle specification refers to the angle of the fan of water with a delivery pressure of 40 psig. Thus, the fan of water from the 6570 may be so narrow that gaps in the field are obtained.

These are two nozzles in the 80xxx series between the 8070 and 80200 which may improve the simulation of the artificial rain spectrum to natural rain but no information as to these nozzles spectra are available. All of the nozzles tend to have too many small drops although this tendency is reduced somewhat in the 6570 nozzle. This, slight improvement may be made by choice of nozzles but it would seem that a completely different type of nozzle is required to fully duplicate natural spectra.

DROP-SIZE DISTRIBUTIONS IN NATURAL RAIN

Climatic Distributions

A large collection by the Illinois State Water Survey of drop-size distributions obtained in natural rains in various climatic regions was used to determine average distributions corresponding to rainfall rates equalled or exceeded 0.01%, 0.1%, 0.5%, and 1.0% of the time in each region. (Data for this work was provided by support from U. S. Army Atmospheric Science Laboratories, Fort Monmouth, New Jersey, and Frankford Arsenal, Philadelphia, Pennsylvania). Although raingage charts have been available through the courtesy fo the Atmospheric Science Laboratories at Fort Huachuca, these charts have not aided in the analysis for short time rain rates. The chart scale of 8 days in 12 inches precludes analysis in the time scale required to produce one-minute rainfall rates. The rates corresponding to these frequencies are tabulated in Table III. These rates were determined from frequency curves (Fig. 12) prepared by D. M. A. Jones as part of the work of AFCRL Contract F19628-69-C-0070. Raingage data from Woody Island, Alaska, were used to represent arctic regions , that from Panama to represent the

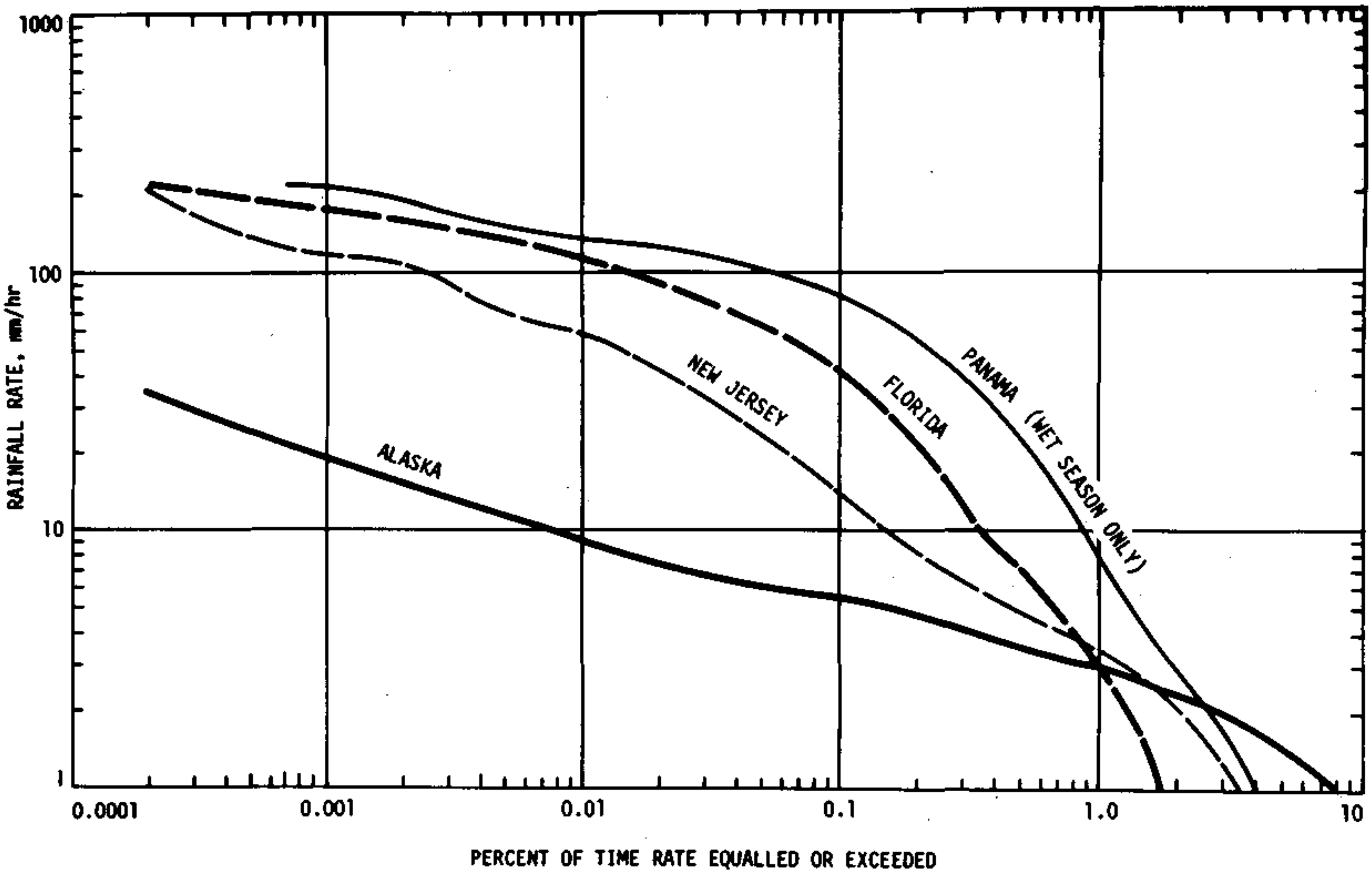

Figure 12. The frequencies of occurrences of 1-minute rainfall rates at various locations

tropics, and that from New Jersey to represent temperate climatic regions. The temperate-tropical frequency in Table III is based on the New Jersey, Florida, and Panama data. Data from these three locations were grouped together to produce a single frequency of occurrence relationship, because it is believed that this is the best estimate of an average region where rainfall is deemed sufficient to affect military operations. This temperate-tropical relationship is weighted slightly towards the semi-tropical (i.e., Florida) climate by virtue of the sample size.

Table III. Rainfall rates (mm/hr) equalled or exceeded for the indicated percentages of the time in various climatic regions.

	0.01%	0.1%	0.5%	1.0%
Arctic	9.0	5.4	3.7	3.0
Temperate	55.2	15.20	4.8	3.3
Tropical	132.0	84.0	27.0	8.4
Desert	64.0	31.0	7.9	3.6
Temperate-Tropical	95.6	45.6	13.3	5.2

The frequency curves are based on 1-minute accumulations and are for total time (not just rain time). Approximately one year of data was used for all locations except Panama, where data from only 104 days of operation were available, all taken between June and November, which are the rainy months of the year. Raingage charts suitable for calculating 1-minute frequencies are not available for the dry season in Panama, but all frequencies would, of course, be expected to be smaller than indicated by the Panama "wet season" curve on Figure 12. It should be emphasized, however, that all the curves of Figure 12 are in terms of percentage of total time, rather than percentage of rain time.

The desert data were obtained in the vicinity of Flagstaff, Arizona, and probably do not represent a good climatic desert. In fact, variabilities of rainfall in desert areas may be extremely large and a climatic average

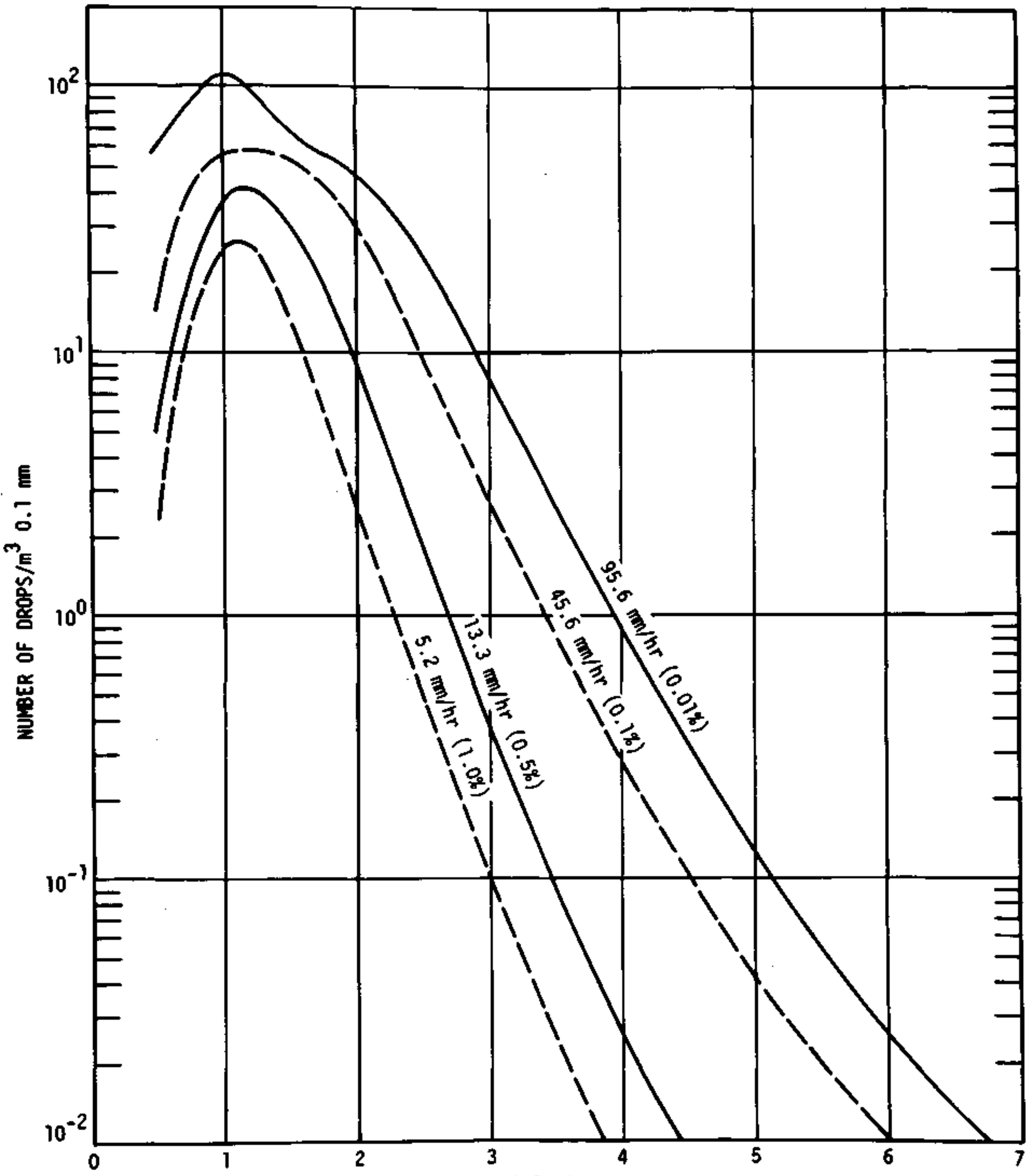

Figure 13. Average drop-size spectra for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0% of the time (These curves are for all available data from nine locations in all major climatic zones around the world.)

extremely difficult to obtain.

If, instead of considering the frequencies of rainfall rates to the total time, the reference is made to rain time, Table IV results. This table is based on the same data as used in Table III but refers to the percentage of rain time. Thus, this table yields the conditional probability of rainfall rate given that it is raining. The value for the 0.01% rain time in the desert climate is an extrapolation of the data. Only 5000 minutes of data are available and 10,000 is the minimum required to estimate the 0.01% frequency. As expected, all rates in Table IV are higher than rates in Table III, but this is particularly true at 1% frequency levels. At this level, all but the arctic climate showed an increase by more than 10 times while the 0.01% levels were changing by about 2 times. This is an indication of the skewness of rainfall rate frequency curves.

The set of average distributions in Figure 13 is based on all data available from 9 locations around the world. All the samples having rainfall rates within ±12% of the desired average rate were included in each of the four classes. Rainfall rates and other parameters were then calculated for the average distributions. The number of samples (distributions) used in each average varies with rate, ranging from 927 for the 5.2 mm/hr distribution to 154 samples for the 95.6 mm/hr distributions.

Table IV. Rainfall rates (mm/hr) equalled or exceeded for indicated percentages of rain time in various climatic regions.

	0.01%	0.1%	0.5%	1.0%
Arctic	15	8.2	5.8	4.8
Temperate	140	72	37	24
Tropical	218	139	115	98
Desert	130	80	59	40
Temperate-Tropical	189	121	87	69

Figures 14, 15, and 16 show, respectively, similar distributions for

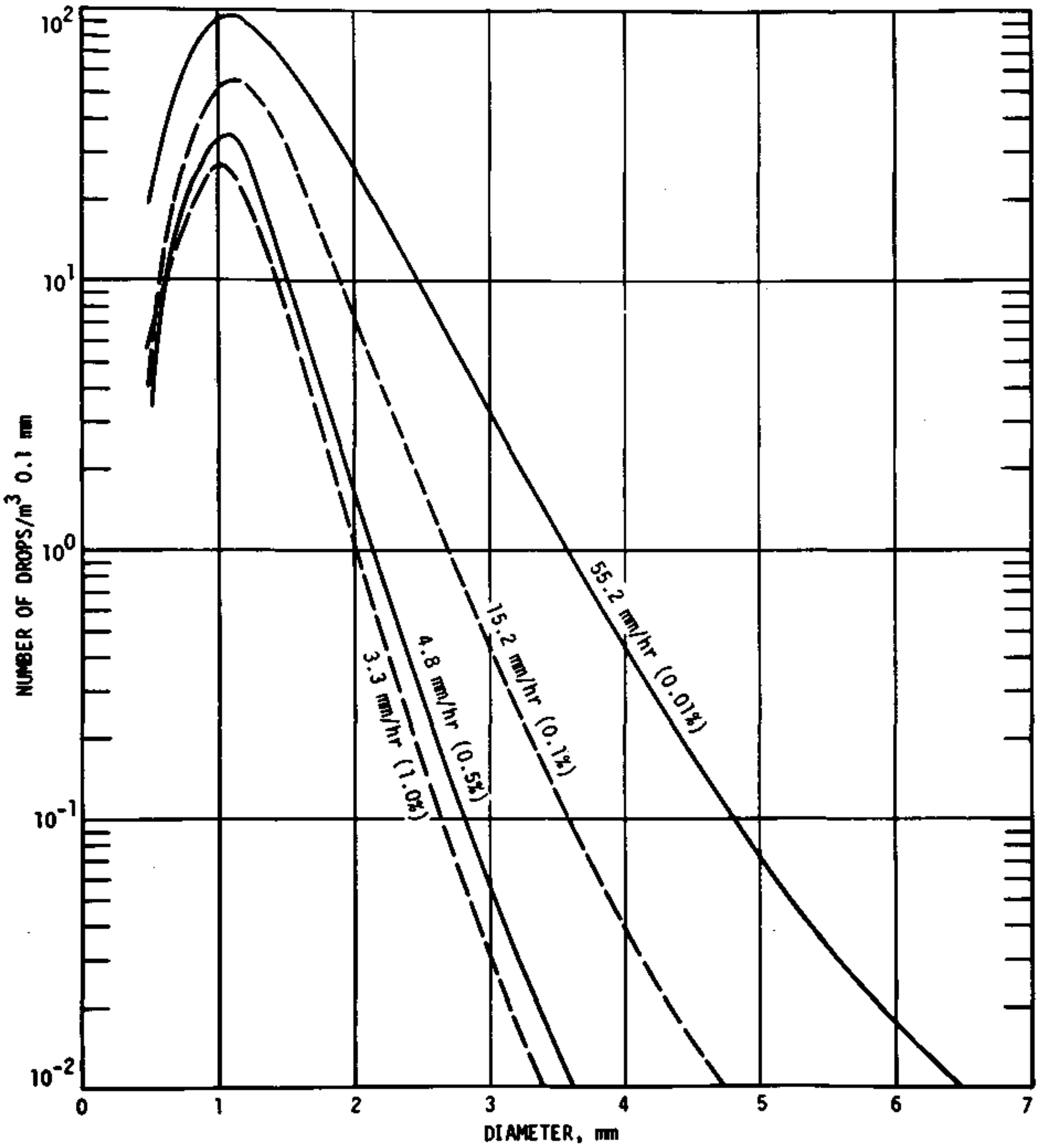

Figure 14. Average drop-size spectra for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0% of the time (These curves are for temperate climates.)

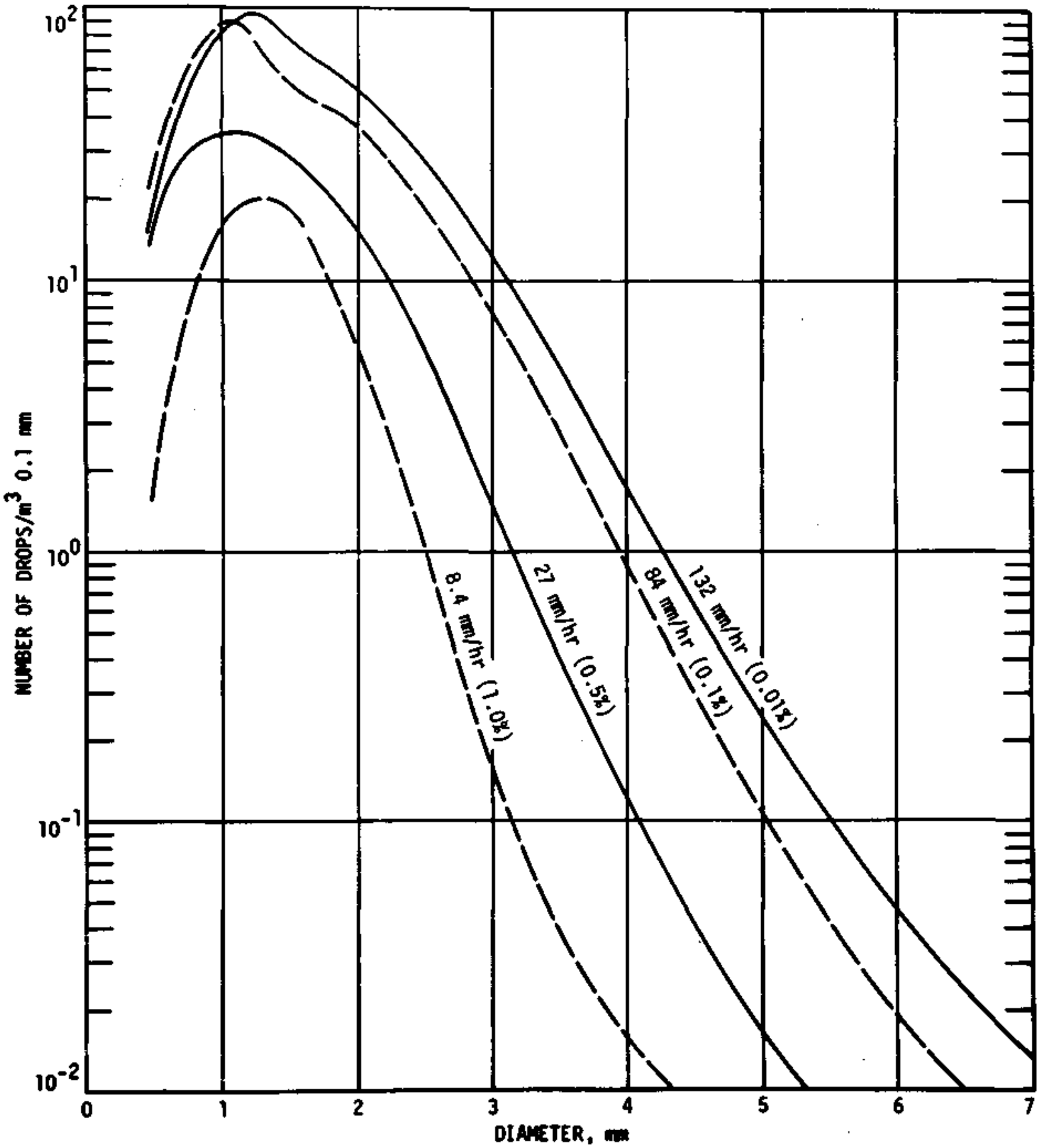

Figure 15. Average drop-size spectra for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0% of the time (These curves are for tropical climates.)

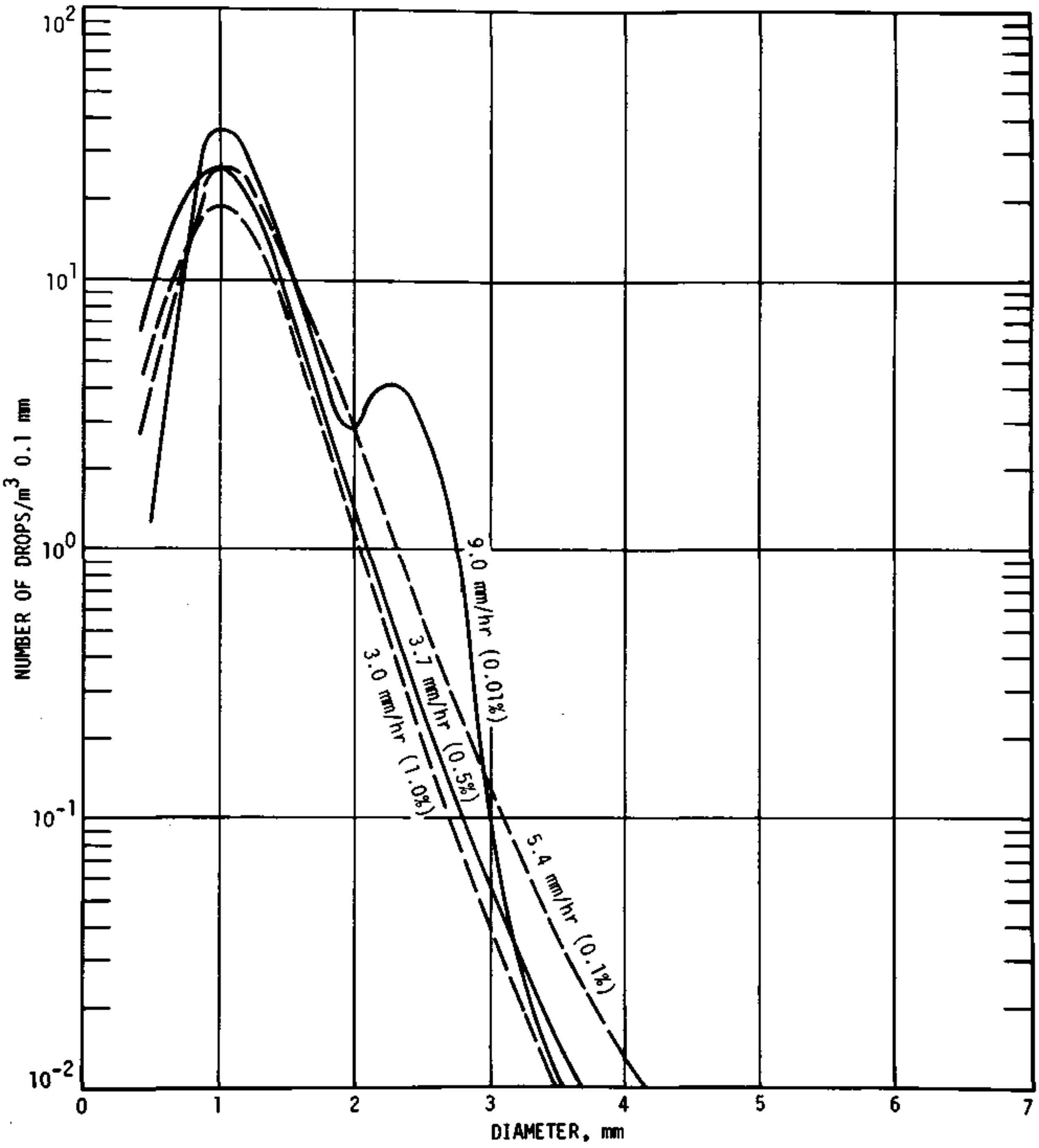

Figure 16. Average drop-size spectra for natural rainfall rates occurring 0.01, 0.1, 0.5, and 1.0% of the time (These curves are for arctic climates.)

"temperate", "tropical", and "arctic" climates. The temperate zone curves are a combination of Illinois, New Jersey, and North Carolina data, the tropical distributions are from Panama and Indonesia data. Only the data from Alaska were used in the arctic curves.

Average Rainfall Rate Along a Line

The point frequencies are useful design statistics for many applications but for some purposes knowledge of the rainfall rate along a path would be more appropriate. Thus, for considerations of the damage to a fuze, erosion on a projectile, or electromagnetic attenuation, the average rainfall rate along the path of travel is of more importance than the value of rainfall rate at just one point. Detailed calculations of this parameter are underway and at this time only preliminary results are available from earlier pilot studies.

A path length of 20 miles is the only path length available at this time and 4 raingages were located on this path. Five-minute rates were used in order to minimize the timing errors between gages. Frequencies were based on 10 storm days having a total of 12.3 hours of rain, all of which was summer rain in Illinois in 1964. Table V shows the frequency of occurrences of the average rainfall rate along the 20 mile path for both rain time and total time.

Table V. Average rainfall rate (mm/hr) along a 20-mile path equalled or exceeded for indicated percentage of rain time and total time.

	0.01%	0.05%	0.1%	1%
Rain time	34.0	31.0	29.4	21.7
Total time	27.8	21.7	18.3	3.0

One interpretation of this table is that, in general, the very high rates do not extend for distances of 10 miles. For instance, the rainfall rate appropriate to the point frequency of 0.01% of rain time is about 150 mm/hr and if this rain rate were in existence for 10 miles and the next 10 miles had no rain, an average rate of 75 mm/hr would result. This is over 2 times the average rate appropriate for the same frequency. It is also evident that the average rate does not change quite so rapidly with frequency until one approaches the 1% of total time frequency. Thus, the storms tend to have an average rate which is more nearly stable than the peak rate. It is very possible (and may even be likely) that this is a result of the small sample that is used in this analysis. It is particularly difficult to determine extreme values (i.e., rate frequency of 0.01%) with small samples.

CONCLUSIONS

The drop-size spectra are well known for both types of artificial rain fields at Holloman Air Force Base. Neither type of simulated rain is completely representative of natural rain drop spectra. Figure 17 shows, on one figure, the two simulated rain drop distributions and the tropical rain distribution corresponding to a rain rate of 132 mm/hr. In general, the artificial rain of the artillery field is some 9 times as intense as the tropical rain of 132 mm/hr. In the smaller drop-sizes there are many more small drops in the simulated rains than in any natural rains. At drop diameters larger than 2.6 mm, the natural distribution lies between the two simulated distributions. In general, similar results are obtained for the higher rainfall rates. Thus it would appear that realistic testing requires a combination of the simulated fields. Some considerations of the necessary assumptions for the validity of the test and a scheme whereby the appropriate combination can be determined follow in the Recommendations of this report.

The frequency of occurrence of various rainfall rates for the four major climatic regions have been obtained. The rainfall rates represented by the 1% frequency of occurrence are surprisingly low. These data have been based

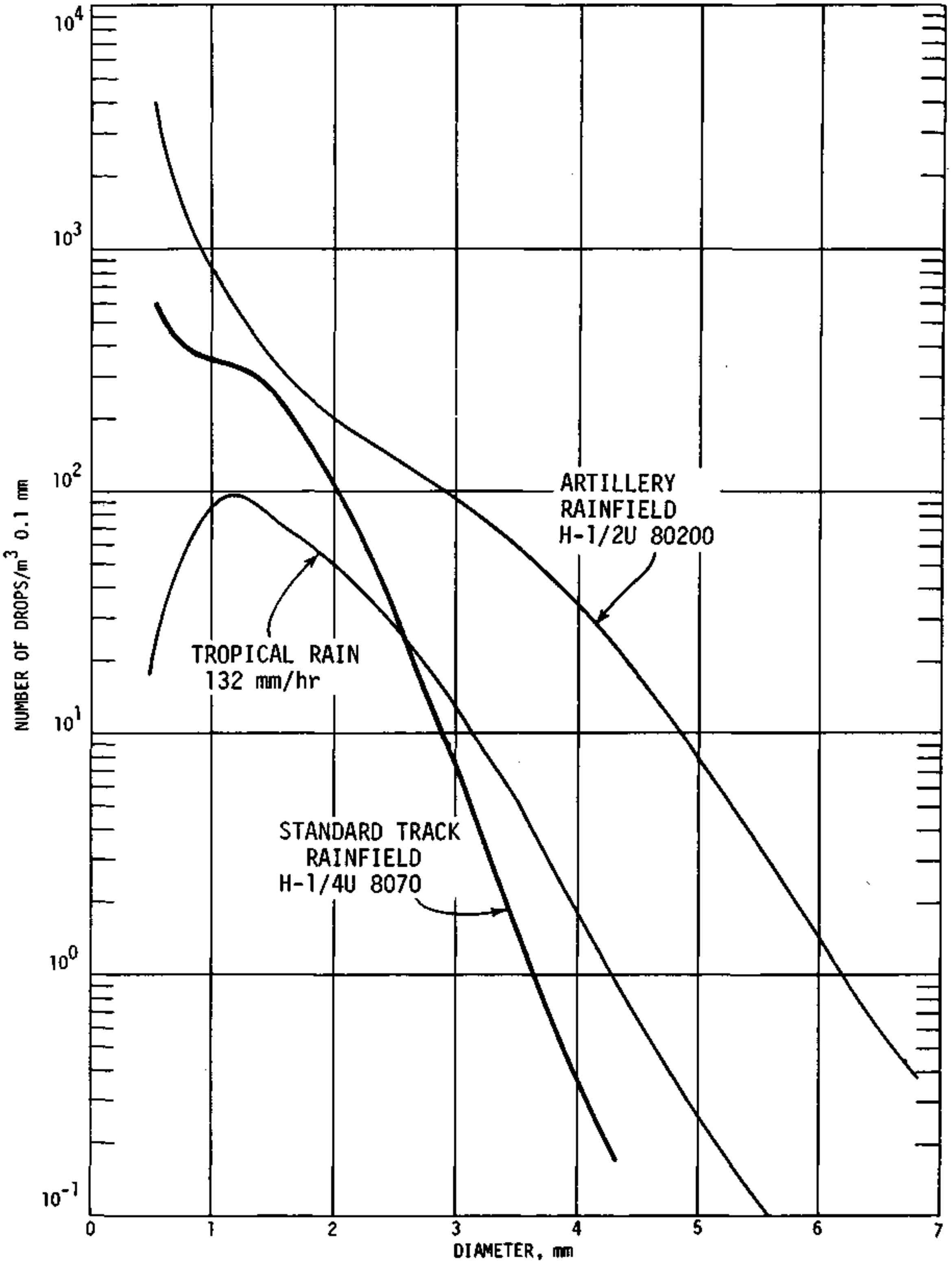

Figure 17. Drop-size spectra for the artillery rainfield, the standard track rainfield, and for the 132 mm/hr tropical rain

in all cases on relatively small samples for climatic work. In general, only a year is available at each location.

Several things can be noticed in these distributions. First, the frequencies of rainfall rates vary, as might be expected, with the various climatic regions. The shape of the distributions are different. The temperate curves have narrower distributions with modes in the 1.0- to 1.5-mm drop-size region, while the tropical distributions are wider. The arctic distributions are all very close together due to the very narrow range of rainfall rates that occur in such climates. Rates greater than 18 mm/hr, or 0.71 inch/hr, occur for only 5 minutes per year. This rate would be exceeded in Panama 0.65% of the time, or 57 hours per year. The arctic drop-size distributions have a bimodal characteristic for all rates greater than 7.5 mm/hr. A slight tendency to bimodal distributions has been noticed at several other locations, such as Panama, but not as distinctly as in the Alaska data.

RECOMMENDATIONS FOR TESTING WITH EXISTING RAIN FIELDS

General Recommendations

Use of the artificial rain fields at Holloman Air Force Base in testing specimens for rain damage can be very useful and can be related in a general manner to the natural rains. One recommendation for imporving the field is better control of nozzle alignment in the horizontal plane. In the region where quick disconnects are used for nozzle interchange, there are no mechanical stops provided and the nozzle is free to rotate around the vertical axis. It is believed that the differences exhibited in Figures 2 through 6 are indicative of the magnitude of errors due to nozzle misalignment. A means of "keying" the disconnects so that rotation is reduced, and the use of a jig for initial alignment of the nozzles would imporve this condition.

Routine calibrations of the rain fields are considered necessary and are recommended. The time interval at which calibrations should be made is not known, but at least a check on the spectra (using the flour pan technique) should be made for each series of tests. More complete spectra measurement should be made occasionally using the automatic spectrometer recently purchased by Holloman Air Force Base from Illinois Institute of Technology Research Institute. The calibration using the spectrometer will easily reveal the condition of the nozzles, as well as operating conditions and alignment accuracy.

It is believed that the optimum condition of water pressure and vertical nozzle angle are now being employed in the field and, thus, varying these parameters will not yield better matches of these spectra to natural spectra. There remains the possibility of using an intermediate nozzle to the H-l/4 U 8070 and the H-l/2 U 80200. These intermediate nozzles would increase the large drop concentration from that of the H-l/4 U 8070, making the large drop densities more nearly appropriate. The small drop size densities would probably remain high. The new nozzle would require determining new vertical angles and pressures in order to place the water in the test area. Figure 11 is an estimate of the drop size spectrum from the 6570 nozzle according to data supplied by Spray Systems Inc. Since sorting takes place between this total output spectrum and the spectrum measured in the field this spectrum can only be considered as a first estimate.

Using the present system a combination of nozzles is recommended as the most practical means of accomplishing simulation of natural rainfall. This procedure is outlined in the following sections.

Conditions Necessary for Realistic Track Testing

It has been shown that drop concentrations along the track from either the standard rain nozzle (H-l/4 U 8070) or the deluge nozzle (H-l/2 U 80200) are much higher than in natural rains. Thus, in order to assess the results of fuze testing on the track to occurrences in nature, some account for the increased concentrations is necessary. To properly and completely account for these differences between natural rains and the track rain fields will require a mathematical model describing the damaging effects of rain. Such a model does not exist; however, some approximations can be made which will allow some reliable inferences to be drawn.

The first assumption is that whatever effect is under investigation, it will be independent of the time between drop collisions. This very important assumption allows "accelerated testing" to be a valid procedure. The assumption requires that two drops produce the same net effect whether the time between their impacts is 1 microsecond or 1 hour. For some materials this assumption is surely incorrect for sufficiently small time periods. Thus, if the material has elasticity, deformation due to one drop may be restored completely after a given length of time. The second drop would then repeat the process and the final effect would be little to no damage if the limit of elasticity were not exceeded. On the other hand, if the second collision had occurred while the material was still distended from the first collision, the limit of elasticity may well be exceeded and damage result. In the absence of any prior information as to the nature of this time-dependence effect, all of the data has been analyzed assuming complete independence of this effect.

The second important consideration in correlating test track simulated rain with natural rain is the manner in which the effect is responsive to the distribution of water into drop sizes. The literature on rain erosion seems to be highly divided as to the effect of size distribution.* Provided one knows how the effect varies with drop diameter, the effect of natural rains could be related to the effects from the simulated rain field along the test track even though the water is distributed in different manners between drop sizes. However, it would appear that only rarely will the damage mechanism be understood sufficiently well that a correction for the artificial rain spectra can be made. Thus , a duplication of the shape of the natural rain spectra to the shape of the artificial rain spectra is desirable and, as far as the effects of the drop size are concerned, it is desirable to maintain the same relative number of large, medium, and small drops.

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* Rain Erosion and Associated Phenomena
U. S. Department of Commerce N68-19401-427 , 1967

Accelerated Testing

Accelerated testing is defined here to mean the possibility of relating the damage due to a relatively short distance in an artificial field to a longer travel through natural rain. Since testing on the track is expensive, the ability to perform accelerated testing certainly appears attractive, and under most adverse conditions would appear to provide an "overtesting" condition. In other words, it would seem that there are no instances where a short time between impacts would produce less damage than the same two impacts a longer time apart.

If it is assumed that the total effect is independent of the time between impacts, the artificial rain field may be compared with natural rain field by means of a concept of test ratios. The test ratio is defined as the ratio of the distance in natural rain to the distance in the artificial rain such that a test item would experience the same number of impacts under both conditions. If the manner in which the water is distributed into drop sizes is the same in both cases, a unique test ratio results. Conversely, if the drop spectra are different, then the test ratio can be defined as the ratio of distances such that the number of encounters with drops larger than a particular diameter are the same. If a prior knowledge as to the damaging size of water droplets is available, these partial test ratios are applicable directly.

Tables VI and VII are the calculated test ratios for both rain nozzles of the artificial fields as compared to the natural rain, based on a frequency of occurrences of 0.01, 0.1, and 0.5 percent of the total time. The fact that there is no column in which the test ratio remains constant is an indication of the lack of correspondence between the spectra in nature and that in the artificial field.

Combining Artificial Spectra

Again, assuming complete independence of damage effect with time between impacts, conbinations of nozzles can be used to provide a better (i.e., closer to the natural spectrum) testing environment. As was indicated previously, if the partial test ratio remains fixed as the drop diameter changes, the spectrum

Table VI. Test ratios for the deluge nozzle (H-1/2 U 80200) as compared to various values of natural rain*

	All Data (world-wide)			Temperate Zone Data			Tropical Zone Data		
Frequency of Occurrence (%)	0.01	0.1	0.5	0.01	0.1	0.5	0.01	0.1	0.5
Rainfall Rate (mm/hr)	96	46	13	55	15	5	132	84	27
Drop Diameters (mm)									
6.0	45	--	--	60	--	--	24	60	--
5.5	42	127	--	63	--	--	20	51	--
5.0	42	126	--	68	--	--	21	49	338
4.5	36	119	--	72	--	--	20	42	306
4.0	28	98	1228	68	716	--	16	30	231
3.5	19	71	678	50	471	--	11	20	145
3.0	13	40	319	32	263	2257	8	13	76
2.5	7.9	22	125	18	124	803	5.7	9.1	36
2.0	5.3	11	39	11	48	232	4.5	6.5	20
1.5	4.5	7.6	17	6.8	18	54	3.9	5.7	14
1.0	4.4	7.9	15	6.1	13	24	4.3	5.5	14
0.5	8.0	16	31	12	26	49	8.8	11	26

* Note: This table computed on the basis of number of impacts with drops larger than the diameter indicated.

of the artifical rain is equivalent to the one of natural rain. Since the standard nozzle does not provide any drops above 4.5 mm, the easiest manner to effect a mix of drop sizes is to choose one portion of the deluge nozzle distribution and determine the average test ratio for diameters larger than 4.5 mm. After choosing this average, the number of standard nozzles required to produce an equivalent test ratio for 1.0 to 2.0 mm drops is determined. Thus, for example, suppose it is desired to test an object under conditions corresponding to the tropical data at 0.01% frequency. For diameters above 4.5 mm, the test ratios for the deluge nozzle given in Table VI are 21, 20,

Table VII. Test ratios for the standard nozzle (H-l/4 U 8070) as compared to various values of natural rain*

	All Data (world-wide)			Temperate Zone Data			Tropical Zone Data		
Rrequency of Occurrence (%)	0.01	0.1	0.5	0.01	0.1	0.5	0.01	0.1	0.5
Rainfall Rate (mm/hr)	96	46	13	55	15	5	132	84	27
Drop Diameters (mm)									
4.5	0.2	0.7	--	0.4	--	--	0.1	0.3	2
4.0	0.3	1.2	15	0.8	8.6	--	0.2	0.4	2.8
3.5	0.5	1.7	16	1.2	11	--	0.3	0.5	3.5
3.0	0.7	2.3	19	1.9	16	135	0.5	0.8	4.5
2.5	1.1	3.2	18	2.6	18	116	0.8	1.3	5.3
2.0	1.8	3.5	13	3.5	16	77	1.5	2.2	6.5
1.5	2.6	4.3	9.5	3.8	10	31	2.2	3.2	7.7
1.0	2.8	4.9	9.3	3.8	8.0	15	2.7	3.4	8.4
0.5	3.1	6.2	12	4.8	10	19	3.5	4.3	10

* Note: This table computed on the basis of number of impacts with drops larger than the diameter indicated.

24, and a choice of 22 is made. At 1.0 mm diameter the test ratio of the deluge nozzle is 4.3 so that 22 - 4.3, or 17.7, is required from the standard nozzles. This can be obtained by using standard nozzles in the ratio of 17.7:2.7 or 6.5, since the test ratio of standard nozzles to tropical 0.01% frequency is 2.7 from Table VII. The track would be arranged so that for every 2 deluge nozzles there were 13 standard nozzles. The average test ratio of the combined field is found by dividing the design constant, 22, by the number of nozzles required to produce it. In the example there are 6.5 standard nozzles and 1 deluge nozzle, thus the average test ratio would be 22/7.5 or about 2.9. If a total of 1000 ft of this rain field were utilized, the test item would hit about the same number of drops as it would in the natural rain in a distance of 2900 feet.

Table VIII. Expected number of encounters per square centimeter of area in natural and artificial rain

Drop Diameter (mm)	Deluge Nozzle in 46 m	Standard Nozzle in 300 m	13:2 Combined Artificial Field in 346 m	Natural Tropical Rain of 132 mm/hr in 1 Km	Percent Error in Number of Raindrops in the "Combined" Artificial Rain Relative to a Natural Tropical Rain
0.5	18	18	36	2.0	+1700
1.0	4.4	9.9	14.3	9.5	+47
1.5	1.4	7.3	9.1	8.0	+14
2.0	1.1	3.1	4.2	5.0	-16
2.5	0.62	.9	1.52	2.7	-43
3.0	0.44	.2	0.64	1.3	-50
3.5	0.28	.04	0.32	0.5	-36
4.0	0.14	.01	0.15	0.2	-25
4.5	.064	--	.064	.06	+7
5.0	.035	--	.035	.02	+75
5.5	.013	--	.013	.01	+30
6.0	.004	--	.004	.01	-60

The actual values of the expected number of the expected number of drops encountered in the two fields, as combined in a 13:2 proportion, as well as each nozzle individually, is shown in Table VIII. The last column indicates the percentage differences between the expected number of collisions in natural (tropical) and in the combined artificial rain. The percentages are admittedly-high in some areas (the very small drops and the very large drops), but overall it would appear realistic testing (± 50%) could be obtained for drop sizes between 1.0 and 4.5 mm. In practice it would be necessary to group all of the deluge nozzles in one or more 400-foot sections of rain track since the water pressure is different for the different nozzles. This grouping then requires a further assumption with respect to the damage mechanism. It must be assumed that the order of impacts of drops has no effect on damage produced and, under some circumstances, this is probably not true. For instance, it is believed that the M564 fuze was suffering deterioration due to multiple impacts of raindrops and that a final drop produced the detonation of the fuze. It is possible that the fuze might well sustain one or more impacts with large drops when no erosion damage had previously occurred. However, after some erosion there is no doubt that one big drop impact will produce fuze functioning and, thus, failure.

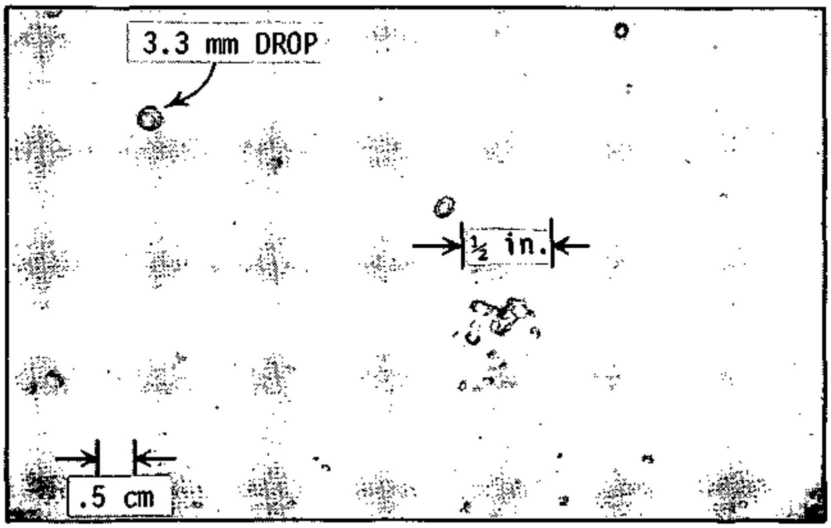
It may be possible to intermix nozzles within one manifold section by placing constrictions in the risers which are feeding the deluge nozzles. This would reduce the effects of all the large drops being located in one area of the track and, in effect, produces a more homogeneous mix of concentration of drops and liquid water content. Further this allows the test specimen to experience the same mix at all the velocities of the sled. Since generally the sled is slowing down while traversing the rain field and since the damage is related to the velocity, it is desirable to have the same spectra throughout the velocity profile.

Appendix

One phenomena which was seen on rare occasions is not duplicated in nature. An example of a mass of water is shown in Figure A-1. This illustrates the phenomenon of occasionally obtaining large ill-defined masses of water. These large masses are completely unstable and must have relatively short lifetimes but are still sufficiently long to be seen occasionally with the drop camera. It may be that these occur as a result of either a flaw in the nozzle or, perhaps, a partially clogged nozzle. They were not evident during data collection and were only noted much after data had been collected. Therefore it was not possible to examine the nozzles for damage.

These large masses of water occur quite infrequently and therefore would not contribute to general erosion effects. It is possible, on the other hand, to have single impact with such a mass which may do considerable damage.

An estimate of the density of these masses can be obtained by dividing the number of occurrences (22) by the total volume measured (about 400 m^3) which yields a density of about one ill-defined mass in 18 cubic meters. A fuze such as the M564 would have to tranverse 100 Km of this rain field before the probaility of one encounter becomes as great as 0.5.



App 1. Illustration of drop photographs showing ill-defined mass of water

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13. ABSTRACT

Drop-size measurements of the simulated rain fields at Holloman Air Force Base are reported. These measurements are compared with drop-size spectra from natural rains in various climatic regions. Average drop-size spectra for tropical, temperate, and arctic climatic regions are presented for rainfall rates of 1, 0.5, 0.1, 0.01 percent of total time. In general, there are too many drops in the simulated fields in comparison to natural rains. Particularly apparent are the large numbers of small drops in the range less than 1.0 mm. Even under accelerated test criteria the small drops occur too frequently. In general the simulated field using the H-1/2 U 80200 nozzle (artillery field nozzle) represents a drop density of about 9 times as heavy as natural tropical rain of 132 mm/hr. At drop diameters larger than 2.6 mm, the natural distribution lies between the two simulated distributions. It would appear that realistic testing requires a combination of the simulated rain fields.

Recommendations are made for utilizing the simulated fields in such a way as to make them more nearly simulate natural rains.

DD FORM 1 NOV 65 **1473** REPLACES DD FORM 1473, 1 JAN 64, WHICH IS OBSOLETE FOR ARMY USE.

Security Classification

14. KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Rain Erosion						
Holloman Rain Test Facilities						
Rainfall Rate Frequencies						
Raindrop Spectra						
Rainfall Simulation						
Munitions Effectiveness in Rain						